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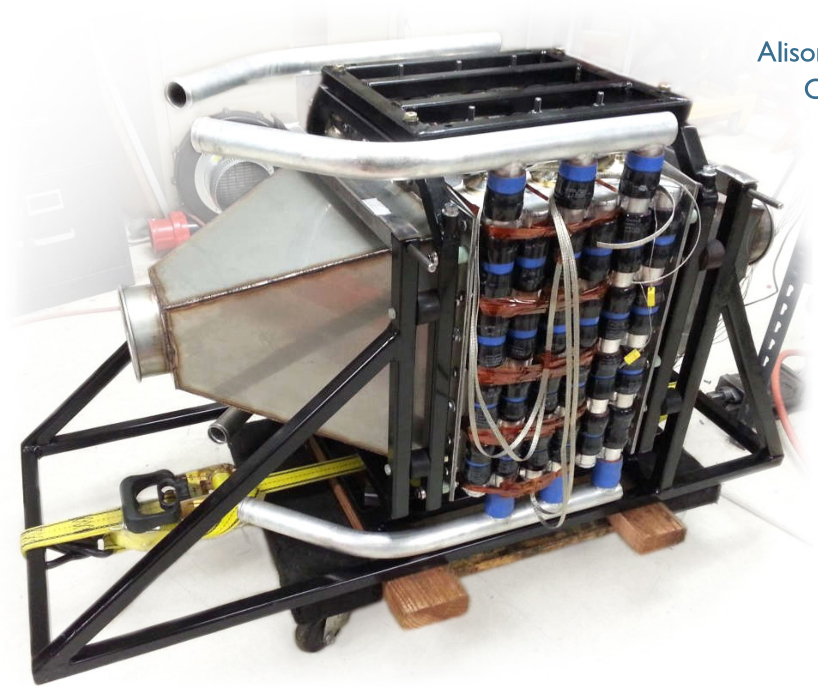
FTA Bus Efficiency Enhancements Research and Demonstration: Thermoelectric Generation Demonstration at LYNX

SEPTEMBER 2019

FTA Report No. 0142
Federal Transit Administration

PREPARED BY

Alison Smyth and Erik Bigelow
Center for Transportation
and the Environment



U.S. Department of Transportation
Federal Transit Administration

COVER PHOTO

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Metric Conversion Table

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liter	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: volumes greater than 1000 L shall be shown in m^3				
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
TEMPERATURE (exact degrees)				
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C

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13. ABSTRACT
This document is the final report to the Federal Transit Administration (FTA) covering the project performance and results for the development, build, and demonstration of a thermoelectric generator for use on a diesel bus. The thermoelectric generator was built by Hi-Z, Inc., and installed on a 2007 GILLIG diesel bus owned and operated by the Central Florida Regional Transportation Authority, dba LYNX. The report contains an overview and includes a summary of work completed, involved partners, difficulties encountered, data results, lessons learned, advancements made, and recommendations for future research. This document will also serve as a source of information to be used by organizations in the industry for future projects. This is the final report for the thermoelectric generator demonstration project; all work reported is complete and final.

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ABSTRACT

This document is the final report to the Federal Transit Administration (FTA) covering the project performance and results for the development, build, and demonstration of a thermoelectric generator for use on a diesel bus. The thermoelectric generator was built by Hi-Z, Inc., and installed on a 2007 GILLIG diesel bus owned and operated by the Central Florida Regional Transportation Authority, dba LYNX. The report contains an overview and includes a summary of work completed, involved partners, difficulties encountered, data results, lessons learned, advancements made, and recommendations for future research. This document will also serve as a source of information to be used by organizations in the industry for future projects. This is the final report for the thermoelectric generator demonstration project; all work reported is complete and final.

EXECUTIVE SUMMARY

The Center for Transportation and the Environment (CTE) managed the design, build, testing, and demonstration of a thermoelectric generator, which was demonstrated in Orlando, Florida, by LYNX Transit. The Federal Transit Administration (FTA) has sponsored this project as part of the Bus Efficiency Enhancements and Demonstration program.

The original project goal was to design and build a thermoelectric generator (TEG) and then install the generator on a diesel bus to measure fuel economy improvements to the generator. Due to various project challenges, the original scope had to be modified. The generator was installed and demonstrated, but not connected to the bus electrical system. The team was able to estimate projected fuel economy improvements due to the generator following one month of operation.

The project consisted of multiple phases—data gathering, design, build, initial testing, installation, final testing, demonstration, data analysis, and commercialization plan development. During the data gathering phase, the team identified and quantified the characteristics of the bus that would feed into the design of the TEG and its mounting system. This included exhaust flow rates, exhaust temperatures, bus dimensions, and relevant CAN signals. The team learned that different buses in the LYNX fleet had different engine and exhaust treatment systems which significantly impacted the exhaust temperature. With this information, a specific bus, Bus 811, was identified for this project.

Once the team finalized the design parameters, Hi-Z began design of the TEG and FSEC began design of the data acquisition system. With this information, Hi-Z decided to proceed with a three-stage design to maximize power output without inserting too much back-pressure into the exhaust system. The team also identified the presence of regeneration events, a key process of the diesel particulate filter system, which resulted in extremely high exhaust temperatures. These elevated temperatures had the potential to damage the TEG, so Hi-Z designed a dump valve system to divert the exhaust away from the TEG during these regeneration events.

FSEC worked closely with Hi-Z to identify the relevant data collection channels and procure a logger that could record the data and communicate it in near real-time. To communicate the data in real-time, the team needed to install a cellular hot spot on the bus so that the data logger would have access to Wi-Fi.

Once the design was finalized, Hi-Z procured parts and began building the TEG. Before assembling the full generator, Hi-Z conducted testing on a single stage of the heat exchanger. The test results fell within the predicted ranges.

However, upon disassembly of the system, Hi-Z discovered a structural failure of the heat exchanger. Stress analyses were conducted to evaluate the failure mode and implemented changes to the heat exchanger design. Additionally, there was a complication with the heat exchange design discovered during the manufacturing process. The design required very thin fins, which were difficult to manufacture, and there was a concern about their durability. To deal with this, Hi-Z and the manufacturer modified the design to have thicker fins, offset such that that fins on the top and bottom halves of the heat exchangers would overlap slightly and the distance between the top and bottom halves would be the same as originally designed.

FSEC built the data logger, including an external case, and shipped it to Hi-Z for testing. This testing was successful.

Hi-Z conducted laboratory tests with the TEG after build and prior to shipment to LYNX. To conduct these tests, Hi-Z obtained a waste oil burner and built a testing apparatus that would simulate the exhaust of a diesel bus. During this testing, the TEG generated approximately 1,000 watts of power.

After completion of the testing, Hi-Z shipped the TEG to Orlando, FL. Hi-Z led the installation process, with assistance from ITB and LYNX. It took approximately one week to mount the TEG onto the bus, test the dump valve, install the data acquisition system, and manufacture and install covers for the equipment.

Once this was completed, LYNX drove the bus to the Kennedy Space Center (KSC) for testing on private roads at KSC, testing performance at highway speeds, simulating transit service, and evaluating the impact of the HVAC system on TEG performance. During this testing, the dump valve worked as expected, and the TEG generated over 1100 Watts of power.

Having deemed this successful, LYNX put the bus into revenue service. The bus operated on the same block throughout most of the demonstration, and there were no reported differences in driver or passenger experience.

Approximately one month into the demonstration, Hi-Z noticed a significant decrease in power output. Upon investigation by ITB and Hi-Z, the team determined that a tree branch had damaged the valve connecting the cooling system to the TEG, resulting in an overheating event.

The TEG was decommissioned and the bus returned to its original state.

FSEC performed an analysis of the data from the demonstration, predicting what the fuel economy improvements and fuel cost savings from installing a TEG on a transit bus might be. There are a number of variables that influence these findings, including time in service, route characteristics, ambient temperature, and vehicle configuration. For this application, FSEC determined that the operator could save about 180 gallons of diesel per year per bus, which, at $3.20

per gallon of diesel, would be approximately $600 dollars per year. Based on the commercialization plan, this means that a TEG would have an eight-year payback.

The next step in moving the TEG to commercialization is to conduct another demonstration, this time connecting the generator to a bus electrical system to obtain better data regarding the fuel economy savings as a result of the TEG.

SECTION 1

Introduction

The Center for Transportation and the Environment (CTE) led a team in the development of a thermoelectric generator (TEG) for demonstration as a part of the Federal Transit Administration's (FTA) Bus Efficiency Enhancements and Demonstration (BEERD) program. CTE managed the overall project; Hi-Z Technology Inc (Hi-Z) designed, built, and installed the thermoelectric generator; International Trade Bridge (ITB) provided on-site support and coordinated efforts to test the bus on private roads at the Kennedy Space Center (KSC) in Florida; the University of Central Florida's Florida Solar Energy Center (FSEC) built a data acquisition system and performed an analysis of all data gathered during the demonstration; Energy Florida developed a commercialization plan for the technology; and the Central Florida Regional Transportation Authority dba LYNX provided the bus, maintenance facility, and support and operated the bus during the one-month demonstration. This report summarizes the entire project, including the development of the generator and its demonstration in Orlando.

The final outcomes of the project were slightly different than originally proposed. The project expected to use a cash cost-share source, which was not available when the grant started. CTE worked with the project team to identify new sources of cost share and slightly re-scope the project to address the smaller total budget.

Additionally, the bus originally proposed for this project was scheduled to be decommissioned at the end of the project. During the course of the project, LYNX expanded its service, necessitating retaining the bus in service after the demonstration period. To minimize any potential risk to the bus, the project team decided not to connect the TEG to the bus electrical system during the demonstration. The team operated the bus in revenue service with the TEG installed and measured the energy produced and consumed by the TEG to estimate fuel economy savings from integration of the TEG into the bus system.

Bus Efficiency Enhancements and Demonstration

FTA's Bus Efficiency Enhancements Research and Demonstration (BEERD) program was developed to promote the development and demonstration of energy efficiency-enhancing technologies for buses used in public transportation.

The Center for Transportation and the Environment

CTE specializes in facilitating the rapid development, commercialization, public understanding, and acceptance of advanced transportation technologies and alternative fuels to implement solutions to achieve energy and environmental sustainability. CTE has worked with various organizations to develop and demonstrate economically-feasible sustainable transportation technologies and was a prime recipient of three FTA BEERD projects. This report covers the work performed under FTA award BEERD Thermoelectric Generation Demonstration at LYNX Transit (GA-26-7212).

Project Partners

In addition to CTE serving as project manager, several organizations comprised the overall team to develop this project:

Hi-Z Technology, Inc. – Hi-Z developed, built, and installed the thermoelectric generator for this project. Hi-Z is a small business focused on manufacturing commercial bismuth telluride modules and performing research and development in the field of advanced material/module and thermoelectric systems (waste heat recovery, generators, self-powered appliances) development. It holds intellectual property for gapless eggcrate thermoelectric module fabrication and for waste heat recovery systems and various thermoelectric generators.

International Trade Bridge, Inc. – ITB provided on-site support during the TEG installation, testing, and demonstration. It also worked with the KSC to allow the team to test the vehicle with the TEG installed on the Space Center's private roads. ITB is a small business that provides engineering and technical support services to number of different clients.

University of Central Florida's Florida Solar Energy Center (UCF-FSEC) – UCF-FSEC developed and built a data acquisition system integrated with the TEG and the bus controller area network (CAN) system. It collected data throughout the demonstration and provided an independent third-party analysis of the data to estimate the fuel savings resulting from the TEG operation. FSEC's mission is to research and develop energy technologies that enhance Florida's and the nation's economy and environment and to educate the public, students, and practitioners on the results of the research.

Energy Florida – Energy Florida developed a commercialization plan for the thermoelectric generator. Energy Florida is a non-profit organization that develops technology demonstration capabilities to support economic development across the southeastern US, Latin America, and the Caribbean.

Central Florida Regional Transportation Authority dba LYNX – LYNX provided the bus for the project and operated it in revenue service with the thermoelectric generator installed. LYNX is the regional transportation authority providing and coordinating transportation mass transit services within the three Florida counties of Orange, Osceola and Seminole.

Thermoelectric Generator Technology

Thermoelectric generator technology, first developed for spacecraft, has been used for a number of different applications, including automotive, military vehicle, and diesel truck usage. This project aimed to explore the extension of the application of thermoelectric technology to diesel transit buses.

Thermoelectric generation depends on a temperature differential across a material surface. The difference in temperature between the "hot side" and "cold side" of the thermoelectric materials generates an electric current that can be applied to an electrical circuit.

In this project, the goal was to use the bus exhaust heat to warm the "hot side" and a coolant to keep the "cold side" colder. The resulting electric current could then be used to take load off the vehicle alternator, improving vehicle fuel economy.

SECTION

2

Design and Development of Thermoelectric System

This project applied Hi-Z's existing thermoelectric technology to a transit application for the first time. As such, multiple measurements of the bus needed to be taken, including physical dimensions and exhaust temperatures and flow rates.

Bus Specifications

LYNX decided to use a 2007 GILLIG 40' ft transit bus with a Cummins 8.9L ISL diesel engine with a diesel particulate filter (DFP) for the project. To design the thermoelectric generator (TEG), Hi-Z needed to know the exhaust mass flow and temperature for this vehicle. These data turned out to be difficult to obtain.

The team initiated an investigation regarding what data could be obtained from the CAN data link port that could provide necessary inputs to the design and how datalogger hardware and software could support this need. Cummins provided extensive documentation of what their engine system CAN port could provide as data messages. The team learned that some of the data messages were only available to Cummins personnel using its proprietary Cummins Engineering Tools Datalogger (ETD). The Cummins engineer responsible for GILLIG support stated that some of the mass flow data could be derived only with direct Cummins support. The team attempted to obtain, but never received, this support from Cummins.

GILLIG suggested a data logger and software system for use during the TEG demonstration. The team procured this logger and was able to configure it to for initial design data capture.

In addition to understanding the exhaust flow, the team needed to determine where and how to mount the TEG to the bus. On-site examination of one of the buses revealed that a very congested space at which the post-diesel particulate filter exhaust pipe is routed may not be practical as a TEG installation site. Roof mounting was considered the most practical location for TEG mounting, which would involve connecting the TEG in place of the diffuser (Figure 2-1).

Discussions with GILLIG resulted in a better understanding of the roof construction. The fiberglass roof skin was fastened to metal support structures, including one large support at the rear of the roof that could be drilled into for attachment of the TEG system base plate.

On November 3, 2016, ITB and FSEC visited LYNX to measure the bus exterior (Figure 2-2).

Figure 2-1

Components of diesel bus exhaust system

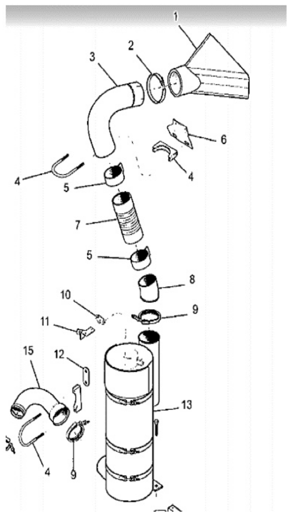
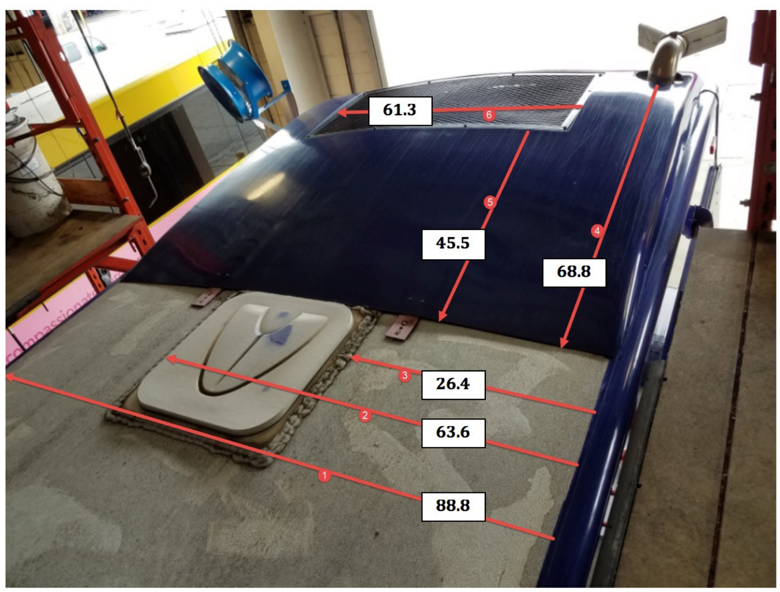


Figure 2-2

Bus 814 measurements—bus height 125", 15" of clearance in garage



On November 28, 2016, FSEC returned to LYNX with a data logger to connect to a bus. On this visit, Bus 804 was available, and the data logger was connected to it. After comparing the channels available on Bus 804 with the desired list from Hi-Z, it was found that many of the temperature channels were not available on Bus 804. The reason that Bus 804 did not support all the required channels was that it had a "black" engine (so named because the engine block is actually black). These engines do not have a regeneration system and do not support data collection for all the relevant channels. Additionally, buses with black engines operate at lower temperatures and would not be ideal for Hi-Z's TEG design.

Unfortunately, Bus 814 was out on a route, and it was not available for data collection. After discussions with LYNX personnel, it was presumed that Bus 814 had a "red" engine, one that contained a regeneration system and operated at a higher temperature, but this could not be confirmed. Bus 717 was available that had an engine similar to Bus 814, and it was agreed to connect the data logger to that bus.

A configuration file was created for the data logger to collect data from the available channels at a rate of 1 sample per second. The logger was initially plugged into the back of the bus, within the engine compartment. Due to concerns about heat causing damage to the logger, FSEC installed the logger in the front of the bus in a compartment above the driver.

The day after the data logger was installed, LYNX operated Bus 717 on a typical route, after which the logger was removed from the bus. This was a different bus than that ultimately used for the demonstration (Bus 811). However, Bus 811 also had a red engine, and these data were considered sufficient for design purposes.

While analyzing the data, FSEC observed that not all the channels provided "good" data (data that varied in an expected manner). For example, the "Engine Speed" channel contained data that varied up and down between 700 and 2100 rpm, which was consistent with the vehicle speed data ranging from stop (idle) to 100 km/h. Although the accuracy of the data could not be confirmed, at least several channels displayed appropriate variation in values, and these were considered "good." Examples of "good" channels are shown in Figures 2-3 through 2-5.

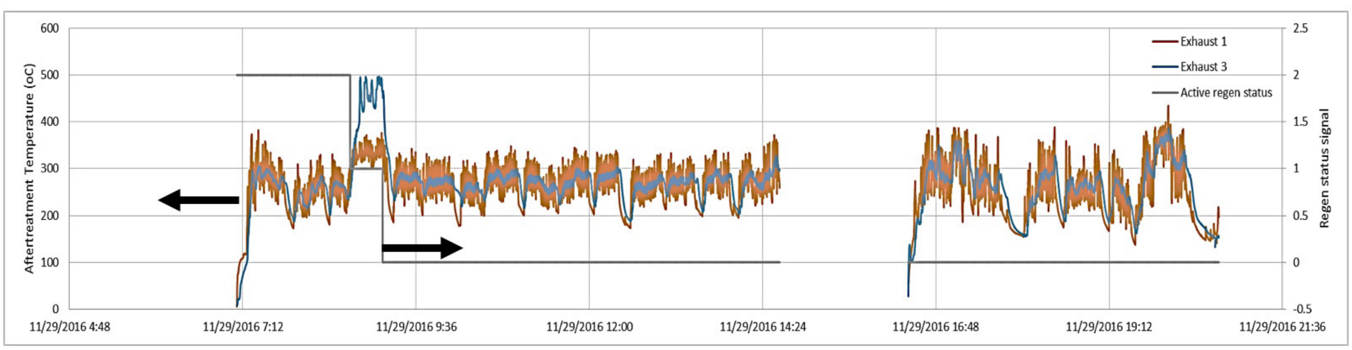


Figure 2-3

After-treatment exhaust temperatures (blue and orange) and active regen signal (gray)

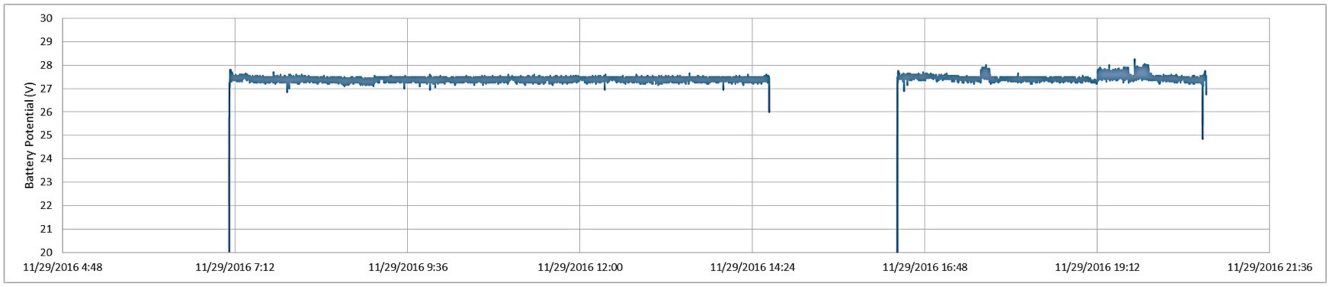


Figure 2-4

Battery potential

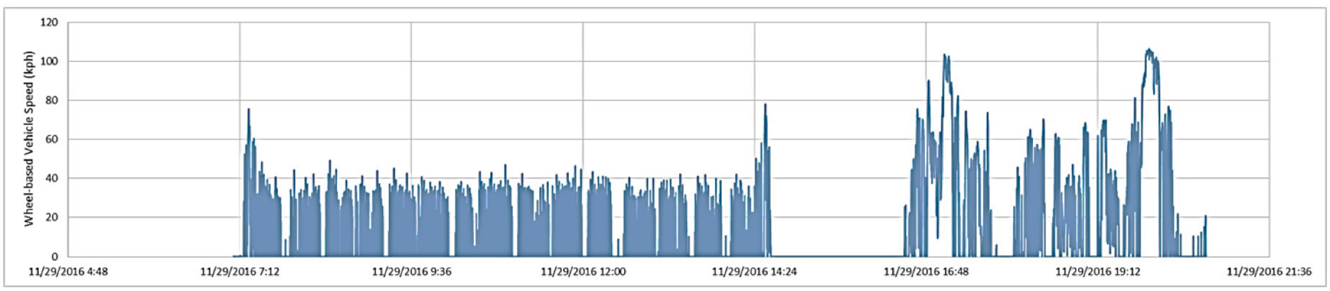


Figure 2-5

Wheel based vehicle speed (km/h)

Some channels could clearly be distinguished as "bad," meaning the data collected from them was clearly erroneous. An example of this was the "Hour" channel, which contained no data, except for the occasional "6" value. Some temperature channels were also easily identified as "bad," as the temperature value (1774.97˚C) never changed and was clearly in excess of any reasonable value. It is possible that these channels either lacked the sensor or the sensor was damaged. None of these channels was considered critical to TEG operation or evaluation, and they were not investigated further.

Other channels could not be identified as "good" or "bad" because the range of reasonable values was not known and the bus may not have been operated for a sufficiently long period to cause a change in the values. These channels were labeled as "unknown" and needed to be clarified with HEM Data, the logger provider. Table 2-1 summarizes all channels according to observations after the single-day test.

Table 2-1

Channel Status, Based on Data Collected from Single Day of Operation

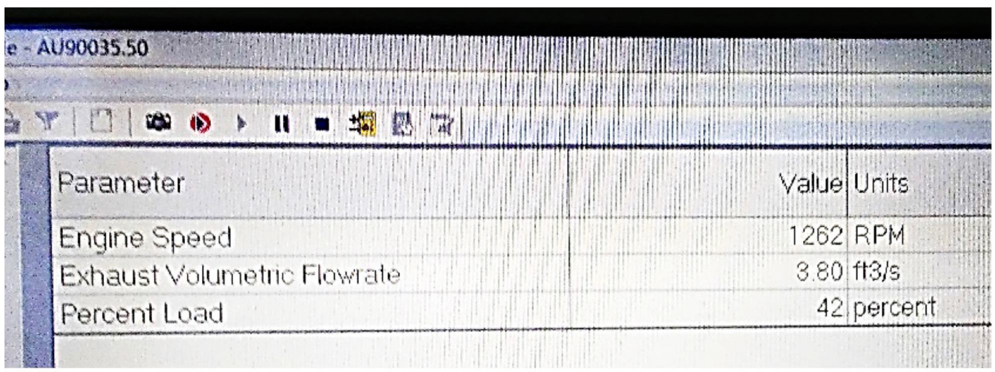
Channel Name	Status
Engine Percent Load At Current Speed	Good
Actual Engine – Percent Torque	Good
Engine Speed	Good
After-treatment Diesel Particulate Filter Active Regeneration Status	Good
Exhaust System High Temperature Lamp Command	Good
After-treatment 1 Exhaust Temperature 3	Good
After-treatment 1 Exhaust Temperature 1	Good
Engine Fan 1 Estimated Percent Speed	Good
Engine Coolant Temperature	Good
Engine Oil Temperature 1	Good
Wheel-Based Vehicle Speed	Good
Battery Potential / Power Input 1	Good
Transmission Output Shaft Speed	No data
After-treatment 1 Diesel Particulate Filter Outlet Temperature	Constant at 1774.97°C
After-treatment 1 Diesel Particulate Filter Intake Temperature	Constant at 1774.97°C
After-treatment 1 Exhaust Gas Mass Flow Rate	Constant at 13107
Seconds	Mostly null, occasional "15"
Minutes	Mostly null, occasional "28"
Hours	Mostly null, occasional "6"
Month	Mostly null, occasional "3"
Day	Mostly null, occasional "12"
Year	Mostly null, occasional "2121"
Engine Fuel Temperature 1	Constant at 215°C
Engine Turbocharger Oil Temperature	Constant at 1774.97°C
Engine Intercooler Temperature	Constant at 215°C
Engine Charge Air Cooler Thermostat Opening	Constant at 102%
Ambient Air Temperature	Constant at 1774.97°C
Engine Exhaust Temperature	Constant at 1774.97°C
SLI Battery 1 Net Current	Constant at 130 A
Alternator Current	Constant at 255 A
Road Speed Limit Status	Unk
After-treatment Diesel Particulate Filter Passive Regeneration Status	Unk
After-treatment Diesel Particulate Filter Status	Unk
After-treatment 1 Exhaust Temperature 3 Preliminary FMI	Unk
After-treatment 1 Diesel Particulate Filter Outlet Exhaust Temperature Preliminary FMI	Unk
After-treatment 1 Exhaust Temperature 1 Preliminary FMI	Unk
After-treatment 1 Diesel Particulate Filter Intake Temperature Preliminary FMI	Unk
Fan Speed	Unk

Several attempts were made between November 2016 and March 2017 to configure the HEM Data logger to request the proprietary exhaust flow rate data stream, but none were successful. Some consideration was given to trying to derive the exhaust gas flow rates using models, but this was determined to be equally difficult, given that some vital information (e.g., turbocharger speed) was also proprietary. Given the timeframe of the project, the team decided that it needed to proceed without the data logger recording exhaust flow rate data.

As an alternate approach, LYNX permitted the recording of the laptop screen that displayed the engine load (in percent), the engine speed (in rpm), and the exhaust flow rate (in ft^3/s). An example of the screen is shown in Figure 2-6. The bus was then operated for about 40 minutes.

Figure 2-6

Image of laptop screen displaying parameters of interest



FSEC collected the data from these images into a spreadsheet to create an empirical map of exhaust flow against engine load and engine speed. Although data were collected in 1 rpm and 1% increments, the table was created in 100 rpm and 5% increments, and data within these steps were averaged. Any gaps in the data were eliminated through assuming a linear change between adjacent values. Some values were also removed (e.g., a flow rate of 1.7 ft^3/s at 25% load and 900 rpm did not seem realistic), and a maximum flow rate of 18 ft^3/s was assumed for high rpm values.

It should be emphasized that this approach does not adequately address dynamic changes with the exhaust. This is because as the bus operates, the turbocharger within the engine "spools-up," meaning it provides additional manifold pressure to increase the flow of air into the combustion chambers. This is a mechanical approach, and there will be some inertia to the turbocharger for a period of time after the engine load is reduced. This inertia causes the actual exhaust gas flow rate to not be perfectly linear with respect to engine load and speed. However, it was the best approach available.

Using the empirical map obtained from this method, FSEC calculated the exhaust flow rate using a test run obtained in February 2017. FSEC also had the actual exhaust flow rate data from the LYNX laptop for this run. Exhaust flow rates were obtained using the empirical map approach, and these were compared against the actual values obtained from the LYNX laptop. The results indicated that the empirical approach did approximate the exhaust gas flow rate, although there were significant errors that resulted (Figure 2-7).

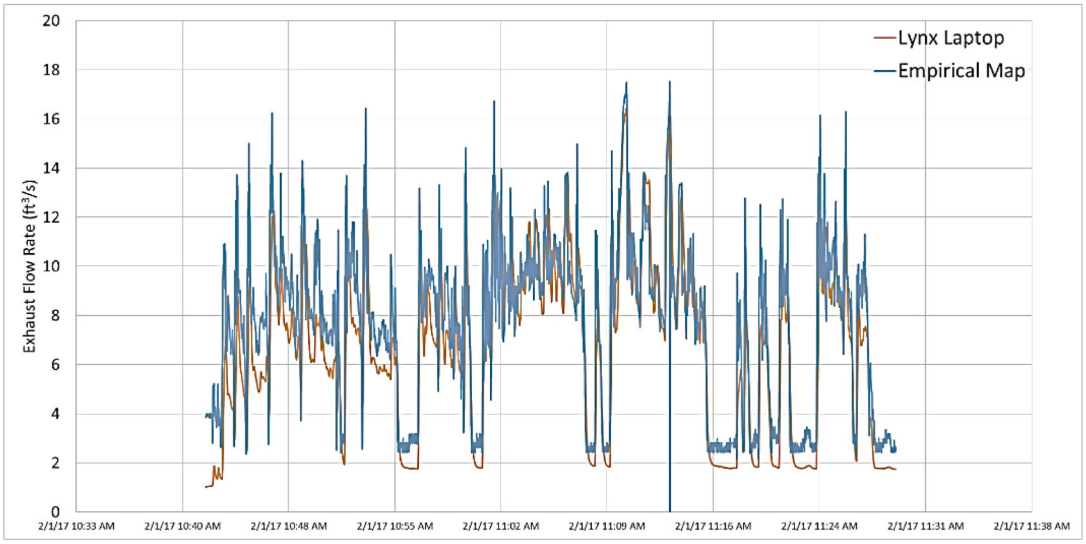


Figure 2-7

Comparison of exhaust flow rates obtained from LYNX laptop and empirical map

The empirical approach was then used to estimate the gas flow rates for the week-long testing that occurred in December 2016 and January 2017. Figure 2-8 shows the estimated flow rate for one day.

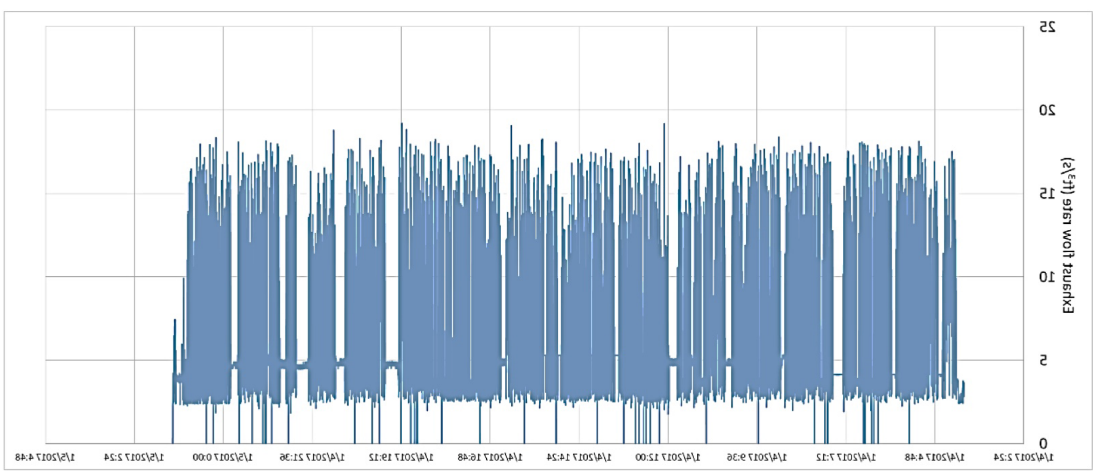


Figure 2-8

Empirically-obtained exhaust flow rate data from

LYNX also shared some operational lifetime data, including the amount of time the bus operates in different engine speed regimes, as shown in Figure 2-9. This screenshot shows the percent of time that the bus operates at a given percent torque and engine rpm. The scale is not accurate, but it can be seen that the bus operates nearly a quarter of all time at low rpm (less than 875) and between 30% and 50% torque. The correlation between "% engine load" and "% torque" was not perfectly clear, but they were similar in scale.

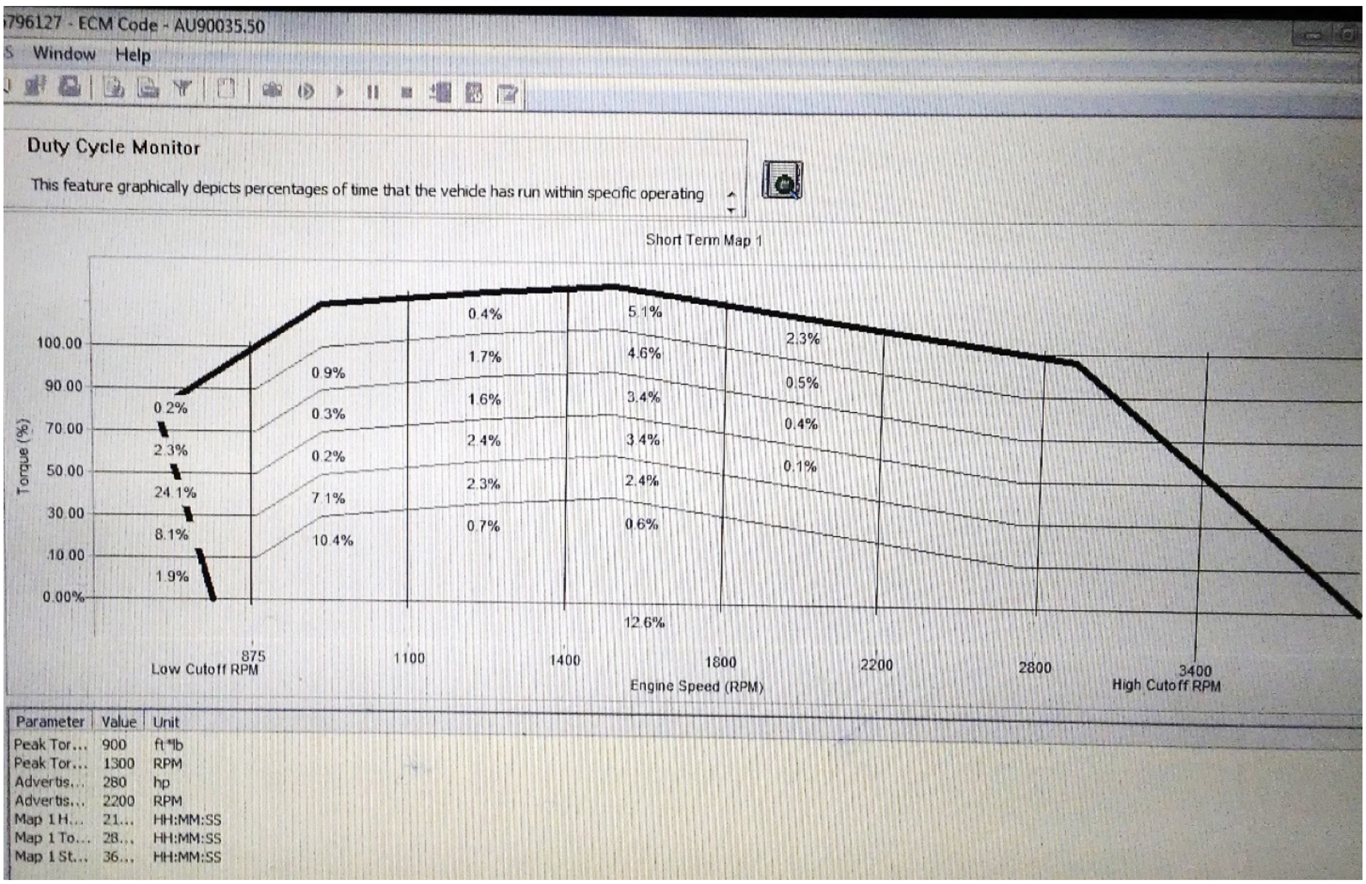


Figure 2-9

Screenshot of Bus 811 operational lifetime

Using the data from Figure 2-9 and the empirical map, FSEC determined that the bus exhaust flow rate was approximately 3–8 ft^3/s for roughly 63% of the time. Another 25% of the time, the exhaust flow rates were between 8 and 16 ft^3/s. The final 12% of the time was not defined in the operational lifetime data obtained from Lynx.

Preliminary Design and Computer Modeling

While the team gathered information on the exhaust flow rates and temperatures, Hi-Z began initial design work. This involved updating Hi-Z's existing heat exchanger design to reduce flow restrictions and distribute thermal energy as evenly as possible throughout the heat exchangers. More detailed descriptions of Hi Z's design and testing are provided in Appendix A.

Hi-Z initially planned to use a single-stage TEG design, with 17 heat exchangers (8 hot side and 9 cold side). This had the advantage of minimizing the system backpressure while maximizing the power output of each module, resulting in a cheaper and smaller TEG. The downside of this approach was that the exhaust gases leaving the TEG would still have considerable thermal energy that could be used by a second TEG. Although adding a second TEG would produce more power, it would add cost and, because the gases would be cooler, it would produce less power than the first TEG. It would also add to the back pressure of the system.

Hi-Z developed a computer model for the single-stage design and simulated power production using bench test data from Cummins while waiting for the actual bus exhaust data (Figures 2-10 and 2-11). That model estimated that, assuming the engine was operating near full load, the TEG could be expected to produce 2,000W_e of power if the cold side was kept at as low a temperature as possible. In stop-and-go traffic on a hot day with less efficient cooling, the power could fall below 1,500W_e. A small rise in the cold side temperature would result in the loss of significant power. Additionally, if the engine was not operating near a full load, the power output would be less.

Figure 2-10

2kWe TEG

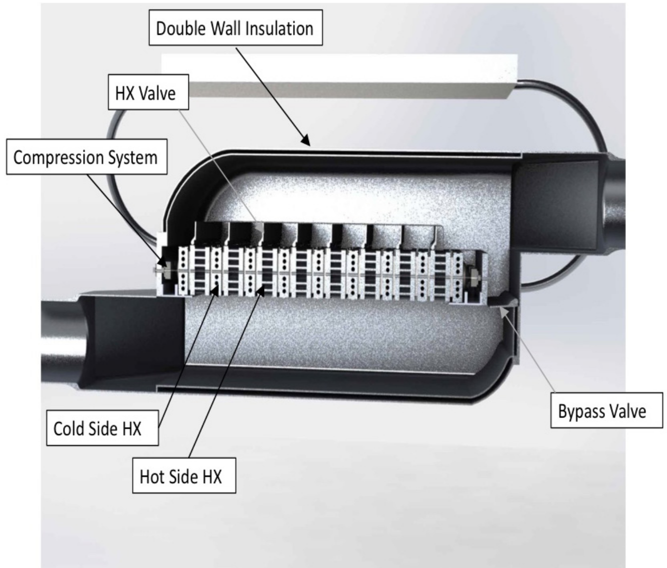


Figure 2-11

Cross section of 2kWe TEG

Once Hi-Z received the exhaust flow and temperature information, it determined that a single-stage approach would not be the most effective for a diesel transit bus application and eventually settled on a three-stage TEG design. This would increase the back-pressure in the system. Early simulation results of the three-stage design indicated that the increase in backpressure would be 0.3 to 0.4 psi, and LYNX indicated that the bus exhaust system would be able to handle up to 2 psi of backpressure. Given this information, the team determined that the three-stage TEG design would be acceptable. A preliminary rendering of a four stage TEG design is shown in Figure 2-12.

Figure 2-12

Initial rendering of multi-stage TEG design

The next step in the computer modeling was to add multiple flow channels. Only one flow channel had been modeled for the single-stage TEG; for the full system, Hi-Z modeled 12 channels.

In the preliminary 12 channel modeling, each of the 12 channels consisted of 4 stages. Preliminary modeling suggested that a 350°C exhaust gas flowing at 1,600 cfm would generate about 38 watts of power in the first stage of each channel, for a total first stage power of 456 watts. The second stage would produce about 32 watts per channel, for a total of 384 watts, the third stage would produce 26 watts per channel, for a total of 312 watts, and the last stage would produce 20 watts per channel, for a total of 240 watts. This resulted in a total estimated TEG power of 1,392 watts.

Mounting System

Another key consideration in the design of the TEG was the mechanism for mounting the TEG to the bus. Hi-Z designed a frame to hold the TEG and attach to the support beams in the roof of the bus. It also configured the system to be powered by the bus electrical system. The bus would power the data acquisition system, water pump, and fan. The mass of the system also needed to be minimized. The actual TEG weight was approximately 400 pounds. The mounting system also contained load cells to measure the tension on the rods used to hold the system together, such that Hi-Z would know if there was any unusual stress on the system.

LYNX requested that the bus with the TEG installed be as visually similar to their other buses as possible. To this end, Hi-Z decided to mount sheet metal covers over the TEG on the rear streetside of the bus, and the DAQ was mounted on the rear curbside of the bus. This would simulate the covers on CNG buses and hide the TEG from passenger view.

Dump Valve

During analysis of the bus data, FSEC raised the issue of regeneration cycles for cleaning the diesel particulate filter (DFP) and the potential impact it could have on the TEG. FSEC examined data from a week of on-route data collection of Bus 811 between December 25, 2016 and January 4, 2017. The regen cycle appeared clearly as an increase in the outlet temperature of the diesel particulate filter. The analysis indicated that a regen event occurred every 20.5 hours of operation during the week-long period, with one regen event occurring after only 1.5 hours of operation. The average regen event lasted 29 minutes, with an average maximum temperature of 650°C.

The TEG, designed to optimize power production at standard exhaust temperatures closer to 300°C, would not be able to withstand exposure to the high temperatures experienced during regeneration. To avoid damaging the TEG during regeneration, Hi-Z developed a dump valve to divert exhaust away from the TEG during regeneration events. The diverter valve system was designed to remove the TEG from the exhaust flow when the temperatures reached 400°C.

Two high-temperature exhaust valves performed this function with the use of a microcontroller and electric motors. The valves operated such that when one was open the other was closed. For instance, during normal operation, the valve on the TEG side of the valve assembly (left side of Figure 2-13) remained open while the valve on the diffuser side of the assembly (right side of Figure 2-13) remained closed. One thermocouple detected when the exhaust temperature exceeded 400°C and triggered activation of the dump valve. The other thermocouple was inserted into a well on a stage 1 heat exchange and activated the dump valve if the heat exchanger exceeded 95°C. The control logic would actuate the valves if one or both of these conditions was met. The TEG would be completely isolated from the exhaust flow during high temperature events.

Figure 2-13

Dump valve assembly mounted on bus

Data Acquisition System (DAQ)

Once FSEC had specifications for the data logger and the bus interface requirements, it developed the framework for the data collection system by specifying data acquisition modules, relays, and cabling needs (Figure 2-14). It determined that the data logger should be placed in a cabinet near the back of the bus interior during operations to minimize the impact on bus operations and protect the logger from the external environment.

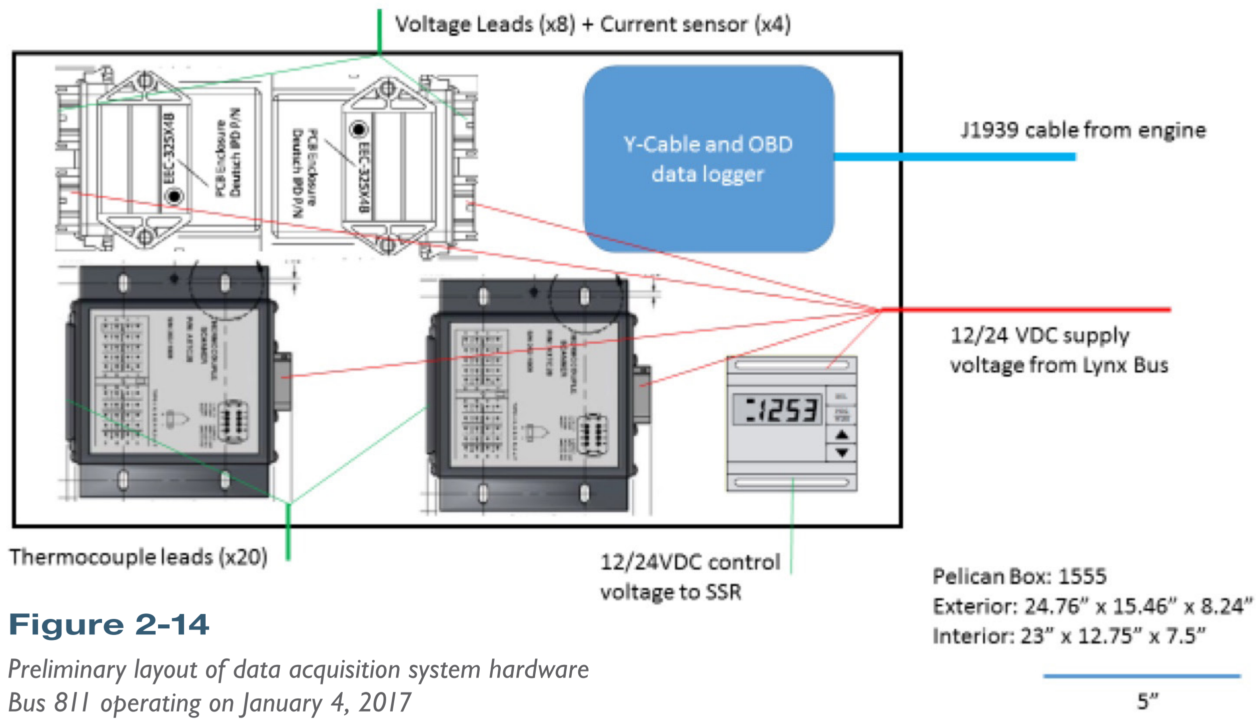


Figure 2-14

Preliminary layout of data acquisition system hardware Bus 811 operating on January 4, 2017

The project team decided that the logger should be configured for Wi-Fi so that data could be transmitted in near real-time during the demonstration. This required additional work from FSEC, ITB, and Hi-Z. Hi-Z developed the interface for viewing the data collected by the DAQ in real-time, and FSEC configured its servers to communicate with the data logger and store the data. FSEC tested the data logger and its ability to connect to the LYNX garage Wi-Fi. This functionality was limited, so ITB identified a cellular router that could be used to generate the Wi-Fi signal on the bus. Hi-Z requested a number of data signals to be collected, including data from 48 thermocouples and 15 analog signals from the TEG stages and modules.

SECTION

3

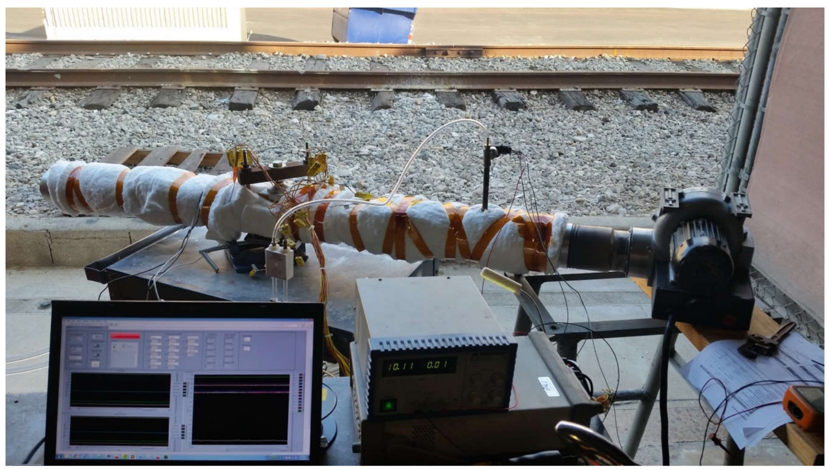
System Test and Delivery

Single-Stage Testing

Hi-Z began testing a single-stage heat collector in the third quarter of 2017. The test assembly (Figure 3-1) was operated at 310°C and 1000 in^3/s to match the expected bus operating conditions. At steady state, each of the two modules produced a consistent 2.06V at 21.5W. The back pressure was measured to be 0.090 lb/in^2 with a temperature difference of approximately 250°C across the module. The results were within predicted simulation ranges (Figure 3-2).

Figure 3-1

Test setup for single-stage heat exchanger



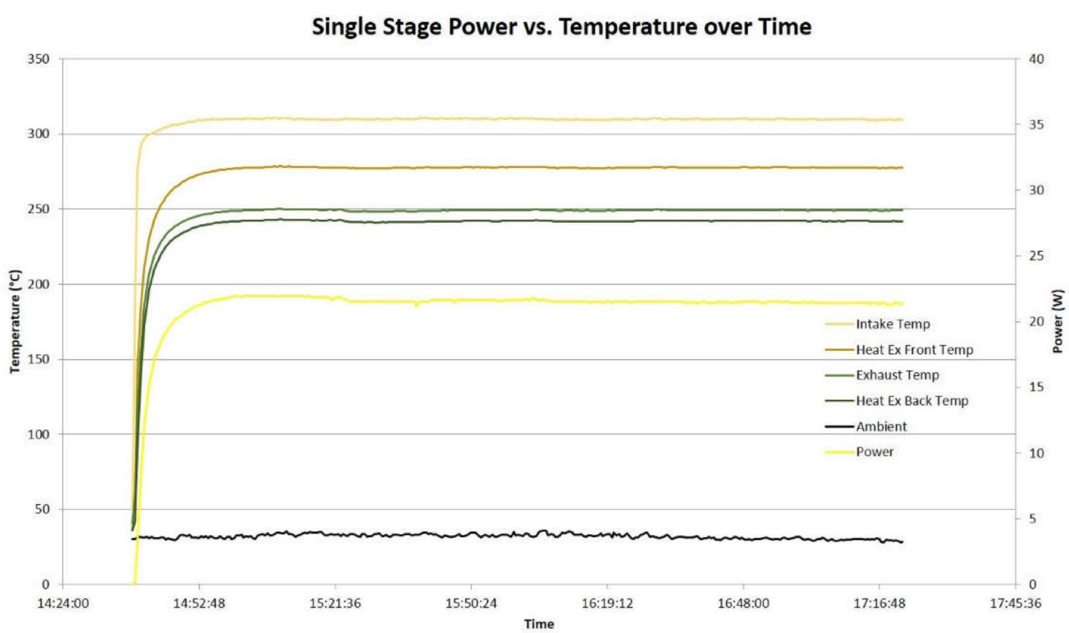


Figure 3-2

Results of initial single-stage testing

For further testing, Hi-Z thermally cycled the single-stage heat collector for 6.5 hours (Figure 3-3). The test assembly was operated at gas temperatures ranging from 210°C to 350°C and 1000 in^3/s. The top module produced an average of 17.4 watts with a max power of 24 watts. The bottom module produced an average of 16.5 watts with a max power of 23.1 watts. All results were determined to be nearly within predicted simulation ranges. The 1-watt difference between the two modules was consistent throughout the test and was theorized to be caused by a structural failure of the heat exchanger. Upon disassembly of the test unit, it was determined that during testing, the top module kept proper contact with the hot side heat exchanger but the bottom one did not, which increased the thermal barrier between the bottom module and heat exchanger. This confirmed that the power difference was caused by a structural failure

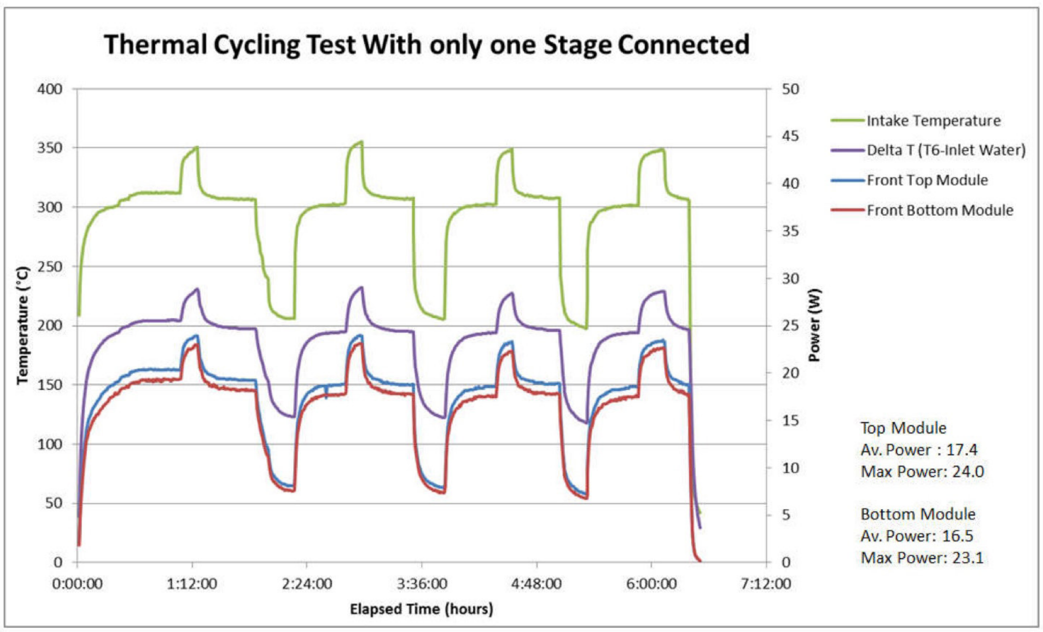


Figure 3-3

Thermal cycle data

Structural Analysis and Redesign

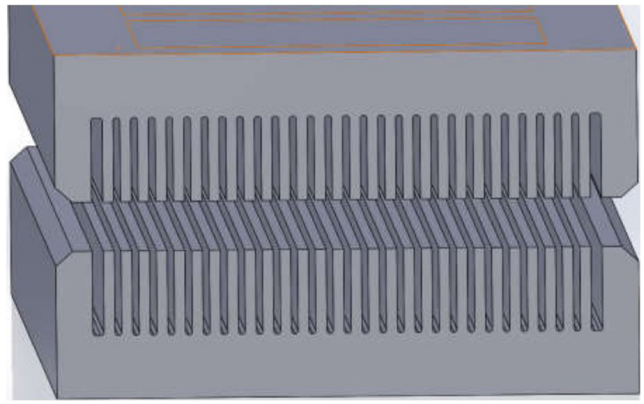
After the test unit failed to perform structurally, Hi-Z ran extensive stress analyses to determine the mode of failure and took steps to prevent it from occurring during the next round of testing. Hi-Z added two new features designed to withstand loads of more than double what was initially expected. Two upright braces would support the pressure from the module. Additionally, the top and bottom surfaces were thickened from ¼ inch to ½ inch. The ideal pressure to be applied to the heat exchanger through the module was 200 psi. For testing, Hi-Z applied 400 psi to the heat exchanger, and the resulting

Von Mises stress was calculated to be approximately 800 psi—well below the material's yield strength of 2470 psi at steady state temperature.

Another heat exchanger redesign needed to be made due to limitations of the extrusion process. The original design can be seen in Figure 3-4.

Figure 3-4

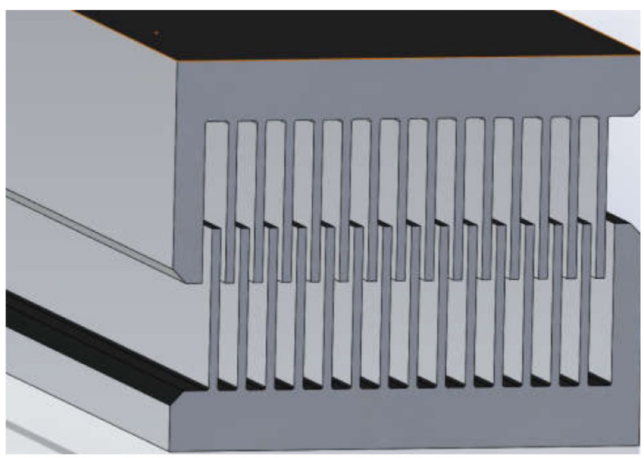
Original heat exchanger design



The fabricator was concerned that the small space between the long narrow fins would be a weak point in the extrusion tool and would be susceptible to failure. To allow a larger gap (and, therefore, a wider feature in the tool) between the fins, it was decided to use longer fins that alternate between the two sides of the HX (Figure 3-5).

Figure 3-5

Final heat exchanger design with longer fins

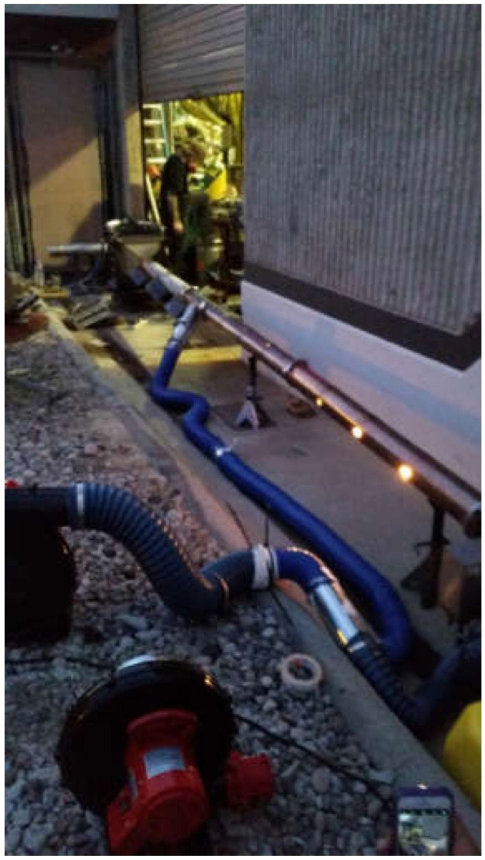


Assembly Testing

Hi-Z assembled the TEG and began testing the complete system in the first quarter of 2018. A waste oil burner was used to simulate the bus exhaust for testing purposes. The burner and testing system is shown in Figure 3-6.

Figure 3-6

System for simulating bus exhaust



During testing, the hot sides of the modules in the first stage operated at 250°C, the modules in the second stage operated at 210°C, and the modules in the third stage operated at 182°C. This was close to what was predicted. In the first test, the TEG was cooled using Hi-Z's internal water loop, and the cold sides of all three stages were at about 55°C. When operated under these conditions, the TEG produced about 1,285 watts of electrical power. This is the power that was predicted.

The TEG was then cooled using a radiator with fans directing cooling air through the radiator. In this case, the cooling system was unable to provide adequate cooling to all three stages. The third stage remained at 40°C, the second stage rose to 60°C, and the first stage operated at 100°C. Under these conditions, the TEG produced more than 800 watts of electrical power.

The coolant flow was then redirected in such a way as to provide more cooling to the first stage, where it is needed the most. This was done by restricting flow to the third stage and reducing flow resistance to the first stage. Once this was done, the power from the TWHR increased to 988 watts.

FSEC also sent the DAQ to Hi-Z to test system compatibility. These tests were successfully completed prior to shipping the entire assembly to Orlando in April 2018.

SECTION

4

System Installation

Hi-Z began installing the system onto LYNX Bus 811 on April 30, 2018, and completed the installation on May 9, 2018. As shown in Figure 4-1, the TEG frame was securely mounted to the bus roof in the pre-designated position.

Figure 4-1

TEG mounted on bus roof

Several components of the integration design had to be finalized upon installation due to unknown factors that could be explored only on site.

The TEG mounting hardware was not determined during the initial integration design. The material type of the roof sub-frame on the bus was unknown at the time, and the exact location of the sub-frame cross members could only be estimated. It was known, however, that the sub- frame was constructed from metal rectangle tubing. Because of this, blind insertion hardware was initially proposed for use as the main anchors. After a thorough inspection of the roof and sub-frame, it was found that the structure was constructed with thin wall aluminum tubing. This was determined to be an insufficient mounting interface for blind insertion hardware. Instead, four holes were drilled through the roof cross members and into the interior of the bus. Grade 8, 3/8" hardware was then inserted through the curbside of the TEG frame and into the holes in the roof. The bolts terminated on the underside of an extruded piece of aluminum trim that ran the entire length of the bus. A steel flat bar was then drilled and installed over the aluminum extrusion and bolts to distribute the load more evenly. Grade 8 Nyloc nuts were then used to secure the bolts in place. The roadside of the

TEG frame lined up with a piece of 2” x 2” aluminum angle that was previously used to mount the cowling. This angle was already securely anchored to the corner support beam in the roof sub-structure. The TEG frame was then bolted to this aluminum angle with Grade 8, 3/8” hardware and Nyloc nuts. The DAQ, radiator frame, and resistor bank were mounted in the same manner.

After the TEG was installed on Bus 811, several pre-qualifying tests were performed to ensure proper system integration and operation. The first test was designed to determine proper function of the diverter valve during a regen cycle. This valve was designed to divert exhaust gases away from the TEG and out to the atmosphere during a regen cycle. After the TEG was installed, the diverter valve and valve control system were installed, as shown in Figure 4-2. Before the exhaust was routed to the TEG, the bus was taken to an outside area of the LYNX facility and the regen cycle was started manually by a LYNX mechanic. The valve was programmed to divert the exhaust flow away from the TEG once the inlet temperature reached 300°C.

Figure 4-2

Diverter valve mounted to bus exhaust

The data in Figure 4-3 show the temperatures present at the diverter valve thermocouple before, during, and after a regen cycle. This thermocouple was positioned immediately before the diverter valve and after the regen apparatus. The valve was visually observed to open and close at the desired temperature of 300°C (dump valve trigger temperature). These recorded temperatures were compared to the values displayed by a LYNX mechanic’s computer and were virtually identical for the duration of the regen test. With this information, it was determined that the valve mechanism was working properly and the exhaust system could be connected directly to the TEG.

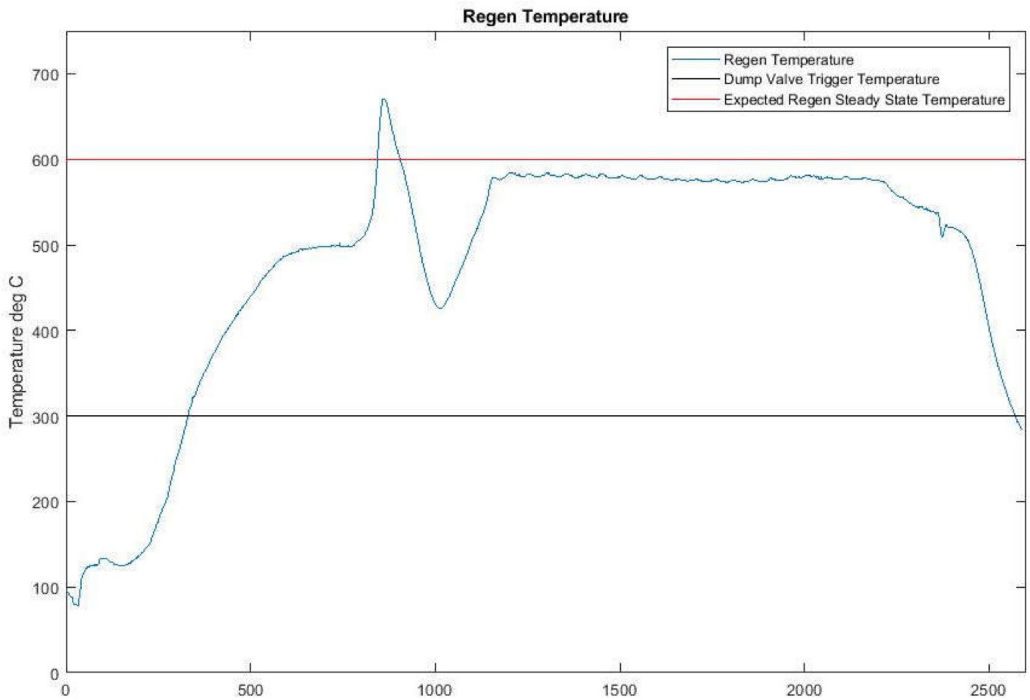


Figure 4-3

Diverter valve temperature data

SECTION 5

System Testing at Kennedy Space Center

ITB coordinated closely with the Kennedy Space Center (KSC) to ensure the team had access to KSC private roads for system testing prior to the in-service demonstration.

Testing of the TEG began on May 10, 2018, with a drive from the LYNX bus facility to KSC. Hi-Z provided a chase vehicle for the trip to KSC to watch the system for any obvious signs of failure or other points of interest. Hi-Z also had the design engineer ride along on the bus to manually check TEG temperatures and communicate with the chase vehicle. The only issue that arose during the trip to KSC was that the diverter valve bypassed the exhaust away from the TEG during highway speeds and redirected back to the TEG at slower speeds. The monitored temperature data confirmed that the inlet temperature was exceeding 300°C; this caused the valve to divert the exhaust away from the TEG, as it was programmed to do.

Once the bus arrived at KSC, Hi-Z reprogrammed the valve trigger temperature to 400°C. For the duration of the testing at KSC and the return trip to LYNX, the diverter valve was observed to stay open the entire time (no regen cycles were observed).

During the testing at KSC, the DAQ did not properly upload the data, so voltage output data were collected by hand and used to calculated power output (Figure 5 1). The maximum power output was 1,122 watts, which exceeded the laboratory simulation results. The bus was traveling at 56 mph when the measurements were taken.

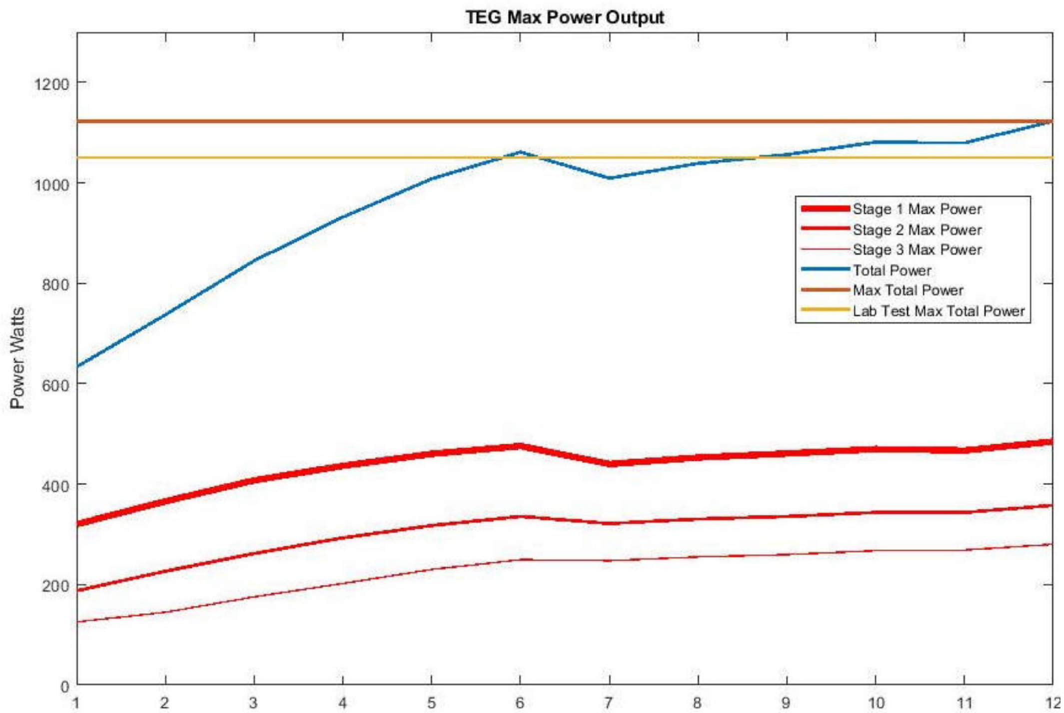


Figure 5-1

Manually-collected TEG max power output data

SECTION

6

In-Service Demonstration

The bus operated in service with the TEG installed from May 17 through June 13, 2018. The bus operated on the same block throughout most of the demonstration. There was no reported differences in driver or passenger experience.

Although the DAQ did not function properly during the testing at KSC, the problem was resolved upon returning to LYNX, and data were collected during the in-service demonstration. FSEC used this to perform a thorough analysis of the TEG operation (described in "Data Analysis and Results").

Hi-Z performed a system check on June 9 and 10. There was some evidence that tree branches had scraped the TEG covers, but the system was not damaged. The Wi-Fi hot spot for uploading the data had been turned off, so Hi-Z restarted it.

On June 12, Hi-Z noticed a significant change in measured temperature and that the TEG power output had dropped to nearly zero. The bus was pulled off its route until the project team could send a technician to investigate.

Demonstration End

ITB conducted an inspection of the TEG system following the TEG power output failure. A T-fitting connecting the radiator to the TEG had broken, and the project team suspected a tree branch caused the damage, as evidence of scraping could be seen on the TEG covers. The pump circulating the coolant through the TEG system had pushed all of the coolant out through the broken fitting, which resulted in overheating. This caused the heat shrink hose clamps to fail, which impacted the system wiring.

As the planned month-long demonstration period had ended, the team did not repair the TEG. LYNX shipped the TEG to Hi-Z on July 3, 2018, which then conducted a thorough post-mortem on the generator. An additional finding was that the washers used on the clamping system overheated and flattened, reducing the clamping force on the TEG.

SECTION

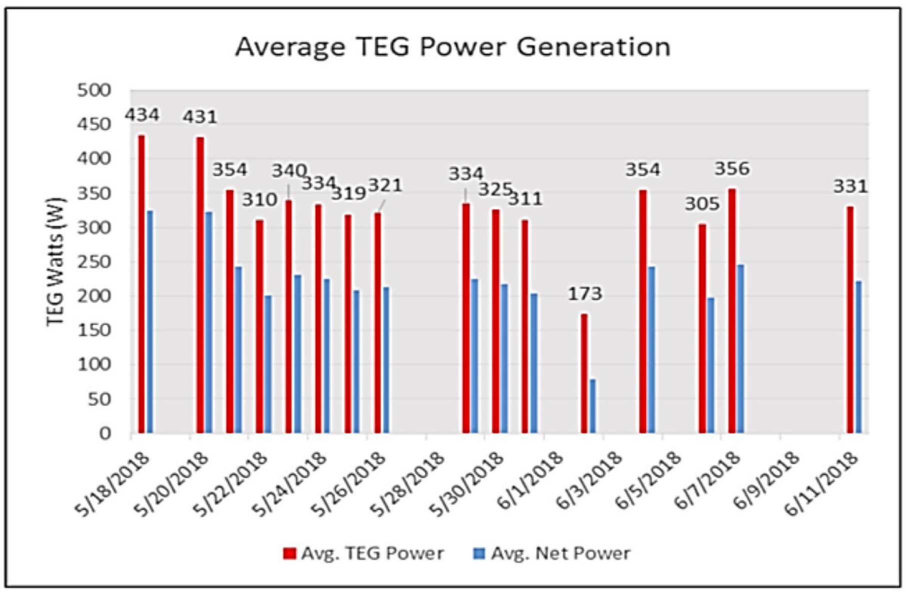
7

Data Analysis and Results

FSEC determined the power output from the TEG during the month-long demonstration on selected LYNX routes (Figure 7-1). The first two days of the demonstration were on a different route than the rest of the demonstration and showed significantly higher power output (430 watts compared to 320). This indicated that route characteristics had a significant impact on the power output of the TEG. Also, June 2 had a much lower power output than the rest of the period. FSEC determined that the low average power output was due to an extremely long layover period on that day. It appears that the bus was left running between a morning and afternoon pull-out, resulting in long idle times and low average power output.

Figure 7-1

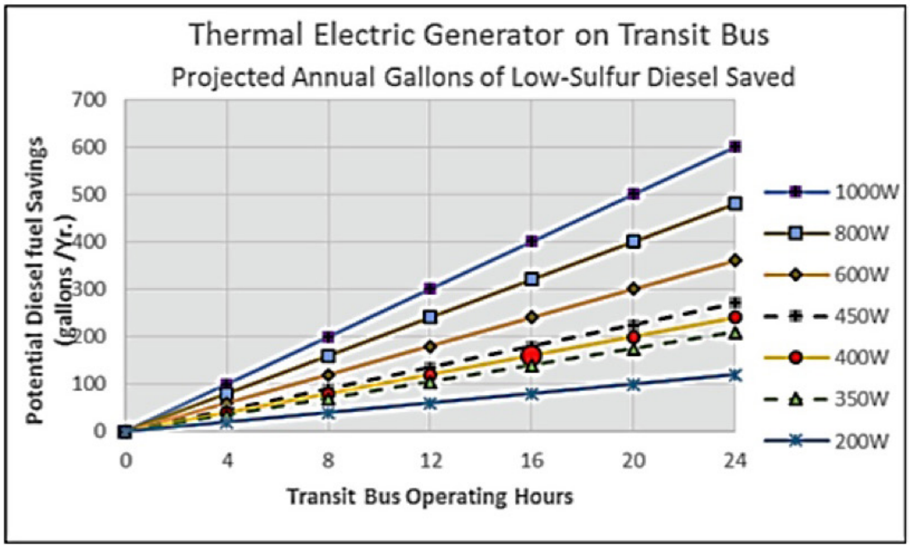
Average TEG power generation over course of month-long demonstration in service at LYNX

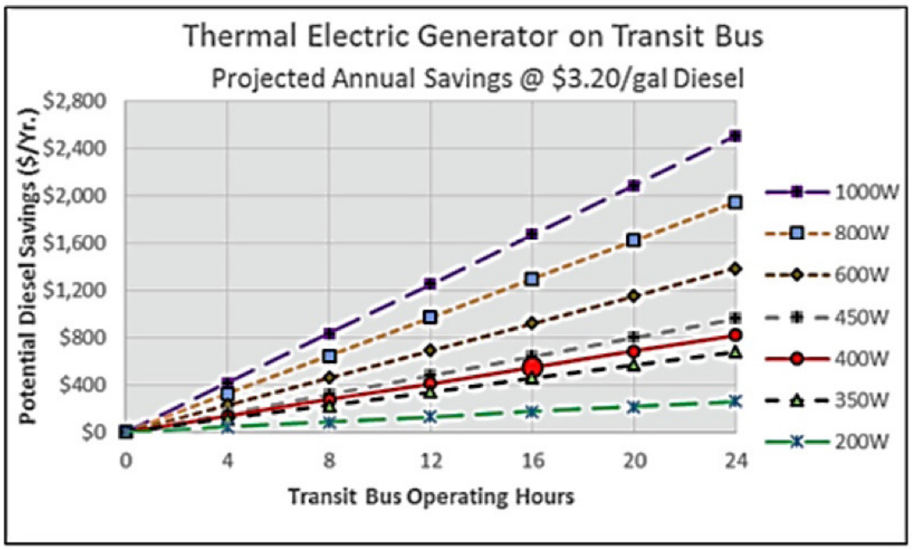


FSEC used these data to estimate the fuel economy savings that LYNX would have seen had the TEG been connected to the bus's electrical system. Figure 7-2 shows these projected savings in terms of gallons of diesel and cost. The large red dot represents the savings for this thermoelectric system on this route; the other lines show how an agency's savings would change if the power output of the TEG was increased or decreased, either due to different generator designs or different route characteristics.

Figure 7-2

Projected fuel savings in terms of gallons of diesel and cost with TEG installed and offsetting load of alternator





For this thermoelectric system and the operating conditions of the demonstration, the operator could save about 180 gallons of diesel per year per bus, which, at $3.20 per gallon of diesel, would be approximately $600 dollars per year. Further details regarding FSEC's analysis and methodology can be found in Appendix B.

SECTION

8

Commercialization Plan

Energy Florida led the effort to develop a commercialization plan for the TEG (Appendix C), with efforts focused on an overall market assessment for thermoelectric technology on heavy-duty vehicles. The TEG can be applied relatively easily to different vehicles, and expanding the available market for the generator beyond transit buses to school buses and long-haul trucking could lead to increased production volume, decreased cost, and increased product viability.

Energy Florida also explored the market size of compressed natural gas (CNG) vehicle technologies. Over the course of the project, the team learned that CNG vehicles have higher exhaust temperatures, which could lead to a greater temperature differential between the hot and cold sides of the generator and increased electricity production.

Through discussion with LYNX, Energy Florida identified key production considerations for transit agencies in addition to cost impacts. One consideration was that LYNX would need a bus OEM to include the TEG in its specifications list and support the equipment in the event of a failure. Another was that the size of the generator would need to be decreased; LYNX wants the generator to fit within the existing design of the bus and its engine compartment. The TEG would also be more easily adopted if it could reduce vehicle downtime and maintenance. For example, LYNX staff said that the bus alternators generally need to be replaced every 3–5 years; if a TEG could reduce the load on the alternator and, therefore, extend its lifespan, this would result in reduced maintenance costs for LYNX.

Based on the cost analysis conducted by FSEC, under the conditions of this demonstration, a transit agency could save approximately $600 per year through the use of a TEG. Hi-Z estimated a sale price of $5,000. In this case, the payback period for a TEG would be over 8 years, significantly shorter than the 12 year lifespan of transit buses.

The next step in moving the TEG to commercialization is to conduct another demonstration, this time connecting the generator to a bus electrical system to obtain better data regarding the fuel economy savings as a result of the TEG.

SECTION 9

Conclusions

Through this project, the team successfully designed, developed, built, installed, and demonstrated a thermoelectric generator on a transit bus in service. Several key learnings should be carried forward into future phases of TEG development:

- The connection between the cooling system and the thermoelectric generator needs to be better protected. This could potentially be ameliorated through working more closely with a vehicle OEM to integrate the TEG into the vehicle design.
- Mounting the TEG onto CNG-powered buses may result in increased fuel economy benefits relative to diesel-powered buses.
- The dump valve system design to protect the TEG from high temperature regeneration events operated successfully and should be considered in future designs.
- Hi-Z detailed a number of design considerations to improve upon during a future installation (Appendix A), including replacing the heat shrink hose clamps with another material to reduce the likelihood and magnitude of damage during exposure to high-temperature conditions.

Overall, this project successfully demonstrated thermoelectric technology in a transit application and laid the groundwork for future related efforts.

APPENDIX

A

Hi-Z Final Report

Hi-Z prepared a technical report detailing the specifics of the TEG development, testing, operation, and post-mortem

Thermoelectric Energy Generation Demonstration at LYNX Transit

2018 Final Technical Report

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August 2018

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Part 2- Project Description

The goal of this project was to develop and demonstrate a thermoelectric power generator that could be used to provide power for vehicle accessories and reduce the amount of power required from the alternator during normal operations. Earlier versions of the proposed system have been demonstrated on automotive, military vehicle and diesel truck applications. These projects were funded by the Department of Energy, National Science Foundation and the Department of Defense. This technology can now provide a new way to reduce transit engine demand and achieve reductions in fuel consumption and emissions. The project will apply this technology, initially developed for spacecraft, and transition this work to transit systems with a waste heat recovery system that is expected to generate 1400 watts of power. The heat energy contained in the vehicle's exhaust was to be recaptured and converted to useful electricity. This is energy that would otherwise be expelled into the atmosphere.

The technical aspects of this project that are covered in this report were accomplished through the following 5 tasks:

Task 1: Design and development of a 2 kW nominal Thermal Waste Heat Recovery (TWHR) system

Task 2: TWHR system test and delivery

Task 3: System installation on selected bus

Task 4: System validation at the Kennedy Space Center (KSC) facility

Task 5: Florida Solar Energy Center (FSEC) Independent Evaluation

The project will identify pathways for future development and commercial production, which could enable a 5% reduction in fuel use and corresponding emission reductions. The utilization of the Kennedy Space Center as a site for clean energy and transportation technology development in partnership with regional transit operators will create a commercialization pathway for federally funded technology research and development.

Part 3- Task Break-Down and Execution of Technical Objectives

<u>Task 1 – Design and Development of a 2 kW Nominal TWHR System</u>

Cold-Side Heat Exchanger Design and Fabrication

The cold-side heat exchangers (HXc) used on this project were taken from Hi-Z's new stock supply, totaling 15 altogether. This heat exchanger design had been used on a prior Thermoelectric Generator (TEG) project and had shown that it was able to withstand similar temperatures and clamping pressures that were expected to be experienced during this project. They were, however, determined to be too flow-restrictive as the results from the previous project had shown. Hi-Z was able to perform a redesign to reduce flow restrictions while providing a more even distribution of cooling throughout the heat exchangers.

The exchangers were originally extruded from 6063 aluminum and then machined on each module mounting surface to be flat and parallel with respect to each other. They featured a single inlet and single outlet that were positioned on one end of the heat exchanger as seen below in figures 1 and 2. Each of these ports measured 0.310" in diameter, the same as the channels running the length of the heat exchangers. It was observed that this configuration provided a complex flow path and an uneven cooling profile. When the coolant enters through the input and flows along one side of the heat exchanger, it absorbs heat and the coolant temperature rises by the time it reaches the end of the first straight run. When the coolant starts to flow down the other side of the heat exchanger towards the outlet it is already 'pre-heated' and is unable to remove as much heat from the module surface on that side. This results in a smaller ΔT across the module which in turn lowers the power output of the modules.

In order to increase coolant flow rate, both ends of the heat exchangers were cut off to allow clear and even access to the three channels that ran the lengths of the heat exchangers. Both ends were notched once for each set of three channels with a half-round cutout as seen in figure 3. The diameter of the cutouts measured 1.25" and allowed the larger hose fitting, seen in figure 4, to be welded securely in place. There are several different configurations of these hose fittings which can all be seen in figure 8.

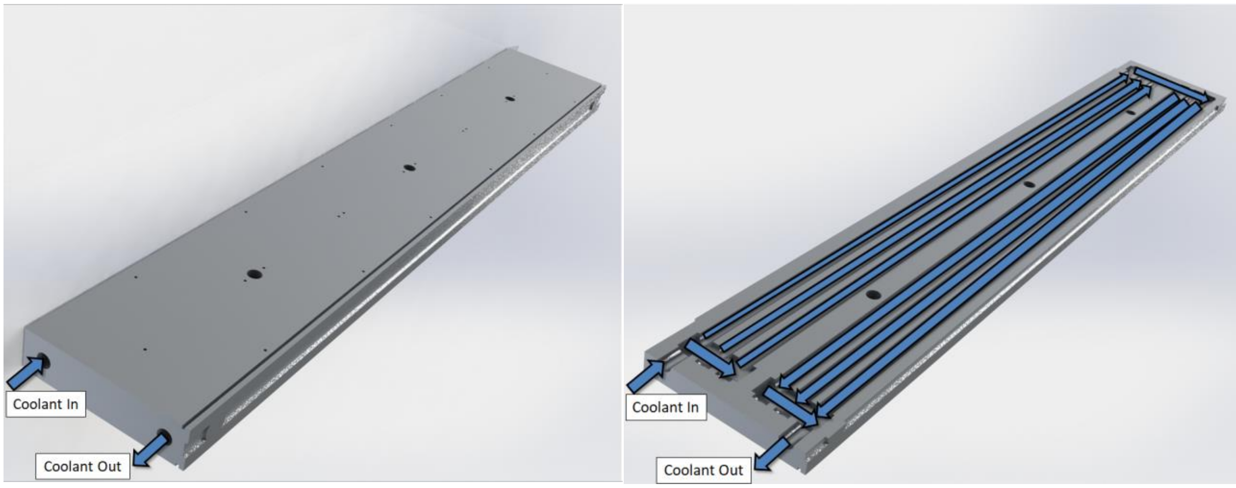


Figure 1, 2. *Old-Style HXc Configuration*

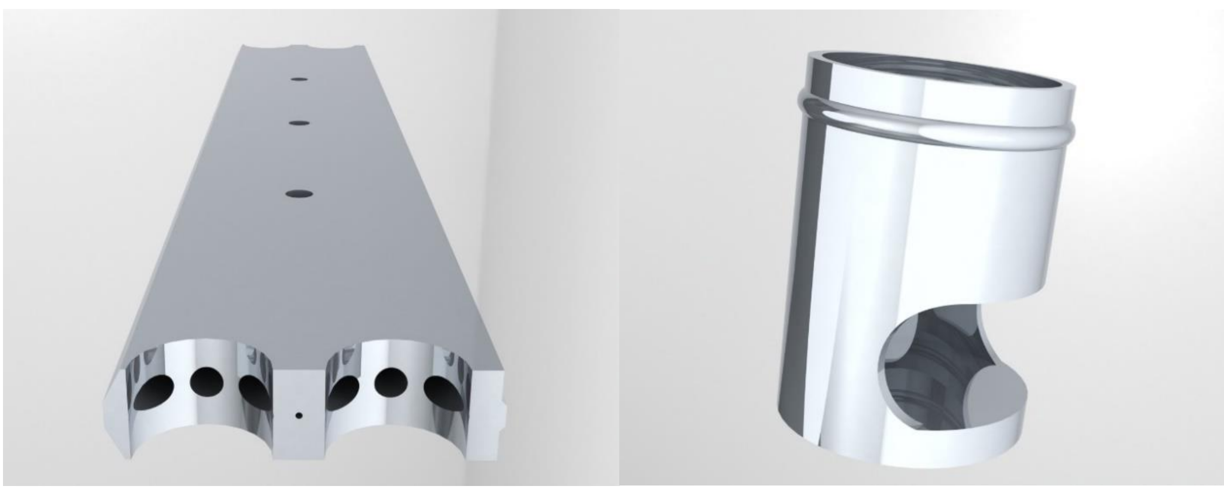


Figure 3, 4. *Modified HXc and Hose Fitting*

To address the ‘pre-heating’ of one side of the heat exchangers, the flow for one half of the channels was directed to one side of the TEG and out to the radiator. The flow for the other half of channels was directed to the opposite side of the TEG and out to the radiator (figures 5, 6). This allowed the coolant to quickly extract more heat from the modules at a faster rate by using separate paths.

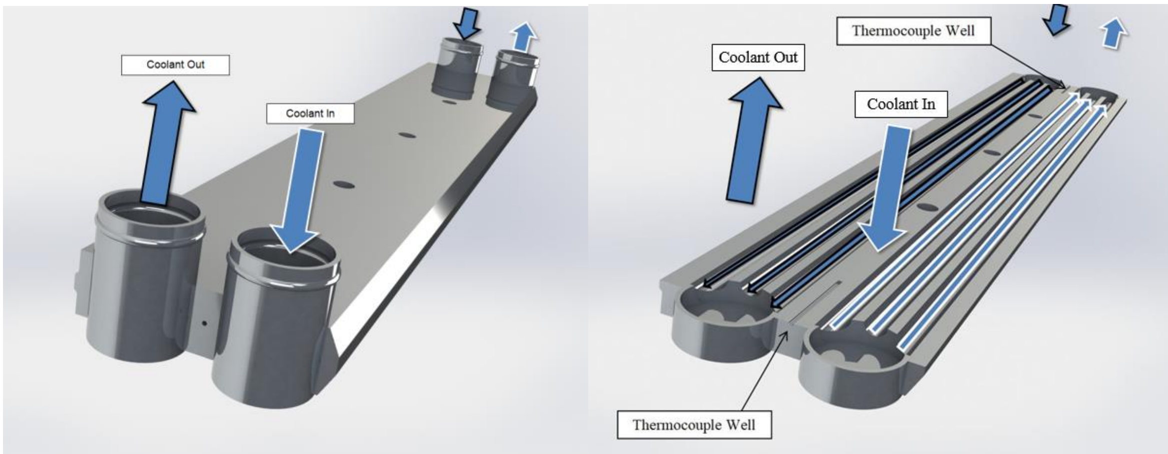


Figure 5, 6. *Improved HXc Configuration, Final Design*

Hot-Side Heat Exchanger Design and Fabrication

The hot-side heat exchangers (HXh) used for this project required much more effort than the cold sides to design and fabricate. Initially the TEG was to feature a single-stage design, similar to the image in figure 7. This decision was based on engine data provided by Cummins since directly measured exhaust flow data for the bus was not available.

Once preliminary data from the bus to be used for testing became available it was obvious that there was not enough energy in the exhaust gases to support a 2 kW single pass TEG. In a single pass TEG the exhaust gases are passed through a single heat exchanger and then vented. This is considered to be an optimal configuration because all of the modules are heated with the highest temperature gas available.

While a single pass TEG will have the highest energy density, a more efficient TEG can be fabricated by passing the exhaust gases exiting the first heat exchanger through a second heat exchanger to recover even more energy. The second stage modules will produce less power than the modules in the first stage since the gases are not as hot, but additional electricity will be generated from the same gas.

Since the exhaust gasses contain an insufficient amount of energy to support a 2kW single pass TEG, it was decided to use the same number of modules to fabricate a three-stage TEG as seen in the CAD model of the final configuration (figure 8). The modelling suggested that when the exhaust gases are at their peak projected temperature (350°C), a three stage TEG with 96 modules will generate about 1,400 watts of electricity.

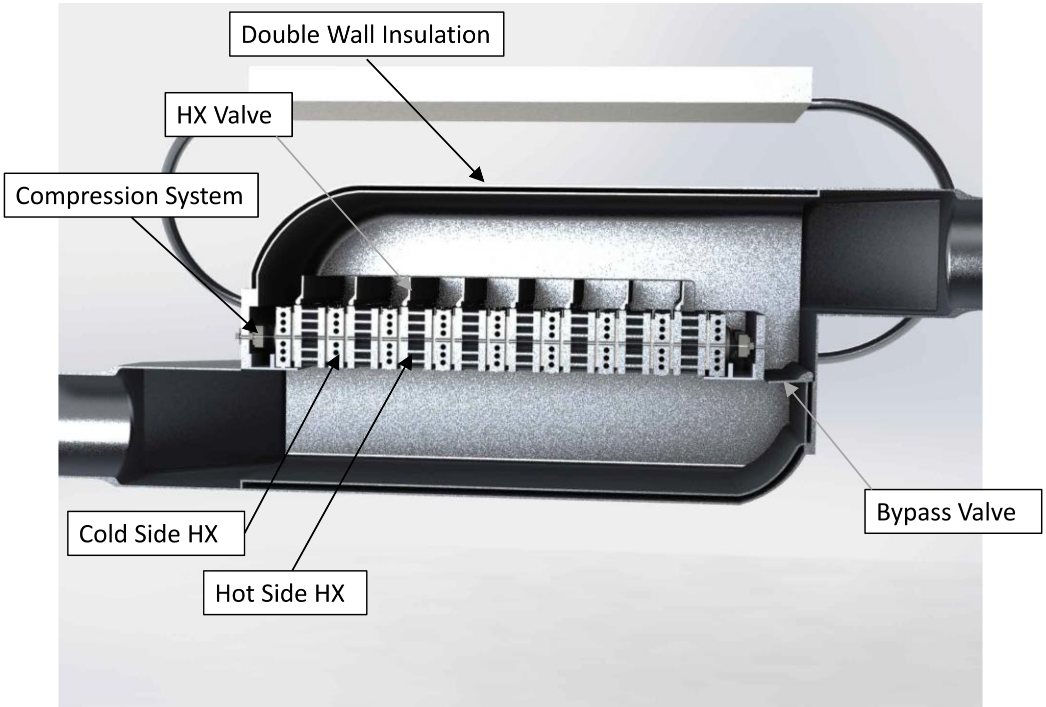


Figure 7. *Initial Single-Stage TEG Design Concept*

Figure 8. *Final Three-Stage TEG Design Configuration*

One drawback of a three-stage TEG is that it causes higher back pressure on the vehicles engine than a single pass TEG. It was not possible to determine an acceptable back pressure for the system but it was reported that the emission systems on the model of bus to be used in the testing is about 2 psi. Early simulation results for the three-stage design suggested that the back pressure was anticipated to be from 0.3 to 0.4 psi which was determined to be acceptable.

After completion of the flow simulations, the heat exchanger profile seen in figure 9 was determined to be ideal for the three-stage concept. It was decided that simulations alone were not enough to move forward with fabrication of these units so a prototype unit was constructed. Because the desired material for this application, 6063 T5 aluminum, is typically only available in extruded form, a substitute was chosen to build the prototype with. 1100 H112 aluminum was chosen for its thermal and structural properties which are near identical to those of 6063 T5 aluminum. This experimental heat exchanger was machined on a mill with a slitting saw to create the fins. The mating surfaces of both halves were drilled in several places to accept roll pins which would position the heat exchangers straight, relative to each other. Once the fabrication of this unit was completed, a test apparatus (figure 10) was designed and fabricated as well. This device was designed to apply the required 200 psi of pressure that the modules need in order to obtain intimate mating surfaces with the heat exchangers and ceramic wafers. The small cold side heat exchangers were taken from Hi-Z's stock supply. Even though the water ports on these heat exchangers were smaller than the improved design, both top and bottom cold-side exchangers were supplied with separate coolant lines from Hi-Z's chiller system. The projected coolant flow rate was still lower than what it would be with the improved design but only by a negligible amount.

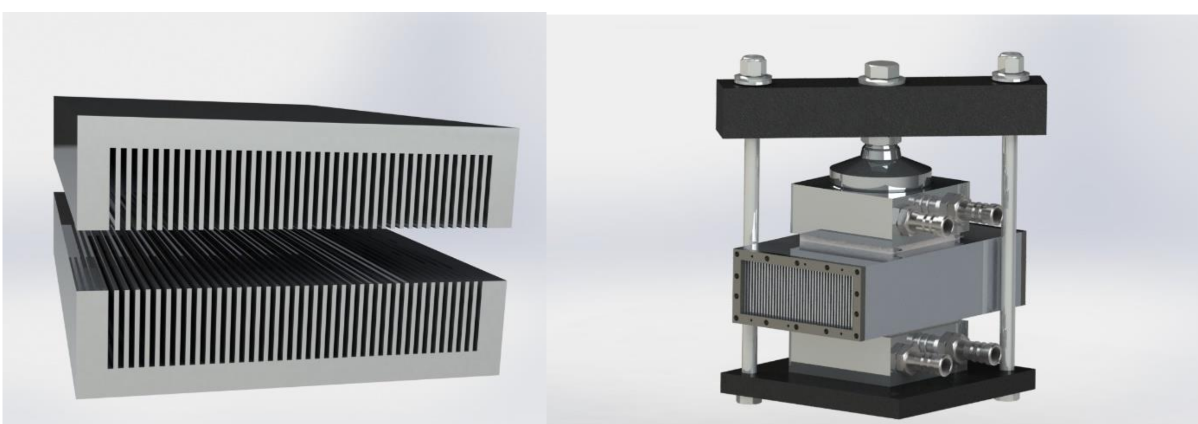


Figure 9, 10. *Prototype HXh and Test Apparatus*

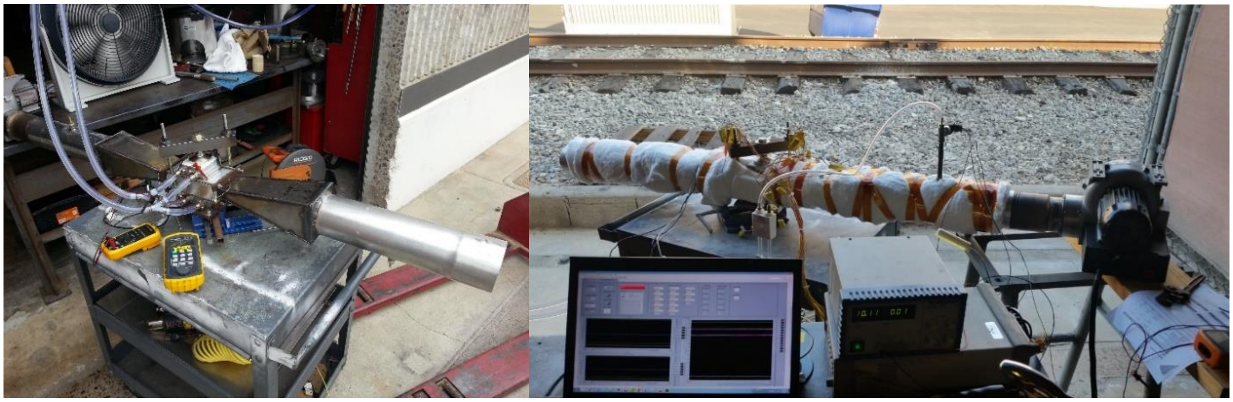


Figure 11, 12. *Test Setup for Single-Port/Stage Heat Exchanger*

Hi-Z tested the prototype heat exchanger (figures 11 and 12) for just over two hours in order to obtain a baseline data set. The plot from that test is exhibited below in figure 13 for a single module. The intake air was heated to $310°\ C$ with a flow rate of $1000\ \left(\frac{in^3}{s}\right)$ to match the expected bus operating conditions for one port. At steady state, each of the two modules produced a consistent 2.06V at 21.5W. The back pressure was measured to be $0.090\ \left(\frac{lb}{in^2}\right)$ with a ΔT of approximately $250°\ C$ across the module. All of the results were determined to be within predicted simulation ranges.

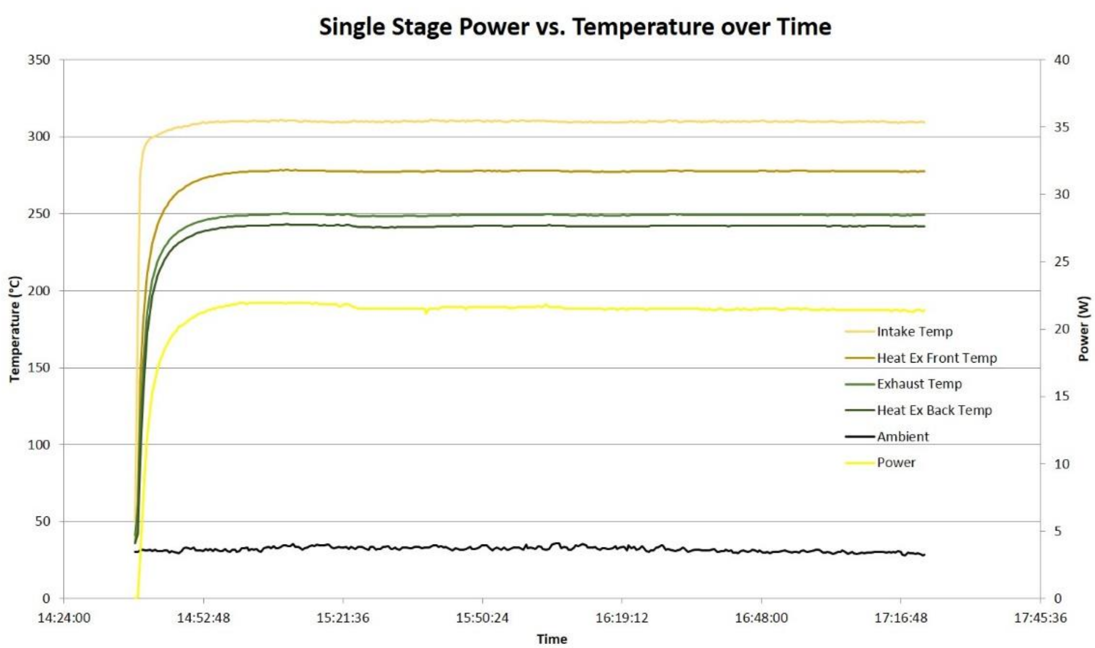


***Figure 13**. Single-Port/Stage Power vs. Temperature Curve*

For further testing, Hi-Z thermally cycled the single port/stage heat collector for 6.5 hours. The plot from that test is exhibited below (figure 14). The test assembly was operated with inlet gas temperatures ranging from $210° \, C$ to $350° \, C$ and $1000 \, \left(\frac{in^3}{s}\right)$. The top module produced an average of 17.4 watts with a max power of 24 watts. The bottom module produced an average of 16.5 watts with a max power of 23.1 watts. All of the results were determined to be nearly within predicted simulation ranges. The 1 watt difference between the two modules was consistent throughout this test and was theorized to be caused by a structural failure of the heat exchanger. Upon disassembly of the test unit, it was determined that during testing, the top module retained proper contact with the hot side heat exchanger while the bottom one did not. This improper contact increased the thermal barrier between the bottom module and heat exchanger which resulted in a lower ΔT across the module. This confirmed that the power difference was in fact caused by a structural failure which can be seen in figures 15 and 16. The fins had buckled under pressure and ended up occluding the flow through the heat exchanger. This occlusion, however, did not cause a significant increase in back pressure of the unit.

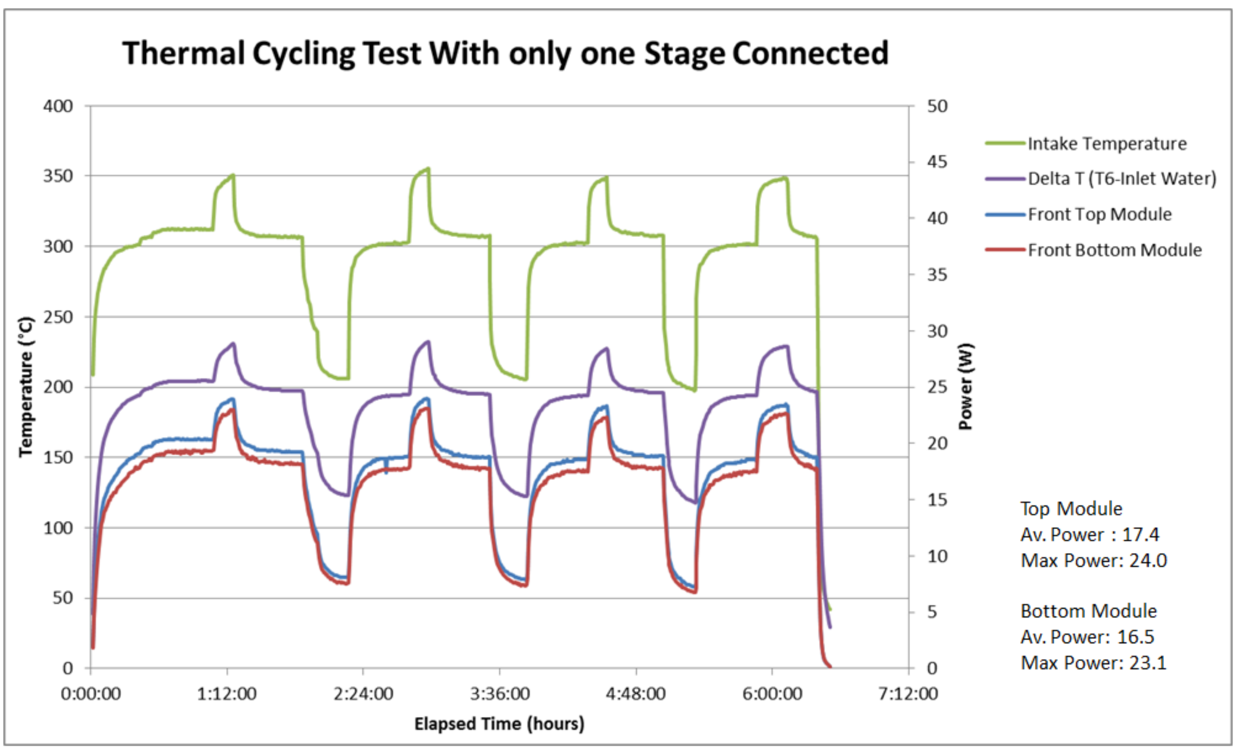


Figure 14. *Single-Port/Stage Thermal Cycling Data*

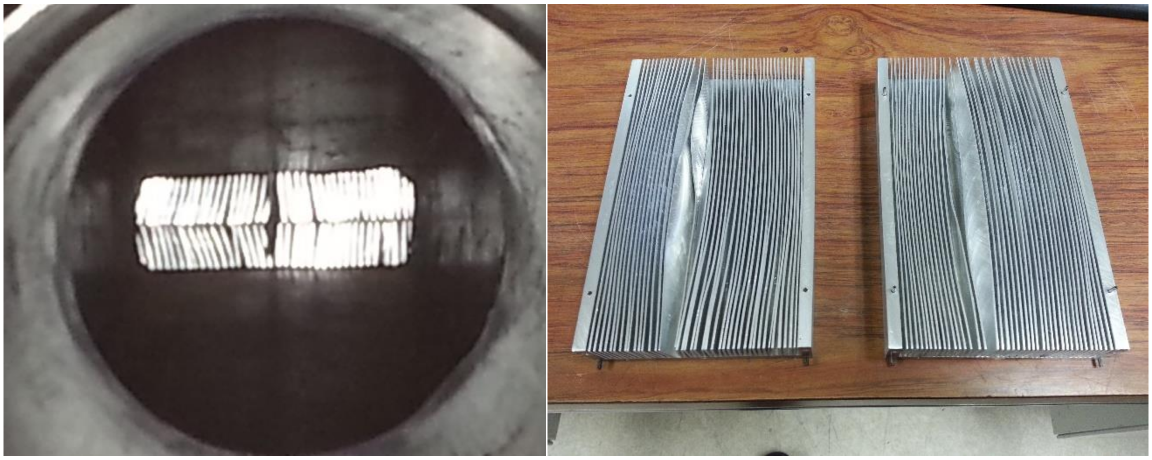


Figure 15, 16. *Structural Failure of Prototype Heat Exchanger*

Once the condition of the heat exchanger had been thoroughly analyzed, the fins were carefully straightened and the module mounting surfaces were milled flat. The heat exchanger and testing apparatus were then reassembled with a second clamping mechanism and four HZ-20 modules. Testing the modified setup allowed Hi-Z to anticipate the effect of a multi-stage system. The results of those tests are exhibited in the figures 17 and 18.

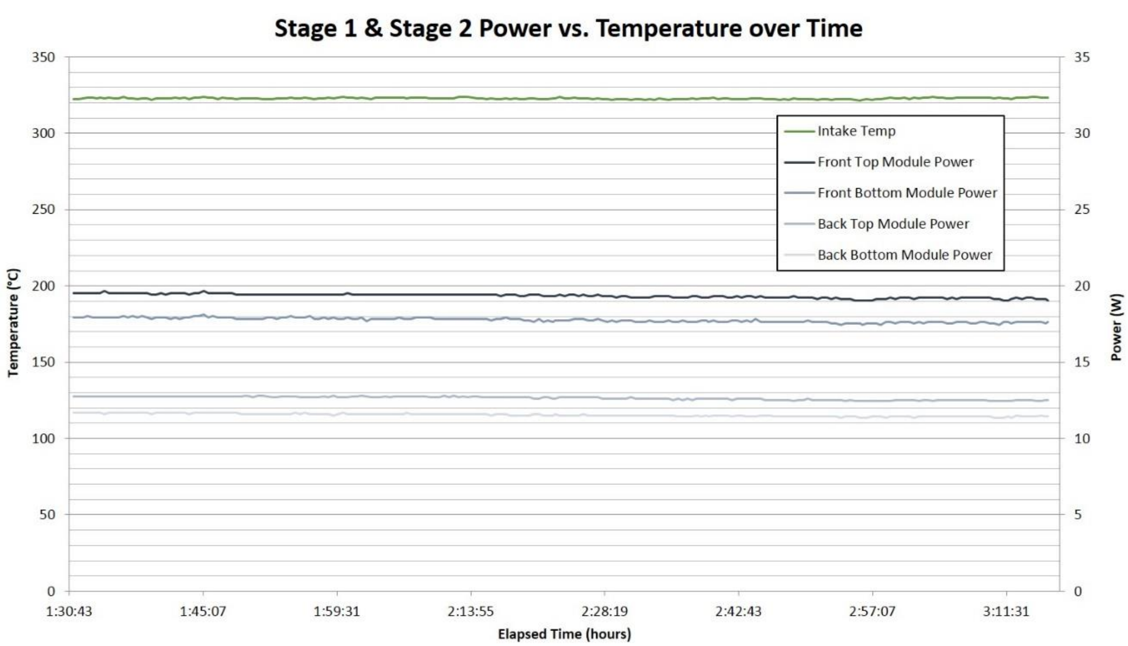


Figure 17. *Stage 1 and 2 Steady State Testing Data*

The first stage modules produced a total average of 37.10 watts with the top and bottom modules independently producing 19.35 and 17.75 watts respectively. The second stage modules produced a total average of 24.19 watts with the top and bottom modules independently producing 12.65 and 11.54 watts respectively. The average ΔT for the first stage heat exchangers was 200.82 °C and the average ΔT for the second stage heat exchangers was 159.59 °C. When calculated, this shows that there is a 21% decrease in ΔT between the first and second stage modules.

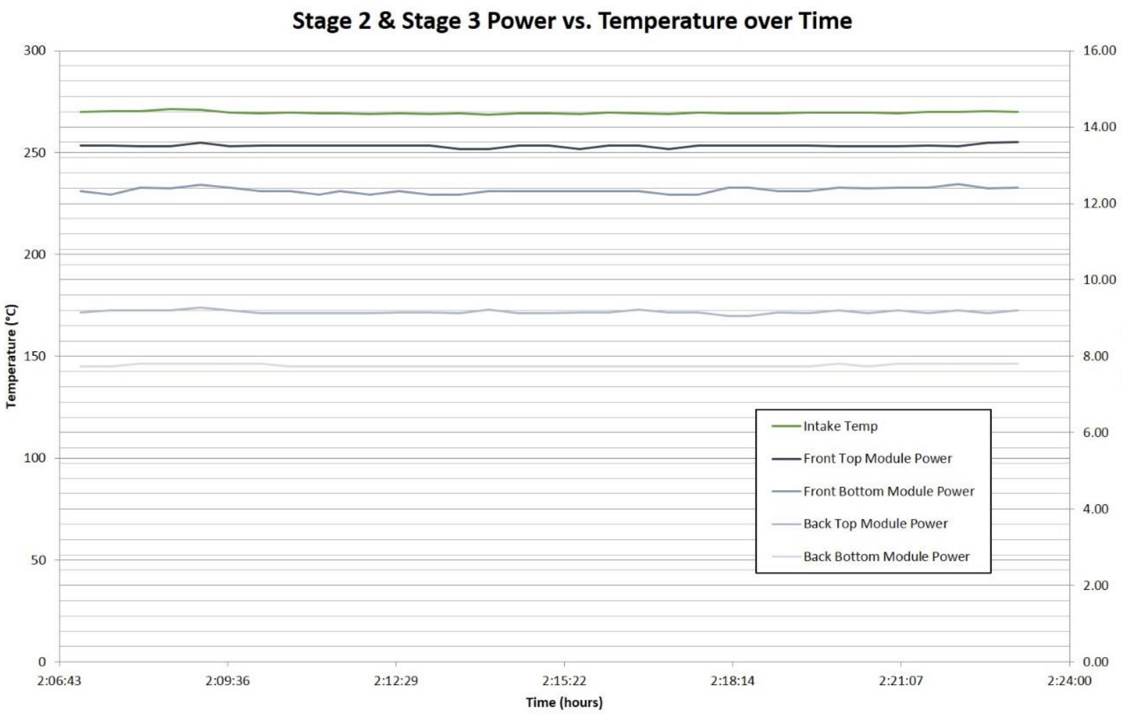


Figure 18. *Stage 2 and 3 Steady State Testing Data*

To simulate operation of the second and third stages, the intake temperature was adjusted so the ΔT of the front section of the HXh was near the ΔT that the back section of the HXh was during the last test. The second stage modules produced a total average of 25.86 watts with the top and bottom modules independently producing 13.51 and 12.35 watts respectively. The third stage modules produced a total average of 16.92 watts with the top and bottom modules independently producing 9.16 and 7.76 watts respectively. The average ΔT for the second stage heat exchangers was 161.65 °C and the average ΔT for the third stage heat exchangers was 129.50 °C. When calculated, this shows that there is a 20% decrease in ΔT between the second and third stage modules. This thermal performance was determined to be acceptable and no further testing was performed on this unit.

After the test unit failed to perform structurally, Hi-Z ran extensive stress analyses to determine the mode of failure and took steps to prevent it from occurring on the final design. As shown in figure 19, the top and bottom surfaces of the revised design were thickened from ¼ inch to ½ inch. The sidewalls were thickened as well and weld grooves were added to join the two halves.

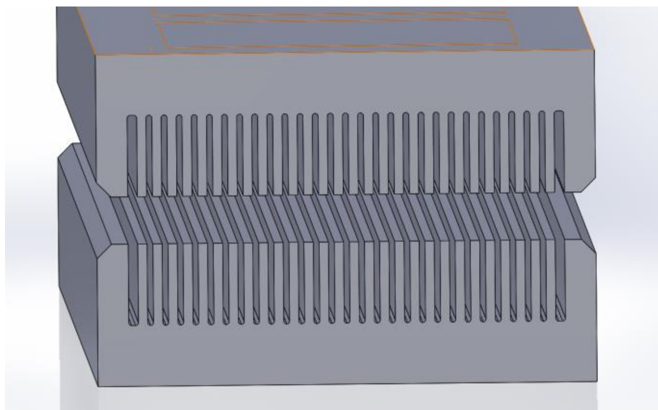


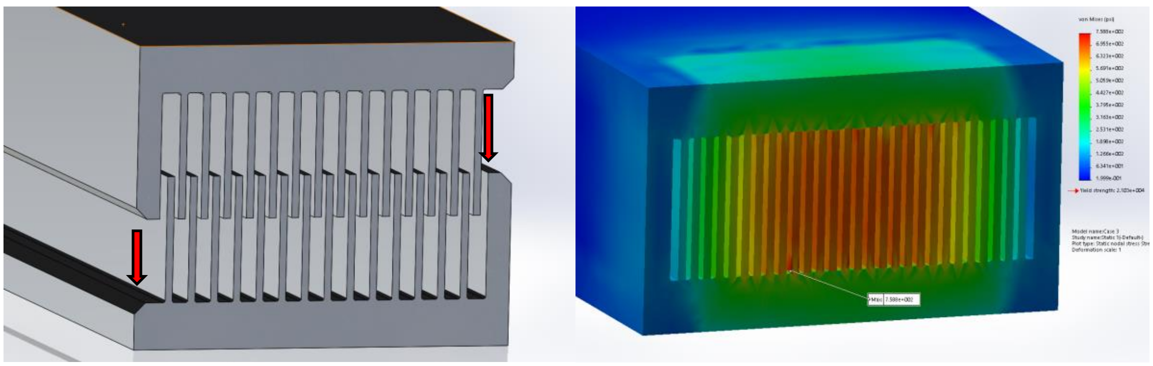
Figure 19. *Two-Part HXh, Initial Production Design*

With the experimental and simulation data, Hi-Z was ready to order the first batch of heat exchanger extrusions.

After a discussion with the extrusion manufacturer, it was determined that this particular heat exchanger design could not be extruded with more than 50% confidence due to some profile characteristics. As seen in figure 19 above, the gaps between the fins are nearly the same width of the fins. This is the constraint that the manufacturer could not meet due to the fragility of the die that would be used. The gaps are typically required to be near double the thickness of the fins.

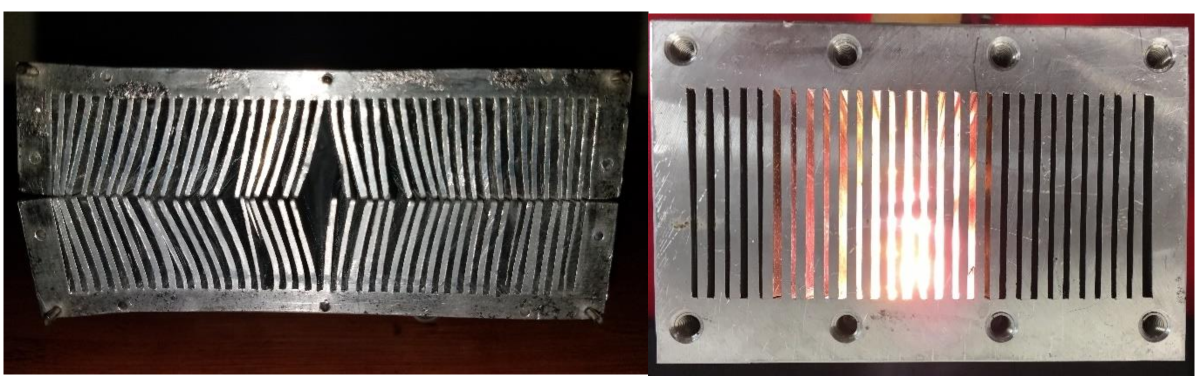
Now knowing the constraint details of the extrusion process, Hi-Z performed a redesign on the heat exchanger in order to meet the requirements of the manufacturer. The revised heat exchanger seen below in figures 20 and 21 were determined to meet the manufacturer's requirements with 100% confidence in their manufacturability. The number of fins per side were reduced by half to allow for wider gaps between them. To keep the fin area the same as the previous design, the fins were lengthened to fill the larger gaps on the opposing heat exchanger. Additionally the longer fins were designed to physically contact the opposing side base material for structural support and conduction purposes. The outside dimensions, weight and fin surface area remained the same as the previous design. The thermal simulations of this revised design showed a negligible difference from the previous design, although slightly less efficient due to fin lengths.

As seen in figure 20 and 21, the new revised profile performed well under compression. The revised design indicates maximum concentrated stresses of approximately 760 psi while the previous design showed around 800 psi, both of which are well below the material's yield strength of 2470 psi at steady state temperature.



Figures 20, 21. *Two-Part HXh, Final Design*

Another advantage of this design is that the terminal ends of the fins are captured with the base of the opposing side's fins. As seen in figures 22 and 23, this will prevent the deflecting and buckling that occurred on the prototype heat exchanger.



Figures 22, 23. *Damaged Prototype HXh vs Final Design HXh*

Both faces of the finished HXhs were drilled and tapped in 8 places each to allow a secure fastening point for a flow distribution plate on the final assembly (figure 24). The tapped holes were fitted with stainless steel Heli-Coil® inserts to better distribute forces that would arise during thermal expansion. The holes in the distribution plate were oversized to nearly double the size of a loose fit for the chosen hardware, also to allow for thermal expansion. Anti-Seize Lubricant was added to all fastening hardware for this plate and a stack of 3 series-parallel Belleville washers were installed on each screw as seen in figure 25 below. Previous TEGs built at Hi-Z had experienced a high failure rate of mounting hardware due to shear and tension forces experienced during thermal expansion of similar components. The oversized holes and washer stacks were both intended to prevent these forces from concentrating on the mounting hardware.

Figure 24, 25. *Flow Distribution Plate and Belleville Washer Stacks*

When the HXhs were cut to length, the fins developed burrs from the process and were not removed during fabrication. Hi-Z tried several methods to remove them but sandblasting proved to be the fastest method which also gave the best results. A single row version of the flow distribution plates (figure 26) were cut by waterjet to act as masks for this process. This ensured that the module mating surfaces were protected during sandblasting.

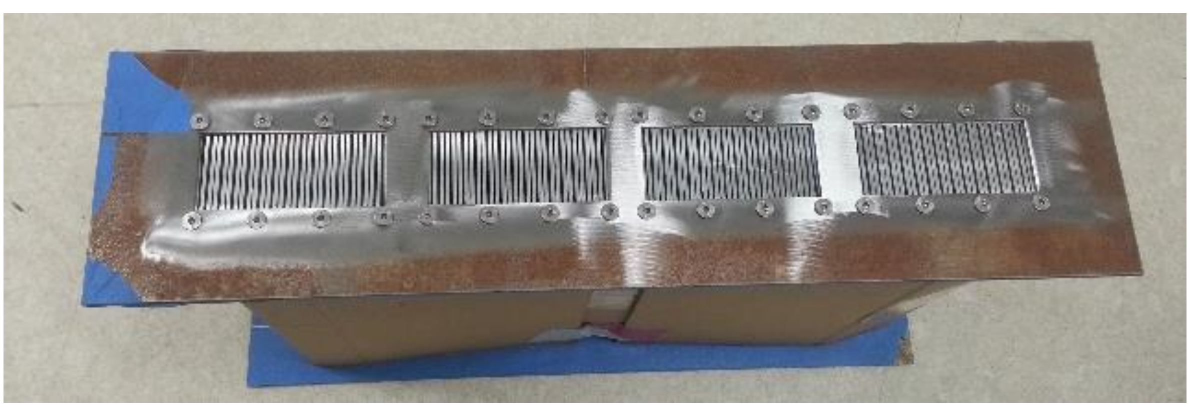


Figure 26. *Sandblasting Mask for Burr Removal*

Electrical System Design and Fabrication

The 96 HZ-20 modules used in this TEG were manufactured with a flexible braided wire which is equivalent to 14 Gauge stranded wire. The entire system of modules was connected with the same braided wire. The connections were made with a high temperature solder and a resistance soldering gun. The 32 modules in each stage (figure 27) were connected in series and each stage was then connected to a single load resistor (figure 28). R1=8.3 ohms, 500 watt. S1=metal whetted relay.

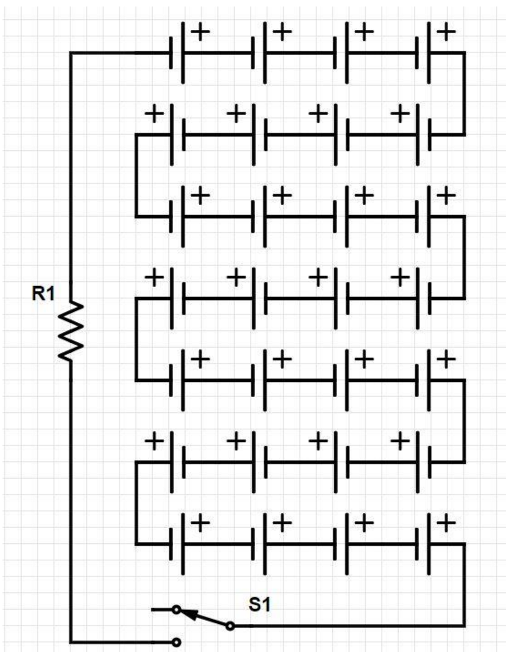


Figure 27, 28. *Single-Stage Wiring Diagram and Resistor Bank*

Clamping Mechanism

Several experiments and simulations were conducted to determine the strongest and lightest configuration for the clamping mechanism. Special donut load-cells (figure 31) were purchased to measure the tension on each rod during these experiments. In the past, rated Belleville washers were used to estimate these forces by measuring their compression distances but this method was determined to be insufficient for this project. The load cells were later incorporated into the final design (figure 29), one for each tension rod. Multipurpose O1 tool steel bar, 3/4" thick, 3/4" wide was chosen for the primary structure of the clamp ends as a result of these experiments. They exhibited a near unmeasurable plastic deformation after thermal cycling at 2000 lbf tension. The ceramic wafers seen below (figure 30) are intended to help thermally isolate the clamping mechanism from the HXcs.

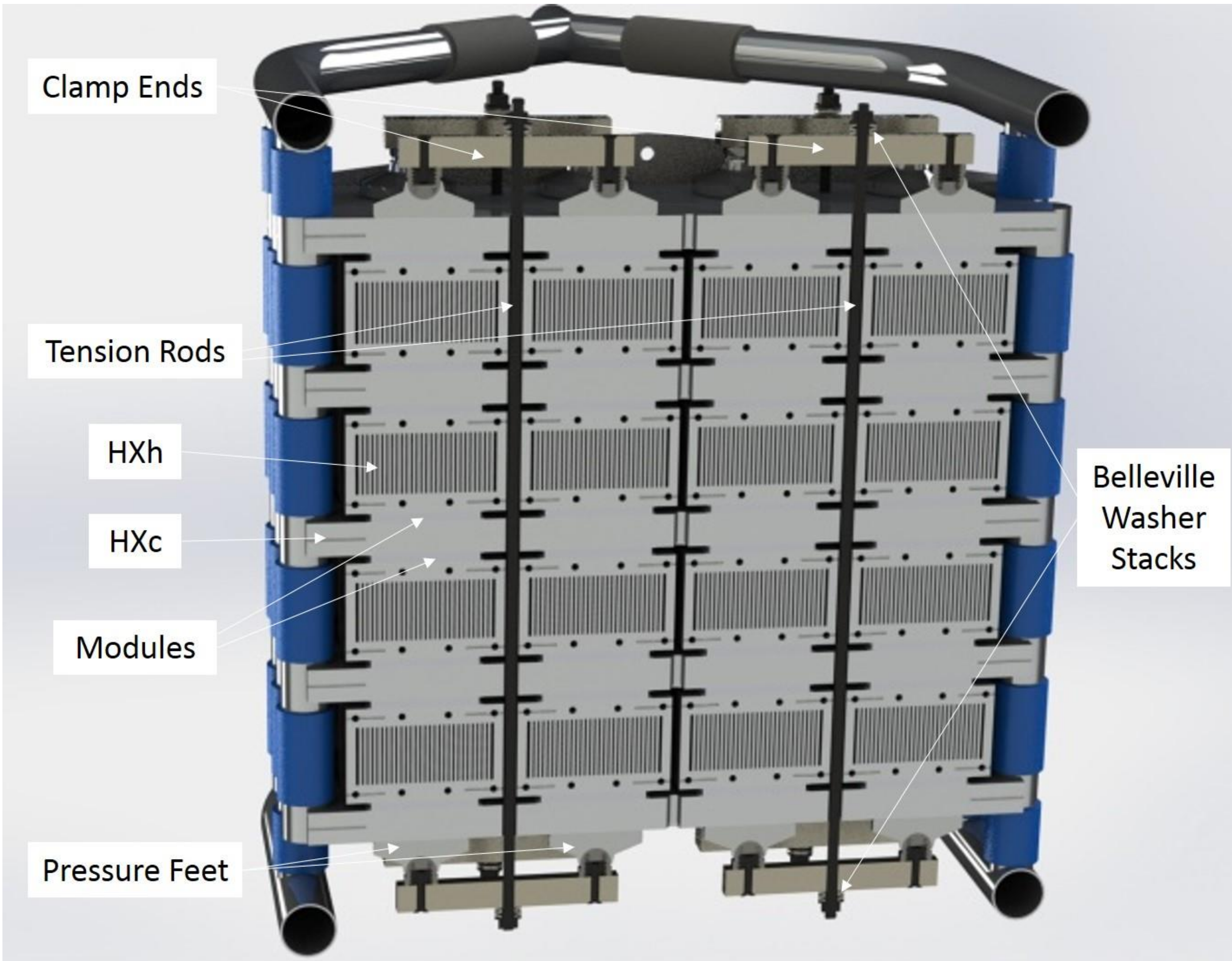


Figure 29. *Clamping System Section View*

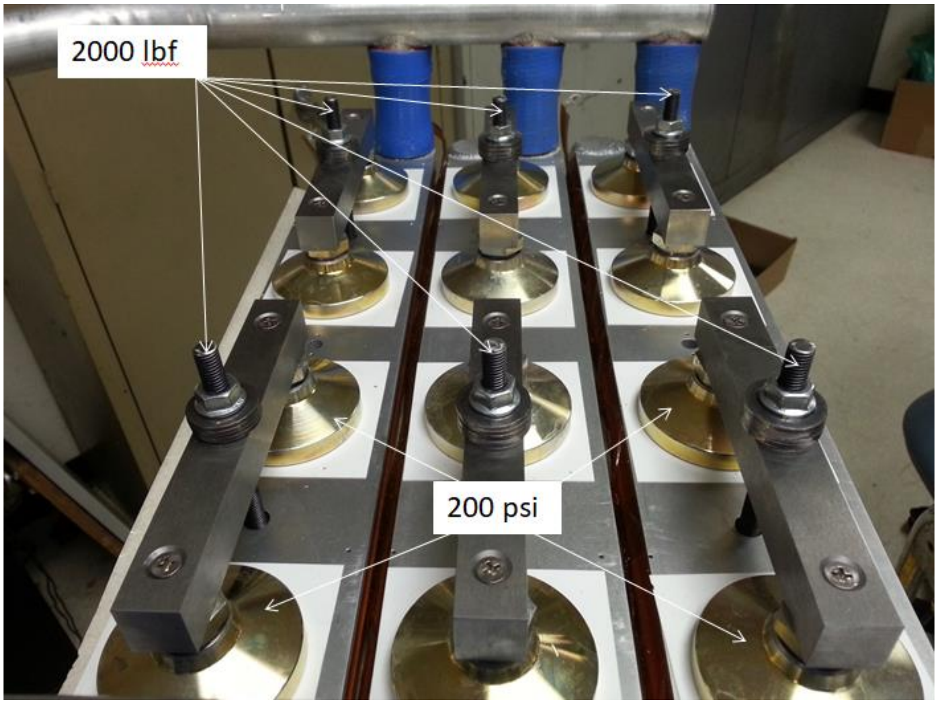


Figure 30. *Clamping System*

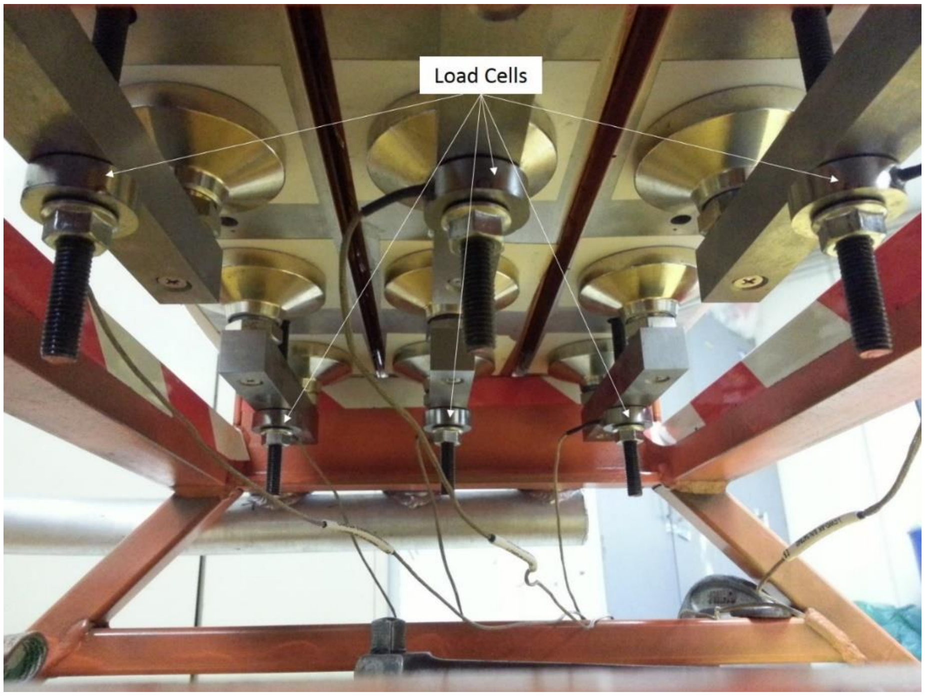


Figure 31. *Load Cell Configuration*

Diverter Valve and Control System

Because the bus performs a regeneration (regen) cycle as part of its emission control process, the exhaust will periodically reach temperatures of 600 °C which is too high to run through the TEG. The diverter valve system (figure 32) was designed to remove the TEG from the exhaust flow when the temperatures reached 400 °C. There are two high-temperature exhaust valves that perform this function with the use of a microcontroller and electric motors. The valves operated opposite of each other so when one is open the other is closed. For instance, during normal operation the valve on the TEG side of the valve assembly (left side of figure 33) remained open while the valve on the diffuser side of the assembly (right side of figure 33) remained closed. The valves and the motor/gearbox that actuated them were off-the-shelf parts intended for drag car exhaust diversion (figure 34). The microcontroller was an Arduino UNO which was fitted with a mechanical relay shield and two thermocouple amplifiers. One thermocouple was used to divert the exhaust away from the TEG when the exhaust temperature exceeded 400 °C. The other thermocouple was inserted into a well on a stage 1 HXc which was used to divert the exhaust away from the TEG when the HXc exceeded 95 °C. The control logic would actuate the valves if one or both of these conditions were met.


Figure 32, 33. *Diverter Valve Assembly*

Figure 34. *Diverter Valve*

Suspension Frame and Damping System

Since the TEG was designed for a mobile application, a damping system was designed into the frame structure that secured the TEG to the bus (figures 35 and 36). The system was designed to isolate the TEG and it's components from impulse forces and vibrations. Bellows were also added to the TEG inlet and outlet to help facilitate X, Y, Z movement allowed by the damping system. 8 off-the-shelf vibration-damping sandwich mounts (neoprene) were used to achieve this effect.

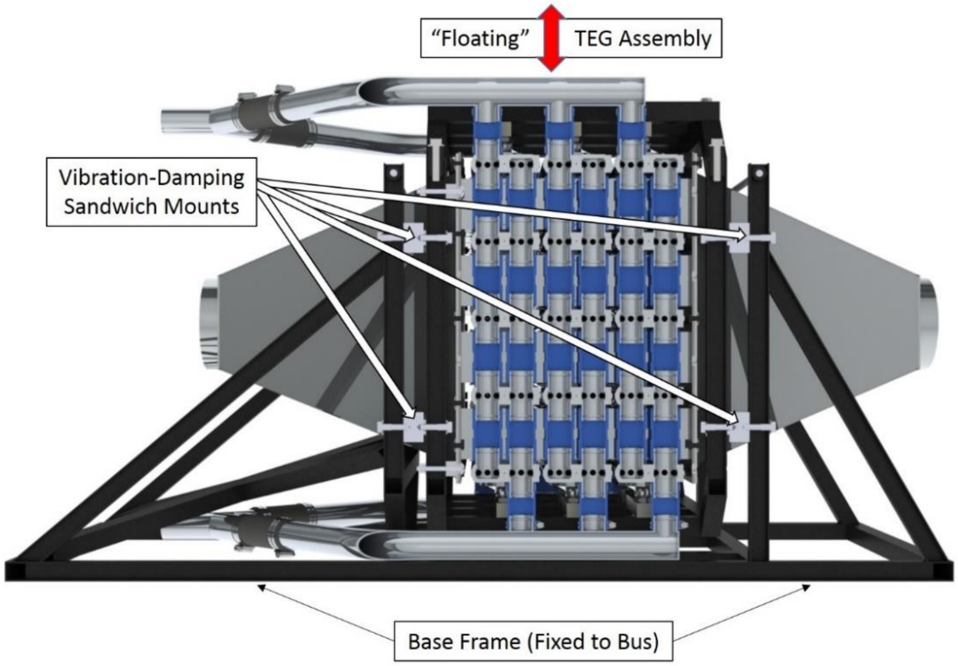


Figure 35. *TEG Mounted in Frame*

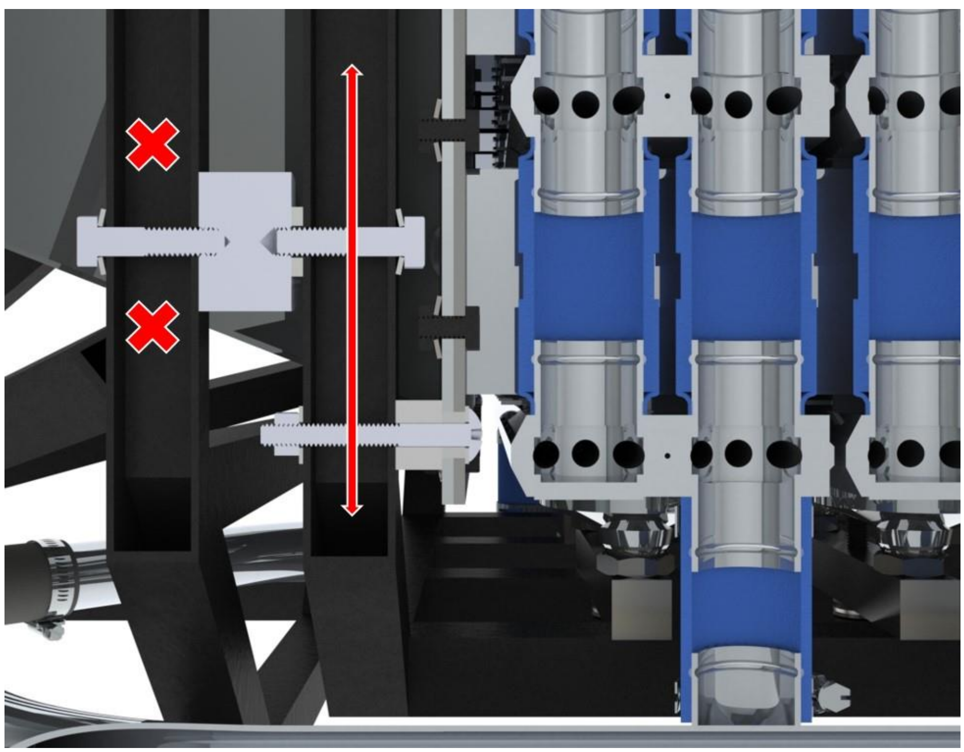


Figure 36. *Section View of Damping Point*

<u>Task 2 Preliminary TWHR System Test at Hi-Z</u>

For full system laboratory testing, an all fuel burner was acquired and can be seen in figure 38 and 40. As seen in figure 41 the average ΔT for the first stage heat exchangers was 201.88°C, the average ΔT for the second stage heat exchangers was 160.51°C and the average ΔT for the third stage heat exchangers was 134.44°C. When calculated, this shows that there is a 20% decrease in ΔT between the first and second stage modules. This results in a 4.88% difference with the 21% that was predicted through the testing of the prototype heat exchanger. Because the stage 1 to stage 2 ΔT decrease was slightly less than predicted in the full size TEG, these results were determined to be acceptable. It can also be seen from the data that the ΔT decrease between stage 2 and stage 3 modules was 16% which gives a 22.22% difference when compared with the 20% that was predicted. Again because the stage 2 to stage 3 ΔT decrease was considerably less in the full size TEG than predicted, these results were determined to be acceptable.

In the first test the TEG was cooled using Hi-Z's internal water loop which produced about 1,286 watts of electrical power. This is 91% of the 1400 watts of power that was predicted. When the system was cooled by a radiator and fans, it produced 970 watts. Even though this is 69% of the predicted power, it was expected that the air flow through the radiator while attached to a moving vehicle would increase and make up the difference in power. These results were also determined to be acceptable.

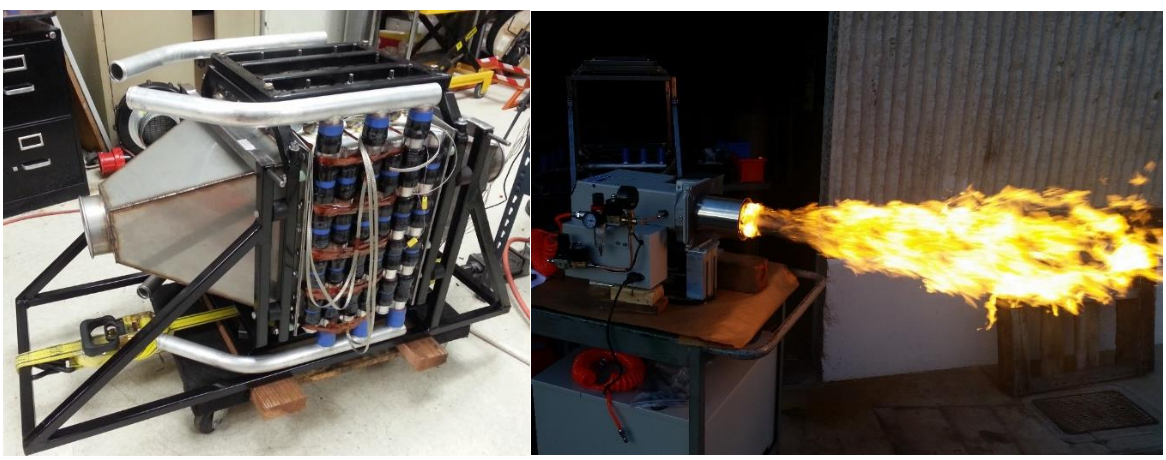


Figure 37, 38. *Assembled TEG and All-Fuel Burner*

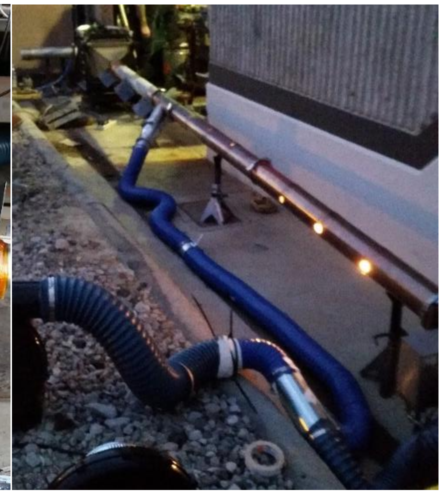



Figure 39, 40. *Full TEG Test Using Internal Cooling Loop and Burner Assembly*

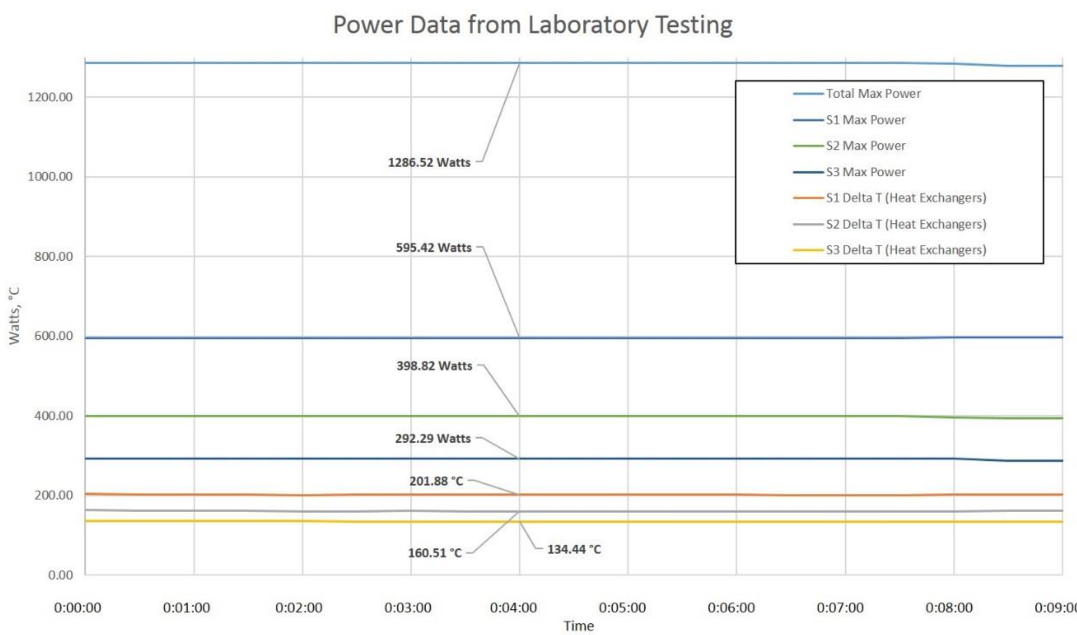


Figure 41*. Full TEG Testing Data Using Internal Cooling Loop*

<u>Task 3 – System installation on selected bus</u>

Validate Pre-service Performance

After the TEG was installed on bus 811, several pre-qualifying tests were performed to ensure proper system integration and operation.

The first test performed was designed to determine proper function of the diverter valve during a regen cycle and/or TEG overheating. This valve is designed to divert exhaust gasses away from the TEG and out to the atmosphere during a regen cycle or if the TEG's cooling system reaches temperatures above 90 °C. After the TEG was installed the diverter valve and valve control system were installed as seen in figure 42. Before the exhaust was routed to the TEG, the bus was taken to an outside area of the LYNX facility and the regen cycle was started manually by a LYNX mechanic. The valve was initially programmed to divert the exhaust flow away from the TEG once the inlet temperature reached 300 °C.

Figure 42. *Diverter Valve Mounted to Bus Exhaust*

The data seen below in figure 43 shows the temperatures present at the diverter valve thermocouple before, during and after the regen cycle. This thermocouple is positioned immediately before the diverter valve and after the regen apparatus. The valve was visually observed to open and close at the desired temperature of 300 °C as seen by the 'Dump Valve Trigger Temperature' line below. These recorded temperatures were compared to the values displayed by the mechanic's computer and they were virtually identical for the duration of the regen test. With this information it was determined that the valve mechanism was working properly and could be connected directly to the TEG. The TEG's cooling system was also tested to make sure the diverter valve would isolate the TEG during an overheating event. Since it would be dangerous to the TEG to intentionally overheat it to perform this test, the thermocouple that was inserted in a stage 1 HXc was removed and heated to 90 °C several times. During this test the diverter valve was observed to isolate the TEG from exhaust gasses when the thermocouple measured above 90 °C and reopen the TEG to exhaust gasses once the thermocouple measured below 90 °C. Again this function was determined to be operating properly and the thermocouple was reinserted into the stage 1 HXc.

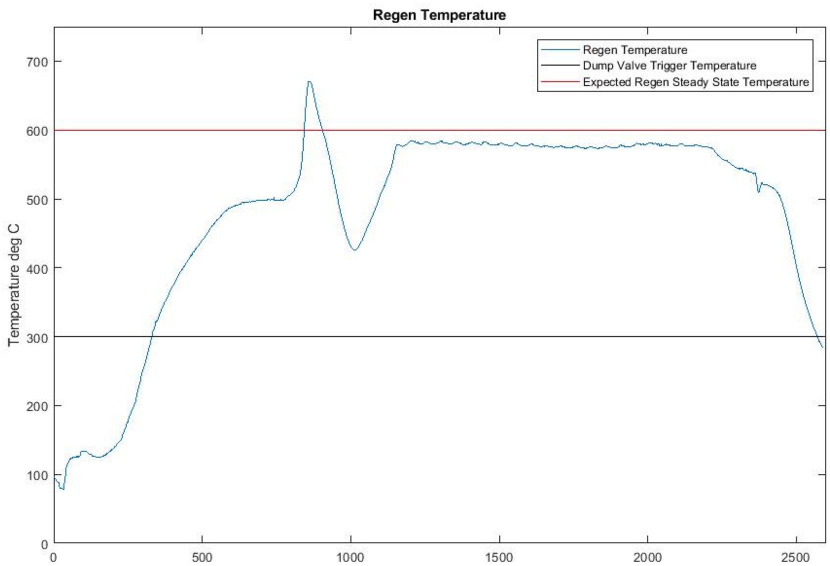


Figure 43. *Diverter Valve Temperature Data vs Sample Number*

Complete Vehicle Integration Design/Vehicle Integration Design Review

Several components of the integration design had to be finalized upon installation due to unknown factors that could only be explored on site. The TEG mounting hardware was not decided upon during the initial integration design. The material type of the roof sub-frame on the bus was unknown at the time and the exact location of the sub-frame cross members could only be estimated. It was known, however, that the sub-frame was constructed from metal rectangle tubing. Because of this, blind insertion hardware was initially proposed for use as main anchors. After a thorough inspection of the roof and sub-frame it was found that the structure was constructed with thin wall aluminum tubing. This was determined to be an insufficient mounting interface for blind insertion hardware. Instead, 4 holes were drilled through the roof cross members and into the interior of the bus. Grade 8, 3/8" hardware was then inserted through the curbside of the TEG frame and then into the holes in the roof. The bolts terminated on the underside of an extruded piece of aluminum trim that ran the entire length of the bus. Steel flat bar was then drilled and installed over the aluminum extrusion and bolts to distribute the load. Grade 8 nyloc nuts were then used to secure the bolts in place. The roadside of the TEG frame lined up with a piece of 2" x 2" aluminum angle that was previously used to mount the cowling. This angle was already securely anchored to the corner support beam in the roof sub-structure. The TEG frame was then bolted to this aluminum angle with Grade 8, 3/8" hardware and nyloc nuts. The DAQ, radiator frame and resistor bank were all mounted in the same manner.

Install TWHR System on the Bus

The installation of the TEG onto bus 811 began April 30th and was completed May 9th. As seen in figure 44, the TEG frame was securely mounted to the bus roof in the pre-designated position. No serious obstacles were encountered during the install, but the metal fabrication required to mount all of the components was labor intensive and was conducted for nearly the entire duration of the operation.

Figure 44. *TEG Mounted on Bus Roof*

<u>Task 4 – System validation at KSC facility</u>

Collect In-service Data

After the demonstration period at LYNX ended the in-service test data was collected and processed. The data acquisition system that FSEC used for the project uploaded about 40 data points every minute to their server in an IOS file. Software would then convert the .ios files to .csv files and make them available on the web for download. Typically there would be approximately 100-300 individual files uploaded per day. In order to access performance data in near real-time, Hi-Z developed a Matlab program (figure 45) that would retrieve these files from the web and combine them into a single file for each day. The program would self-update when new files were available to download and plots could be made to quickly visualize important operational parameters in case of a malfunction.

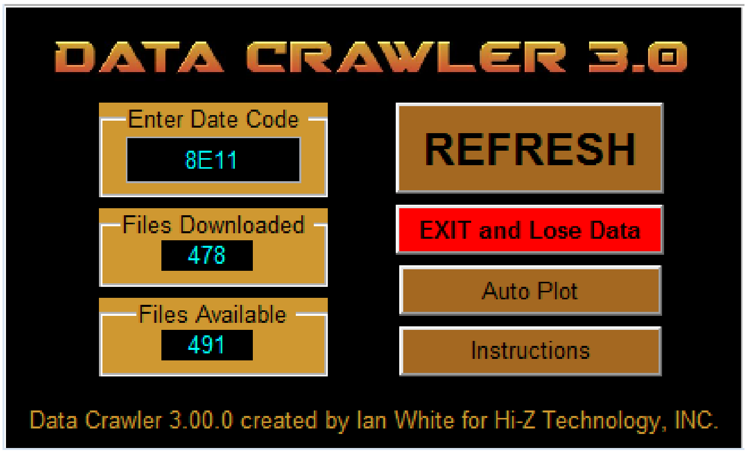


Figure 45. *Data Processing Program Provided by Hi-Z*

Kennedy Space Center Test Data

Testing of the TEG began on May 10th starting at LYNX. Hi-Z provided a chase vehicle for the trip to KSC to observe the system for any obvious signs of failure or other points of interest. Hi-Z also had the design engineer ride along on the bus to manually check TEG temperatures and to communicate with the chase vehicle. The only issue that arose during the trip to KSC was that the diverter valve bypassed the exhaust away from the TEG during highway speeds and redirected back to the TEG at slower speeds. The monitored temperature data confirmed that the inlet temperature was exceeding 300 °C and because of that the valve operated as it was programmed to do. Because the internal temperatures of the TEG were measured to be within acceptable values for this part of the test, the valve trigger temperature was reprogrammed to 400 °C once the bus arrived to KSC. For the duration of the testing at KSC and for the return trip to LYNX the diverter valve was observed to stay open the entire time (no regen cycles were observed).

During the testing at KSC, the DAQ wasn't properly uploading the data so the voltage output data was collected by hand and calculated into the values seen in figures 46-48. The majority of the data collected during the testing at KSC was done at highway speeds with a maximum speed of 64.97 mph. It can be seen from figure 47 that the power output reached a maximum of 1126 watts with an engine speed of 1625.1 RPM and a 101% engine load. This output exceeded the laboratory simulation results for radiator cooling which was 970 watts, a 14% increase. The increase in power output was anticipated due to the higher air flow rate through the radiator at highway speeds.

Overall the maximum output was still 80% of the 1400 watts that was predicted. This has been determined to be due to the fact that the TEG never actually reached steady state temperature during the testing at KSC. When the max power in figure 46 was recorded, the bus had come to the end of the test track and had to stop to turn around. Both the temperature and power data points before the maximum were still increasing in magnitude when the bus had to stop. If the bus had continued until a steady state was reached, it is probable that the power output could have reached the expected 1400 watts. During the testing at KSC, the data logger wasn't recording exhaust input temperatures of the TEG so this cannot be included in the analysis.

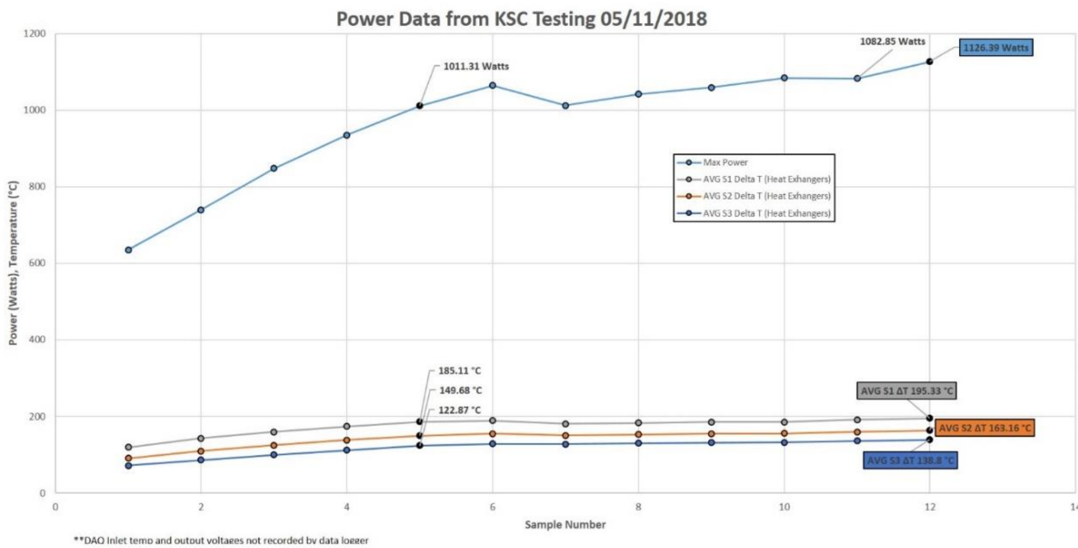


Figure 46. *TEG Max Power Output and S1, 2, 3 HXΔT*

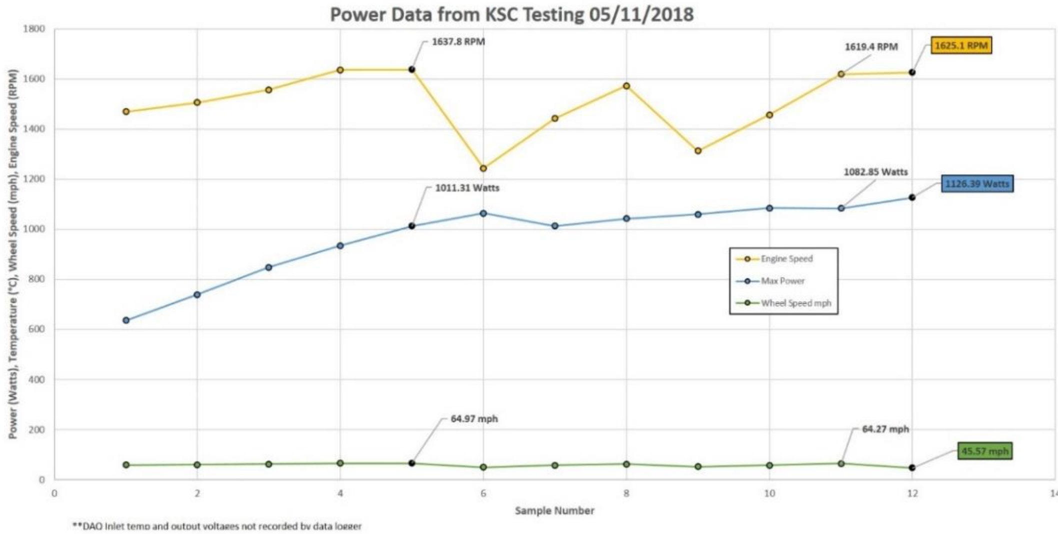


Figure 47. *TEG Max Power Output, Wheel Speed and Engine Speed*

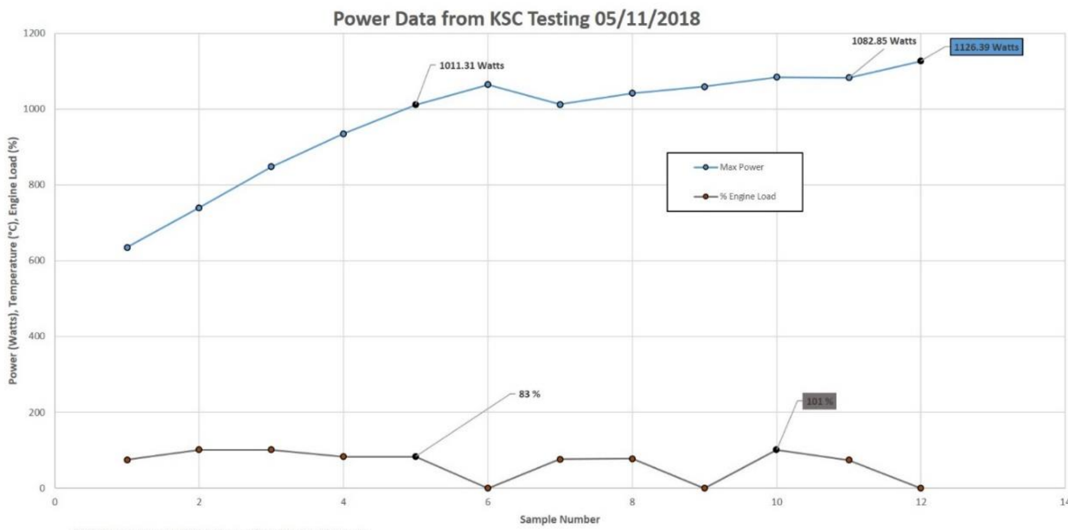


Figure 48. *TEG Max Power Output and % Engine Load*

After the bus returned to the LYNX facility, the problem with the DAQ was resolved and data could then be retrieved from it via the internet. Below (figure 49) is a temperature plot of typical test data that was collected during route testing. At 2.1E4 seconds on the x-axis the regen cycle can be seen as a large temperature spike at the TEG inlet and immediately following, the TEG heat exchangers cool down significantly until the regen cycle finishes. This shows the correct operation of the diverter valve system.

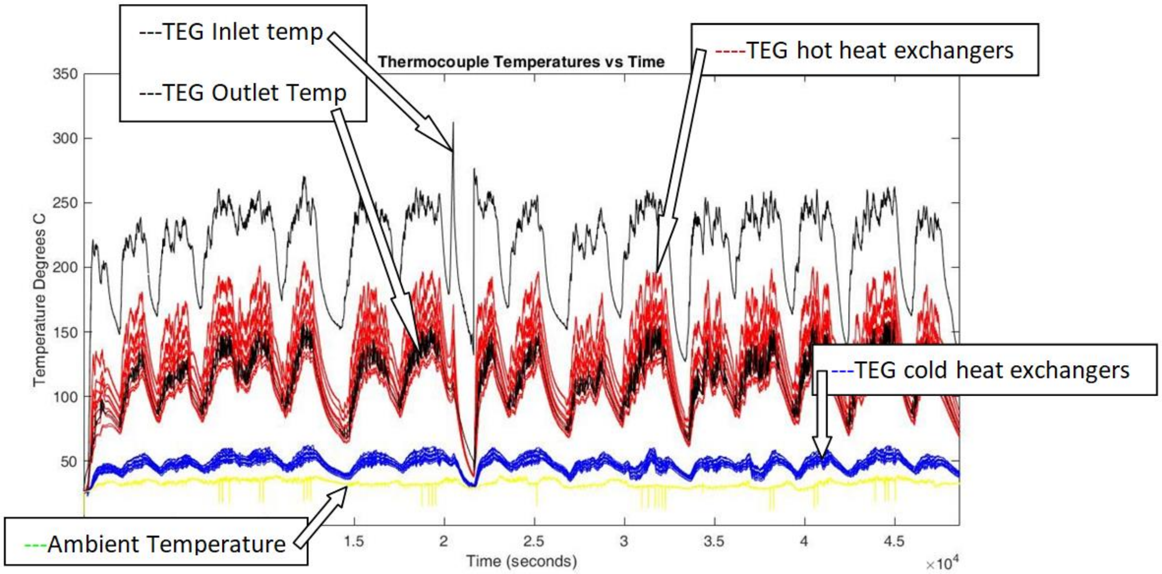


Figure 49. *DAQ Collected and Data Crawler Processed Temperature Data Example*

<u>Task 5 – FSEC Independent Evaluation</u>

Stage 2 Voltage Output Approximation

Between May 10th and June 9th the TEG voltage output data was collected from stage 1, 2 and 3. During this period, stage 2 consistently recorded 0.00 volts for every data point so a technician from Hi-Z was sent to LYNX to determine the cause. The voltage output signal from stage 2 was determined to be present at the DAQ connection which was labeled as terminal # (1 & 125). The electrical connections at the DAQ were inspected and determined to be securely fastened. The stage 2 output signal wire was then disconnected from terminal # (1 & 125) and connected to terminal # (1 & 2). Terminal # (1 & 2) was not being used and allowed for the same 0-10 volt input as terminal # (1 & 125). As a result, the stage 2 voltage readings were then found to be present in the data that was collected from this point on. The bus only ran for two days after the correction, June 11th and 12th. A tree branch strike destroyed part of the cooling system and the TEG was decommissioned immediately do to extensive heat damage. The only usable stage 2 voltage output data came from June 11th, the data for the following day was useless because the TEG was overheating and was not producing meaningful voltage data for any stage.

Terminal #	Description	Signal	Module Type-Number-channel
1 & 124	Stage 3 regulated output	0 - 10V	ADAQ1400-1-8
1 & 125	Stage 2 regulated output	0 - 10V	ADAQ1400-1-9
1 & 126	Stage 1 regulated output	0 - 10V	ADAQ1400-1-10
1 & 2	Stage 1	0 – 10V	ADAQ1400-1-5

Figure 50. *Voltage Input Terminal Allocation*

Figure 51 takes the voltage output from stage 2 and determines what percentage of voltage it is as compared to stage 1 and stage 3 voltage output. Since stage 3 often operates at temperatures which produce very little voltage it can be seen that there is less data that linearly corresponds to stage 2. Because of this, the relationship between stage 2 and stage 1 was chosen to estimate the linear percentage correlation for the unrecorded stage 2 voltage data (pre-June 11th). Assuming a linear correlation, stage 2 voltage was determined to be an average of 78.38% of stage 1 voltage at any point in time within the circled area. The data is more stable here than anywhere else so it was chosen for this purpose. The standard deviation of the data from 78.38% was calculated to be 3.14%. The circled area below includes both open and closed circuit voltages.

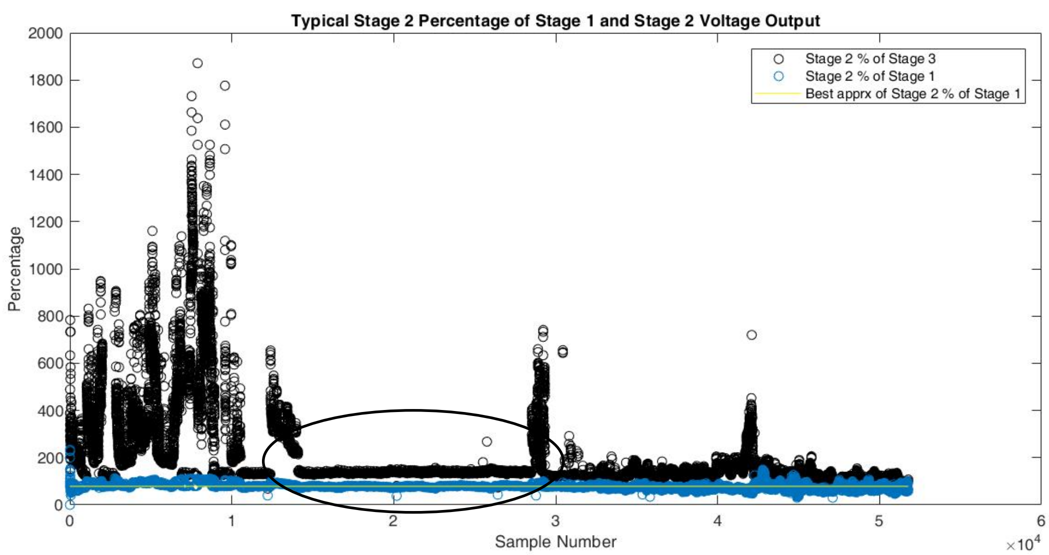


Figure 51. *Data from 06/11/2018*

Figure 52 gives a closer look at a section of the circled data range. Stage 1, 2 and 3 are the actual recorded data and the thicker yellow plot is the estimated stage 2 voltage which was calculated by the method described above. The thickness of the estimated plot line is due to a larger plot symbol that was used. In order to quantify the similarity of the estimated plot vs the recorded data plot, the area under each curve was calculated. When compared, the percent difference between the two areas was determined to be 1.94%.

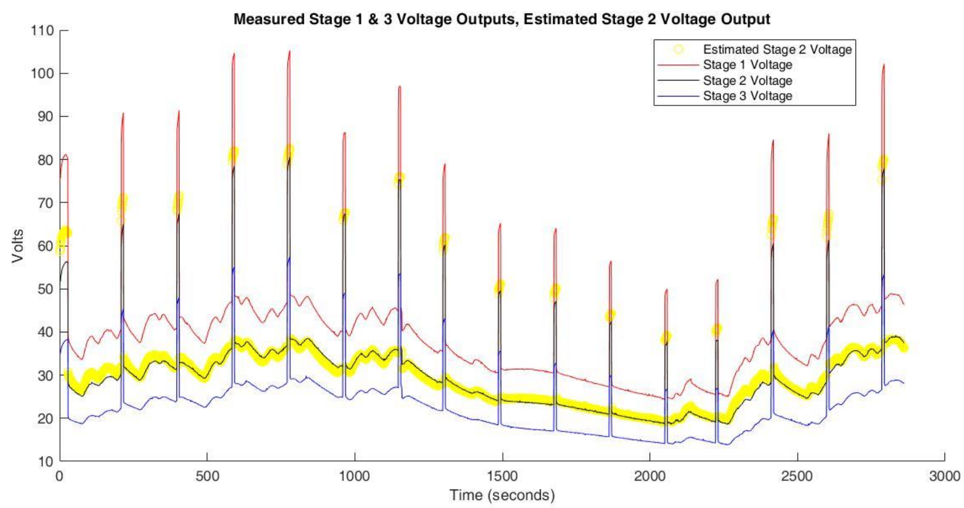


Figure 52. *Circled Data from Figure 51 Route Operation Test Results*

As seen in figure 53 below, the daily average max power varied significantly during route testing. It can be seen that the max power was highest for the first two days of operation, May 18th and 20th. The average max power produced for these days was 425.32 watts while for the remainder of the testing the average was 311.37 watts. Most of the data from June 2nd was corrupted and will not be included in this discussion.

It can also be seen from figure 53 that the power output of the TEG correlates with the exhaust inlet temperatures, the ΔT at the heat exchangers (with an exception of a slight deviation on June 7th) and the % engine load. This is a clear indication that the performance of the TEG did not diminish over the testing period; it just didn't receive the high temperature and flow rate that it did on the first two days of route testing. From the data it was also determined that the most probable cause of the power output difference from 425 to 311 watts was the change in routes. For the two days with the highest output, the bus was operated on routes 104, 106 and 113. The remainder of the routes that were run were mostly 48 and 49 with a single run on route 15. At the time of this report submission it is unknown what the differences are in the routes and why they would cause a change in TEG performance.

The heat exchanger ΔT (HxΔT) does not reflect the actual temperatures that are present on each side of the modules. There is a temperature loss across each interface of the module and heat exchanger which is equal to 15 °C per side when the HxΔT is equal to 230 °C. This temperature loss decreases approximately linearly as the HxΔT becomes less than 230 °C. Because each stage has multiple hot and cold heat exchangers, the individual heat exchanger temperature readings were averaged for each stage and then for the entire day. This results in the S1, 2, 3 HxΔT values seen below.

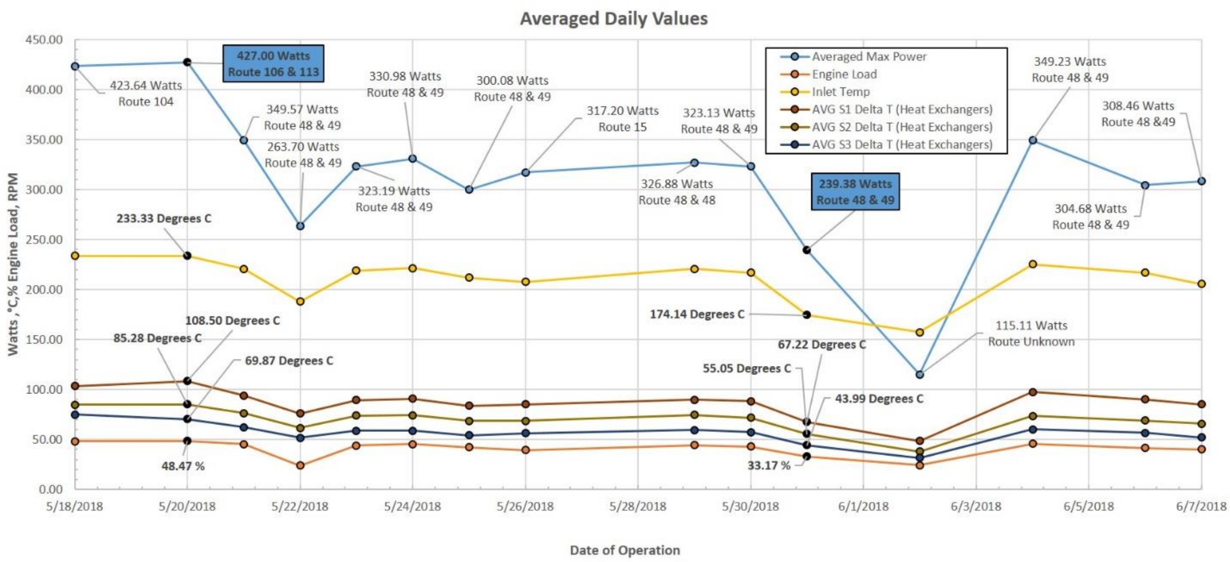


Figure 53. *Average Daily Max Power, Intake Temp, % Engine Load and S1, 2, 3 ΔT*

The relationship, as seen in figure 54, between average daily engine speeds and average daily power outputs show a near direct correlation as well, again with the exception of June 7th.

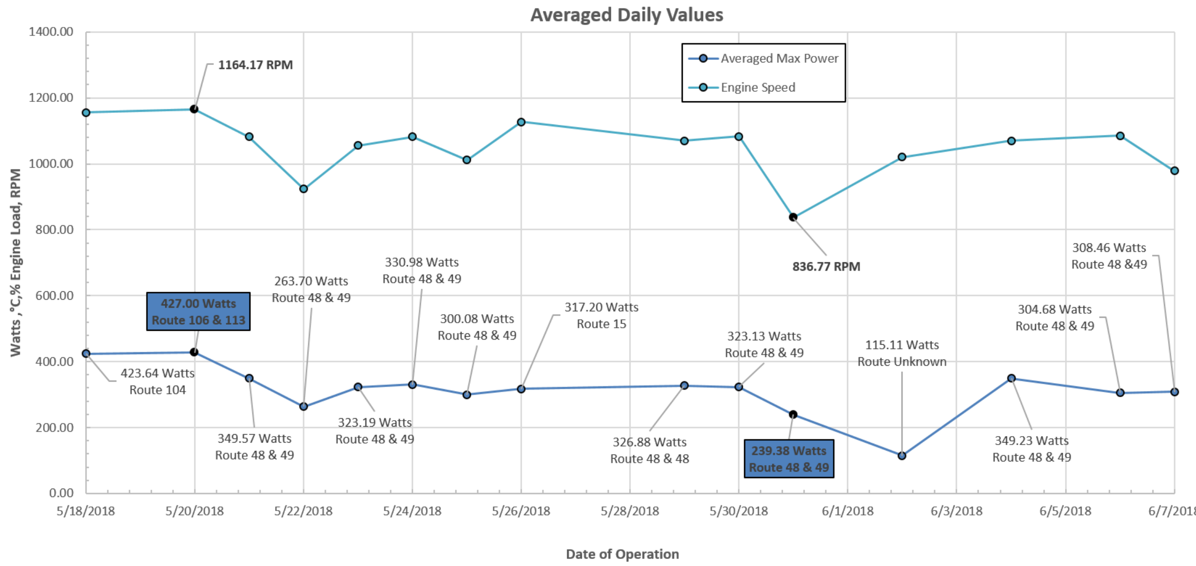


Figure 54. *Averaged Max Power and Engine Speed*

The correlation between average daily power output and average daily ambient temperature, however, is not as straight forward as was expected. As can be seen from figure 55, whenever ambient temperature increases or decreases the power output increases and decreases respectively. It was expected that there would be an inverse relationship between the two due to cold side heat exchanger temperatures being dependent on ambient air temperatures but this does not seem to be the case. Figure 56 shows they have a similar trend but it does not appear to be a direct cause and effect. It is probable that the intermittent load that the air conditioning system puts on the engine is responsible for these unexpected relationships. During the KSC testing, it was observed that when the air conditioning was turned on, there was a significant increase in TEG power output. The DAQ channel for the interior cabin temperature measurements was not functioning during the test so an accurate analysis on this matter cannot be performed.

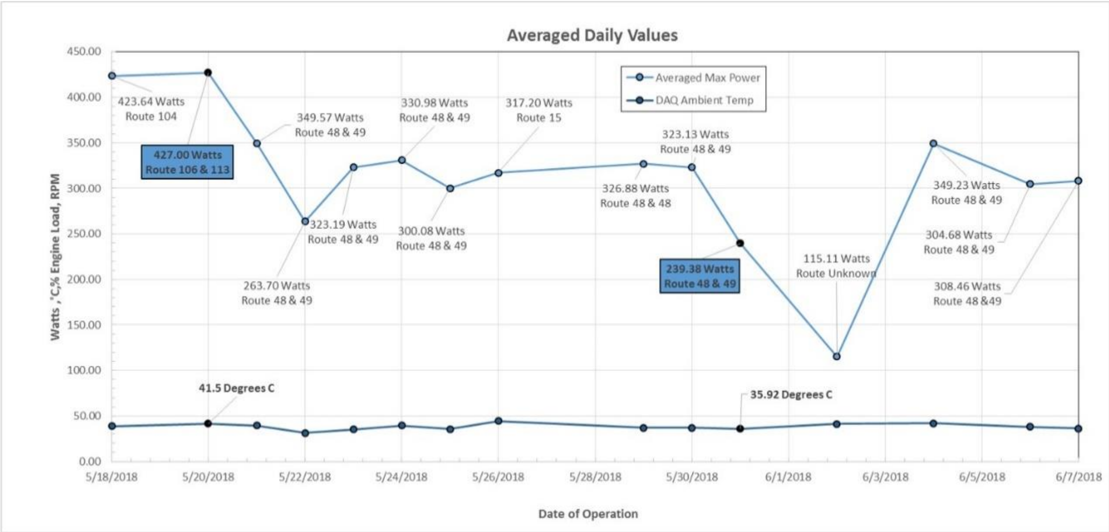


Figure 55. *Averaged Max Power and Local Ambient Temp*

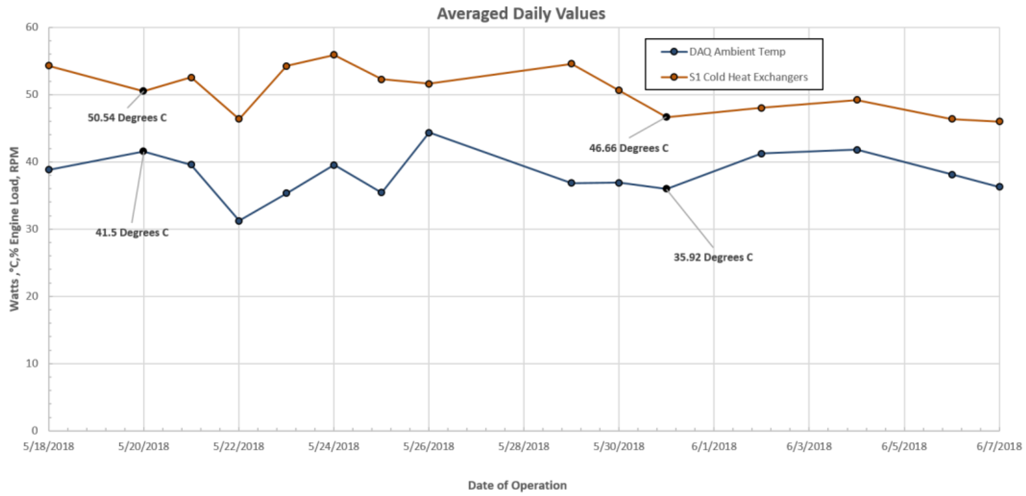


Figure 56. *Averaged S1 Cold-Side Heat Exchanger Temp and Ambient Temp*

When the daily averaged max power is plotted with the daily ridership and trip distance (figure 57) it can be seen that there is no obvious correlation between the data sets. In order to see the effect of these conditions on the power output a more in-depth analysis would have to be done for each individual day.

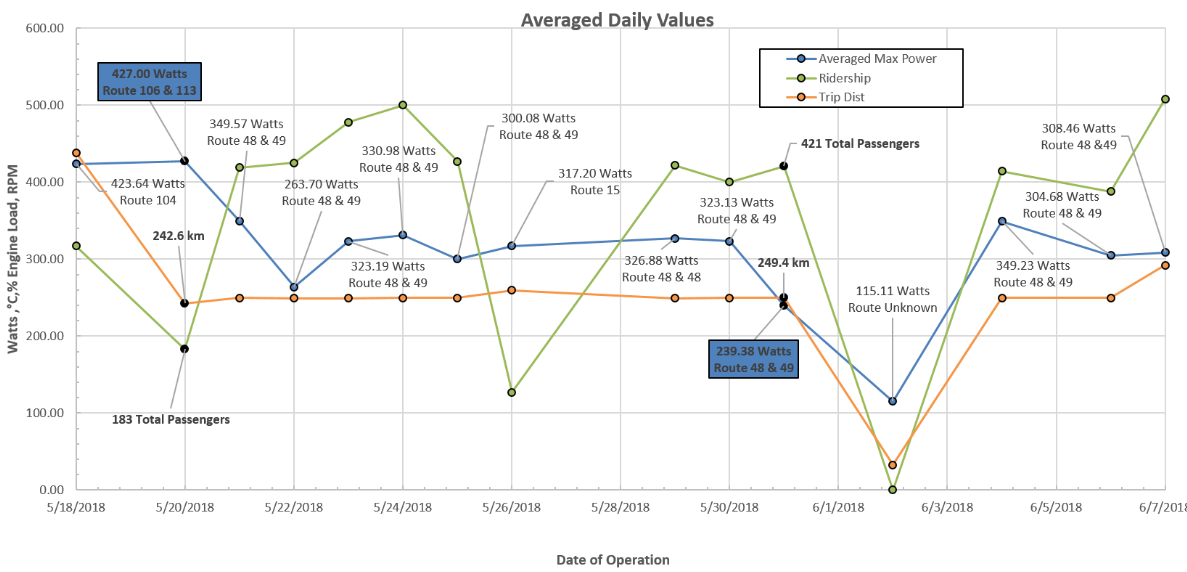


Figure 57. *Averaged Max Power, Ridership and Trip Distance*

$$V_{open} = \left(\frac{V_{open(max)}}{2}\right)$$

$$Power = \left(\frac{V^2}{R}\right) = \frac{\left(\frac{V_{open}}{2}\right)^2}{R_{internal}} = \left(\frac{\left(V_{open}\right)^2}{4 \times R_{internal}}\right)$$

Figure 58. *Max Power Calculation*

Part 4- Post Service Inspection and Analysis

As mentioned above, the TEG suffered an overheating event as the result of a tree branch strike which destroyed the cooling system. Upon initial inspection it was determined to have been damaged beyond the scope of a field repair. Steps were immediately taken to decommission and remove the TEG from the bus. The filler neck seen in figures 59 and 60 was the critical point of impact from the tree branch. The radiator and TEG shrouds protected the rest of the system from any damage. The coolant loss began at this point and once the TEG started overheating, the heat shrink hose clamps on the TEG melted (figure 62) and the system was nearly emptied of coolant.

The Gates POWERGRIP® SB clamps have a safe operating temperature range of -40 °C to 150 °C. The polymer egg crate incorporated into the modules melts at 350 °C but as long as the cold side of the module remains below 250 °C, the HZ-20 modules are designed to withstand periodic temperatures up to 400 °C. It can be seen in the test data (figure 64, regen cycle) that the cold-side heat exchangers reached temperatures of nearly 350 °C while the hot-side heat exchangers experienced temperatures exceeding nearly 400 °C.

Figure 59, 60. *Before and After Coolant Filler Neck*

Figure 61, 62. *Before and After Heat Shrink Hose Clamps Melted*

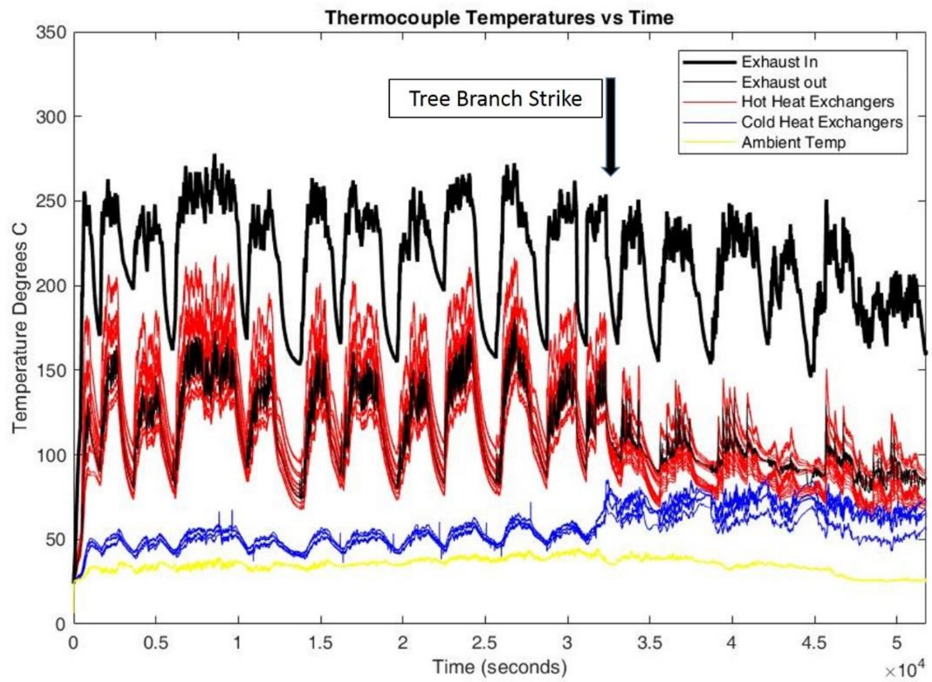


Figure 63. *Temperature Data from overheating event (6/11/2018)*

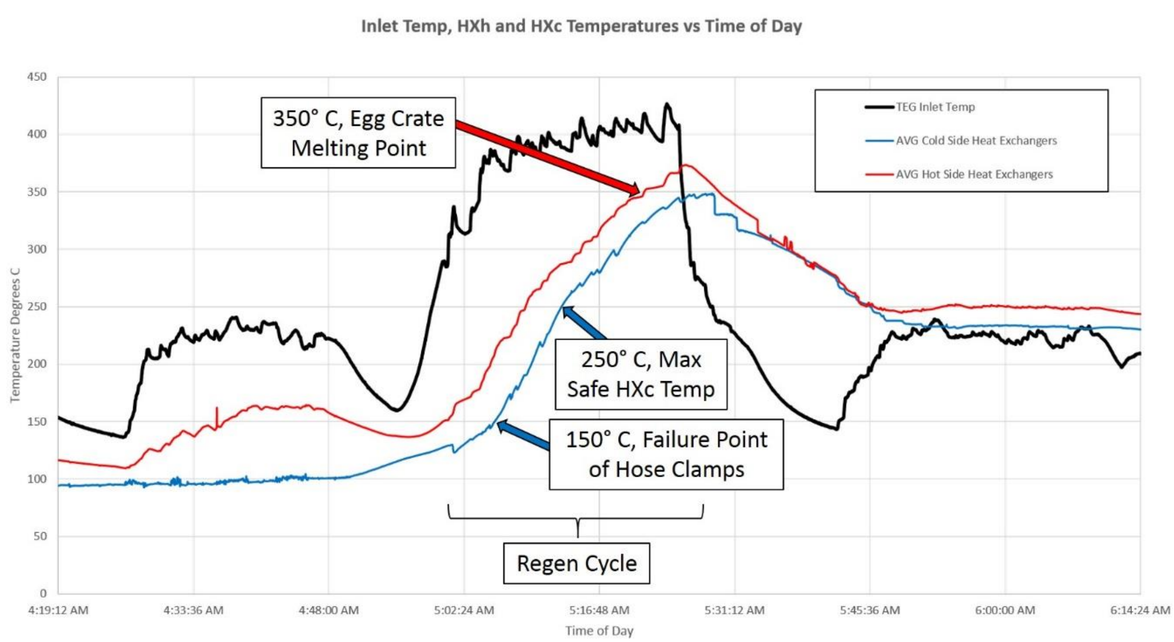


Figure 64. *Temperature Data from overheating event (6/12/2018)*

The overheating of the TEG could have been prevented but unfortunately part of the diverter valve control system that was designed to detect higher than normal temperatures, failed to operate properly. The microcontroller was programmed to read the thermocouple that was inserted into a stage one HXc and when temperatures above 90 °C were detected, the valve would divert the exhaust away from the TEG and into the atmosphere. Special attention was given to this valve system during installation and was tested with a heat gun to verify proper operation. This procedure was conducted several times throughout the installation and no problems were detected in its operation.

The cause of this failure was determined to be a faulty reading of the thermocouple mentioned above. The temperature data in figure 65 shows heat exchanger temperatures during operation, hot (red), and cold (blue). When the hot-side thermocouples read an average of approximately 200 °C, several of the cold-side thermocouple readings began to dramatically fluctuate from low to high with a variance high of about 65 °C. It is unknown how the microcontroller read these errant signals but it is theorized that due to their presence in the data, the valve control program could not interpret the readings and the >90 °C temperature was never recognized. Further testing would have to be done to prove this but it is simply not in the scope of this project to perform those tests. Hi-Z will review this problem independently of this project to ensure that there is no such failure on future projects. It should be noted that several of the thermocouples for the HXhs were found to be broken off and damaged beyond repair upon delivery of the TEG. Hi-Z has already determined these thermocouples are too fragile for extensive field testing and more robust alternatives are being investigated.

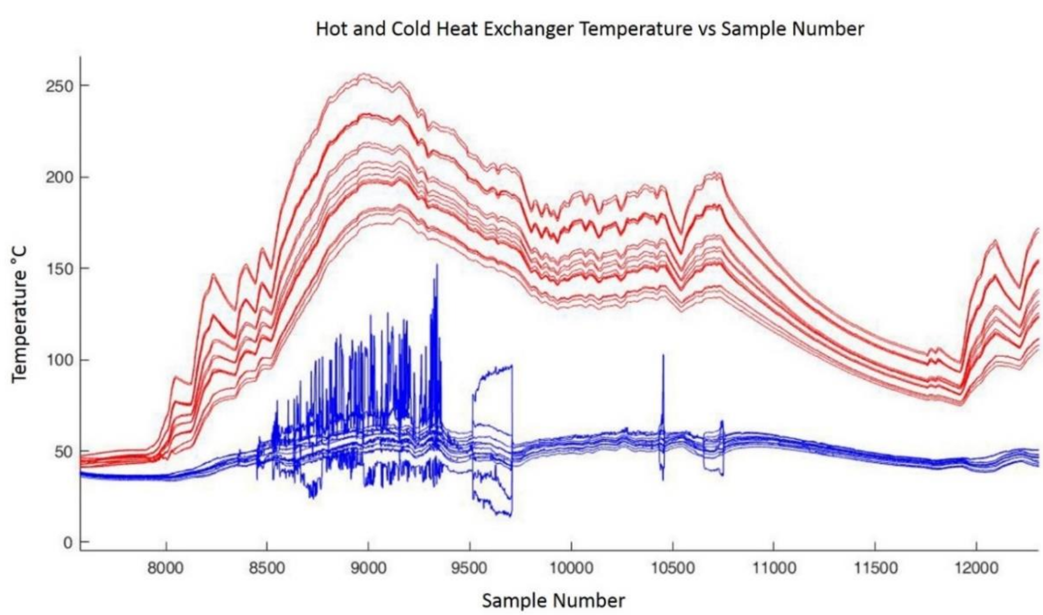
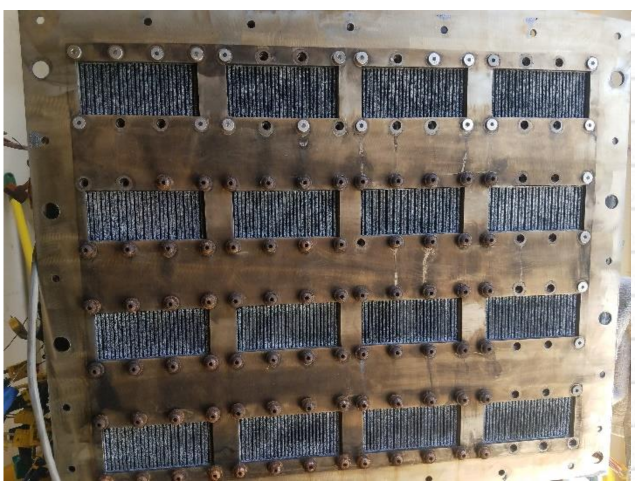


Figure 65. *Sample Data of Hot and Cold Temperature Anomalies*

Upon receiving the TEG back from LYNX, it was observed that the heat exchangers had accumulated soot deposits (figure 66). The soot was thick enough in some places to occlude the passageways but this seems to be due to the inconsistent spacing of the heat exchanger fins during manufacture. Several of these passages are visibly narrower than the average passage and this is where the deposits were located. Hi-Z contracted a vender to power wash the TEG to remove all of the soot deposits from the heat exchangers. The cleaning was considered to be successful as all of the passageways were cleared of the minor obstructions that the soot caused. This method of cleaning has been determined suitable for a regular preventative maintenance task for future projects.

The heat exchangers were also analyzed for physical deformation that may have occurred from the overheating event that the TEG experienced. First the heat exchangers were removed from the assembly and then the module mating surfaces were carefully cleaned. Nine measurements were taken per module mating surface from top to bottom of the heat exchangers with deep jaw Vernier calipers totaling 27 per heat exchanger. As can be seen in the table in figure 67, there were no discernable differences throughout the heat exchangers. Hi-Z is confident that these heat exchangers are in nearly the same structural condition as they were when the TEG was originally assembled and could be re-used if necessary. The modules, however, were damaged to a point that they can no longer be used. The plastic egg crates completely melted and the majority of module leads became unsoldered (figure 68).



	A	B	C
1	2.563	2.563	2.563
2	2.563	2.563	2.564
3	2.563	2.563	2.563
4	2.563	2.564	2.563
5	2.563	2.563	2.563
6	2.563	2.563	2.563
7	2.563	2.563	2.563
8	2.563	2.563	2.563
9	2.563	2.563	2.563

Figure 66, 67. *Hot-side Heat Exchanger before Cleaning and Measurements*

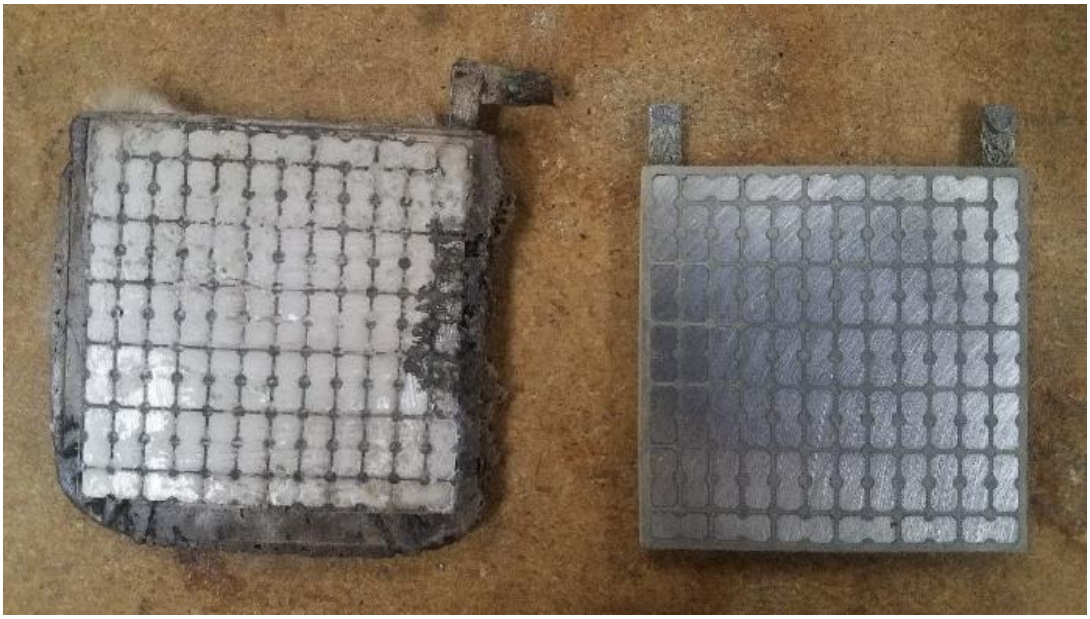


Figure 68. *Overheated Module and New Module*

Part 5- Assembly Considerations and Observations

Thermal Grease Type &Thickness

Prior experience has shown that the thickness of thermal grease to be placed on each side of the ceramic wafers was should be "as thin as possible". For this project the thermal grease was carefully and evenly applied with a solvent brush. Many other techniques of application were tried, (rolling, scraping etc.) but brushing on the grease proved to provide the best quality thin coverage. A Conquest West and Boron Nitride mixture was used.

Ceramic Wafer Size

The ceramic wafers chosen for this project were 0.120" larger in both length and width than what has been used for the HZ-20s in the past. The chosen wafers measure 3"x 3" and have the same thickness (0.01") as the previously used wafers. It was found that the larger wafers made assembly much easier because they didn't have to align exactly with the modules to provide full coverage.

Module type

The modules that were chosen for this project are the Hi-Z, HZ-20s. This particular batch was made by a previous vendor named Zhao. They contain 2/3 more material than the current HZ-20. A total of 96 modules were used on the TEG, 32 modules for each stage.

Module Thickness

For all of the modules chosen for the TEG the variance in thickness from one module to another was determined to not exceed 0.001”. All module thicknesses were measured and grouped together so that each horizontal layer of modules was as uniform as possible.

Module Preparation

The modules were all carefully inspected and cleaned in an ultrasonic bath. Leads were positioned away from the hot side (intake) of TEG to prevent overheating of the solder connections.

Roll Pins vs Template, Kapton Tape

On a previous TEG build, a pattern of press-fit spring pins were pressed into the surfaces of the heat exchangers in order to restrict the movement of modules and wafers during assembly. These features proved to be problematic during the build process of that TEG. The modules and wafers would get hung up on the pins and would prevent the heat exchangers from coming together. For this DOT build, the modules were located in place by glass-fiber insulation that was pre-cut around the modules. The modules were also taped down to the heat exchangers with Kapton tape. There were considerably less problems with this method than that of the other. Seen below is how the modules were located on the heat exchangers. The material seen in figure 69 is polyimide but it was replaced by the high R value glass-fiber insulation mentioned above. 3 layers of glass-fiber were used with a layer of aluminized Kapton in between each. The Kapton layer (figure 71) was used to reduce the radiant losses between the hot and cold-side heat exchangers.

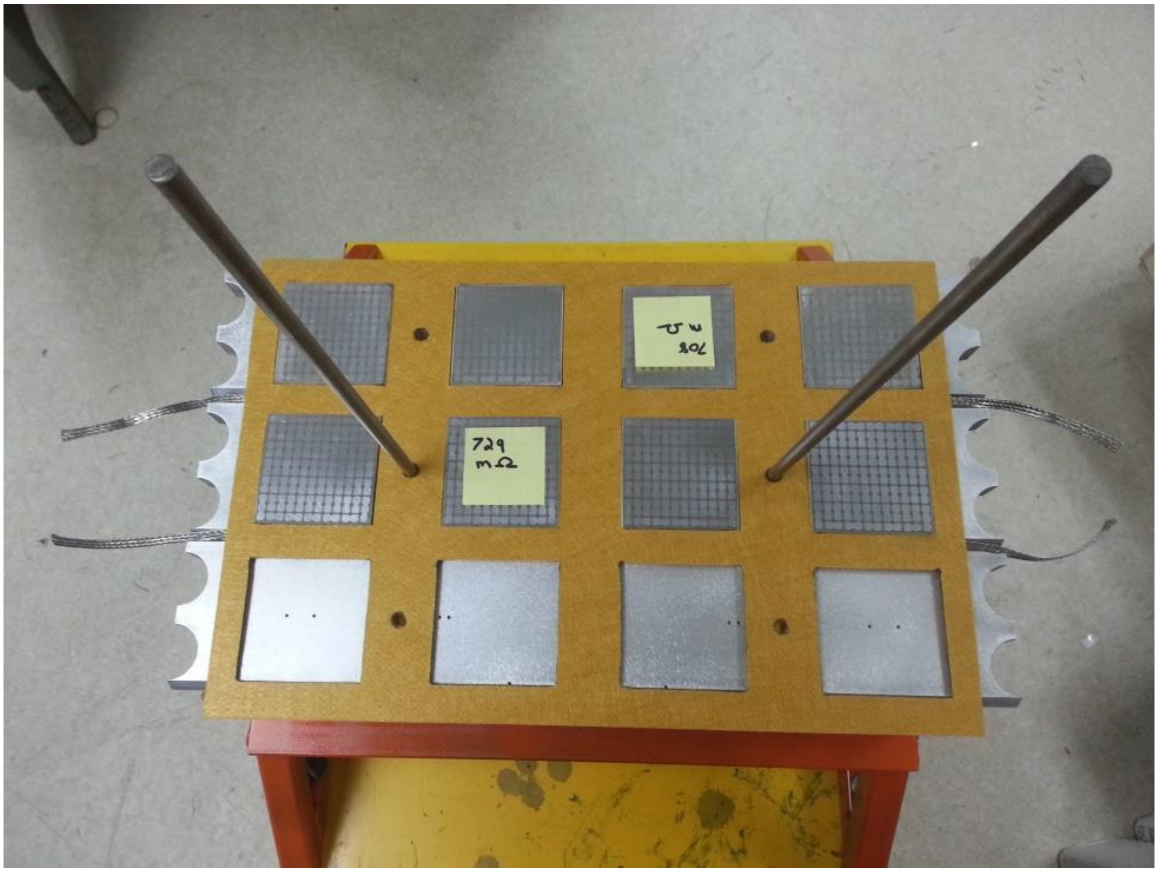


Figure 69. *Base layer of HXc and insulation layer*

Assembly Jig

For a high quality and structurally sound build to occur, a jig had to first be built (figure 70). This jig allowed the assembly team to secure the base of the TEG down to a cart in order to build from the bottom up.

Figure 70. *Assembly Jig and first layer of heat exchangers, modules and insulation*

Figure 71. *Aluminized Kapton layer of MLI*

Hose Clamps

The majority of hose clamps used on the TEG were Power Grip heat shrink type. They have a much lower profile than conventional worm-drive clamps and they adjust themselves to maintain tension over a wide temperature range.

Cooling Loop Direction/Configuration

The TEG cooling loop starts at a single 1.5" hose fitting and ends at a 1.5" hose fitting. These fittings were located on the top and bottom of the TEG. Several configurations of the cooling loop were setup and experimented with. The system that gave the most favorable results positioned the coolant inlet on the bottom and outlet on the top. Both top and bottom inlets pointed in the forward position of the TEG.

Leak Testing

All of the liquid cooled heat exchangers and manifolds were leak tested at Hi-Z with the water chiller system (figure 72). None of the welded joints showed any sign of leakage. After the TEG was assembled, there were several leaks from the Power Grip fittings. Once the TEG was operated at temperature, the Power Grip fittings shrunk and sealed the leaks. No other leaks were found during the duration of the testing phase.

Figure 72. *Leak testing cold-side heat exchangers*

Part 6- Contacts

Key Hi-Z Participants

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APPENDIX

B

Independent Evaluation

FSEC prepared a detailed report explaining the methodology behind their analysis and their findings from the demonstration period.

FLORIDA SOLAR ENERGY CENTER®
Creating Energy Independence

Evaluation of Thermo-Electric Generators to Increase Transit Bus Fuel

FSEC-CR-2086-18

September 31, 2018
(Revised Report 10/08/18)

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Executive Summary

The Florida Solar Energy Center (FSEC), under contract to the Center for Transportation and the Environment (CTE), provided technical assistance and performed independent review of data recorded from a 1.2 kW thermoelectric generator (TEG) system (figure E1) . Under this application, the TEG utilizes hot exhaust gases as energy source from a transit bus diesel engine and generates useful electricity. Project team members consisted of Hi-Z Technology Inc., providers of thermoelectric system, International Trade Bridge (ITB) and Energy Florida (non-profit organizations) which provided guidance on applications for thermoelectric development and commercialization. A forty foot diesel bus (Gillig) was provided for the TEG retrofit by the Central Florida Regional Transportation Authority (LYNX) in Orlando which acted as a project partner.

Figure E-1. Core of thermo-electric generator (TEG) unit prior to installation on a transit bus exhaust system.

Prior to the experimental route transit setup, FSEC provided technical assistance by configuring a suitable data acquisition system. The experimental data acquisition consisted of measuring and validating volumetric exhaust tail pipe flow which amounted up to 16.4 cubic feet per second (ft^3/sec). Another important topic investigated was elevated temperatures of the exhaust as a result of the regeneration ("Regen") cycle, which is related to the periodic diesel particulate filter process typically found on buses. The periodic "Regen" cycles had to be considered due to elevated temperatures (>600 ^oC) which can exceed the TEG materials operational design temperatures. Ultimately a control system was implemented by using the "Regen_Active_Signal" provided by the bus Controlled Area Network (CAN) which activated a flow diverter exhaust valve to avoid damage to the TEG. These controlled events had a significant impact on the ability of TEG to reach its maximum energy recovery potential.

The TEG was retrofitted atop the bus roof, including a cooling radiator with dual fans (240 watts) and water pump (90 watts) and other low power control peripherals. Controlled Area Network (CAN) measurements were automatically recorded on a mini logger on board, where data recoded values were stored using a one-second interval following start-up electrical ignition. Thermoelectric measurements (i.e, temperatures and voltages) were measured by a roof mounted data acquisition system utilizing a custom wire harness cable retrofitted into the bus along with the CAN data. All measurements were merged and compressed into a data file and transmitted in near real-time (every 10 minutes) via cellular network to a dedicated FSEC server, where it was further processed. Demonstration of the thermoelectric system began during a simulated transit route at Kennedy Space Center (KSC) Florida, where the TEG recorded a peak of 1,126 watts and averaged a power capacity of 971 watts during the one-hour transit route period. Further operation of the TEG was evaluated under LYNX transit routes in Orlando, FL from May 18 through June 12, 2018 where the average power generated was somewhat lower. During transit route demonstration, the power generated by the TEG was delivered to a fixed load (8.3 ohm power resistors) affixed on the back of the rooftop in a well vented enclosure.

Nevertheless, power generated by the TEG could be used to reduce the bus alternator load or store energy to serve other ancillary electrical systems.

Recorded voltage data was essential in determining the actual power generation of the TEG during operation. A controller was designed to open the electrical power circuit using low resistance relays to momentarily measure the open voltage across the three thermoelectric stages that composed the TEG. Based on the known fixed resistance load and electric formulae applicable to thermoelectric devices, the flowing current for each of the stages was determined. Delivered power to the fixed resistance load was then calculated. Figure E2 represents the dynamic power generated during a transit route on May 18, 2018, where the TEG was able to generate power exceeding 600 watts and momentarily approaching 800 watts peak. Net power is also shown where the power utilized by the cooling components of the TEG heat exchanger is taking into consideration. On this day the TEG would be able to generate an averaged 327 watts (net) after the auxiliary power expended for cooling was subtracted. Although the amount of passengers on the bus were unknown, it achieved an average of 3.3 mpg with air conditioner and TEG parasitic cooling load on the alternator.

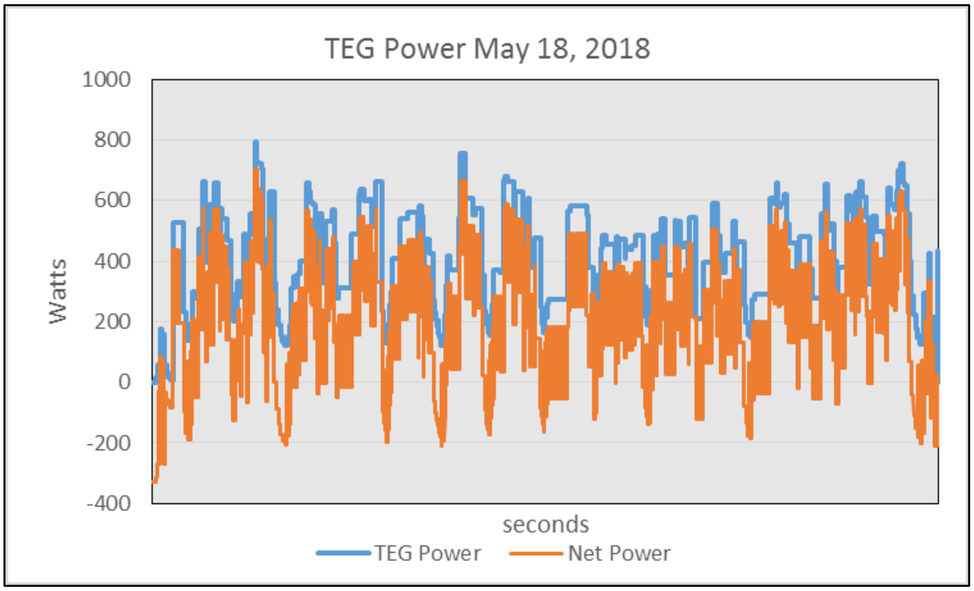


Figure E-2. TEG power and Net power generation for transit activity on a Lynx bus, Orlando, FL.

During transit route demonstration, the cooling components of the TEG were operated continuously. However, further improvements to the cooling controls could be implemented to reduce ancillary power during those periods the bus is in motion. For example, airflow passing through the cooling radiator when the bus exceeded 10 mph could negate the parasitic power (240 watts) of the radiator fans which imparts a penalty by additional load to the bus alternator.

Data analysis was performed on transit routes by setting an ancillary power reduction (-240W) threshold at seven miles per hour (7 mph) using the CAN wheelbase speed. Similarly when the bus was standing still at 0 mph, only pump power of 90 watts to circulate cooling fluid was subtracted as penalty in the net power calculations. These two conditions would omit the need for cooling fan power. Averaged results comparing TEG power and net power as adjusted for ancillary cooling components can be observed in figure E3 for the period ending on June 12th, 2018. Route trajectory (including stops) and average speed had an impact on power generation as was the case for May 18 and May 20.

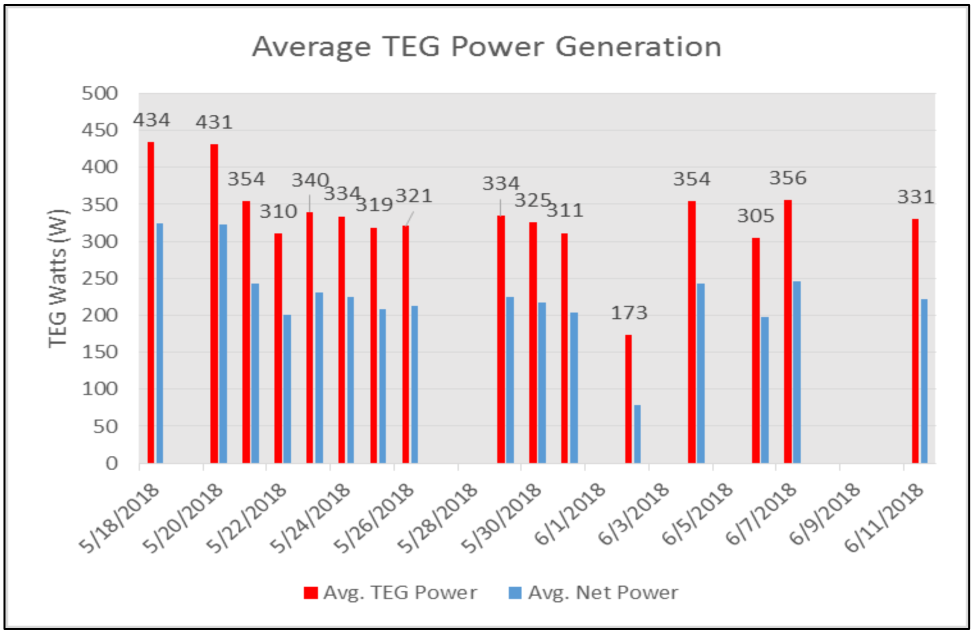


Figure E-3. Averaged TEG and Net power generated during transit routes for the period ending in June 11, 2018.

Engine operating revolutions per minute during transit routes was also analyzed. Results observed are similar in distribution to other findings reported which are applicable to bus transit operation. Figure E4 shows the average percentage of occurrences in histogram form (rpm bins) and found that the highest percentage of alternator operation appears in the lower idle region (1600 rpm). The Gillig bus alternator has an engine to belt pulley ratio of 1:2.

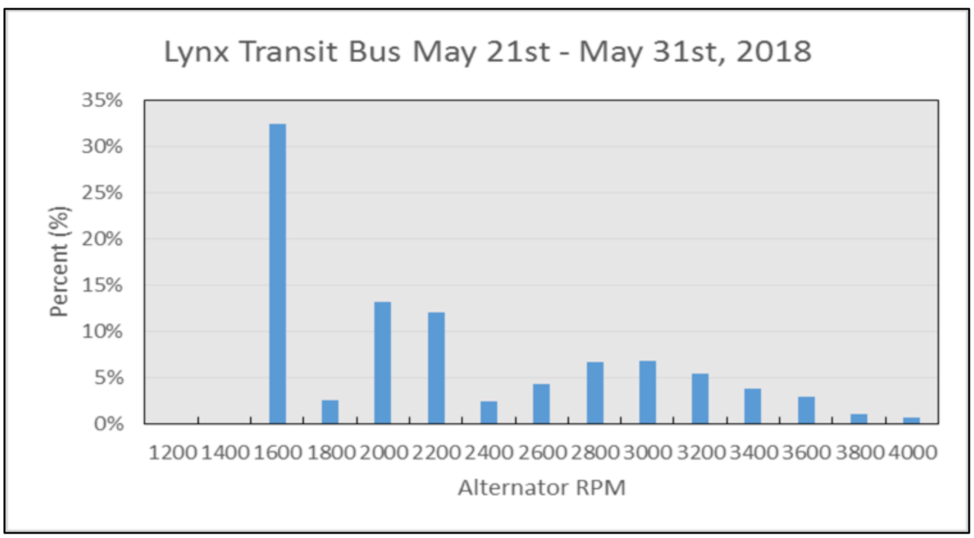


Figure E-4. Histogram showing rpm bins and percentage of total occurrences for the bus alternator.

Engine efficiency was then analyzed against recorded variables such as revolutions per minute (rpm), fuel delivery rate and engine torque. Figure E5 shows the averaged engine efficiency as function of revolutions per minute (rpm) using data for actual recorded fuel rate and instantaneous torque. Each of the bars representing "rpm" are given a weight based on the findings presented in figure E4.

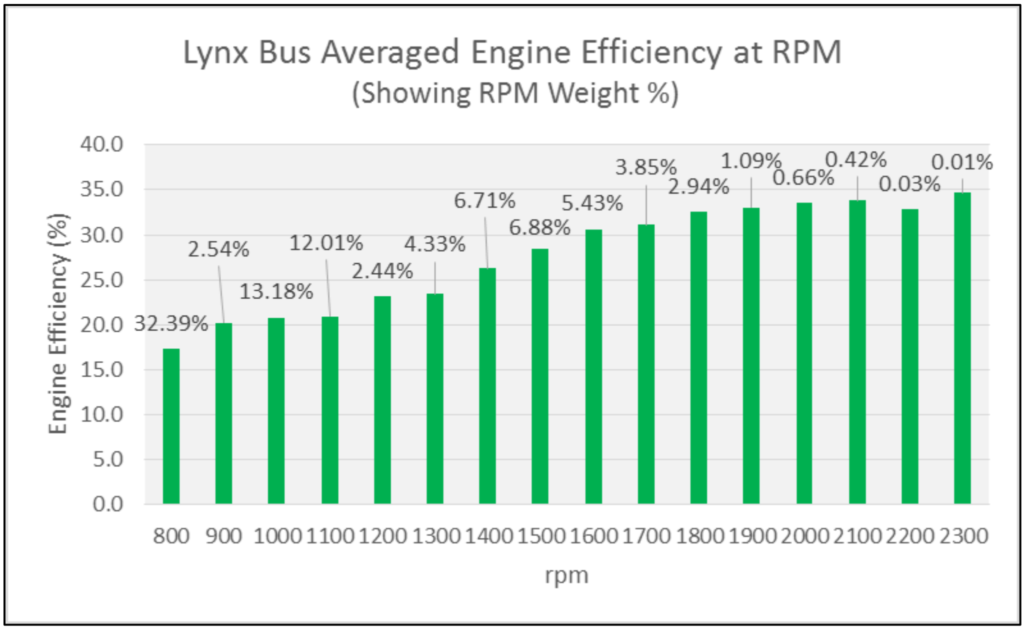


Figure E-5. Calculated engine efficiency as function of revolutions per minute (rpm). Bars shown on the chart show the percentage (%) of instances the engine operates at given rpm's.

A search on the type of alternator used on the Gillig transit bus (Niehoff C701) revealed its operating range of efficiencies as published in performance map by the manufacturer. A research presentation found by the Center of Diesel (MN), indicated that the alternator on a 40-foot Gillig bus provides about 4.5 kW of electrical power when operating the air conditioner. Based on these findings and the additional 0.33 kW the TEG ancillary equipment imposes on the alternator, it was concluded the alternator operates in the 65% to 70% efficiency range. Therefore, by compounding the efficiency of components leading to electric generation, a simple methodology for estimating fuel savings was derived. The weighted rpm efficiency of the engine (22.1%) and the efficiency of the alternator (65%) leads to a theoretical fuel saving calculation of 0.197 equivalent gallons of low sulfur diesel (or 0.195 gallons regular diesel) for every kilowatt-hour of avoided alternator generated electricity. Figure E6 illustrates the efficiency chain of a diesel engine to alternator generation path.

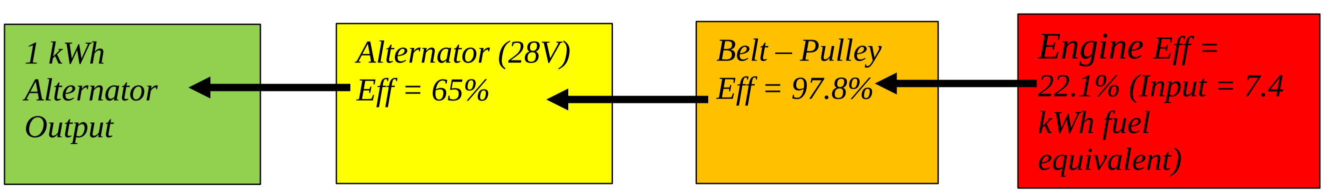
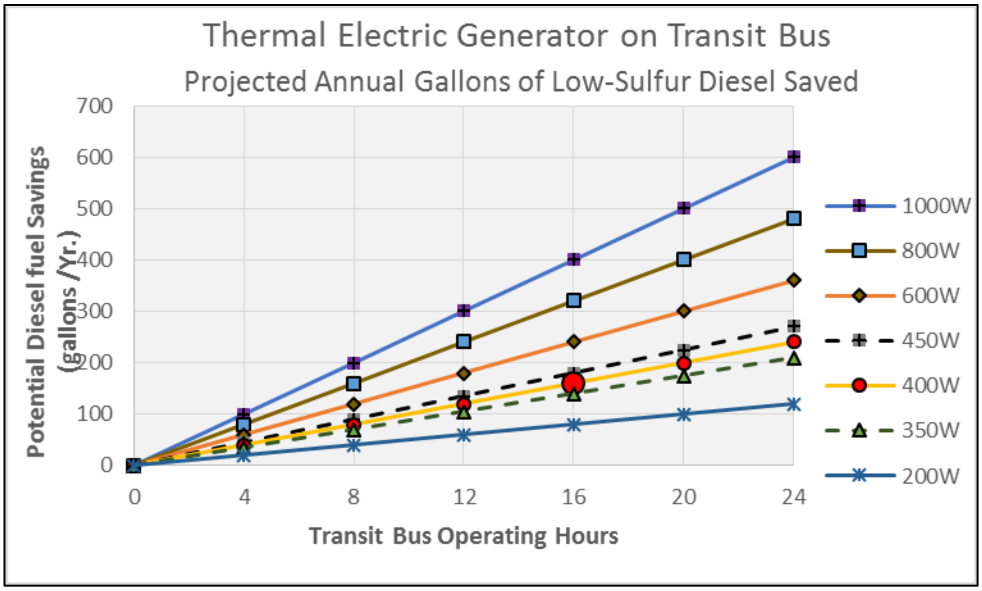


Figure E-6. Engine to alternator electric output efficiency chain. It takes 7.4 kWh of equivalent input fuel energy to generate 1 kWh of altenator generated electricity.

However, the experimental exercise of injecting electric current into a bus electrical system to reduce engine torque was not performed in this study. The resulting acceptance of electricity by an alternator which ultimately would reduce torque forces on an engine are still unknown. Therefore, a 50% TEG energy utilization acceptance factor was used in a model to estimate of fuel savings. Figure E7 and E8 presents the projected one-year potential for fuel (gallons/yr.) reduction and projected annual savings at various TEG capacities (200-1000W).



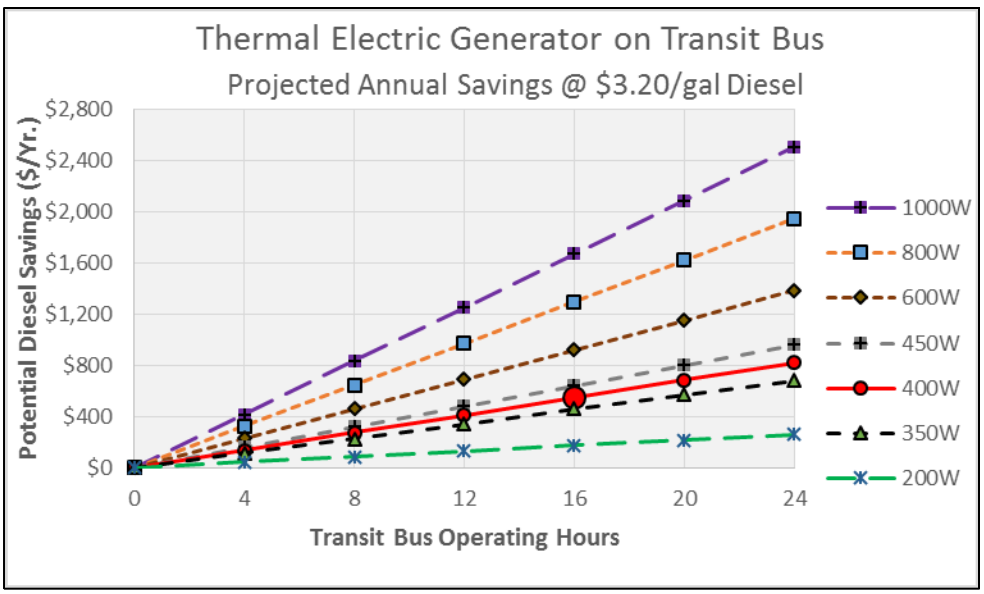


Figure E-7 and E-8. Estimated diesel fuel and projected savings at various TEG capacities.

The plot also indicates, along the 400W projection line, a larger symbol (circle) representative of savings potential ($513/yr. @ $3.20/gallon) demonstrated by the TEG in transit route operation. This represents about 1% fuel savings for a bus with a rating of 3.2 mpg operating an average transit route of 155 miles per day over 16 hours. With improved controls design, energy recovery and fuel savings can improve upwards along the projected lines. To reach a 2% fuel savings level the TEG would have to generate about 750 watts on average or generate an average of 450 watts with an alternator power acceptance multiplier factor of 0.75.

1.0 Introduction

Figure 1. Core of thermo-electric generator (TEG) unit and LYNX Gillig transit bus on background.

The Florida Solar Energy Center (FSEC), under contract to the Center for Transportation and the Environment (CTE), provided technical assistance and performed independent review of data recorded from a 1.1 kW thermoelectric generator (TEG) system (figure 1) . Other project team members consisted of Hi-Z Technology Inc., providers of thermoelectric system, International Trade Bridge (ITB) and Energy Florida (non-profit) which provided guidance on thermoelectric applications development and commercialization. A 40 feet Gillig diesel powered bus was provided by the Central Florida Regional Transportation Authority (LYNX) in Orlando which acted as project partner.

The TEG utilizes hot exhaust gases from a transit bus diesel engine as the source of energy. A TEG was retrofitted atop the bus roof top, including a water pumped cooling radiator, fans and other peripherals. Measurements were automatically recorded on a on-board data logger following bus electrical ignition. Data was immediately recorded at 1- second interval from the bus Controlled Area Network (CAN) system along with added thermoelectric data channels. Data was also transmitted in near real-time via cellular network to a dedicated FSEC server where it was processed. Temperature, voltage and current data were used to determine the power generation capabilities of the TEG during bus transit operation between May and June of 2018. Analysis of data determined the power capacity of the TEG during operation, but also calculations were derived on the potential to reduce the bus alternator electrical load which ultimately could save gallons of diesel fuel.

The project goal was to develop and showcase thermoelectric energy recovered from hot gases that otherwise are sent out the bus tail pipe. This energy could be used to provide power for accessories during shutdown and reduce the amount of power required from the alternator during operations. The technology can provide a new way to reduce transit engine demand and achieve reductions in fuel consumption and emissions. The system utilizes thermoelectric technology initially developed for spacecraft that utilizes waste heat recovery system that is expected to generate 1000W of power to support bus electrical systems. Results and lessons learned identify pathways for future development and commercial production, which could enable a reduction in fuel use and corresponding emission reductions.

2.0 Project Background

2.1 Volumetric Exhaust Flow Measurements

During 2017 and early 2018, FSEC concentrated efforts in verifying data significance and data quality verification as recorded from the bus CAN system. For example in February 2017, the bus was driven over a 40 mile route. FSEC then analyzed collected data for volumetric tailpipe flow. The bus engine control module (ECM) data – as read from a connected laptop display – was compared for accuracy to the CAN data recorded into the on-board storage module. The correlation between ECM and CAN data was not perfect, but it provided a reasonable estimation of the volumetric flow rate, and likely to be within 10% of the final value. These exhaust gasses appear to flow within the range of 3 to 17 cubic feet per second (ft^3/s). Volumetric flow measurements were instrumental in helping HI-Z finalize the design of the TEG apparatus. A detailed discussion on the volumetric flow analysis ca be found in Appendix A as reported in February 2017 (P. Brooker).

2.2 Bus Emission Filtration - Regeneration Cycle

Programming for CAN data channel extraction and verification of other usable data channels was accomplished during the following months. Of significance importance was the regeneration (“regen”) cycle activity on the bus emission system and the elevated high temperatures exhibited during activation. Understanding the “Regen_Active” signal behavior enable a proper design of additional controls to ensure that high temperature exhaust is properly diverted away from the TEG unit. CAN data showed that there are three channels on that relate to regen events: Passive, Active, and Force. Only the “Regen_Active” signal appears to change during this period, and it was found to have three bit states: 0, 1, and 2. When the exhaust temperature data was compared to the “Regen_Active” temperature, it was found that high temperatures were most often correlated to a “Regen_Active” bit = 1, although there are times when high temperatures will exist with a bit state of 0 and 2. When the Regen_Active bit is 1, the diverter valve will be operational causing the exhaust flow to travel away from the TEG unit. Details of the “Regen” activity on the bus can be found in Appendix B as reported by P. Brooker in March 2018.

Eventually, the data acquisition system was then sent to Hi-Z in California to verify data acquisition of the thermoelectric temperatures and voltage channels. Final verification of data acquisition, where both the CAN data and the thermoelectric data channels were logging properly did not occur until May 11, 2018. Another important topic investigated was elevated temperatures of the exhaust as a result of the regeneration (“Regen”) cycle which are related to the periodic diesel particulate filter process typically found on diesel buses. The periodic “Regen” cycles are considered important to a thermoelectric system due to elevated temperatures (>600 ^{o}C) which can exceed the TEG materials operational design temperatures. Initially the regen cycle appeared to have a periodic time interval (20 hrs).However, data analysis revealed that a “regen” event can be initiated at other time intervals. These findings were relayed to the Hi-Z team to help finalize the thermoelectric system configuration and operational controls. Ultimately, it was decided to implement a relay based control scheme tied to the “Regen_Active_Signal” provided by the bus Controlled Area Network (CAN). The relay would provide a direct signal to an exhaust flow diverter valve bypassing the TEG heat exchanger. These controlled events had a significant impact on the ability of TEG to reach its maximum energy recovery potential.

3.0 Data Acquisition System

The data acquisition consisted of split J-type cables and a HEM data logger with micro-SD card (Figure 2 and Figure 3). Analog to Digital modules were used. The data logger being used for the TEG project consists of a Y-cable with a male J1939 receptacle on one end, and OBD and female J1939 receptacles on the other (photo 2). An OBD data logger with a 4GB micro-SD card was also supplied (photo 3), which was then connected to the OBD port on the Y-cable. When the male J1939 port can be connected to the bus’s J1939 receptacle, the data logger can continuously collect data while mechanics can access the bus diagnostics through the female J1939 port on the Y-cable.

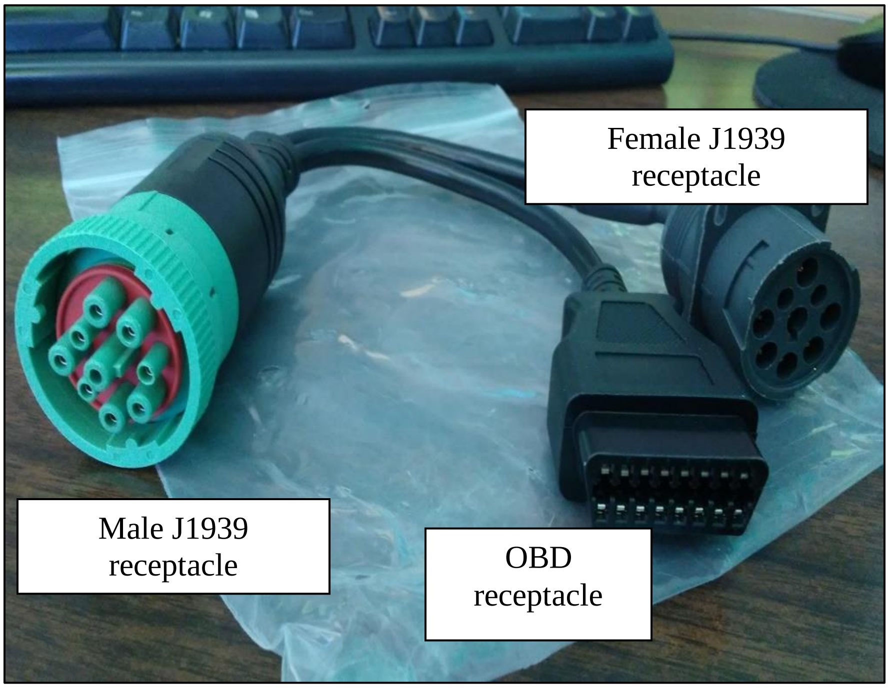


Figure 2. HEM Data Y-cable.

Thermoelectric (TEG) voltage and temperature measurements were recorded by an analog to digital (A/D) converters. These converters were house inside a steel casing attached on a steel rack which was mounted to the bus rooftop. Thermocouples and voltage measurement wires were then routed inside water tight tubing. The arrangement can be seen in photo 3 (bottom) prior to making all connections. In all more than 96 channels of data were recorded into the on-board data logger. These ae listed in Appendix C

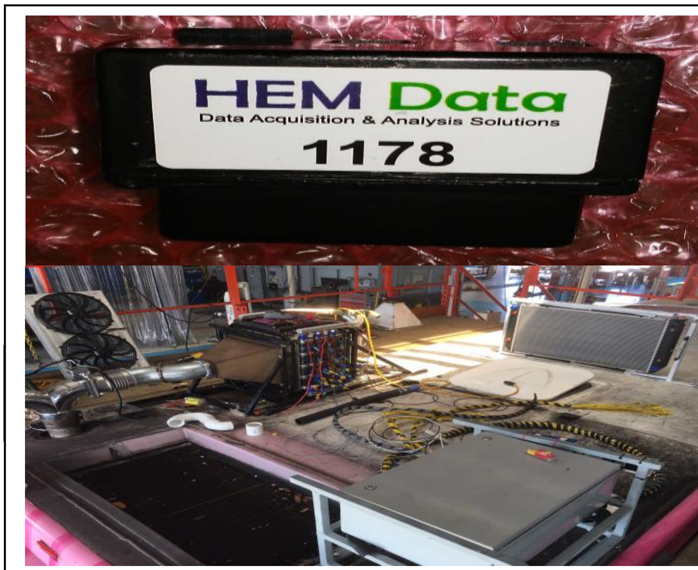


Figure 3. HEM data logger (top). Data acquisition system mounted on roof top (bottom right).

4.0 LYNX Transportation

The Central Florida Regional Transportation Authority (LYNX) in Orlando, FL acted as a project partner. According to their website they provide an impressive service to the central Florida community. The following is an excerpt from their website:

> **"LYNX is proud to provide public transportation services for Orange, Seminole and Osceola counties. Our 77 daily local bus routes (called Links) provide more than 105,000 passenger trips each weekday spanning an area of approximately 2,500 square miles with a resident**

population of more than 1.8 million. Small portions of Polk and Lake counties are served as well."

According to the American Public Transportation Association modal data (2012), LYNX is ranked #37 by unlinked passenger trips and miles. It also attained # 4 ranked under Bus Rapid Transit in urbanized areas in the U.S.

Lynx provided essential project resources such as a diesel buses, personnel interaction, and hosted with their service garage and tooling machinery. Lynx utilizes a variety of transportation buses which utilize diesel (table 1) and natural gas fuel . One of those vehicles is the Gillig standard bus with a six-cylinder Cummins diesel turbo engine (8.9 liter). The 42 feet long bus features a 43-plus seating and 75 maximum passenger capacity. The bus has a storage capacity of 120 gallons of diesel fuel tank.

Figure 4. TEG unit hoisted during retrofit installation day (May 01, 2018)

The picture shown in figure 4 was taken during the day of installation, where the TEG unit was hoisted onto the roof bus. Supporting frame for the TEG was welded and assembled at the LYNX machine shop facility during the previous days.

Table 1. Specifications of a Gillig transportation Bus

Model	Coach 40' x 102"
Engine	Cummins ISL 07, 280 HP
Exterior Height	136 in.
Floor	Low Floor
Fuel Options	Diesel
Fuel Capacity	120 gal.
GVWR	39,600 lbs. (Diesel)
Headroom	77 in. to 95 in.
Length	40 ft.
Passenger Capacity	75
Seating Capacity	43-plus
Transmission	Asm: ZF 6HP594C
HVAC:	Thermo King 22-54157-021

5.0 Bus Alternator

Energy losses incurred by a belt driven alternator can amount to around 19% of the fuel input energy on a combustion engine. These losses are inferred on a energy conversion chart published in the white paper by M. Bradfield [Remy, Inc.]. The purpose of outfitting a thermal electric generator (TEG) to a transit bus is to contribute power to the bus electrical system, therefore reducing the electrical load imposed to the alternator. When electrical currents within the alternator are decreased, losses are reduced, mostly due to heat from ohmic losses. The Gillig bus utilizes a 28 volt regulated Niehoff C701 alternator. The Gillig bus engine features a crankshaft pulley with a 1:2 gear ratio to the alternator as shown in figure 5. Therefore, the alternator spins at a rate of twice the revolutions of the engine shaft pulley.

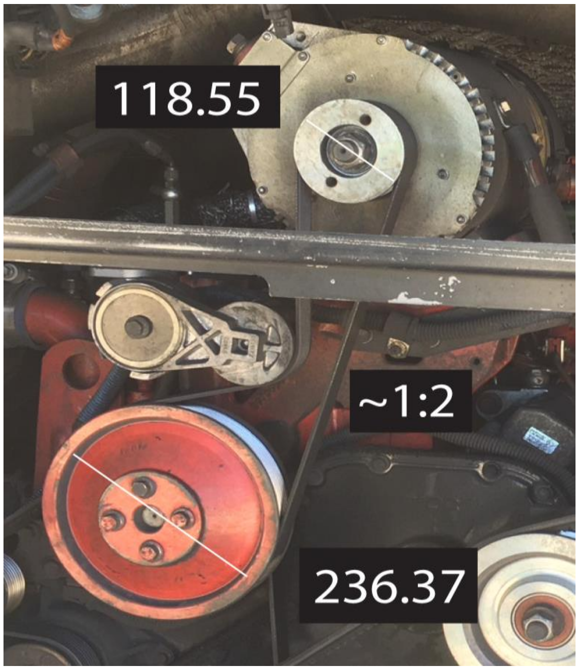


Figure 5. Engine crankshaft to alternator pulley gear ration 1:2 on the Gililg diesel engine bus.

5.1 Alternator Energy Losses

A belt driven alternator generates power via the linkage to the engine crankshaft. Power generation along with losses incurred in the mechanical process can be defined by the following power balance equation:

$$Power\ Input = Power\ Mech\ Loss + Power\ Mag\ Loss + Power\ elecLoss + Power\ ElecOut$$

Input power is provided by engine's mechanical energy conversion from diesel fuel. The highest losses within the alternator occur due to electrical loss. These are referred to as ohmic losses occurring within the alternator stator windings and diode rectification losses. Ohmic losses produce heat loss due to electric resistance and voltage drop of the rectification diodes when the alternator is generating power. Magnetic losses represent the inefficiency of iron and core losses as the magnetic active circuit operate under hysteresis due to magnetic field alignment and eddy currents.

5.2 Belt Pulley – Mechanical Losses

Mechanical losses due to bearing friction and air (shear) resistance only represent about 2% to 2.2% of the input energy to an alternator. The mechanical losses of an alternator spinning between 764 and 4300 rpm was calculated using a third order equation fit as published in a vehicular technology IEEE Paper. [Sohn, J., et al.]. Figure 6 shows the calculated mechanical losses (N·M) incurred by a belt driven alternator at various spinning revolutions per minute (rpm).

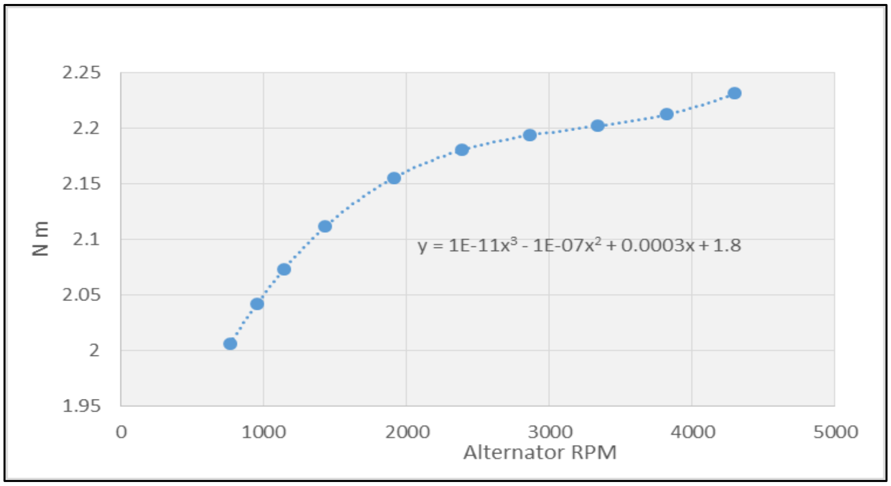


Figure 6. Calculated mechanical losses for typical alternator revolutions of a C701 bus alternator.

The range of mechanical energy losses (watts) shown in table 2 does not vary substantially between idle and the high rpm's when the alternator operates as it is linked via belt to the engine crankshaft of the Gillig Bus.

Table 2. Mechanical losses of a belt driven alternator expressed in watts as function of alternator revolutions per minute (rpm).

rpm	W
763.9	2.01
954.9	2.04
1145.9	2.07
1432.4	2.11
1909.9	2.15
2387.3	2.18
2864.8	2.19
3342.2	2.20
3819.7	2.21
4297.2	2.23

5.3 Alternator Performance Map

In order to determine the fuel savings potential of a bus outfitted with a TEG, the performance chart of the C701 Niehoff alternator was examined. Figure 7 presents the performance map of a C701 alternator as published by a Niehoff distributor.[1] The performance chart defines output amperes on the y-axis and alternator revolutions per minute (rpm) on the x –axis. A generic alternator efficiency map, defining efficiency areas (denoted in green) was graphically layered over the C701 manufacturer chart.[2] Based on Gillig bus engine operational rpm data (discussed in the next section), the alternator operates at twice (2x) the revolutions of the engine crankshaft. The alternator operating range can be defined within the area below the red curve and to the left of the orange dash-line shown at 4500 rpm. Because of the alternator operating on a Gillig BRT bus can typically supply up to 4.5 kW, this would indicate that currents of 160 amperes or higher would flow through the alternator voltage regulator (28V).[3] In actual TEG transit demonstration, parasitic power of the TEG (330W) would push the alternator to produce an additional 12 amperes, where the total currents supplied by the alternator & voltage regulator system would be in the range of 172 amperes. Overall this would indicate that the alternator would be operating within the 65-70% efficiency range.

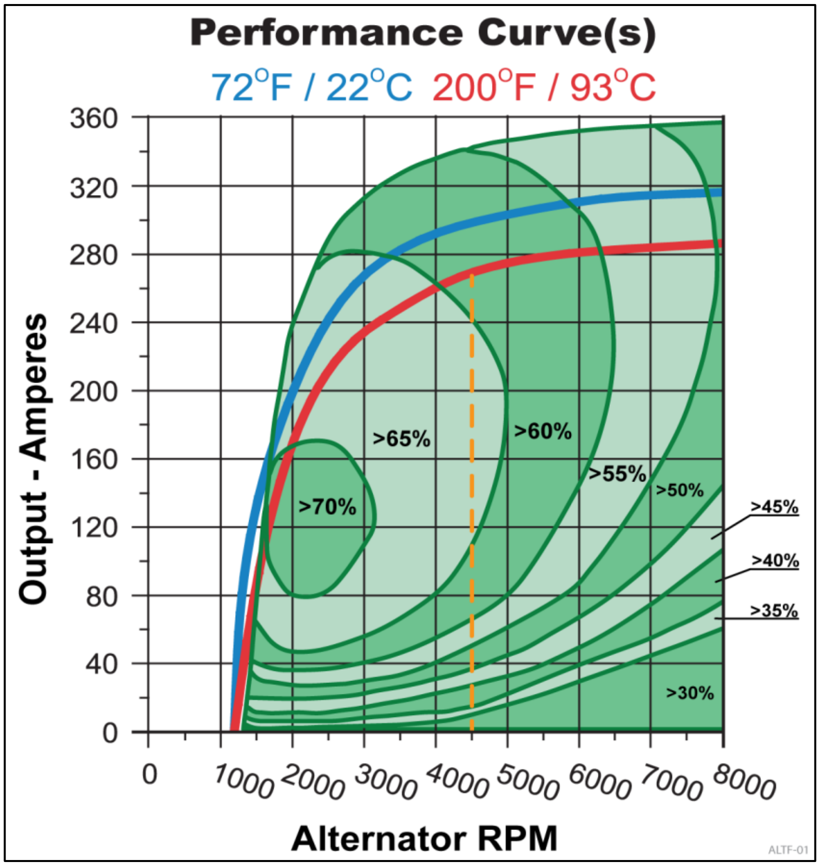


Figure 7. Niehoff C701 Alternator: Area below red curve and orange dash line defines the operating output (Amps) and efficiency (%) areas for the bus alternator based on RPM data recorded for those days in service.

[1] http://elreg.com/wp-content/uploads/pdfs/C701_Brochure.pdf

[2] The reference generic efficiency map by Remy Inc. appears to apply to 12 V alternators. The original chart scale included currents up to 180 amperes on the Y-axis and revolutions (rpm) up to 8000 on the x-axis – the C701 alternator would not operate under the highest rpm range shown.

[3] As indicated in a presentation by W. Northrop from The Center for diesel research in Minnesota. (http://www.cts.umn.edu/sites/default/files/files/sessions/3-northrop.pdf)

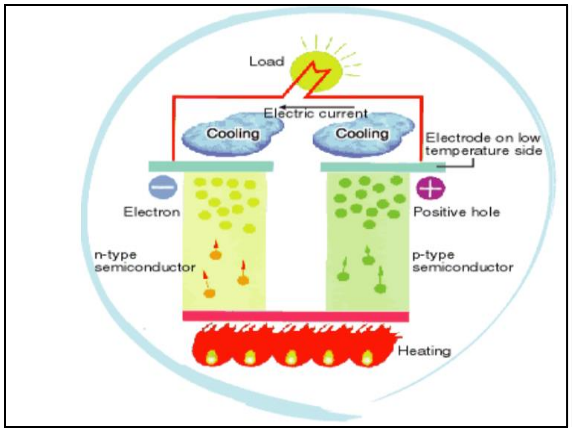
6.0 Thermoelectric Modules

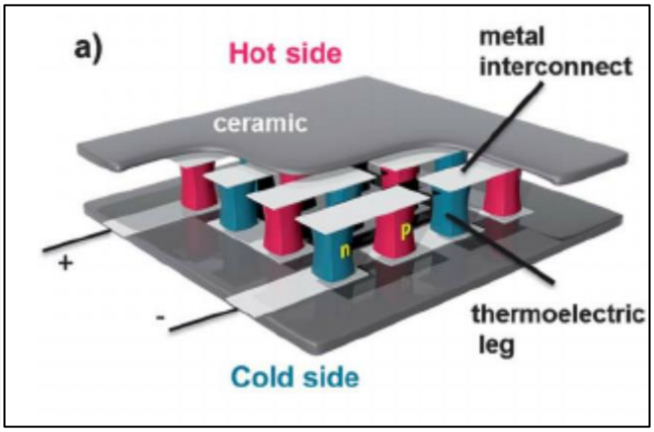
The thermoelectric modules utilized in the transit bus demonstration were supplied by HI-Z (CA). The bismuth-telluride based semiconductor modules utilized are a variation of their HZ-20 products. They were described by HI-Z as having slightly higher output than their similar HZ-20 but with different proprietary chemical anti-oxidant composition. [4] The HZ-20 modules are 2.95 inches in width and length. They are designed for waste heat recovery and renewable energy among other applications. [5] Some of the cell thermal properties and generation characteristics are listed in Table 3. Figure 8 and 8a illustrate the connection to a load and composition of a thermo-electric cell.

Table 3. Hi-Z HZ-20 thermoelectric cell properties

Design Hot Side Temperature	230°C (450°F)
Design Cold Side Temperature	85°F (30°C)
Maximum Continuous Temperature	480 °F (250 °C)
Power *	19 watts
Load Voltage	2.38 V
Internal resistance	0.3 ohms
Current	8 amps
Open Circuit Voltage	5.0 V
Efficiency	4.5%

* At matched load





Figures 8: Illustration of thermoelectric device modules and connection to a load (provided by Hi-Z)

7.0 Thermoelectric Retrofit System on Bus Rooftop

The thermo-electric (TEG) system, as retrofitted for demonstration into the Gillig bus,consisted of four major components (figure 9):

- thermoelectric heat exchanger and cooling manifold assembly
- Bus exhaust, Flange and wrap around ("U") exhaust and diverter valves
- Cooling radiator, Fans and pump
- Power resistor bank Load (not shown)

[4] Personal conference call communication with Hi-Z staff and other project team members (July 2018)
[5] http://hi-z.com/wp-content/uploads/2016/08/HZ-20-Datasheet.pdf

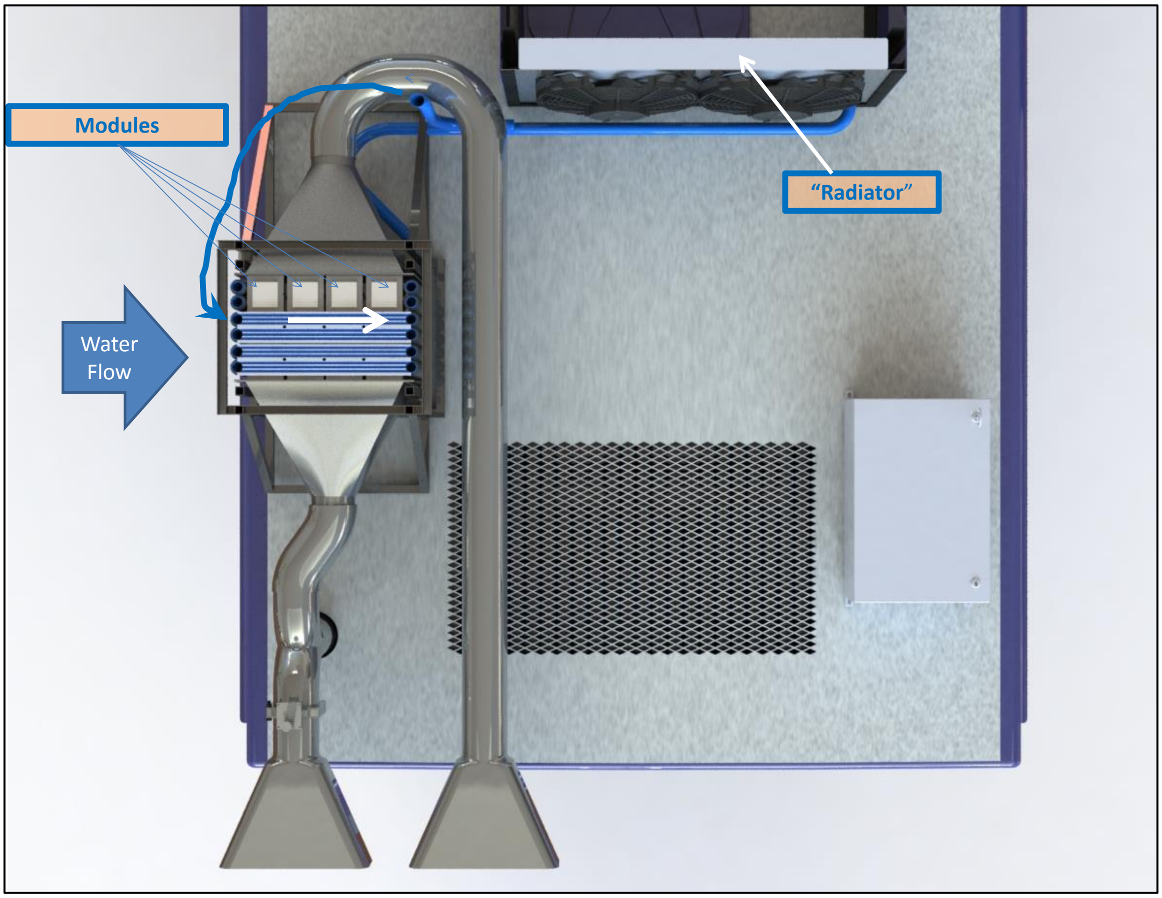


Figure 9. Thermoelectric system as retrofitted on bus roof top (rendering courtesy of Hi-Z).

7.1 TEG heat exchanger anatomy

The thermoelectric heat exchanger device consisted of layered aluminum finned block sections (4 x 4) allowing passage of the engine's hot exhaust gases. It was designed to minimize flow resistance which helps with engine backpressure. A total of ninety-six (96) thermoelectric modules were arranged into four horizontal layered sections which exposed the thermo modules to hot and cooling surfaces sections (see figure 10). Pumped cooling fluid (water) which flows to and from a dedicated rooftop mounted radiator, entered horizontal heat exchanger plates from both left and right sides. Thermoelectric modules were wired in series and subdivided into three stage circuits (stage 1, 2 and 3). These would provide three independent voltage stages proportional to the segmented temperature areas within the heat exchanger (i.e, front to back high, medium and low as hot gasses entered and exited the heat exchanger assembly – see figure 11).

Figure 10. Sectional layers of the TEG allow passage of the engine exhaust gases.

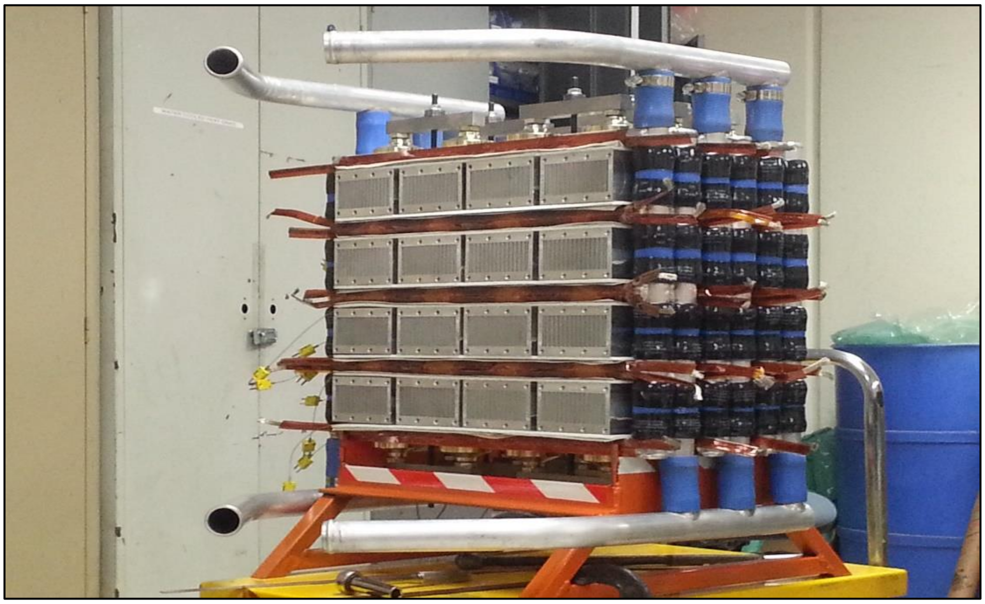


Figure 11. Vertical cooled sections of the TEG represented Stage 1, 2 and 3.

As a result, the stage circuit exposed to the incoming exhaust (highest temperature) generated the highest power (stage1), followed by the medium (stage 2) and lower (stage 3) circuits. The various level of voltages generated by the TEG can be seen in figure 12. Voltage level measurements for stage 2 were not recorded by the data acquisition system at the beginning of the transit route demonstration. To determine the missing stage 2 voltages, they were estimated by Hi-Z using a trapezoidal integration equation. However, the calculation methodology was later verified, following a re-wire of the data acquisition which allow the missing voltages to be recorded on available empty channels of the logger.

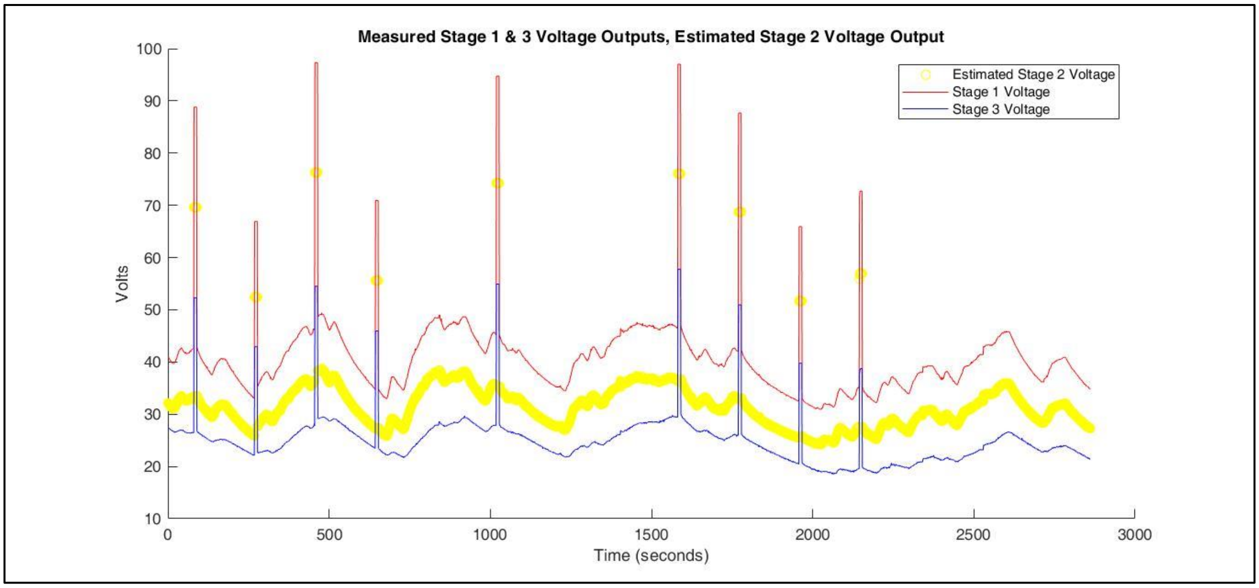


Figure 12. Voltage levels generated by the TEG on May 15, 2018. (plot source: Hi-Z).

The voltage spikes for each of the stage circuits seen in figure 12 are attributed to the electrical control circuitry imposed, where the open voltage was measured as the TEG circuits were disconnected from the load via power relays. Open voltage measurements were necessary to calculate the internal resistance of the TEG stage.

8.0 TEG Power

The power generated within the thermoelectric material can be calculated, as it is always proportional to the internal resistance (*r*), and increases as temperature gradients (ΔT) as shown in the following equation [cited by Sief , Thundat and Calef]:

$$p = \frac{n^2 \ \propto^2 \ (\Delta T)^2}{4r}$$

Where *n* is the number of thermo modules in series and α is the seebeck coefficient of the material. In this case the internal resistance of the module is defined as the ratio between the voltage and the current across the TE material [Glatz, et al, 2006]. This may explain why Hi-Z decided to implement a open voltage (no load) measurement every three minutes to calculate power from voltage measurements as follows:

$$Ri = \frac{Vopen - Vload}{I\ load}$$

Where the load current is determined from a load voltage measurement and the load power resistance (8.4 ohms), which dissipated the energy as heat in the TEG bus system setup.

9.0 Data Analysis

Alternator revolutions per minute (rpm) data recorded during the transit performance of the TEG was taken into consideration. A bin analysis on the alternator rpm data was conducted averaging the performance for the period of May 21 through May 31st. Figure 13 (histogram) reveals the percentage of instances where the alternator operates. The plot bears similarity with other studies, showing that the majority of the time, a bus engine and alternator operates at low idle rpms. [Bradfiled, Remy, Inc; Northrup, Center of Diesel Research]

By examining the C701 alternator performance curve, it can be concluded that when the bus engine is parked or in low idle mode following operator gas pedal depressed, the alternator should be ramping down, operating at around 1500 rpm (750 engine rpm). Under this rotational speed, the alternator cannot produce more than 80 amps at an efficiency of around 65%. Similarly when the alternator operates in the 2000-2200 range (i.e., the next higher percentage bin), currents of 160 amps or higher are achieved.

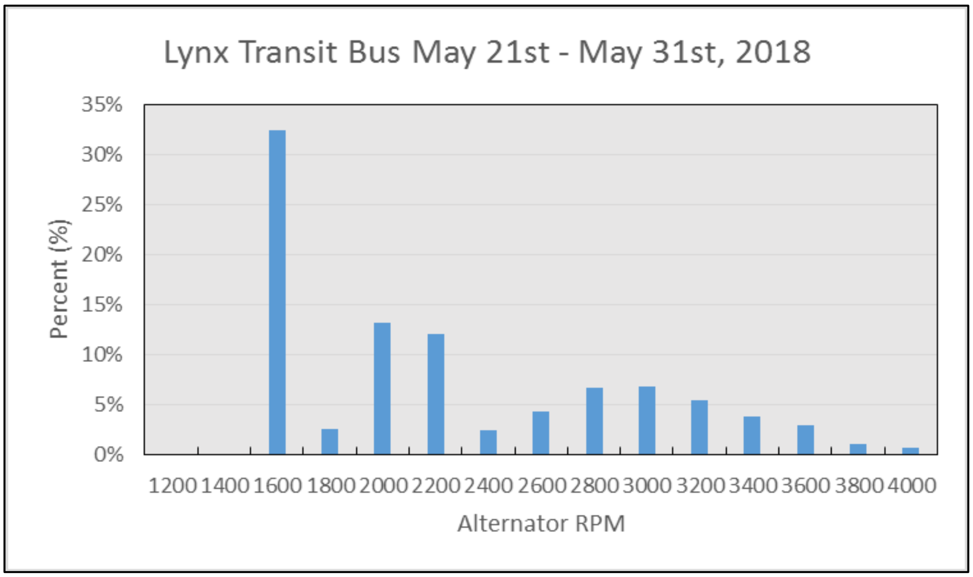


Figure 13. Bin analysis of alternator operational speed during bus route transit for the period ending on May 31st, 2018

9.1 Recorded Data Significance

Substantial effort was put into data acquisition system, which attempted to merge CAN data from the operating bus and additional channels from the thermoelectric generator system. A list of data recorded channels, as indicated in the header of the automated csv files created, can be found in the Appendix C However, analysis of the data recorded revealed the fact that unless the bus is equipped with specific sensory device, data channels throughput of the onboard bus CAN system are simply filled with an arbitrary number. For example alternator current (A) , and charging system potential (V) data channels were simply populated with a “256” and “3276” values which never changed during any of the data days analyzed.

Fortunately engine speed (rpm), fuel consumption (l/h), wheelbase vehicle speed (k/h), trip distance (km), actual engine torque (5) and battery potential (V) data were present and prove useful for the analysis.

9.2 Kennedy Space Center Bus Route Demonstration

Demonstration of the thermoelectric system began during a simulated transit route at Kennedy Space Center (KSC) Florida, where the TEG recorded a peak of 1,126 watts and averaged a power capacity of 971 watts during the one-hour transit route period. The values recorded from which power generation was derived, were calculated manually form voltage readings during transit. Figure 14 presents a plot of the power generation sequence as recorded by the Hi-z and CTE team members present on board during the transit route at KSC which included simulated stops.

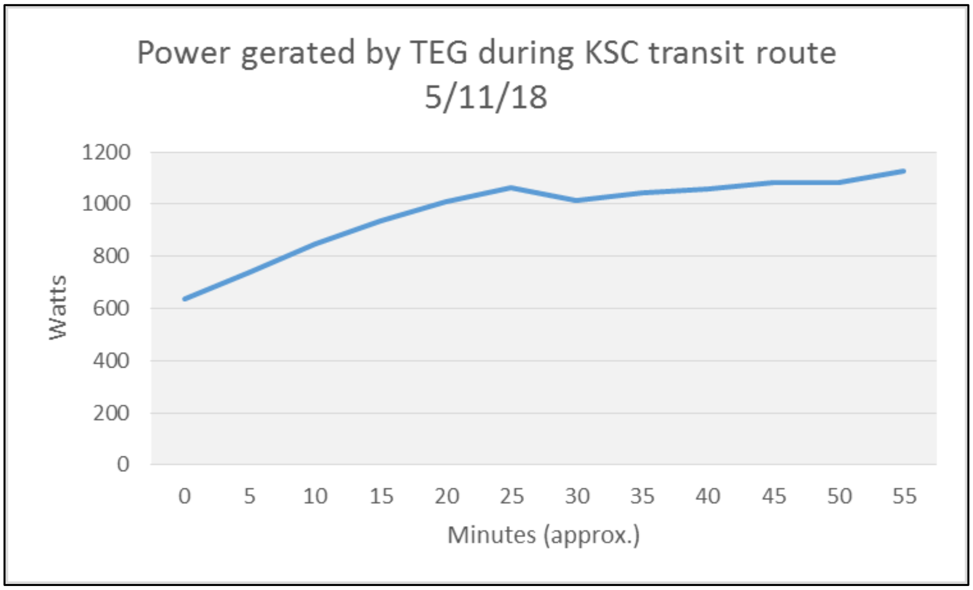


Figure 14. Manual recorded TEG power generation values during KSC demonstration route.

The utilization of the Kennedy Space Center as a site for clean energy and transportation technology development in partnership with regional transit operators is an attempt to create a pathway for federally funded technology research and development.

9.3 Orlando (Lynx) Route Transit Demonstration

Transit route total miles, gallons, and operating hours for period between May 18th and June 12, 2018 are shown in Table 4. Data reported originated from the CAN recorded values recorded "Total Vehicle Distance (km), "Wheel based vehicle speed" (kph) and "Engine fuel rate (l/h). These were also used in calculating the vehicle averaged mpg.

Table 4. Summary of miles driven, gallons, mpg and hours obtained during the demonstration period.

	Trip miles	gallons	mpg	hours
5/18/2018	272.1	82.1	3.3	18.5
5/20/2018	150.6	45.1	3.3	10
5/21/2018	155	57.1	2.7	15.7
5/22/2018	154.8	52.2	3.0	18.5
5/23/2018	154.8	56.3	2.8	16
5/24/2018	155	54.8	2.8	15.2
5/25/2018	155	53.8	2.9	16.5

5/26/2018	161.1	72.1	2.2	22.3
5/29/2018	154.8	56.1	2.8	15.9
5/30/2018	155	52.8	2.9	15.4
5/31/2018	155	53.6	2.9	20.2
6/1/2018	76.5	25.1	3.1	9.8
6/2/2018	20.3	16.5	1.2	
6/4/2018	155	57.8	2.7	15.8
6/5/2018	155.7	58.7	2.7	15.5
6/6/2018	155	51.1	3.0	15.5
6/7/2018	181.6	61.4	3.0	19.6
6/9/2018	0.7	3.8	0.2	2.4
6/11/2018	155.3	52.4	3.0	14.4
6/12/2018	155	52.8	2.9	15.5
Average	158.6	54.3	2.9	16.1

During the demonstration period, the bus exhibited a lower than expected fuel utilization averaging only 2.93 miles per gallon (mpg). Route days highlighted in gray were not used in the averaging process due to insufficient data (6/2 and 6/9) or because there was a long delay between route shift, where the bus was parked and engine ran for more than 70 minutes without moving. This explains the low value of 2.2 mpg May 26th. The best posted mpg's were recorded as 3.3 mpg (5/18 & 5/20) which occurred on the same route, where the bus was operated for 18.5 hours the first day and the latter for about 10 hours. The fuel economy demonstrated falls within the average 3.26 mpg (GGE) as reported for "Transit Bus" by the Federal Highway Administration in Figure 15. [6]

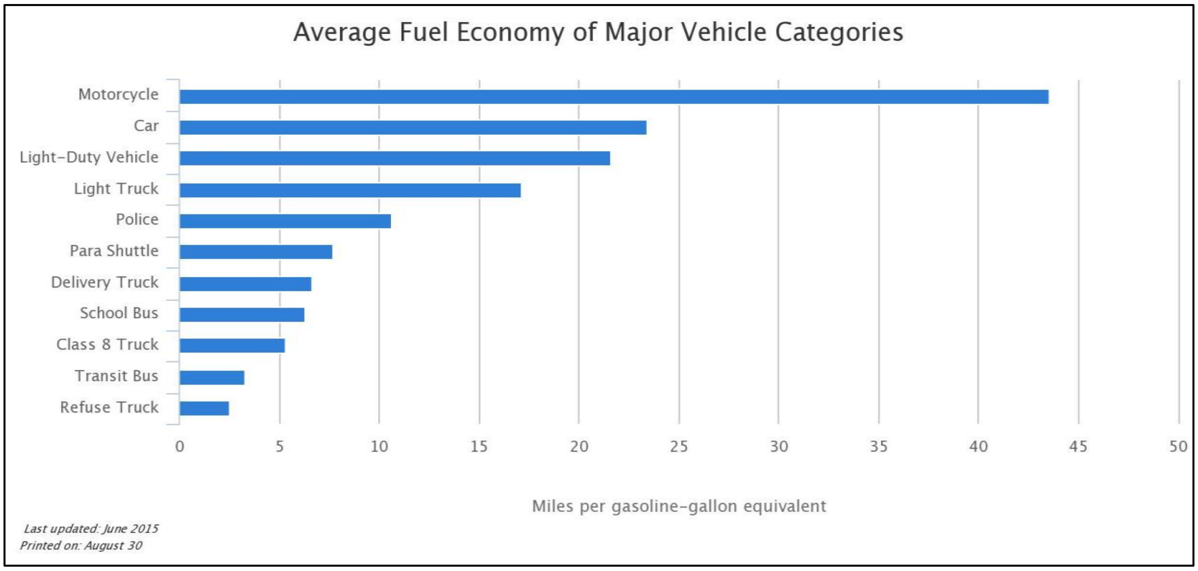


Figure 15. AFDC Fuel economy of transit Bus compared to other vehicle categories.

[6] As reported by the Alternative Fuel Data Center (AFDC) from Source: Federal Highway Administration Table VM-1 and American Public Transit Association's Public Transportation Fact Book Tables 6, 7, and 20. (https://www.afdc.energy.gov/data/10310)

The chart reports fuel economy based on gasoline gallons equivalent (GGE) equivalents. The GGE diesel equivalent of 2.93 (3.32 GGE) is in line with the mpg reported for a diesel Gillig bus as presented by the Regional Transportation Center in 2015 -- 3.96 mpg (Feb), 3.48 mpg (Sept) and 3.33 mpg for October [7].

Figure 16 presents the TEG power generation (left axis) and transit speed (mph right axis) during transit route on May 20th, 2018.

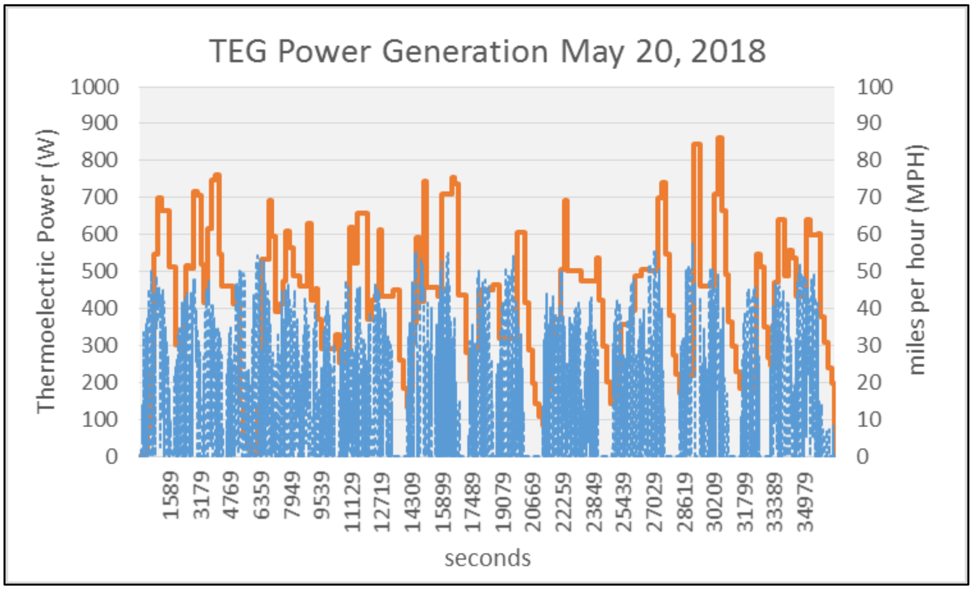


Figure 16. TEG power generation plotted against bus speed on May 20, 2018 transit route.

9.4 Methodology

A search on the type of alternator used on the Gillig transit bus (Niehoff C701) revealed its operating range of efficiencies as published in a performance map by the manufacturer. A research presentation found by the Center of Diesel (MN), indicated that the alternator on a 40-foot Gillig bus provides about 4.5 kW of electrical power when operating the air conditioner. Based on these findings and the additional 0.33 kW the TEG ancillary equipment imposes on the alternator, it was concluded the alternator operates in the 65% to 70% efficiency range. Therefore, by compounding the efficiency of components leading to electric generation, a simple methodology for estimating fuel savings was derived. The weighted rpm efficiency of the engine (22.1%) and the efficiency of the alternator (65%) leads to a theoretical fuel saving calculation of 0.197 equivalent gallons of low sulfur diesel (or 0.195 gallons regular diesel) for every kilowatt-hour of avoided alternator generated electricity. Figure 17 illustrates the efficiency chain of a diesel engine to alternator generation path.

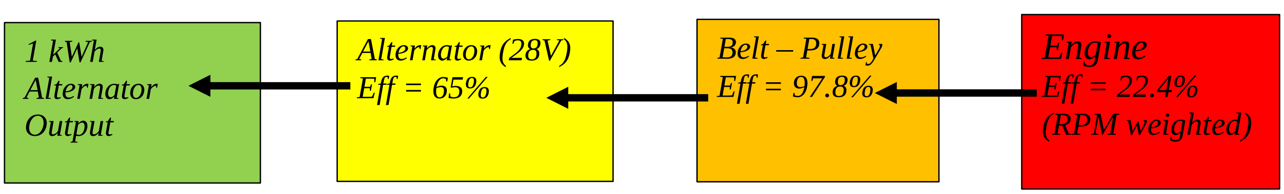


Figure 17. Compounded efficiencies of individual bus components lead to 6.8 kWh of equivalent engine fuel to generate 1 kWh of alternator electricity.

[7] https://www.apta.com/mc/bus/previous/bus2017/presentations/Presentations/Carr_David.pdf

9.5 Transit Data Analysis

Recording voltage data was essential in determining the power capacity of the TEG during operation. A controller was designed to open the electrical power circuit using low resistance relays to momentarily measure the open voltage across the three thermoelectric stages that composed the TEG. Based on the known fixed resistance load and electric formulae applicable to thermoelectric devices, the flowing current for each of the stages was determined. Delivered power to the fixed resistance load was then calculated. Figure 18 represents the dynamic power generated during a transit route on May 18, 2018, where the TEG was able to generate power exceeding 600 watts and momentarily approaching 800 watts peak. Net power is also shown where the power utilized by the cooling components of the TEG heat exchanger is taking into consideration. On this day the TEG would be able to generate an averaged 327 watts (net) after the auxiliary power expended for cooling was subtracted. Although the amount of passengers on the bus were unknown, it achieved an average of 3.3 mpg with air conditioner and TEG parasitic cooling load on the alternator.

During transit route demonstration, the cooling components of the TEG (i.e, pump and radiator fans) were operated continuously. However, further improvements to the cooling controls could be implemented to reduce ancillary power during those periods the bus is in motion. For example, airflow passing through the cooling radiator when the bus exceeded 7 mph could negate the use of parasitic power of the radiator fans which imparts a penalty by additional load to the bus alternator.

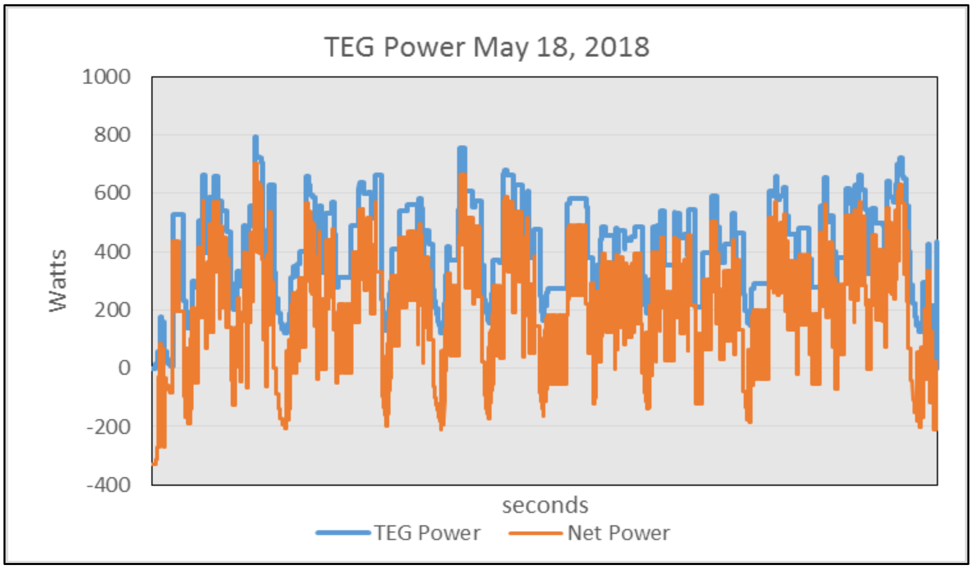


Figure 18. TEG power and Net power generation for transit activity on a Lynx bus, Orlando, FL.

Data analysis was performed on transit routes by setting an ancillary power reduction (-240W) threshold at seven miles per hour (7 mph) by using the CAN wheelbase speed as threshold condition. Similarly when the bus was standing still at zero mph, the exhaust diverter valve could be set to bypass, and only pump power of 90 watts to circulate cooling fluid would be subtracted as penalty for a net power calculation. These two conditions would omit unnecessary cooling power. Averaged results comparing TEG power and net power as adjusted for ancillary cooling components can be observed in Figure 19 for the period ending on June 11th, 2018

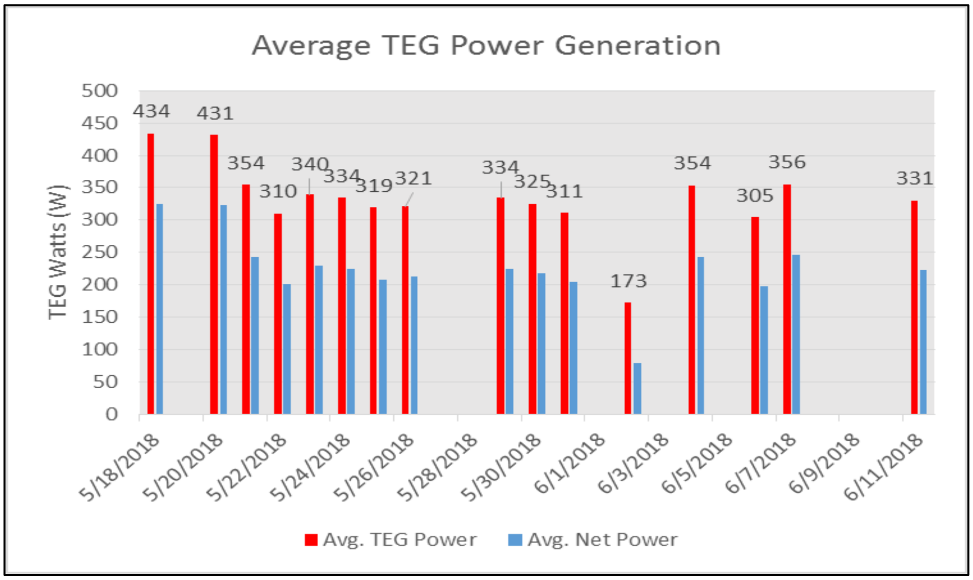


Figure 19. TEG power and Net power averaged daily for the period shown ending in June 11, 2018.

Figure 20 (below) illustrate a summary of power generation by the TEG as it was averaged daily and regressed by group routes. The highest data power line (970 W) shown, formed by two points is the result of data averaged during the KSC route segment (55 min.) and extrapolated to 16 hours. This performance line, represents the maximum this particular TEG system was capable of generating during demonstration (excludes parasitic power). It represents the best performance data seen under sustained generated power. The other two lines represent the performance of two other routes averaging 433 and 344 watts (net) respectively which include conditional parasitic power. The performance on June2nd was omitted from the regression analysis.

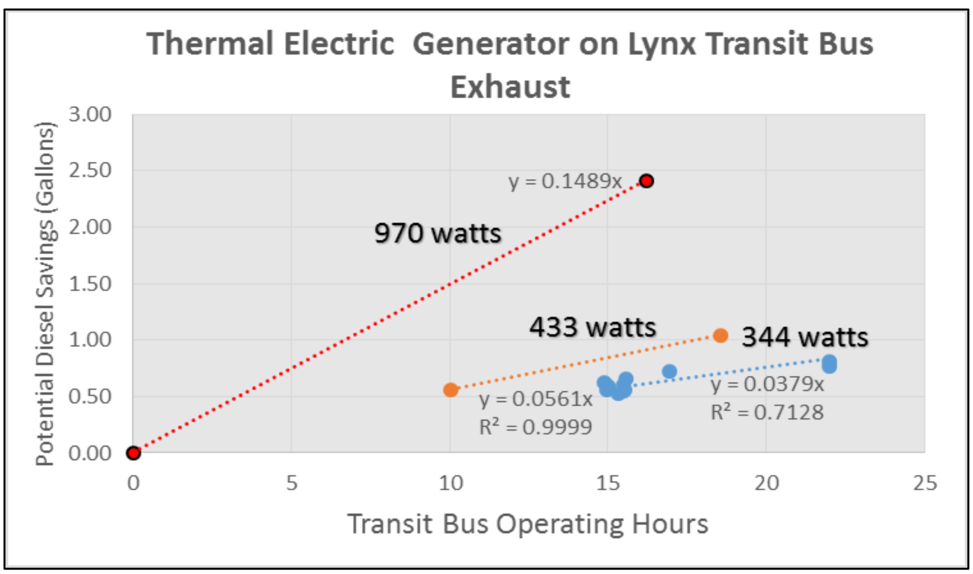


Figure 20. Average daily TEG power (Net) plotted as a function of operating transit hours.

Engine operating revolutions per minute during transit routes was also analyzed. Results observed are similar in distribution to other findings reported which are applicable to bus transit operation. Figure 21 shows the average percentage of occurrences in histogram form (rpm bins) and found that the highest percentage of alternator operation appears in the lower idle region (32% at 1600 rpm). The Gillig bus alternator has an engine to belt pulley ratio of 1:2.

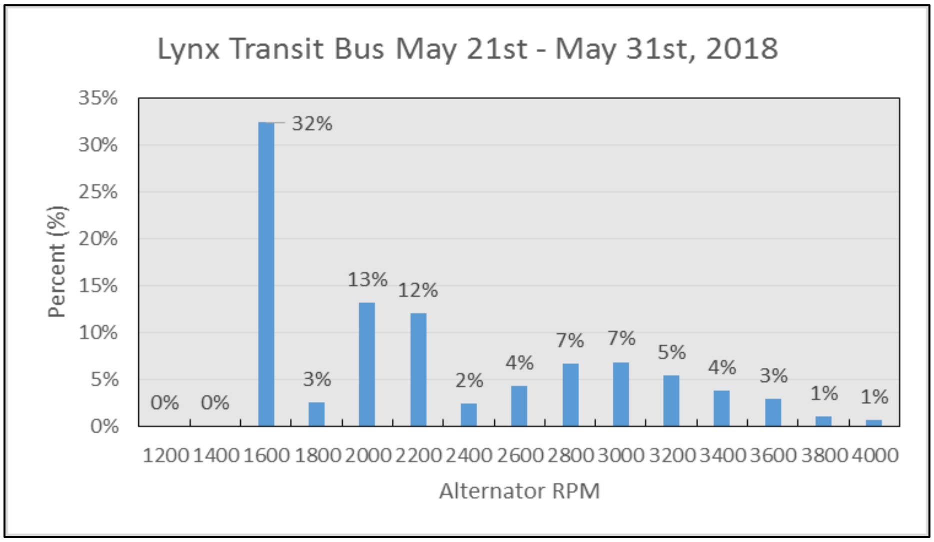


Figure 21. Histogram showing rpm bins and percentage of total occurrences for the bus alternator.

Engine efficiency was calculated by converting instantaneous percent torque measurement (1 second) as provided by the CAN data into torque (Newton-meter). The manufacturer (Cummins) engine specifications are shown in table 5.

Table 5. Cummings Diesel ISL specifications

rpm	Torque (N·M)
863	990
1300	1491

The torque energy was then compared to the amount of fuel delivered as input to the engine (fuel delivery rate from CAN data). Engine efficiency was then plotted against rpm as shown for May 18th in figure 22.

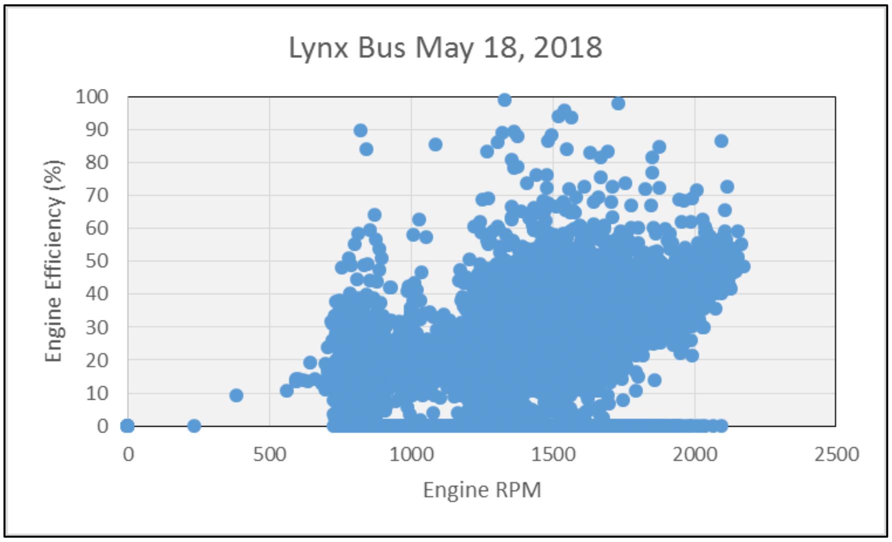


Figure 22. Cummins ISL diesel engine efficiency (one second data) as a function of revolutions per minute (rpm).

Engine efficiency was then analyzed against the recorded revolutions per minute (rpm) data. Efficiencies were averaged by rpm bins on increments of 100 for the range of 800 to 2300 rpm's. The bar plot on figure 23 shows the averaged engine efficiency as function of revolutions per minute (rpm) derived from actual recorded fuel rate and instantaneous torque. The engine efficiency appears to be between 17.3% at the low rpm range of 800 to a maximum of 34.7% at 2300 rpm's.

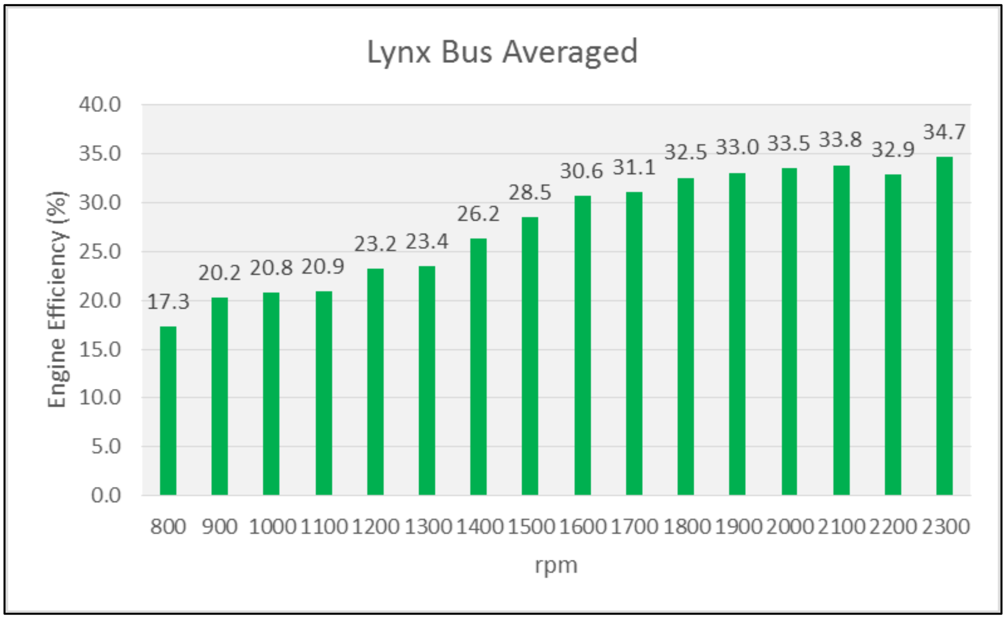


Figure 23. Calculated engine efficiency as function of revolutions per minute (rpm).

On figure 24, each of the bars representing "rpm" are given a weight based on the findings presented in figure 22. For example the engine spends a good percentage of instances (32.4%) at 800 rpm where engine efficiency is 17.3% (i.e., least combustion efficiency).

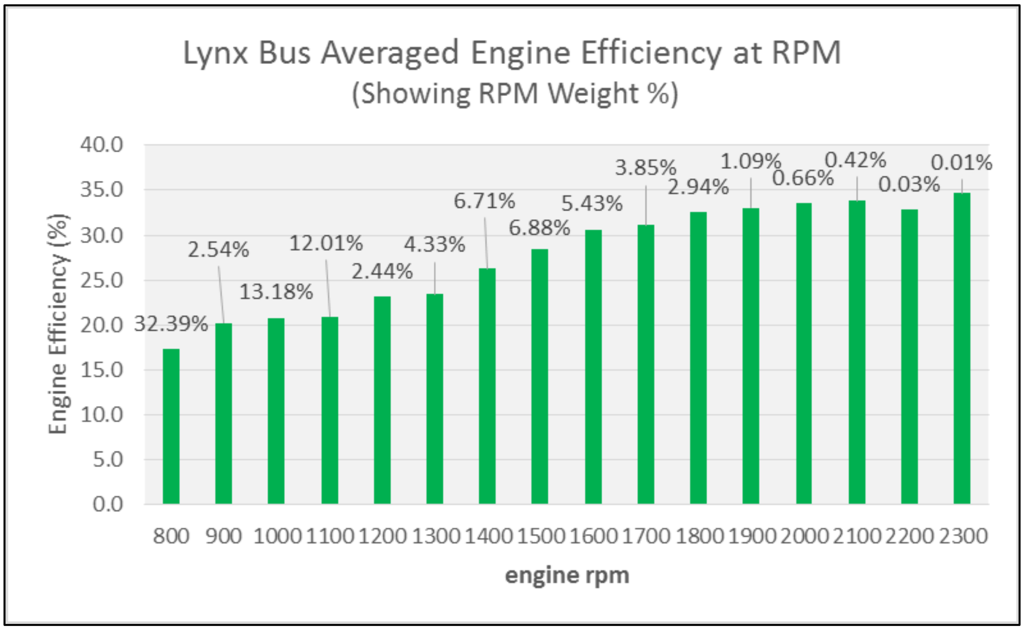


Figure 24. Calculated engine efficiency as function of revolutions per minute (rpm). Bars shown on the chart show the percentage (%) of instances the engine operates at given rpm's.

9.6 Diesel Fuel

The energy content of one gallon of diesel is quantified as having the equivalent of 139,000 BtU's. However, the majority of transit buses in the United States (58%) utilize low sulfur diesel with a energy content equivalent of 128,488 Btus. The historic (10-year) retail price of diesel over the last ten years has fluctuated between $2.00 and $4.30 per gallon.

However, the price of diesel during the 2017-2018 period appears to be increasing as shown in figure 25. The price of diesel thru June 2018 to about $3.25. Average price for a gallon of diesel for the last 12 months has increased by 29.5% since 2017 up to $3.25 (June2018). The average price of diesel for the last 12 months is $2.93 per gallon.

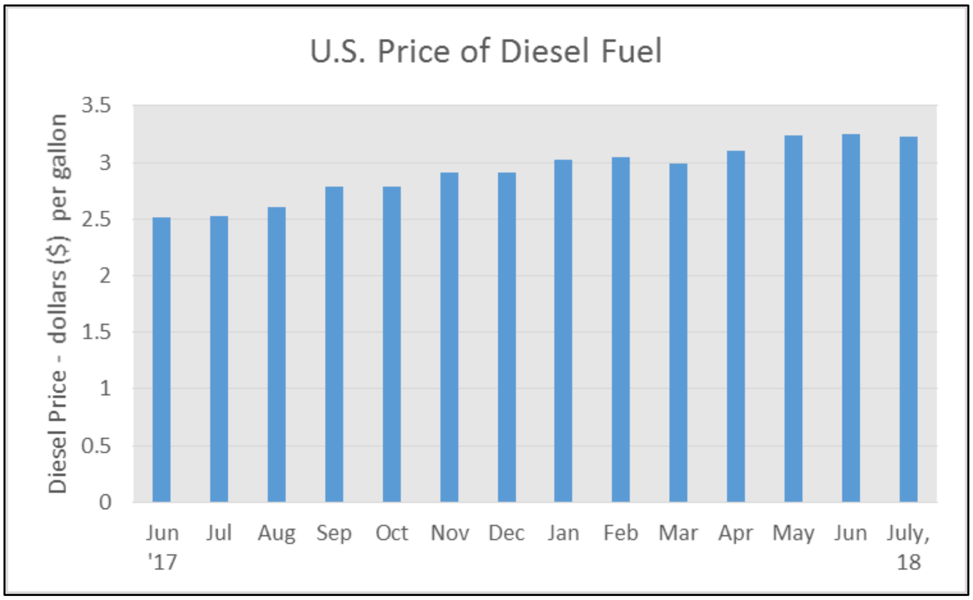


Figure 25. Price of Diesel fuel in the U.S. through July 2018.

On June 11, 2018 the average battery potential (Power Input 1) voltage (V) averaged 27.6. Based on the alternator performance chart, this would indicate that under normal driving behavior -- data showing maximum 4200 rpm alternator , the alternator could provide a maximum of around 270 amperes. (A). Under these circumstances, the Niehoff C701 alternator would be generating on the order of 7.5 kW of power.

10.0 Projections and Economic Analysis

A spreadsheet model was created to evaluate the potential savings of diesel gallons and determine the contribution annual projections of a TEG on a transit bus in service. Assumptions in the model utilized the theoretical compounded efficiency methodology explained earlier in the report. However, the model utilized averaged data as calculated from the empirical data values gathered during the bus transit route. The model allows the calculation of projected values by way of changing input variables (table 6) such as daily hours of transit route service, price of fuel ($/gal.) and ratio of net power to power generated (P_{net} / Power ratio) among others.

Table 6. Input cells of the spreadsheet model

			Select Diesel:	Low sulfur	128.488	(kBtu/gal)		
	Alternator Eff =	0.65	Belt/Pulley Eff=	1	Engine Eff	0.212	(rpm weighted)	
	Pnet /P ratio =	0.750		dc-dc eff. =	0.95	Alternator E-recovery		
Compounded Efficiency				Transit hrs./day		claim =	0.5	
multiplier (gal/kWh)=		0.193		Hours =	16	$/gal	$3.20	

Table 7 is a summary of variables utilized in the above shown spreadsheet model.

Table 7. Description of variables values utilized in the spreadsheet model to calculate potential fuel savings

Variable	Description
Alternator Efficiency	A value of 0.65 (65%) was utilized
Alternator Belt Pulley Efficiency	A value of 1.0 was used in the projections (1.0 = no credit). A value of 0.978 (97.8%) could be used to claim a 2.2% efficiency loss gain if alternator were to be disengaged.
Alternator recovery claim	Assumed alternator acceptance factor for energy injected by TEG (0.5 = 50%)
Compounded Efficiency	Calculated gallons of diesel saved from compounded engine to alternator efficiency chain (0.193 gal/kWh produced)
Engine efficiency	A weighted engine efficiency of 22.1% was used
Pnet to P ratio	Averaged net power to power generated by the TEG. On average the TEG demonstrated a 0.68 ratio, however a ratio of 0.75 was demonstrated on the best performance days (5/18 & 5/20)

10.1 Economic Results

By varying the amount of daily hours for a transit route on the spreadsheet model, a plot was generated (Figure 26) for fuel savings projections (gals/yr.) and along with a table (Table 8) of results. The plot summarize the potential for annual diesel fuel reductions by average TEG

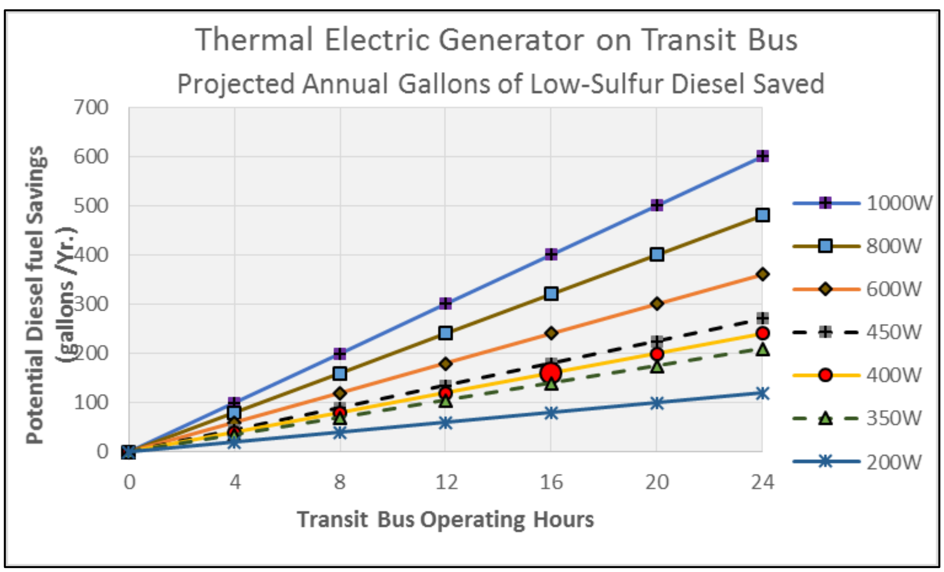


Figure 26. Amount of diesel gallons saved (gals/yr) based on projections calculated by the spreadsheet model.

capacity and operating route hours as shown on the x-axis. The large red circle shown on the plot would indicate amount of diesel gallons (160.3) that could be saved by a TEG generating an average of 400 watts for transit routes of 16 hours per day.

The plot in figure 26 is composed of values shown in Table 8.0, where the annual fuel savings (gallons per year) can be examined by the number of transit route hours and the functional electrical generation capacity of a TEG (200-1000 watts). The 400 Watt row is highlighted, representing the HI-Z TEG system performance average as tested. Higher performance could be easily achieved with system optimization (i.e., faster diverter valve controls and less parasitic cooling energy).

Table 8. Potential for gallons of fuel saved per year

TEG	**Transit Daily Operations - Hours**					
	4	**8**	**12**	**16**	**20**	**24**
Watts	**Gals/Yr**	**Gals/Yr**	**Gals/Yr**	**Gals/Yr**	**Gals/Yr**	**Gals/Yr**
200	20.0	40.1	60.1	80.1	100.2	120.2
250	25.0	50.1	75.1	100.2	125.2	150.3
300	30.1	60.1	90.2	120.2	150.3	180.3
350	35.1	70.1	105.2	140.3	175.3	210.4
400	40.1	80.1	120.2	160.3	200.4	240.4
450	45.1	90.2	135.2	180.3	225.4	270.5
500	50.1	100.2	150.3	200.4	250.4	300.5
550	55.1	110.2	165.3	220.4	275.5	330.6
600	60.1	120.2	180.3	240.4	300.5	360.6
650	65.1	130.2	195.4	260.5	325.6	390.7
700	70.1	140.3	210.4	280.5	350.6	420.8
750	75.1	150.3	225.4	300.5	375.7	450.8
800	80.1	160.3	240.4	320.6	400.7	480.9
850	85.2	170.3	255.5	340.6	425.8	510.9
900	90.2	180.3	270.5	360.6	450.8	541.0
950	95.2	190.3	285.5	380.7	475.9	571.0
1000	100.2	200.4	300.5	400.7	500.9	601.1

Projections for diesel savings in dollars (annual) can be seen in figure 27 and annual dollar ($) values shown in table 9. The plot is based on a diesel cost of $3.20 per gallon, assuming low sulfur fuel is utilized.

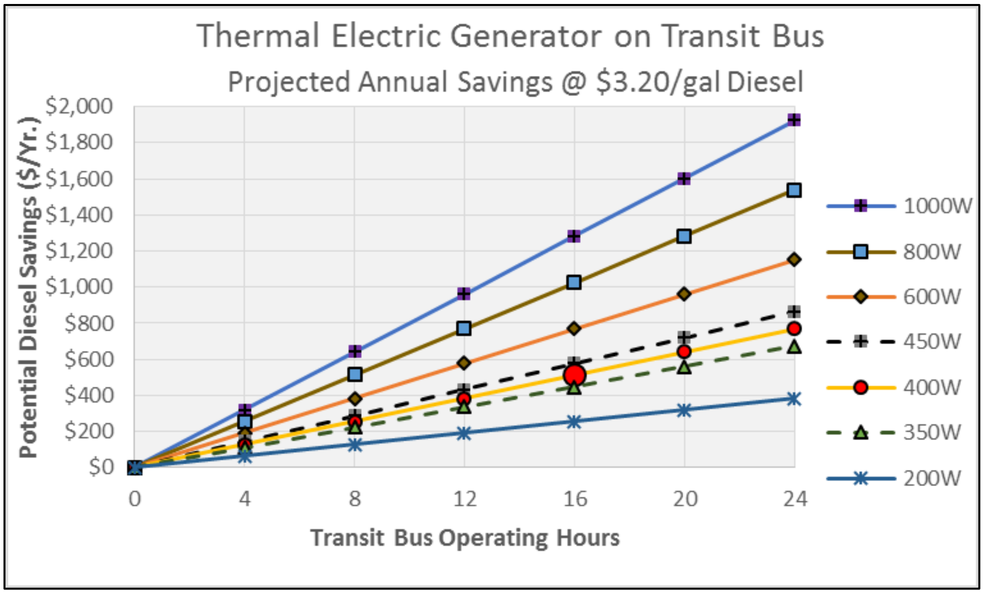


Figure 27. Projected savings ($/yr.) based on diesel fuel cost of $3.20 per gallon.

Table 9 Potential for Savings on Diesel per year at $3.20/gallon

TEG	Potential for Diesel Gallons Savings -Operation - Hours					
	4	**8**	**12**	**16**	**20**	**24**
Watts	**$/yr**	**$/yr**	**$/yr**	**$/yr**	**$/yr**	**$/yr**
200	64.1	128.2	192.3	256.5	320.6	384.7
250	80.1	160.3	240.4	320.6	400.7	480.9
300	96.2	192.3	288.5	384.7	480.9	577.0
350	112.2	224.4	336.6	448.8	561.0	673.2
400	128.2	256.5	384.7	512.9	641.2	769.4
450	144.3	288.5	432.8	577.0	721.3	865.6
500	160.3	320.6	480.9	641.2	801.4	961.7
550	176.3	352.6	528.9	705.3	881.6	1057.9
600	192.3	384.7	577.0	769.4	961.7	1154.1
650	208.4	416.7	625.1	833.5	1041.9	1250.2
700	224.4	448.8	673.2	897.6	1122.0	1346.4
750	240.4	480.9	721.3	961.7	1202.2	1442.6
800	256.5	512.9	769.4	1025.8	1282.3	1538.8
850	272.5	545.0	817.5	1090.0	1362.4	1634.9
900	288.5	577.0	865.6	1154.1	1442.6	1731.1
950	304.5	609.1	913.6	1218.2	1522.7	1827.3
1000	320.6	641.2	961.7	1282.3	1602.9	1923.5

11 Conclusions

The thermal electric generator (TEG), as designed for a diesel bus exhaust application, demonstrated that it can generate peak power bursts in excess of 1100W peak. However, under a transit routes in Central Florida, as retrofitted on a Gillig bus exhaust, the highest peak power recorded was 897 watts (on 5/26/18). Furthermore, the power generated during route service was much reduced, averaging between 344 and 433 watts. This performance depends on a variety of factors including route stop intervals, bus speed and rpm, driver operation and number of passengers -- the latter which was not recorded. Diverter exhaust controls and also thermal capacitance of the heat exchanger also had a noticeable impact on the power generated. A thermal electric generator -TEG, requires a substantial amount of energy expended for cooling of its heat exchanger. This is imperative to establish a temperature difference approaching ~200^{o}C ΔT, the recommended operating range for the Hi-Z thermoelectric cells used. The radiator cooling fans, each rated at 120W (240 W total) and the water circulation pump (90W) imposed a 330 watt of auxiliary energy needed during operation. Although these auxiliary peripherals were constantly turned on during the transit demonstration, cooling fan energy may not be necessary while the bus is in transit at speeds higher than 10 miles per hour (mph).

During transit route between May 21 and June 12, 2018, the TEG supplied current to a fixed (8.3 ohm) resistance, whose power was dissipated as heat into air. In order to obtain current reduction of a bus alternator, a direct current electric injection system (at greater than 28 Volts) would have to be carefully designed. This would require a fast regulated high efficiency dc-dc converter to provide maximum power transfer with buck and boost circuitry to maintain voltage above 28 volts.

Based on literature search, automobile alternators (14V) have an averaged overall efficiency of about 52% [Remy]. However, the Niehoff C701 bus alternator which operate at higher 28 volts, may operate at higher efficiencies due to the higher voltage, brushless design and the range of rpm at which it rotates in a bus engine environment (2:1 pulley ratio, ~1400 – 4500 rpm). Because of the non-linear power generation behavior of the alternator and the maximum rpm's seen under data collected, it was estimated that the alternator can produced a maximum of 269 amps at the regulated 28 volts. This implies that under normal operation, the alternator may generate a maximum of around 7,532 watts (7.5 kW). Furthermore, a study by the center of Diesel in Minnesota, reported that a Gillig bus with running air conditioner supplies about 4.5 kW. This also implies that the alternator would run at about 60% of its maximum generation capacity. Because of the fact that none of the power generated by the TEG was injected into the bus electrical system, at present there is no way to verify the alternator power reduction and acceptance factor for energy injected as sourced from the TEG. This particular topic remains as "unknown" until it is experimentally and empirically verified, therefore funding for this investigation is encouraged. There are in existence electrical models (such as SPICE) that include automobile alternators as a part of open source component libraries which could be used as part of simulation for implementing TEG energy injection. The theoretical modeling work could provide an insight analysis opportunity before empirical research is performed.

During the demonstration period, the bus exhibited a lower than expected fuel utilization averaging only 2.93 miles per gallon (mpg). The best posted mpg's were recorded as 3.3 mpg (on 5/18 & 5/20) on the same route, where the bus route was operated for 18.5 hours the first day and the latter for about 10 hours. Although the mpg demonstrated falls within the average 3.27 mpg reported in figure 14 (as reported by the Federal Highway Administration) it falls short of the mpg reported by other agencies such as APTA (3.6 mpg) and NREL (4.4 mpg) [Kenneth Proc, et al, NREL *NREL/CP-540-40128]* . Southern climate conditions requiring constant operation of air conditioning equipment may explain the lower fuel efficiency demonstrated in Central Florida.

Furthermore, there may be a significant savings opportunity not only for diesel buses but for hybrid buses that still operate using a direct crankshaft belt pulley linkage system. In addition a TEG design for applications with compressed natural gas (CNG) should be considered, as a good percentage (~18%) of transit buses run on natural gas. [8] The utilization of the Kennedy Space Center as a site for clean energy and transportation technology development in partnership with regional transit operators could help create a commercialization pathway for federally funded technology research and development.

Tables analyzing the potential for fuel savings have been presented in this report. These may be used to investigate the economic effectiveness of a TEG depending on transit route hours and average power generation of a particular TEG design (e.g., 400W to 1kW) as retrofitted on a transit bus. Those resulting values were derived by constructing a theoretical model (i.e., compounded efficiency), however using empirical data gathered in the study.

Finally, Lynx personnel communicated that alternators on their buses only last between 3-5 years on average. There may exist the possibility of extending the life of a bus alternator due to lower currents within the armature of the device. The result would be lower operational maintenance costs.

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8 https://www.apta.com/resources/reportsandpublications/Documents/2017%20APTA%20Clean%20Propulsion%20Resource%20Guide_20170710.pdf

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.
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Appendix A

Data Collection of Volumetric Flow Rates Using HEMData Logger

Paul Brooker
Florida Solar Energy Center
University of Central Florida
Feb 27, 2017

Summary

The data logger originally purchased from HEMData was not configured properly to collect volumetric flow rates. It was determined that the only way to obtain these flow rates using the HEMData logger was to simultaneously collect data on the logger and a Lynx laptop. The Lynx laptop is able to record the volumetric flow rates from the bus ECM while the HEMData logger is recording the same signals in the background. After collecting these signals, a correlation was obtained between the Lynx laptop data and the HEMData logger values. This correlation was necessary since the recorded signal on the HEMData logger did not scale linearly with the values from the Lynx laptop. The correlation resulted in less than 2% (average) error between the Lynx values and the HEMData values. The maximum error at any single point is 10%.

After identifying the signal and a correlation to convert the signal data to real flow rates, it was determined that the volumetric flow rate channel must be requested by a data logger in order to be viewed. The original data logger was not capable of making requests, so an upgraded data logger will be purchased that should be capable of requesting the volumetric flow rate signal. Once this signal is collected, the correlation will be applied in order to determine the value of the volumetric flow rate through the exhaust system.

Discussion

A v3 OBD HEMData logger was purchased to collect signals from the CANBus system on Lynx transit buses. This data logger was used several times to collect exhaust gas temperatures, but was not capable of collecting volumetric flow rate data. After discussions with HEMData, it was decided to try to reverse engineer the data stream that contained the flow rate data. This was accomplished by connecting a Lynx laptop to the bus diagnostics port while the HEMData logger was recording in the background. The Lynx laptop was capable of recording the exhaust flow rate, while the HEMData logger silently recorded all the signals being sent on the CANBus system. This approach would allow HEMData to identify the data stream for the flow rate on the CANBus, and then determine an appropriate scaling factor so that the data logger's output would match the values recorded on the Lynx laptop.

The bus was then driven for about 40 minutes, which included periods of start-stop and highway speeds. The data files from the logger and the Lynx laptop were sent to HEMData for analysis. They were able to identify the channel, but were not able to establish a linear correlation between the HEMData values and the Lynx laptop flow rate values.

The data was sent to FSEC for review, and a non-linear correlation was found to have an acceptable fit (see **Figure 1**). The equation for this correlation is:

$$Vol = 0.2873 \times 10^{(0.002353 \times H)}$$

Where
Vol is the volumetric flow rate, in ft3/s and
H is the HEMData recorded signal

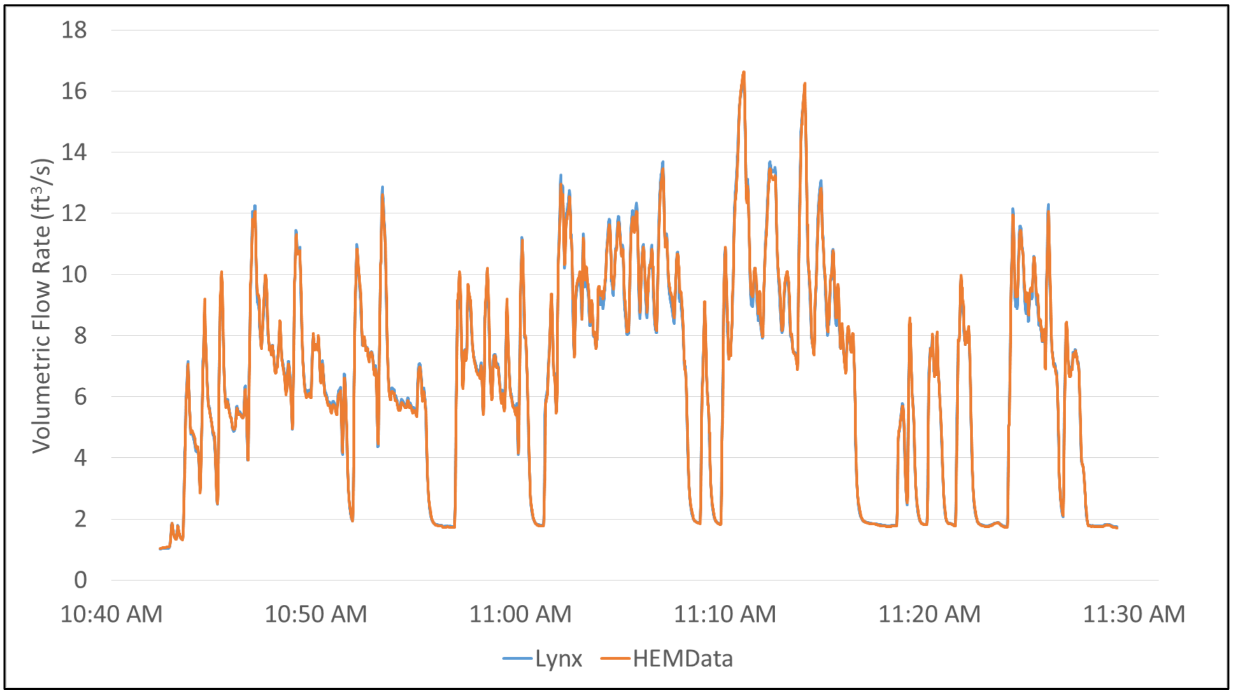

Figure 1. Correlation between data obtained from the Lynx laptop and the scaled HEMData logger values

The correlation is not perfect, but it provides a reasonable estimation of the volumetric flow rate, and is likely to be within 10% of the final value. There appears to be more variability in the signal in the medium range of the flow rate, as shown in **Figure 2**.

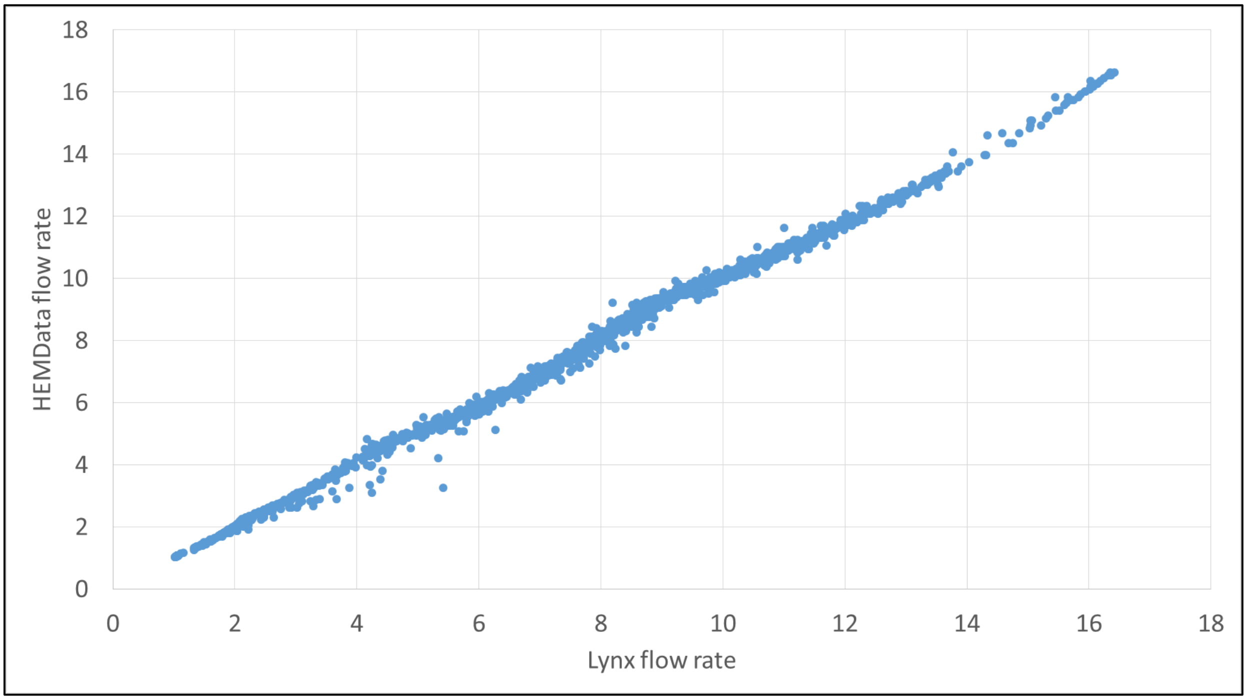

Figure 2. Comparison of HEMData flow rate values and Lynx flow rate values

This correlation was established using Bus 811. It is not known whether or not this correlation would be as accurate on a different bus. Therefore, Bus 811 will be used for collecting flow rate data for use in Hi-Z's design phase. Other buses may be used, but it may be prudent to cross-check the flow rate values from the HEMData logger against flow rates obtained using the Lynx laptop.

During this correlation process, HEMData disclosed that the data stream containing the flow rate data must be requested by the data logger. When the Lynx laptop was connected to the bus, it was requesting the flow rate data, and the HEMData logger was able to record that requested data. However, the v3 data logger is not capable of initiating the request. As a result, a v4 data logger will be purchased, which should be capable of making the request for the flow data. Once the v4 data logger is delivered, it will be installed on Bus 811 for data collection during typical bus operation for a week. This should provide Hi-Z with sufficient flow rate data to be able to design the thermoelectric generator.

Appendix B

Analysis of Regen Events for Bus 811 during January 2018 Operation

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Mar 22, 2018

Summary
Between Jan 4 and Jan 31 2018, the HEMData data logger was installed on Bus 811 and used to monitor several channels on the bus's CAN line, in particular the channels relating to regeneration activity and exhaust temperature. Analysis of the data shows that there are three channels that relate to regen events: Passive, Active, and Force. Only the Regen_Active signal appears to change during this period, and it was found to have three bit states: 0, 1, and 2. When the exhaust temperature data was compared to the Regen_Active temperature, it was found that high temperatures were most often correlated to a Regen_Active bit = 1, although there are times when high temperatures will exist with a bit state of 0 and 2. When the Regen_Active bit is 1, the diverter valve will be operational causing the exhaust flow to travel away from the TEG unit. When the Regen_Active bit is 0 or 2, the diverter valve will not be active, and high temperature flows may reach the TEG, unless other controls are implemented. The operational time between Regen_Active signals was most often 20 hours, with occasional 12-hour and 9-hour spans. At this time, it's not clear what determines the time between Regen_Active events. The purpose of this report is to describe the Regen_Active signal behavior in Bus811 during a month of operation (Jan 4 to Jan 31, 2018). Understanding the Regen_Active signal behavior will enable proper design of additional controls to ensure that high temperature exhaust is properly diverted away from the TEG unit.

Discussion
During normal bus operation, the diesel particulate filter (DPF) captures particulates in the exhaust prior to venting to the atmosphere. While in operation, the filter will periodically undergo a "regeneration" cycle, where the DPF temperature increases to the point to cause complete combustion of particles within the filter. This regen cycle can occur passively or actively. Passive regeneration occurs when the DPF temperature has reached sufficiently high temperatures due to long operation at high loads (e.g. freeway driving). During active regeneration, diesel fuel is introduced into the exhaust stream entering the DPF where it combusts. The heat from diesel combustion causes the DPF temperature to rise dramatically, resulting in exhaust temperatures in excess of 600^{o}C.

<u>CAN-To-Analog Converter</u>
There is a risk of damage to the TEG if excessively high temperatures are introduced to the unit, which is why Hi-Z has incorporated diverter valves into the exhaust flow path. During regen cycles, the exhaust would be diverted away from the TEG and vented directly to the atmosphere. The diverter valve will be controlled by employing a CAN-to-Analog converter that will monitor the "Aftertreatment Diesel Particulate Filter Passive Regeneration Status" (a.k.a. "Regen_Active") signal on the bus's CAN line. The output from this converter will be a voltage signal that can be used to control solenoids operating the diverter valves. **Figure 3** shows the CAN-to-Analog converter and cables required for this connection.

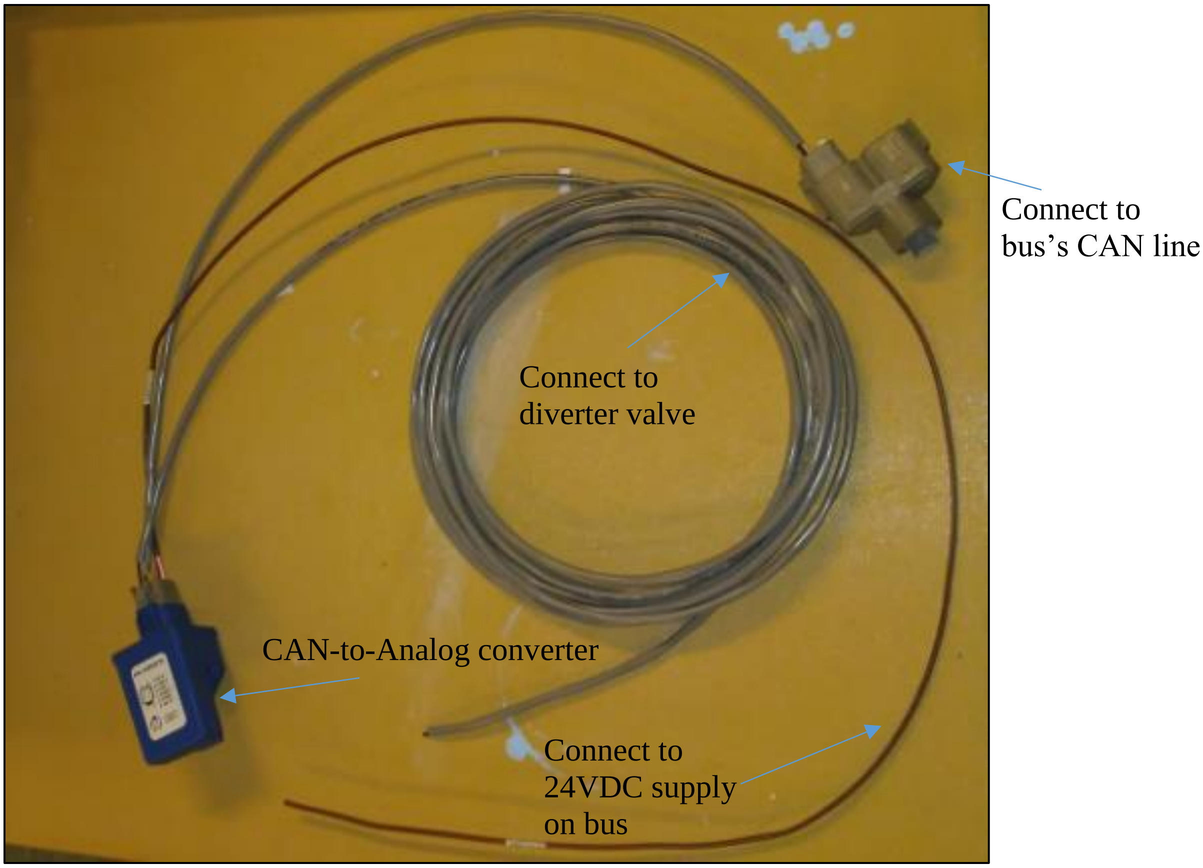

Figure 3. Photo of CAN-to-Analog converter with cables for connecting to bus CAN line, 24VDC supply and diverter valve

Exhaust Temperature and Regen Signals

Figure 4 shows the temperature and regen signal profiles for nearly a month of operations by Bus 811. The blue and orange lines represent the DPF inlet and outlet temperatures, respectively. Note that the DPF outlet temperature represents the temperatures of the exhaust that would enter the TEG. For the majority of operational time, the DPF_TempOut is within the range of the DPF_TempIn values. This is likely due to the relatively large thermal mass of the DPF, causing slower temperature variation in the exhaust stream. However, periodically, the DPF_TempOut values increase dramatically, exceeding 800^{o}C at times. These temperature rises represent active regeneration events, and a more detailed view of an active regen event is shown in **Figure 5**.

The faint yellow lines in these figures represent three different Regen signals; Passive, Force, and Active. The Regen_Passive and Regen_Force signals never change during the entire month, and do not appear to be active on this bus. The Regen_Active signal has three bit states: 0, 1, and 2. Active regeneration appears to occur only when Regen_Active = 1. The Regen_Active = 0 state represents "normal" operation, and the Regen_Active = 2 state appears to be either an error message, or else indicates that an active regen event is about to occur.

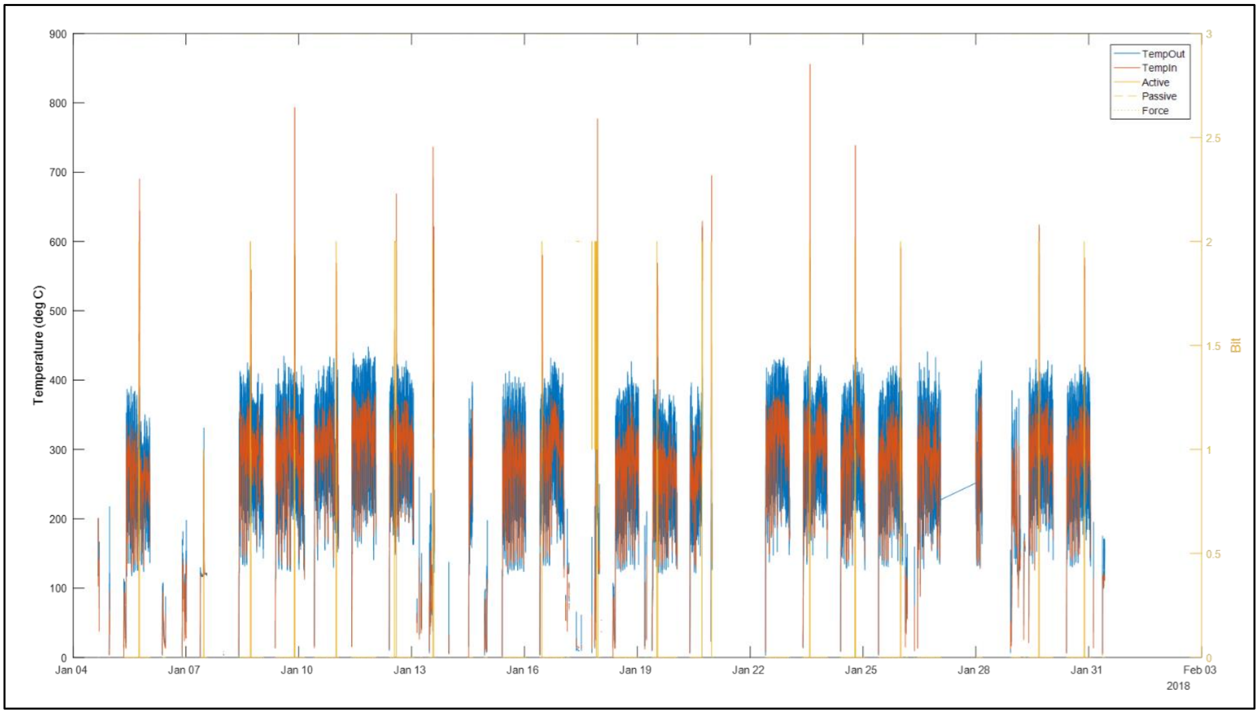

Figure 4. Temperature and Regen signal profiles for Jan 4-Jan 31

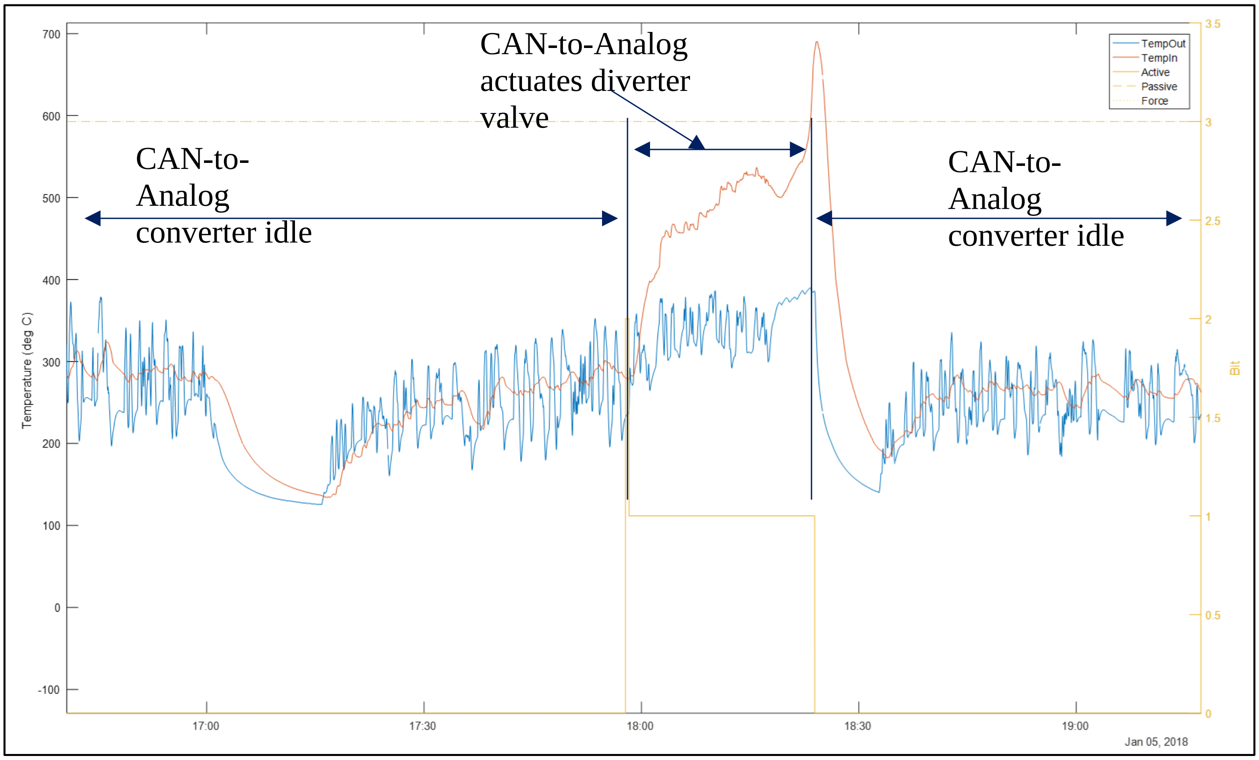

Figure 5. Detailed view of an active regeneration event, showing temperature increase during Regen_Active signal = 1, and high temperatures continuing after regen cycle when Regen_Active signal = 0.

When the Regen_Active = 1 signal is sent, the CAN-to-Analog converter is expected to actuate the diverter valve and the high temperature gases will not reach the TEG. However, during Regen_Active = 0 and Regen_Active = 2, the CAN-to-Analog converter will not actuate the valve. As can be seen in **Figure 5**, there is a risk of high temperatures entering the TEG when the CAN-to-Analog converter is idle due to a Regen_Active = 0 signal. **Figure 6** shows another regen cycle, and indicates that high temperatures can exist when Regen_Active signal = 2.

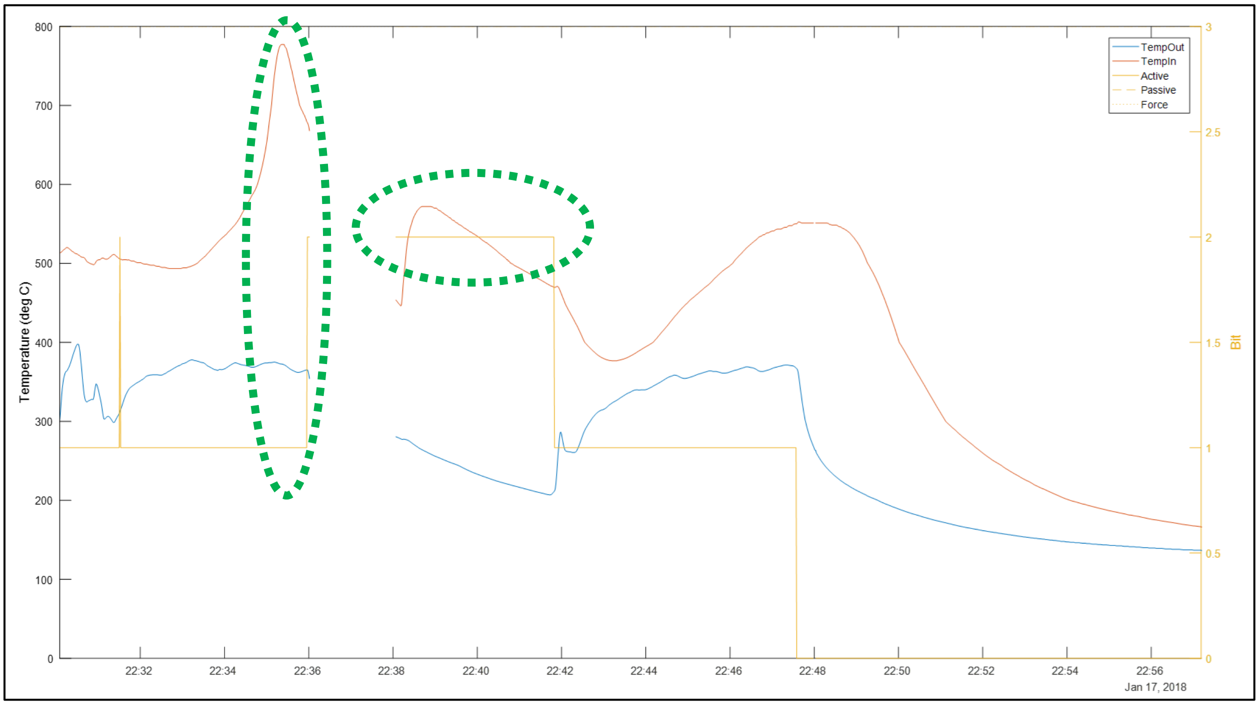

Figure 6. Detailed view of another regen cycle, showing high temperatures can exist when Regen_Active signal = 2

The challenge is that the temperature is not always high for Regen_Active signals 0 and 2. Typically, Regen_Active = 0 indicates low temperature, and this is where the exhaust flow should go through the TEG. Similarly, Regen_Active = 2 usually appears just prior to an active regen cycle, but not always. There were several times where Regen_Active = 2, often just after starting the bus for the day, but the temperature did not rise above 200°C since the bus was shut off shortly thereafter.

The most likely control scenario is probably one where the CAN-to-Analog monitors the bus CAN for Regen_Active = 1, and a thermocouple monitors the gas leaving the DPF. When Regen_Active = 1, the converter will actuate the diverter valve, protecting the TEG from high temperatures during the active regen cycle. Once the regen cycle is over and Regen_Active = 0, the thermocouple will continue keeping the diverter valve actuated to protect the TEG until the gas temperatures drop to acceptable levels, at which point the valve will re-divert gases through the TEG. If Regen_Active = 2 before an active regen event, and the temperature is acceptable, the gas will continue to flow through the TEG without damaging it. If Regen_Active = 2 during or after a regen event, the thermocouple will sense the high temperature and continue diverting the gas away from the TEG.

<u>Regen Cycle Frequency</u>

Two approaches were used to identify regen cycles: temperature-based and signal-based.

<u>Temperature-based analysis:</u> It was found that typical operation could lead to temperatures as high as 386°C. To determine when an active regen event was occurring, the analysis only considered times when the exhaust temperature exceeded 386°C, since these periods only occurred during an active regen event. The time between high temperature events is shown in **Figure 7**. As can be seen, the typical time between

regen cycles appears to be around 20 hours. There are some periods where two high temperature events are only separated by a few hours. These likely represent cases where the bus is shut down in the middle of a regen event, and is started up shortly thereafter.

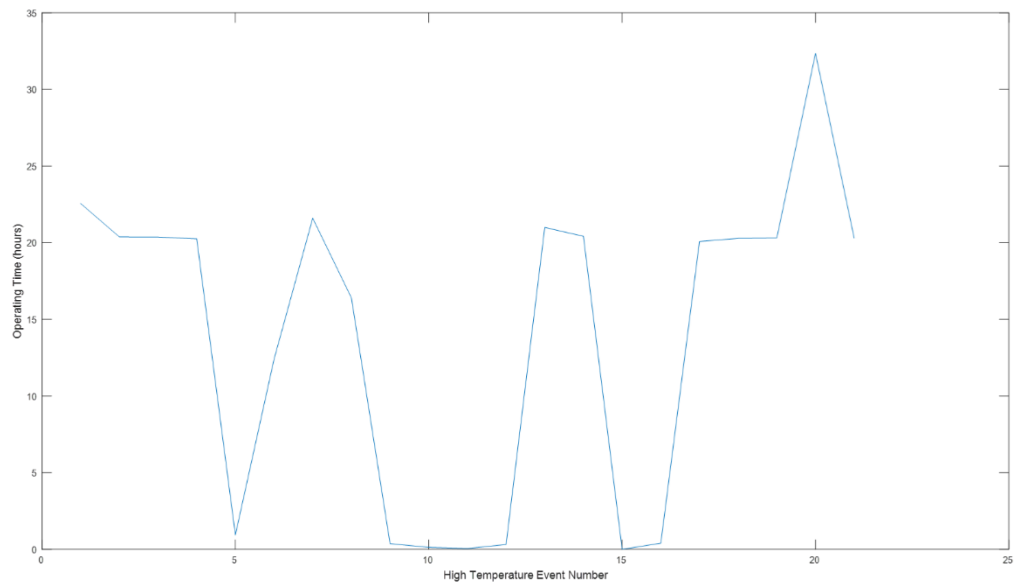

Figure 7. Time between high temperature events, corresponding to active regen cycles.

Signal-based analysis: The operational time between regen events was determined by analyzing the operational time between Regen_Active = 1 signals (see **Figure 8**). As can be seen, the Regen_Active is often sent after very brief periods, and most of these will not result in a high temperature event. However, those signals that occur after several hours of operation (e.g. 9-20 hours) are most often correlated with a high temperature event.

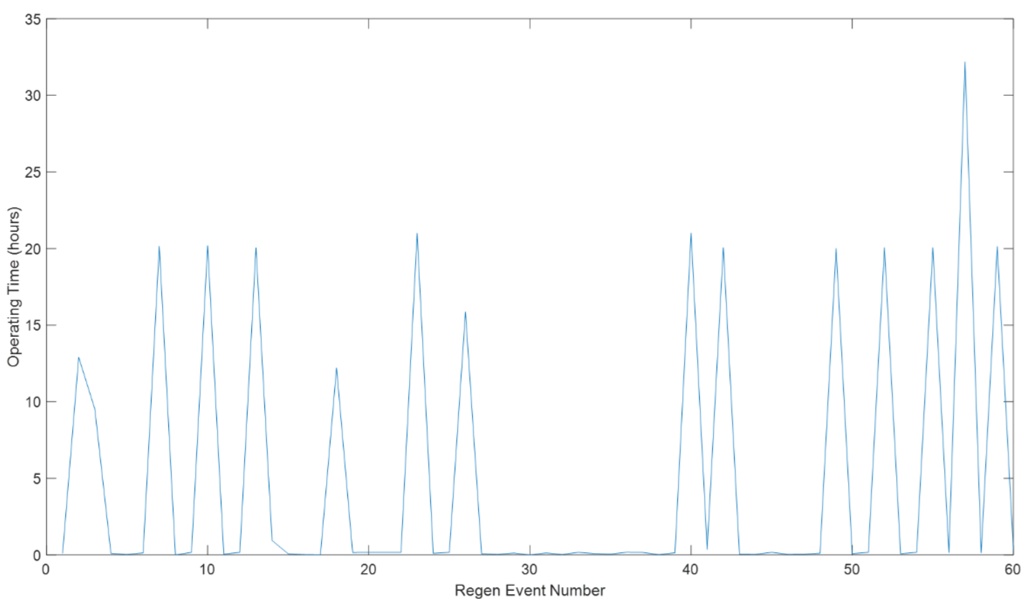

Figure 8. Operational time between Regen_Active = 1 signals

Appendix B Summary

By using the Regen_Active = 1 signal, there is a likelihood that the diverter valve may actuate more frequently than is required, and would divert flow while temperatures are still low. However, this scenario represents a good safety margin to prevent high temperature damage to the TEG, so long as a thermocouple is placed in the stream to ensure the gas temperature has dropped to acceptable levels after the regen cycle. These results also indicate that an active regen cycle appears to occur approximately once every 20 hours.

Appendix C

Thermal Electric Generator (TEG)- Lynx Bus Data

Time,Engine Fan 1 Requested Percent Speed (%),Cab Interior Temperature Command (C),Aftertreatment Regeneration Force Switch (bit),
Request Cab Zone Heating (bit),Engine Percent Load At Current Speed (%),Actual Maximum Available Engine - Percent Torque (%),
Actual Engine - Percent Torque (Fractional) (%),Driver's Demand Engine - Percent Torque (%),
Actual Engine - Percent Torque (%),Engine Speed (rpm),
Engine Demand Percent Torque (%),Aftertreatment Diesel Particulate Filter Passive Regeneration Status (bit),
Aftertreatment Diesel Particulate Filter Active Regeneration Status (bit),Exhaust System High Temperature Lamp Command (bit),
Aftertreatment 1 Exhaust Temperature 3 (C),Aftertreatment 1 Diesel Particulate Filter Outlet Temperature (C),
Aftertreatment 1 Exhaust Temperature 1 (C),Aftertreatment 1 Diesel Particulate Filter Intake Temperature (C),
Stage2-Mod1a hot-out (C),Stage3-Mod1a hot-in (C),Stage2-Mod4a cold (C),Stage1-Mod4a hot-out (C),Stage3-Mod4d hot-out (C),
Stage2-Mod1a cold (C),Stage1-Mod1a hot-out (C),Stage2-Mod1a hot-in (C),Stage3-Mod4d cold (C),Stage3-Mod4a hot-out (C),
Stage3-Mod4b hot-out (C),Stage3-Mod4c hot-out (C),Stage3-Mod1b hot-out (C),Stage3-Mod1c hot-out (C),Stage3-Mod1d hot-out (C),
Stage3-Mod4a cold (C),Stage1-Mod8a cold (C),Stage3-Mod1a cold (C),Stage3-Mod1d cold (C),Stage3-Mod1a hot-out (C),Stage1-Mod6a hot-in (C),
Stage1-Mod6a cold (C),Stage1-Mod7a hot-in (C),Stage1-Mod8a hot-in (C),Stage1-Mod2a hot-in (C),Stage1-Mod2a cold (C),
Stage1-Mod3a hot-in (C),Stage1-Mod5a hot-in (C),Stage1-Mod4a hot-in (C),Stage1-Mod4b hot-in (C),Stage1-Mod4c hot-in (C),
Stage1-Mod4d hot-in (C),Stage1-Mod1c hot-in (C),Stage1-Mod1d hot-in (C),Stage1-Mod4a cold (C),Stage1-Mod4d cold (C),
Stage1-Mod1a cold (C),Stage1-Mod1d cold (C),Stage1-Mod1a hot-in (C),Stage1-Mod1b hot-in (C),Engine Fan 1 Estimated Percent Speed (%),
Fan Speed (rpm),Aftertreatment 1 Exhaust Dew Point (bit),Trip Distance (km),Total Vehicle Distance (km),Engine Reference Torque (Nm),
Engine Coolant Temperature (C),Engine Fuel Delivery Pressure (kPa),Engine Oil Pressure (kPa),Wheel-Based Vehicle Speed (kph),
Engine Fuel Rate (l/h),Engine Instantaneous Fuel Economy (km/L),Engine Average Fuel Economy (km/L),Cab Interior Temperature (C),
Aftertreatment 1 Diesel Particulate Filter Intake Pressure (use SPN 3609) (kPa),Engine Exhaust Temperature (C),
SLI Battery 1 Net Current (A),Alternator Current (A),Charging System Potential (Voltage) (V),Battery Potential / Power Input 1 (V),
Stage 1 (V),Stage 2 (V),Stage 3 (V),Stage 3 regulated output (V),Stage 2 regulated output (V),Stage 1 regulated output (V),
Stage 3 inner module (V),Stage 3 outer module (V),Stage 2 inner module (V),Stage 2 outer module (V),Stage 1 inner module (V),
Stage 1 outer module (V),Load Cell-1 (V),Load Cell-2 (V),Load Cell-3 (V),Manifold Back Pressure (V),Current Interrupt (V),
Stage 1 current (V),Stage 2 current (V),Stage 3 current (V),Stage2-Mod4a hot-in (C),Stage2-Mod4a hot-out (C),
Stage3-Mod4a hot-in (C),Water manifold in (C),Water manifold out (C),Exhaust Flow inlet (C),Exhaust Flow outlet (C),Ambient Air (C)

APPENDIX

C

Commercialization Plan

Energy Florida developed a commercialization plan for the TEG, identifying market sectors for TEG application.

Bus Energy Efficiency Research and Development (BEERD) Program

Thermal Electric Generator (TEG)

Development and Demonstration Project

Commercialization Plan

Prepared by

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October 25, 2018

BEERD Thermal Electric Generator (TEG) Development and Demonstration Project

Commercialization Plan

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I. Project Description, Milestones and Next Steps

Project Description:

Under a research & development project funded by the Federal Transit Administration, the Center for Transportation and the Environment (CTE) coordinated a technical team of subject matter experts to design, build, install, monitor and evaluate a demonstration of a 1.2 kW thermoelectric generator (TEG) system on a diesel-fueled transit bus operated by the LYNX transit system in Orlando, Florida. Under this application, the TEG utilized hot exhaust gases from the transit bus's diesel engine as an energy source and generated electricity which could be used for a variety of purposes on the bus, including offsetting electrical loads from auxiliary equipment installed on the bus, thereby improving the fuel economy of the bus during normal operations. Project team members consisted of Hi-Z Technology Inc., providers of the thermoelectric system, Florida Solar Energy Center, which provided technical assistance and performed independent review of data gathered during the demonstration, International Trade Bridge (ITB) which supported the installation and initial testing of the integrated TEG and bus, and Energy Florida (non-profit organization) which provided guidance on applications for thermoelectric development and commercialization including this report. A forty-foot diesel bus (Gillig BRT) was provided for the TEG retrofit by the Central Florida Regional Transportation Authority (LYNX) in Orlando, which then operated the bus on a normal schedule over the course of the demonstration phase of the project.

Project Milestones

A 1.2 kW Thermal Electric Generator system was designed, built and tested by Hi-Z Technology at its facilities in San Diego, California. Once the TEG system was fully assembled and tested at Hi-Z's facility, it was combined with the data logger provided by FSEC to test the instrumentation of the system. Specialized cowlings to protect the TEG system on the roof of the bus from the elements and/or any external debris it might encounter during the live demonstration were custom-designed, manufactured and tested as well. Once those initial tests were complete, the system, instrumentation and cowlings were shipped to Florida, assembled and installed on the roof of the bus provided by Lynx in late April and early May 2018.

The TEG was retrofitted atop the bus roof, including a cooling radiator with dual fans (240 watts) and water pump (90 watts) and other low power control peripherals. The bus and integrated TEG system were fully instrumented to measure temperatures and voltages observed within and produced by the TEG system during operation. All measurements were merged and compressed into a data file and transmitted in near real-time (every 10 minutes) via cellular network to a dedicated server supported by FSEC, where it was further processed.

Demonstration of the thermoelectric system began during an initial set of road tests and a simulated transit route at Kennedy Space Center (KSC) Florida, where the TEG recorded a peak of 1,126 watts and averaged a power capacity of 971 watts during the one-hour transit route period. Further operation of the TEG was evaluated under LYNX transit routes in Orlando, FL from May 18 through June 12, 2018 where the average power generated was somewhat lower. During transit route demonstration, the power generated by the TEG was delivered to a fixed load (8.3-ohm power resistors) affixed on the back of the rooftop in a well vented enclosure. Nevertheless, power generated by the TEG could be used to reduce the bus alternator load or store energy to serve other ancillary electrical systems in future demonstrations.

Next steps for demonstration of the Thermo-Electric Generation technology

The TEG demonstration project at LYNX has demonstrated that the thermo-electric generator does work and operate in a transit environment utilizing the waste heat from a diesel powered Gillig transit bus to generate electric power at a level of several hundred watts.

Through the course of the installation, testing, and demonstration of the technology, the project team had determined and demonstrated that the operational profile of the bus's route and other performance information has a significant impact on its performance. This demonstration has proven that the operational profile of the bus's activities has a significant and measurable impact on the power output of the thermoelectric generator system, and a corresponding impact on the prospective cost savings that may be anticipated in the installation and use of the system.

Demonstrate Integration of the Thermal Electric Generator with the Electrical System of the Vehicle

Understanding the power generation potential of the system, the next step of commercializing this technology would be to perform a demonstration of the ability of the thermo-electric generator to tie into the electric system of the vehicle. This demonstration would aim to provide empirical evidence that the electric current provided by the thermoelectric generation system can provide either additional charging capacity or help to offset the mechanical and/or electrical load associated with operation of the vehicle's alternator.

This suggested demonstration would "close the loop" to providing an actionable technology that could help provide additional benefits to energy efficiency and fuel economy in buses, long-haul trucks, or other target markets.

This demonstration would help to prove two things: first, that such a charging system would not do any harm to the electrical system of the host vehicle, and second, will allow the team to conduct a more thorough analysis of the specific benefits and operational issues associated with the implementation of this technology in the transportation sector.

This next phase of the demonstration will allow the team to provide a proof of concept that the voltages and power outputs measured during the operation of the original TEG on the LYNX bus during this initial demonstration will be able to have a measurable impact on the efficiency and fuel economy of the operation of a bus, truck or other host vehicle. This will have an impact on prospective investors in the technology which would allow it to move forward to further testing and customization based upon the market profile and needs of those investors and the target markets that they are interested in pursuing for application of this technology.

Individual steps for this next phase could include an initial lab scale proof of concept, that would allow the project team to develop an electric power supply that would simulate the power profile observed during the TEG demonstration. This would be connected to a smaller vehicle (potentially a car) to demonstrate that the type and voltage of power being produced by the TEG would not have a deleterious impact upon the alternator and electrical system of a vehicle. This smaller scale initial demonstration would provide proof of concept regarding how vehicular electrical system(s) would react to the input of power from the TEG or similar systems.

By providing a smaller-scale proof of concept, this initial step would allow for greater instrumentation and control of the system and the gradual introduction of power to the circuit, allowing the project team to gradually ramp-up the input voltage to the system and reduce risk of an adverse impact to the vehicle or its electrical systems.

The initial theory of how this test would operate is that the battery embedded in the system will only take what voltage it needs to charge. Once it is fully charged there are charge protection circuits set up on batteries in most vehicles, which would prevent overcharging of the battery system(s). Likewise, the team's understanding of the impact to the alternator would be that the alternator would naturally self-modulate its output based upon the input coming into the vehicle's electrical system from external electrical sources (such as a battery or an external source such as the thermoelectric generator), and that therefore a separate "smart circuit" controller system to manage the impact of the additional voltage on the vehicle's electric system would not be necessary.

Once the initial proof of concept demonstration is complete, the next step would be to tie a DC (direct current) power supply to a bus or truck electric system to prove the same concept works at that scale.

Then, the next step would be to install a thermo-electric generator unit that is linked up to the electrical systems of the vehicle to prove not only the generation of electricity through conversion of waste heat, but also the linkage of that power generated by the TEG to offsetting load or supplementing generation capacity in the vehicle's own electrical systems.

This last step would ideally be well-instrumented to document empirically the specific impact of the TEG to the electrical system of the host vehicle (whether it is a bus or a heavy-duty truck), and to be able to collect data regarding the impacts on system efficiency. This test would seek to identify the alternator acceptance efficiency factor for the host vehicle tested. Based upon that empirical data and information on the operational profile of the vehicle activities during the demonstration, the team could project prospective operational costs (and cost savings) based upon empirical data from the demonstration.

Regarding the type of vehicle that could be targeted for such a demonstration, a Gillig diesel-powered transit bus (e.g. something closely analogous to the vehicle used in this initial demonstration) would be a logical next step given the significant investment in design and customization of the TEG system for that envelope and set of specifications under the current project. Targeting a similar system would enable reuse of much of the design and engineering work, and the lessons learned in developing the prototype could be analyzed and applied in developing the follow-on system.

Based on the direct empirical information on the power output produced by the TEG unit during normal bus operations, the project team did make an estimate of the savings that might reasonably be expected from the operation of the TEG unit in a diesel transit bus environment. This analysis, performed by the subject matter experts at the Florida Solar Energy Center, suggests that the overall efficiency gain expected from the operation of the TEG (producing approx. 400W in normal operation, and at a 50%

alternator acceptance efficiency on a diesel-fueled transit bus similar to that used in the demonstration) was approximately 1%, or $513 over one year of operation at $3.20/gallon of diesel equivalent.

These projected savings are highly dependent upon 1) the size (measured in power output) of the TEG generator and 2) the alternator acceptance efficiency factor associated with the input of power from the TEG system to the electrical system of the vehicle. In this case the assumed alternator acceptance factor was 50%, but an improvement to 75% in the alternator acceptance factor would double the fuel efficiency benefits observed from the TEG system. Likewise, an increase in the power output of a TEG unit would also change the efficiency benefits observed. The suggested demonstration linking the TEG to a vehicle alternator will help to define the parameters of that alternator efficiency factor much more concretely. This information will be crucial to understanding the overall fuel efficiency benefits that might reasonably be expected from a TEG system in normal operation and help to further define the appropriate parameters for a cost-benefit analysis of the TEG technology relative to other potential technologies that would provide improvements to fuel efficiency for transit buses and/or other applications in the transportation sector.

When applying this activity toward segments of the market that would be of greatest commercial potential, adapting the TEG system in the next phase toward the profile and specifications of a heavy-duty diesel-powered specialty truck chassis could be a great way to initiate design and development of partnerships with a market segment that, if the demonstration is successful, could reap great benefits from this type of technology. Some of the specialty vehicle manufacturers that work in this market segment may have in-house expertise regarding customization and application of add-on technologies to the base truck that may be highly beneficial for adaptation and commercialization of this technology following the next phase of demonstration. Finally, expanding the range of sectors that the TEG technology could help provide efficiency benefits for would help in increasing the production volume(s) and decreasing the unit costs and overall affordability of the technology vis-à-vis implementation in the transit market.

Demonstrate the TEG system with different fuel options – Diesel or Natural Gas

In addition to “closing the loop” in a demonstration of the TEG system through connection to the electrical system(s) of its host vehicle(s), another area of interest relative to future demonstrations would be in testing the thermal electric generation system with a (Compressed Natural Gas) CNG-fueled engine and exhaust system. As CNG systems tend to combust at higher temperatures than diesel-fueled systems, that would theoretically create a higher exhaust temperature and a greater temperature differential within the thermal electric system. As thermal electric generation units operate more effectively with a higher temperature differential between the “hot” and “cold” sides of the unit, the higher exhaust temperatures associated with a CNG system would presumably generate additional electricity from the TEG system and provide a higher theoretical efficiency for the thermal-electric generation system relative to a diesel-fueled engine. The lower emissions profile of CNG buses means that the “re-gen” cycles associated with emissions controls in diesel buses become less of an issue, simplifying the design and implementation of a thermal electric generator for a CNG-fueled engine system.

However, to prove these concepts and demonstrate the efficacy of a thermal-electric system for a CNG-fueled vehicle, a second follow-on demonstration may be needed to pilot the integration of this technology with a CNG fueled vehicle. As many transit agencies are beginning to convert significant portions of their fleets to natural gas-burning vehicles, such a demonstration would also help to open a larger portion of the transit market for this technology and open the door for the TEG technology to provide additional fuel efficiency benefits for both diesel-fueled and natural gas-fueled vehicles.

This demonstration could be conducted on a CNG-fueled transit bus or could be conducted on a CNG-fueled truck and later adapted as a package for use in the transit bus environment. As will be outlined below, the thermal electric generation technology demonstrated during this project has potential applications and markets in both transit bus fleets and trucking operations.

II. Market Opportunities

The following sections of the commercialization plan will review the market opportunities for the thermal waste heat recovery or thermal electric generator technology in a variety of market segments – first in buses (the primary focus for this technology demonstration effort), and then in other segments of the transportation industry – trucks (both tractor trailers and specialty trucking markets) and the marine industry. This will include review of the major segments of each market, and major North American manufacturers within the bus and truck industry who may be candidates for further outreach and engagement as this technology proceeds toward commercialization by the industry.

Domestic Market Assessment for a Thermo-electric Waste Heat Recovery (TWHR) System for Buses

September 2018

The United States Department of Transportation (US DOT) and its agencies keep detailed records concerning buses. This means the US market for transit buses is annually assessed, readily available and the data is no older than two years. The main reasons for these complete data sets are because public school systems are the largest provider of public transportation in the nation and municipal bus systems receive many forms of federal funding.

Before describing the market and its subsectors, a strategic insight should be noted about one of the grant partners LYNX. The Central Florida Regional Transportation Authority operates LYNX, which serves the greater Orlando, Florida area, Orange, Seminole, and Osceola counties with limited service to Polk County with passenger bus service.

LYNX ranks 42nd out of the 50 largest transit agencies for both unlinked passenger trips and passenger miles in the nation. [1] It ranks 29th for passenger miles and 37th for passenger trips. For "rapid" transit LYNX ranks 8th for unlinked passenger trips and 9th for passenger miles. For "demand response" services LYNX ranks 23rd for unlinked trips and 19th for passenger miles.[2]

This makes LYNX an ideal demonstration partner for the TWHR (**T**hermo-electric **W**aste **H**eat **R**ecovery) system, being among the top 50 providers of public bus service, in the top 25 for demand response service and in the top 10 for rapid transit in the US market.

It should also be noted that while not a partner on this grant, that Orange County Florida (which includes the City of Orlando) is ranked 18th in the nation's Top 100 School District Fleets. [3] The District has 1,064 buses and 906 routes with more than 72,000 students transported annually. Mileage for the school year exceeds 17,000,000 miles. This makes Orange County and the Central Florida region an ideal candidate not only for testing but also for sales.

The United States had 888,907 registered buses in service as of 2015.[4] Canada's fleet of registered buses numbers 90,463.[5] With current growth, that number is estimated to surpass one million buses by the end of 2017.

This overview of the market falls into three segments:

1. **School Transportation Systems**
2. **Municipal/Public Transportation Systems**
3. **Commercial Buses/Motor Coaches**

While there are other segments for this market, these are the largest and would see the greatest impact from the introduction of new technologies. The thermo-electric waste heat recovery system converts a portion of the bus exhaust (waste) energy into useful electric power and would allow the bus to store this energy for future use (through its existing battery) or through reduction of load on the alternator. This electricity will be produced and stored when the bus engine is operational and electric power can be used to run HVAC and/or bus electrical accessories when the engine is off. These benefits will be of great value to each of these market segments, although the specific needs, value proposition and return on investment will differ slightly between each segment.

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[1] 2016 Public Transportation Fact Book 67th Edition, American Public Transportation Association, Feb 2017 Available at: www.apta.com

[2] 2016 Public Transportation Fact Book 67th Edition, American Public Transportation Association

[3] Top 100 School District Fleets, School Bus Fleet, October 2014 edition

[4] 2017 Pocket Guide to Large Truck and Bus Statistics, Federal Motor Carrier Safety Administration, June 2017

[5] Statistics Canada, www.statcan.gc.ca

School Transportation Systems Market Summary

The facts speak for themselves. School transportation is the largest public transportation system in the United States. Unless otherwise noted, the following facts are quoted from the "School Bus Fleet Fact Book 2016."[6]

- Total school buses 484,041(in use)
- District owned 203,053
- Contractor owned 116,991
- School buses retire at 16.2 years average.
- Average age of school bus fleets is 9.3 years
- There are 13,506 school districts in the US (some of the smaller districts have united transportation functions with other districts)
- School buses powered by diesel fuel are 55% or 266,226 buses[7]
- The average mid-life cycle overhaul is at the 7/8-year point[8]

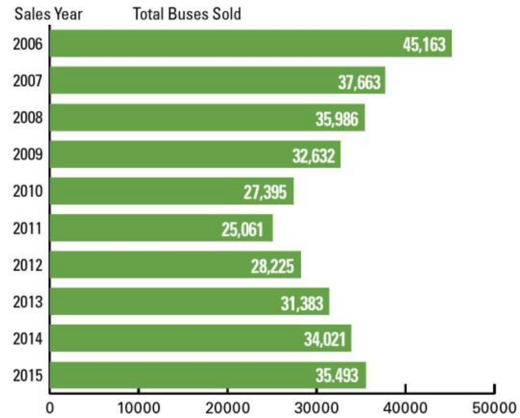
Ownership percentage of school buses

- 62% School District
- 36% Contractor
- 2% State owned

The next 2 tables of the US Bus Sales in total, and by type (2006-2015) are listed, and finally a table demonstrating the 2016 numbers.

[6] School Bus Fleet Fact Book 2016, School Bus Fleet Vol. 61 Issue 11
[7] Diesel Technology Forum; www.dieselforum.org/about-clean-diesel/public-transportation
[8] Bus Lifecycle Cost Model, Volpe National Transportation Systems Center, www.volpe.dot.gov

U.S. Bus Sales (2006-2015)



U.S. Bus Sales (by type)

Sales Year	Type A/B	Type C	Type D	Total
2006	8,165	29,355	7,643	45,163
2007	7,634	23,839	6,190	37,663
2008	5,475	24,148	6,363	35,986
2009	6,266	21,873	4,493	32,632
2010	6,487	18,252	2,656	27,395
2011	5,740	16,908	2,413	25,061
2012	5,447	18,822	3,956	28,225
2013	5,692	21,841	3,850	31,383
2014	6,684	23,715	3,622	34,021
2015	6,560	24,830	4,103	35,493
Change	**-1.9%**	**+4.7%**	**+13.3%**	**+4.3%**
2015 vs. 2014				

Looking just at the U.S., school bus sales rose in all categories except Type A. Overall, there was an increase of 4.3% in 2015 compared to 2014.

Division of bus types in year 2016	**No. Buses**	**% of total**
Type A/B (cutaway van/integrated chassis)	**93,655**	**19%**
Type C (conventional, cowled chassis)	**319,030**	**70%**
Type D (front/rear engine transit style)	**71,356**	**11%**
Total in 2016	**484,041**	**100%**

Th school transportation sector is an outstanding market for this technology by size, by growth, for adaption at mid-life cycle maintenance and since school districts by their nature are very cost-conscious. Perhaps the greatest strength for this market is that it is well connected. Almost every school district belongs to the same associations. Best practices and positive results are readily shared. If something works in one state/county, it is shared nationwide. The usage profile of school buses (specified periods of operation, lots of stops/idling time relative to total operation) may or may not fit an ideal model for the TWHR system (longer periods of operation, fewer stops) depending on the needs of the buses. Also, depending upon the needs of the buses for operation of auxiliary equipment (closed-circuit TV security systems, etc.) the return on investment may vary significantly across jurisdictions.

Municipal/Public Transportation Systems Market Summary

Just like the School Transportation sector, the facts speak for themselves for Municipal/Public Transportation. Unless noted, the facts quoted come from the 2016 Public Transportation Fact Book. [9]

There are more than 1,140 public transportation systems in the United States. Approximately 700 cover urbanized areas and 439 cover rural communities. There are also 278 commuter bus systems operating between urban centers or urban to rural locations.

Buses by far is the largest segment of the non-school public transportation providing 47.6% of the services for passenger trips and 32.5% of passenger miles. Next largest sector is heavy rail with 36.5% of passenger mile and 30.7% of passenger trips. There are 64,573 buses in operation and another 6,053 of commuter buses. The average age of these buses is 7.8 years. Fifty percent of these buses use diesel fuel the next largest power source is CNG/LNG (Liquified Natural Gas) at 22.6%. Public transportation buses use more than 368,000,000 gallons of diesel fuel annually. CNG is growing rapidly in its share of transit buses across the country, as many transit agencies are considering the (generally) lower fuel costs and lower emissions associated with CNG as strong selling points, however implementation of infrastructure for CNG fueling remains a factor limiting some conversions. Canadian public transportation has 16,230 buses.

The next two charts reflect the growth in the public transportation system.

[9] 2016 Public Transportation Fact Book 67th Edition, American Public Transportation Association

Figure 1: Transit Ridership at Highest Level in Four Decades

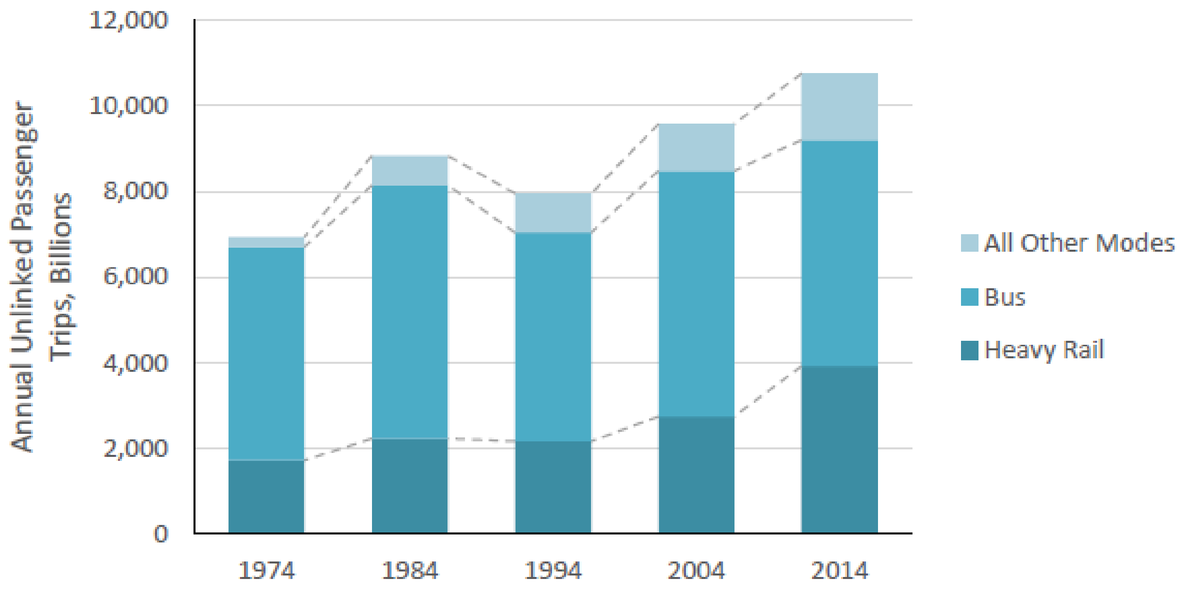
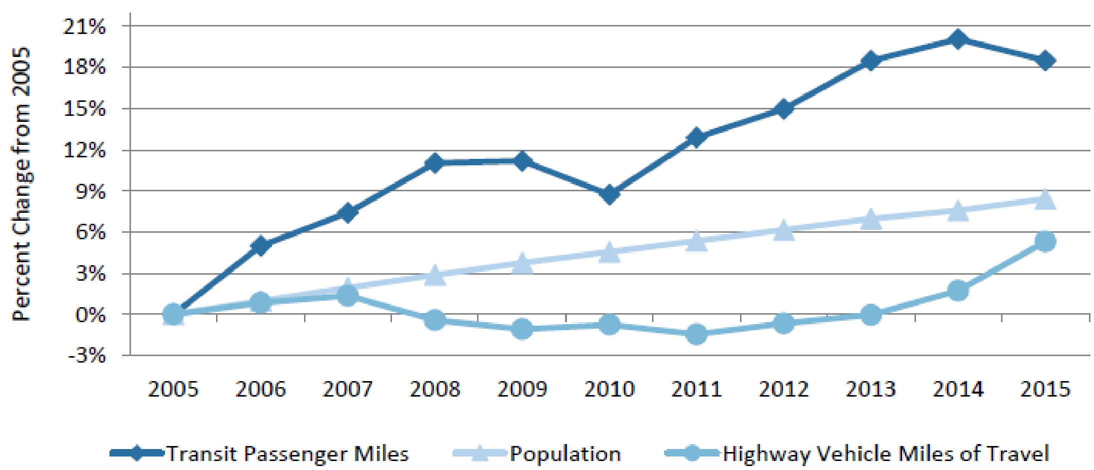


Figure 2: Since 2005 Transit Use Has Grown More Than Population or Highway Travel



Sources: Transit Passenger Miles from *APTA Public Transportation Fact Book* for 2004 through 2015 and estimated from *APTA Public Transportation Ridership Report* unlinked trip data for 2015, Population from U.S. Census Bureau, Highway Vehicle Miles of Travel from Federal Highway Administration *Travel Volume Trends*.

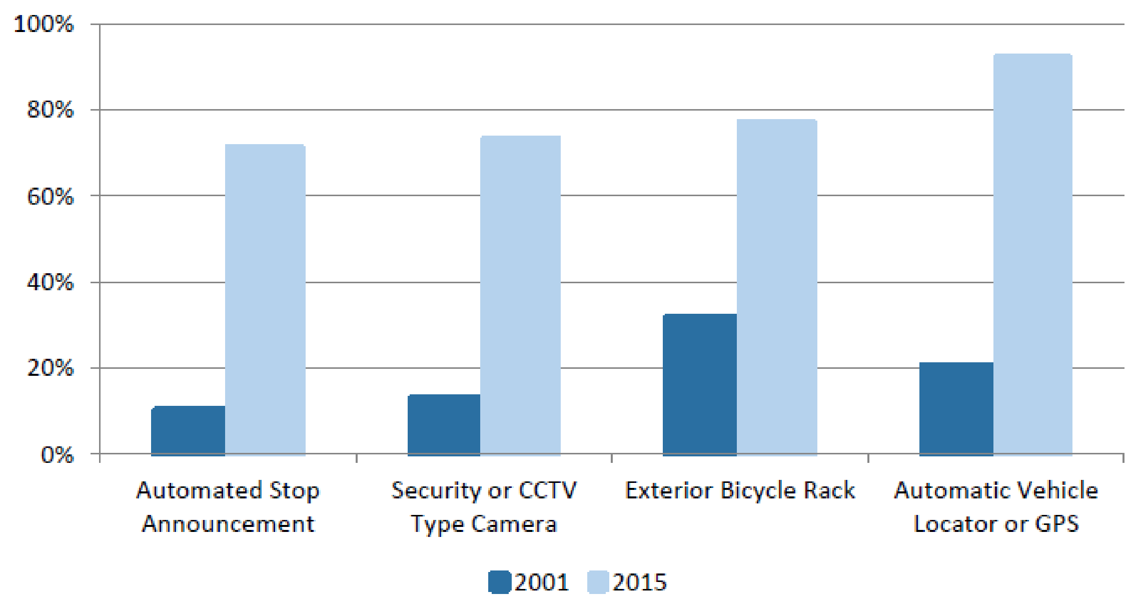
The next two charts are very important for the thermo-electric technology. In the first chart (called Table 9) the first three columns show what equipment is installed in buses. These accessories that use electricity are the key areas for the electric power generated. The second chart (Figure 7) show the growth of use of passenger equipment – three out of four use electricity.

Table 9: Vehicle Equipment by Mode
as of January 2015

Type of Equipment	Bus	Bus Rapid Transit	Com-muter Bus	Com-muter Rail	Hybrid Rail	Heavy Rail	Light Rail	Street-car	Ferry-boat
Two-Way Radio	94.2%	100.0%	91.3%	65.2%	100.0%	38.8%	98.6%	95.3%	88.9%
Public Address System	93.1%	70.6%	95.4%	77.6%	100.0%	96.0%	95.6%	83.3%	88.9%
Automated Stop Announcement	71.2%	100.0%	1.3%	35.3%	100.0%	55.6%	89.8%	69.4%	0.0%
Automatic Passenger Counter	50.0%	100.0%	6.7%	4.2%	75.0%	0.2%	39.5%	41.4%	0.0%
Passenger-Operator Intercom	4.0%	0.0%	5.2%	45.2%	50.0%	70.6%	86.0%	1.2%	53.3%
Security or CCTV Type Camera	73.2%	100.0%	18.2%	5.8%	100.0%	19.7%	57.5%	95.0%	59.1%
Exterior Bicycle Rack	77.1%	29.4%	6.6%	0.0%	0.0%	0.0%	0.0%	0.0%	22.2%
Automatic Vehicle Location or GPS	92.2&	100.0%	89.0%	42.2%	100.0%	15.9%	72.4%	95.7%	77.8%
Traffic Light Preemption	14.1%	100.0%	1.3%	NA	NA	NA	17.4%	16.7%	NA
Restroom	0.0%	0.0%	0.0%	51.9%	0.0%	NA	NA	NA	71.7%
WiFi	6.4%	29.4%	3.2%	9.5%	50.0%	1.4%	0.0%	0.0%	37.8%
Electrical Outlets	1.1%	0.0%	57.9%	53.2%	25.0%	0.9%	16.2%	0.0%	64.4%
Dynamic Destination Signs	8.5%	0.0%	0.0%	0.0%	25.0%	14.2%	5.3%	0.0%	0.0%
Electronic Destination Signs	95.5%	100.0%	89.4%	40.0%	91.7%	56.4%	61.6%	62.8%	0.0%

NA = Not Applicable
Based on a sample from annual APTA *2015 Public Transportation Vehicle Database.*
Vehicle amenities data by mode from 2001 through 2015 can be found in the *2016 Public Transportation Fact Book, Appendix A: Historical Tables* at www.apta.com.

Figure 7: Growth in Percentage of Buses with Passenger Equipment, 2001-2015



Just like School Transportation, Municipal/Public Transportation is an outstanding market for this technology and has all the same advantageous characteristics of size, growth, and opportunity for adaption at mid-life cycle maintenance and municipalities, by their nature, are cost-conscious. Again, just like School Transportation the greatest strength for this market is that it is well connected. Almost every public transportation system belongs to the same associations. Best practices are used, and results are shared. If something works, it is shared nationwide.

Commercial Buses/Motor Coaches Market Summary

The next significant sector within the North American bus market is Commercial Buses and Motor Coaches. At approximately 42,000 vehicles it is 2/3rds the size of the Municipal/Public Transportation Systems segment.[10] While it is a smaller portion of the market, 77% of Commercial Buses/Motor Coaches use diesel fuel, and the percentage of use of equipment within the commercial bus and motor coach segment is more than 25% higher than that observed for school buses or many transit systems. Commercial Buses/Motor Coaches tend to make longer-haul trips than either of the prior market segments, and it is in companies' interest to make efficient use of their existing assets, so the usage profile of this segment of the bus market may be better suited for the TWHR system to operate effectively.

The ownership model and economics of the commercial bus market is much different than the transit environment. The ownership structure in the commercial bus segment tends to be much more de-centralized, with many private operators (rather than public or quasi-public entities) each with smaller fleets. Energy efficiency is of interest to the commercial bus marketplace to the extent that a technology improves an operator's bottom line, but broader policy goals or emissions standards are unlikely to provide much of an additional impetus in this segment.

The commercial bus and motor coach segment appear to be a good opportunity for customer engagement once the technology has been successfully demonstrated but is unlikely to be an "early adopter" during technology testing. Once the technology is available as a package off-the-shelf, this may be a very beneficial segment to pursue for future commercial development of the TWHR technology. For example, one of the largest single private commercial bus operators in the country, Mears Transportation Services, is headquartered in the Orlando area, and services many of the theme parks, cruise lines and convention businesses associated with the Central Florida region. Mears Transportation Services would be a prime candidate for a follow-up conversation regarding potential interest in TEG technology from the private sector transportation services provider's perspective. However, the functionality of the TEG's tie-in with the electronic system of its host vehicle will need to be demonstrated prior to the commercial bus and motor coach segment becoming a significant prospective partner for commercialization of this technology.

Summary of Thermo-electric Waste Heat Recovery Market for Buses:

Overall, there is a very attractive potential market for the Thermo-electric Waste Heat Recovery System for Buses. There are numerous reasons for this assessment:

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[10] Calculated based on statistics in Pocket Guide to Large Truck and Bus Statistics 2017, Federal Motor Carrier Safety Administration, June 2017 Available at: www.fmcsa.dot.gov

- **Public transportation ridership is growing**
- **Miles travelled by buses in most sectors is increasing**
- **Both school and public transportation systems are using more auxiliary equipment requiring electricity**
    - **New amenities (most of which use electricity) are important to younger riders**
    - **Update safety and security systems use electricity**
- **Schools are undergoing a growth spurt, according to the Center of Public Education most states will see an increase of 10% of in school age children by 2030, which is primarily within the South, Southwest and Western United States.**
- **School buses average an age of 9.3 years and public transportation buses have an average age of 7.8 years, with typical service life of approximately 16 years.**
    - **The mid-life servicing is done during years 7 or 8, meaning there is near constant market for new technology to be retrofitted on existing units during their mid-life servicing, or placed on a new bus at the factory or during the initial commissioning immediately after sale.**[11]
- **These markets are well connected and networked. That allows for testing and development and more importantly for sales**
- **Fuel efficiency is a factor in decision making for both school districts and public transportation authorities**

The key insight is that the customers need to have input.

The school districts and public transportation systems need to be involved directly with the development of the product. As noted before, LYNX is a transportation system and is a grant partner, and their input as well as those of other prospective customers should be actively solicited and integrated throughout the execution of future demonstration projects.

Other transit agencies who are early adopters involved in cutting edge technology demonstrations who could be worth approaching or engaging include:

- TriMet in the Northwest - a consistent leader in transit technology demonstrations & pilots
- Dallas Area Rapid Transit another system that tries many different types of technology
- Minneapolis does a lot of work regarding transit projects with their local research university, the University of Minnesota
- The Los Angeles Metro transit might also be worth a look, as many transit agencies in areas that are ramping up for major events (such as LA's hosting of the 2028 Olympics) often embark on

[11] Bus Lifecycle Cost Model, Volpe National Transportation Systems Center, www.volpe.dot.gov

major technology demonstration and implementation programs as part of the preparations for the event.

The insights and feedback from the conversations with transit authorities and other customers during the current project are highlighted in the section on "Insights and Next Steps Based upon Market and Customer Outreach" following the market assessment section of this plan.

Fundamentally, to be adopted, new technologies need to be competitive in price relative to the benefits that they will deliver to the bottom line of transportation fleet operators. If there is customer input in the design and capabilities of the system and customers' requirements can be met regarding performance and cost, a strong market can be expected.

Domestic Market Assessment for a Thermo-electric Waste Heat Recovery (TWHR) System for Trucks

September 2018

Preface:

To understand the market opportunities for a **T**hermo-electric **W**aste **H**eat **R**ecovery (TWHR) System for trucks, one must first understand the weight-classes, fuel-types, and functions of the different segments of the truck market. This section includes a several-paged primer on the domestic market segments, and it leads to a succinct conclusion: the analysis identifies an opportunity to insert thermo-electric generation systems as an option within the customization process for new semi tractors.

OEMs (Original Equipment Manufacturer) and large trucking customers must have valid evidence of both the technical and cost benefits of the technology to adopt the TWHR system as a standard build-option within heavy-duty truck equipment.

Understanding the on-road vehicle fleet market and its very specialized segments is key to identifying and eventually accessing those sub-markets that would find value and make use of a TWHR system.

Market Segments:

The North American on-road vehicle fleet is very diverse, composed of relatively standardized vehicles such as pickup trucks and passenger cars, as well as highly specialized vehicles such as street sweepers and tow trucks. However, these vehicles can be grouped using common physical characteristics and usage criteria, including vehicle type, weight capacity, and duty rating.

On-road vehicles are designed to travel on public streets and motorways and must meet a variety of safety requirements to be operated as such. In addition, each type of on-road vehicle is assigned a weight class that represents the maximum weight that it can safely support, including cargo and passengers. This weight rating is known as the gross vehicle weight rating.

In the U.S., Department of Transportation (DOT) designations are used and are defined as follows:

Passenger Car/Light Truck

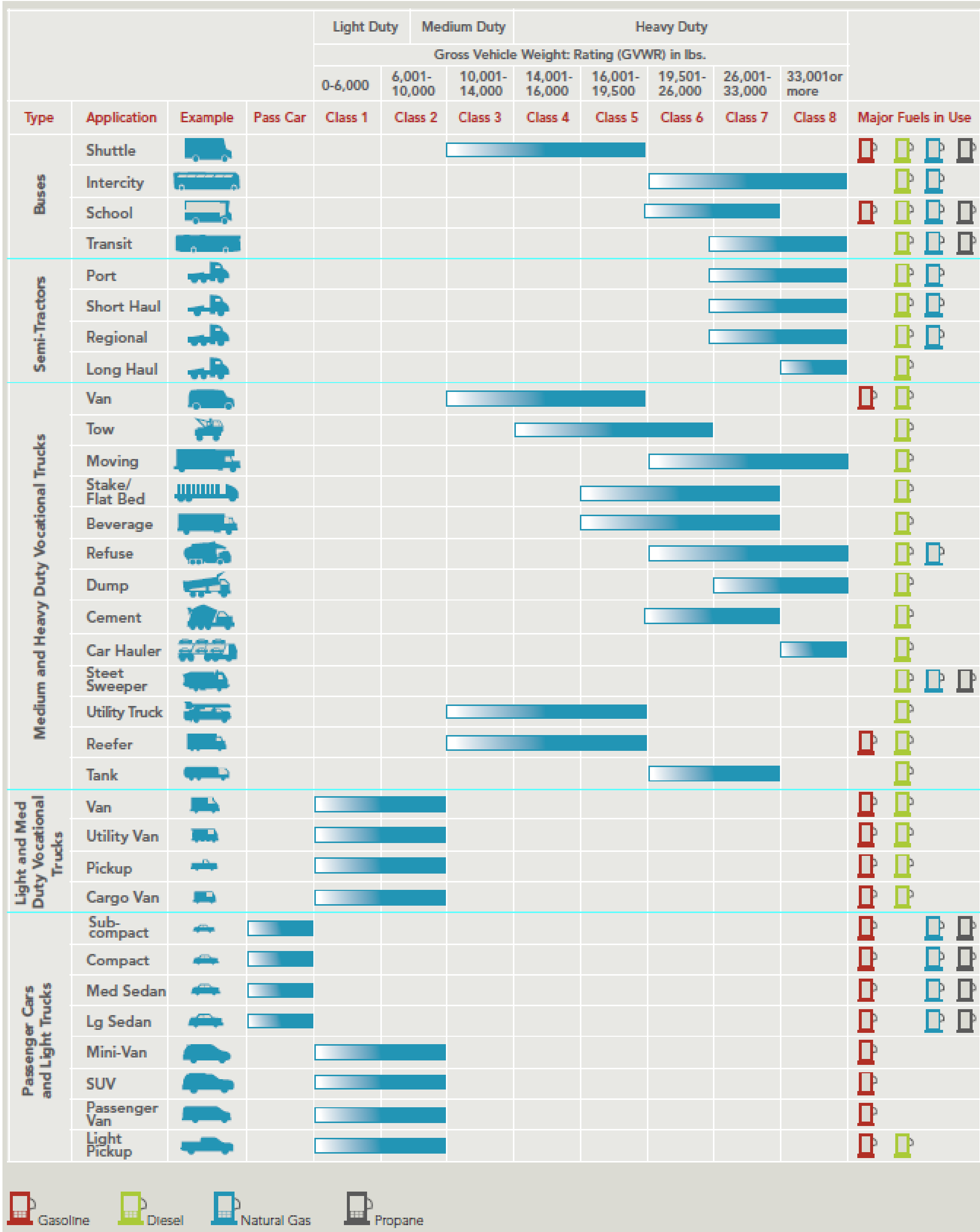
- Class 1: ≤6,000 lbs (light-duty)
- Class 2a: 6,001 to 8,500 lbs (light-duty)
- Class 2b: 8,501 to 10,000 lbs (medium-duty)
- Class 3: 10,001 to 14,000 lbs (medium-duty)
- Class 4: 14,001 to 16,000 lbs (heavy-duty)
- Class 5: 16,001 to 19,500 lbs (heavy-duty)
- Class 6: 19,501 to 26,000 lbs (heavy-duty)
- Class 7: 26,001 to 33,000 lbs (heavy-duty)
- Class 8: ≥33,001 lbs (heavy-duty)

Vehicles are also commonly grouped by weight categories: light-duty, medium-duty, and heavy-duty.

The precise definition of these categories varies significantly. In many industry studies, light-duty is considered to include passenger cars through Class 2a vehicles. Medium-duty includes Class 2b through Class 3 vehicles, and heavy-duty includes Class 4 through Class 8 vehicles. It is not uncommon for a single vehicle to have different weight class designations depending on the equipment installed on the vehicle. These groupings are consistent with those used for emissions certifications and represent a reasonable separation between trucks that are mass produced (light- and medium-duty) and those that are highly customized (heavy-duty). Figure 4 below provides an overview of these groupings for several common vehicle types. [12]

[12] Vehicle Weight Class Overview and Figure 4 adapted from American Natural Gas Assn (ANGA), *US and Canadian Natural Gas Vehicle Market Analysis: Market Segmentation*

Figure 4:
U.S. DOT Vehicle Classes and Fuels in Use for Various Transportation Applications



While there is some overlap in the light- and medium-duty truck markets, gasoline is the dominant fuel for light-duty vehicles. Diesel is the dominant fuel in medium-duty and heavy-duty applications, primarily due to the higher fuel efficiency and torque of compression ignition engines. In applications with relatively low fuel consumption, gasoline competes with diesel for market share. Natural gas has significant market presence in the heavy-duty market segment, including buses, semi tractors, and specific types of "vocational" trucks that are customized to serve specialized applications.

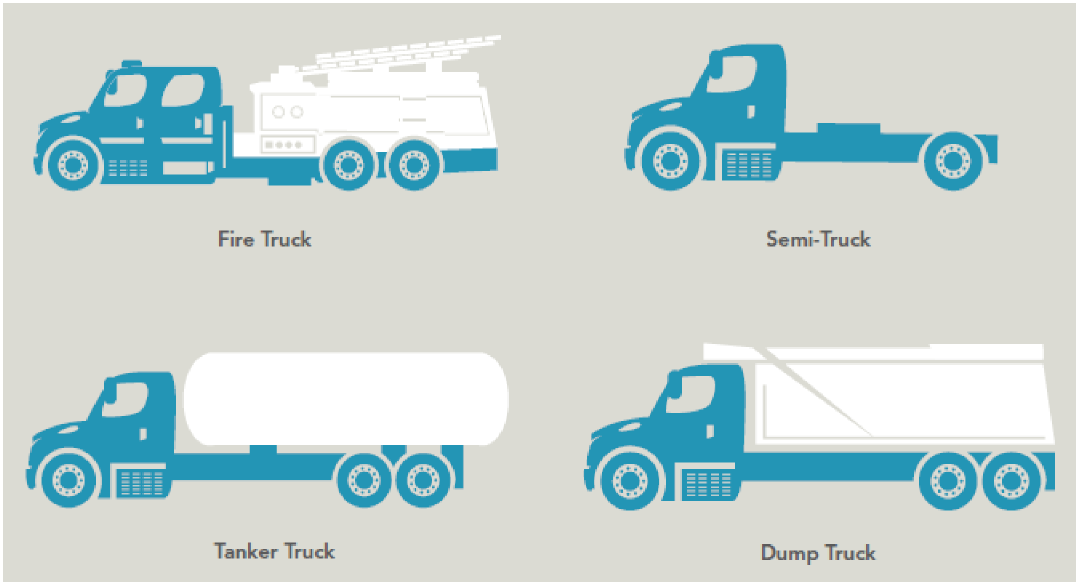
Heavy-Duty Truck Market Dynamics: *Customization is king, and provides an opportunity for new technologies*

The heavy-duty market contains a diverse population of vehicles and can be separated into two general groups: vocational trucks and semi-trucks. Vocational trucks have specialty (purpose-built) bodies and support equipment; examples include cement mixers, street sweepers, and refuse trucks. This generally restricts their use to solely their intended application. Semi-trucks retain versatility by connecting to different trailers but are generally used for goods movement. While vocational trucks may be the most highly customized heavy-duty vehicles, both vocational and semi-trucks can be offered in thousands of configuration options by OEM and numerous aftermarket vehicle modifiers.

Vocational trucks are typically ordered from the truck OEM with only the cab attached to the vehicle chassis. The truck is shipped from the OEM to a body builder that installs a customized body to the vehicle chassis. The same process is used in the medium-duty market when specialized truck bodies are required. In the heavy-duty market, however, the vehicle purchaser typically has many more choices in configuring the vehicle chassis, cab, and engine. Because of the ability to customize the body and chassis, it is possible for the customer to purchase almost any vocational truck as a natural gas truck, provided at least one vehicle OEM offers a natural gas option for the base vehicle chassis.

For example, in recent years Freightliner has offered its M2-112 chassis with the Cummins ISL-G natural gas engine. As shown in the figure below, this chassis can support a wide variety of vocational truck bodies as well as a semitruck configuration. This chassis is designed for Class 7 and Class 8 applications and would not be ideal for medium-duty Class 4 to Class 6 vehicles. Where natural gas options are not available from the vehicle OEM on a chassis in the proper weight class for a specific application, vocational truck purchasers must utilize Small Volume Manufacturers (SVMs) to provide natural gas engine conversions or other customizations as required. This standard practice of customizing heavy-duty vehicles provides a potential opportunity to integrate thermo-electric generation (TEG) system(s) into truck configurations for diesel or natural gas engines and fuel systems without significantly altering the typical heavy-duty vehicle development and purchase process. In that way, a TEG system developed for a single truck chassis could potentially be used across multiple platforms depending on the customization(s) implemented by the SVM or aftermarket provider.

Figure 5:
Customization of a Common Heavy-Duty Truck Chassis for a Variety of Specialized Applications



Semi-trucks do not employ specialized bodies but instead use a fifth wheel to connect to and haul various semi-trailers. Despite the lack of a specialized body, semi-trucks are no less customized by the vehicle purchaser. Because semi-trucks travel more miles annually than any other vehicle type, fleets invest a great deal of time determining the precise combinations of engine, transmission, and drive train that will maximize fuel economy and minimize operating costs. Therefore, there is an opportunity to insert a thermo-electric generation system as an option within the customization process for new semi tractors. It is necessary to demonstrate both the technical and cost benefit of the technology to OEMs and most especially large trucking customers.

Truck Market Opportunities:

1. **New vehicles**

According to ACT Research data, 6,885 natural gas trucks were sold during 2016, up slightly from 6,767 units sold the year before (2015). Driven mostly by engine emission regulations, the agency's forecast calls for 6,900 units for year (2017) – about 4 percent of all heavy truck sales expected for 2017.

a. Total truck sales for 2017 of approximately 172,500 units

b. Total truck fleet on the roads in the US – 11,203,184 in 2015

(FMCSA Pocket Guide to Large Truck and Bus Statistics, 2017)

Frost & Sullivan, in a report released in February 2017, projects market penetration of natural gas heavy-duty trucks to reach 7.2 percent by 2025. This is in comparison to reports a few years ago (2012) that projected upward of 20% penetration of natural gas trucks by 2020. Analysts still believe that the 20% threshold will be reached, but on an extended time horizon (no specific timeline given).

Heavy-duty vehicles account for just over 4 percent of the vehicle fleet but use more than 28 percent of all the transportation fuel in the U.S.[13] The majority of fuel used in the heavy-duty market is diesel fuel due to the higher fuel economy and higher torque of compression ignition diesel engines compared to spark-ignition gasoline engines. With fuel costs constituting such a large portion of total cost of ownership, technologies that provide the ability to improve fuel economy and/or that offer a significant price differential relative to diesel, such as installation of a thermo-electric generator or conversion to natural gas, can each be attractive options to significantly reduce the total cost of ownership.

There are approximately 11 million heavy-duty vehicles in use in the U.S.; about one-third of these are Class 7 and Class 8 semi-trucks used principally for goods movement. Various vocational trucks (excluding refuse trucks) comprise approximately 55 percent of the total heavy-duty fleet. These vehicles range in size from Class 4 to Class 8 and cover a wide range of applications. In most heavy-duty applications, the average truck fuel consumption exceeds 7,000 DGE (Diesel Gallon Equivalent) per year.[14] Note that for applications where vehicles must carry more than 60 DGE of natural gas, it is likely that fuel will be stored as LNG rather than CNG due to space limitations on the vehicle chassis.

In the heavy-duty market, the major cost focus when purchasing a vehicle is typically on total cost of ownership, including acquisition costs, fuel costs, and maintenance. This has traditionally meant that end users would elect to purchase diesel engines. The prevalence of diesel engines is evidenced by the fact that diesel comprises more than 90 percent of the fuel consumed by heavy-duty vehicles.[15] However, in heavy-duty applications that have low mileage accumulation and low fuel use, there has been a shift from diesel to gasoline as fuel efficiency and high mileage durability are less of an issue. Further, decreases in diesel reliability due to additional emissions controls and increases in operating and maintenance costs from these same emissions controls have increased the total cost of ownership for diesel engines. This increase in costs makes total cost of ownership comparisons between diesel and natural gas engines more favorable for natural gas and improves the value proposition for a thermo-electric generation system, whether that system improves the efficiency of a truck with a diesel engine or a truck fitted to burn natural gas.

For thermo-electric generation systems, in 2017 Hi-Z, a commercial developer of thermo-electric generation systems for civilian and military applications, produced an analysis, which estimated that the installation of a thermo-electric generator in a long-haul diesel truck would result in an additional 2.5% improvement in fuel economy and operational costs. This improvement in fuel efficiency would provide a payback period of between two and four years, depending on the initial installation cost and the cost of diesel over that period.[16]

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[13] U.S. Dept of Energy, Energy Efficiency and Renewable Energy "Transportation Energy Data Book" 2012
[14] ANGA, *US and Canadian Natural Gas Vehicle Market Analysis: Market Segmentation* pp 18-19
[15] Ibid.
[16] Hi-Z Inc. "TWHR Cost-Benefit Analysis for Diesel Truck Market" June 2017

Technology and Market Compatibility: The new vehicle, heavy-duty, diesel and LNG truck market has the characteristics that are highly likely compatible for a TWHR system.

2. Retrofits

Retrofitting CNG engines on traditionally fueled trucks – prospects for TEG inclusion

Retrofitting an existing vehicle to install a thermo-electric generation system is another potential "market entry" point for the TEG technology. However, the economics and prospective benefits of retrofitting a TEG system onto a vehicle are heavily dependent on the fuel mix (and expected fuel prices), the age of the vehicle in question, and especially the operational profile of that vehicle. There is a well-established retrofitting market for new fuel systems – driven by industry and policy interest in compressed natural gas vehicles, retrofits from traditional fuels to natural gas remain an interesting option for several types of vehicles. Classes of vehicles that are beginning to implement CNG retrofits en masse include short-haul defined route delivery fleets where retrofits and upgrades to natural gas are being implemented at scale by major logistics firms including Frito-Lay, United Parcel Service and others. However, many of the types of vehicles that are typically retrofitted for CNG operations do not operate under the pattern(s) that would typically be most beneficial for use of a thermo-electric generation system - in other words they run short distances, have a lot of stops and starts and idle time, and generally do not run at high rate for long periods. These types of vehicles are perfect for limiting the amount of exhaust gasses in the local areas where they operate, and the many starts, stops, and idle time will not affect the environment and ultimately people, as much as conventional trucks.

For those elements of the trucking market that do fit the operational profiles that would benefit from a thermo-electric generation system - mostly Class 8 tractors that ply long-range transport routes - most operators (especially smaller independent owner-operators) run trucks for 3 to 4 years and then trade them in for new vehicles. Given lower diesel prices in recent years, the payback period for conversion to natural gas (versus remaining in diesel) is oftentimes longer than rotational cycle(s) that these members of the market expect to have their vehicle.

As referenced in the section on new vehicles above, the payback period for a new TEG system installation is estimated to be in the range of 2-4 years (approximately the same period as the rotation cycle for many long-haul truck owner operators) so the marginal economic benefit of installation of a system is likely to be highly dependent upon the cost of fuel. In today's low fuel price environment, the economics of the market do not currently provide strong incentives for market adoption for most smaller participants in the truck market.

Retrofits at point of rotation/resale in Class 8 tractors

Also, the resale market for used Class 8 tractors is typically for warehouse and short-haul logistical duty, so the added cost of a retrofit of a thermo-electric generation system is unlikely to have much benefit for the users of resale vehicles within the class 8 tractor market either.

Technology Compatibility: The used vehicle, heavy-duty, for short-haul truck segment is a highly unlikely adopter of a TWHR system.

Aftermarket retrofit of a TEG system on a new CNG tractor

There may be a market for retrofits of a thermo-electric generator on existing or relatively new CNG tractors, however the potential for that market depends greatly on the prospective fuel efficiency improvement for a TEG system weighed against the cost and time involved in a retrofit of the TEG system, and the fact that natural gas as a fuel overall is not particularly expensive. This market segment (aftermarket TEG retrofits of existing/new CNG tractors) may be worthy of additional investigation with specific long-haul operators who operate CNG trucking fleets.

Technology and Market Compatibility: The less than 5-year old, CNG tractor for long-haul operations segment has the characteristics that are somewhat likely for adoption of a TWHR system.

Current dynamics of the CNG truck market

In most cases, the CNG market is in a transition between an "early adopter" model and broader acceptance of the technology by more established elements of the trucking community. Regarding CNG, CNG tractors are typically purpose-built new machines purchased by firms who are interested in fuel diversity of their fleet or who have a specific market niche within "green trucking".

Regarding this last segment of the market, the green trucking community, the introduction of hybrid electric power trains and new fully electric powertrains within the Class 8 tractor segment presents a significant opportunity for substitution versus natural gas (CNG or LNG) powered vehicles. Reliability and dependability of electric power trains have not yet been well-established when compared with CNG, which has proven its reliability as a transportation fuel over the years.

Although these new alternative powertrains are more expensive relative to CNG or LNG, the market cachet of Tesla and some of the other players involved may draw some portion of the market away from more traditional alternative fuel vehicles. These developments have the potential to reduce the market opportunity available in the trucking sector for fuel efficiency technologies such as TEG units.

3. Specialized Markets

a. Heavy-Duty: Refuse / Municipal Solid Waste Trucks

The adoption of compressed natural gas vehicles (NGVs) within the Municipal Solid Waste (MSW) segment of the market has seen rapid growth. Refuse/Municipal Solid Waste trucks are a high fuel use application that has shown significant growth in deployment of NGVs. While incentives for natural gas refuse trucks have been available, much of the growth in the market has been driven by regulations mandating clean vehicles.

The refuse truck market segment shares many characteristics with the transit bus market(s). Fuel costs are significant for this sector due to their stop-and-go and PTO (Power Take-Off) operation. Concerns over their environmental impact have driven some purchase decisions. Most of the fleets are run by local governments or by contractors for local governments, so health, safety and environmental regulations and public perceptions are quite important in the procurement and operation of these services. Much of the refuse trucking market has adopted natural gas in response to regulations requiring clean vehicles, and these same regulations may provide a market opening (at the right price) for a thermo-electric generation technology.

Range - Natural gas refuse haulers have been used by several different agencies that have found the vehicle range to be acceptable for their operations. Based on their estimated 85-mile average daily range and fuel economy of approximately 2 miles per gallon, natural gas refuse trucks need a minimum fuel capacity of 40 DGE (Diesel Gallon Equivalent). Most refuse trucks are equipped with significantly more fuel capacity and given the high PTO and other stressors on the engines, may be suitable for TEG systems even if their operational profile is not the same as other candidate sub-segments of the trucking market.

Base - Refuse trucks are typically stationed at one central location or a series of garages throughout the region and benefit from fueling infrastructure and centralized maintenance at fleet yards.

Fueling Infrastructure - Refuse trucks are typically fueled at one central location or a series of garages throughout the region. For the most part, they are anchor fleets in which stations are built specifically to support that fleet. Initial investment into natural gas fueling infrastructure can be large but can also be utilized by a large fleet of trucks and thus provide reasonable return on investment due to the high fuel consumption. Further, there are opportunities for renewable natural gas production and use at landfills.

Fuel Cost Sensitivity - Refuse trucks performing curbside pickup have severe stop-and-go driving cycles and high use of power-takeoff equipment that result in very low fuel economy compared to other heavy-duty trucks. The per-vehicle fuel consumption is high, making fuel costs a major component of total operating costs. The low fuel economy and high use of power-takeoff equipment may make TEG systems worthy of consideration (simply based on the number of hours active each day and the high stresses on the engine) even though the operational profile (short trips, lots of stops) might at first glance seem to be not as ideal a “fit” as desired.

Environmental Policies - Refuse trucks are highly visible vehicles, operating in congested urban environments. In some regions, this has led to regulations requiring significant emissions reductions. Use of low-emissions natural gas trucks has been a common method of complying with such regulations. With the introduction of 2010 EPA-compliant diesel engines, new natural gas trucks will have little advantage over diesel in terms of air pollutant emissions. Increasingly, other environmental factors, such as greenhouse gas (GHG) emissions and noise reduction, will dictate the environmental value of heavy-duty natural gas trucks, including those in the refuse sector. To some degree, thermo-electric generation systems could provide support to the effort to reduce emissions and noise and improve the environmental footprint of these fleets, even if the system itself will not abate emissions at any significant scale.

The economic and public relations impacts of the ability to harness local landfill gas and use it as a power source for the municipal solid waste fleet, as well as the operational dynamics of this community with relatively short, defined routes and centralized fueling and fleet management has led to rapid adoption of CNG infrastructure and powertrains across the country within the municipal solid waste community. This has been accomplished both through retrofits of existing municipal solid waste fleets as well as bulk purchases of CNG-powered municipal solid waste vehicles. The economic benefit of a thermo-electric generator attached to an MSW truck would need to be determined, the size and economics of this market (as well as the operational profile of the engines on these vehicles) could be quite attractive for further exploration as a market opportunity for the Thermo-Electric Generation system. These trucks typically run for hours at a time, six days a week, however, the space constraints and envelope for such a system may require significant customization of a TEG system to this market, which may be an area for a future project or design exploration.

Technology and Market Compatibility: The heavy-duty, refuse truck segment is highly likely to adopt a TWHR system, especially if cost-benefit can be demonstrated to the contractor or local government.

b. Delivery – Package Delivery

Short Range, Defined Route Delivery Fleets: High CNG adoption

As mentioned above, delivery fleets that support short range, defined routes are seeing high rates of adoption of compressed natural gas systems, mainly because the centralized dispatch and fleet management allows for lower up-front investment in infrastructure, which maximizes the benefits of lower marginal costs due to fuel and emissions requirements.

As a segment, package delivery vehicles have several attributes that are conducive to adoption of fuel efficiency technologies and/or alternative fuel systems, including high fuel consumption and high sensitivity to fuel costs. Like many heavy-duty trucks, package delivery vans are typically custom built. This allows fleet purchasers to specify an alternative fuel system or a fuel efficiency technology to be installed within a given vehicle type without necessarily causing significant increases in delivery lead time. The number of major players within the U.S. package delivery segment is relatively small (FedEx, UPS and US Postal Service), so once a package delivery company is convinced of the effectiveness of a new technology, they are able to drive wide implementation of that technology within their fleet(s).

As one example, United Parcel Service (UPS) invested over $100 million in CNG fueling stations in 2016 alone. As of the end of 2016, UPS had almost 1,800 compressed natural gas-fueled package trucks in the United States, as well as nearly 1,400 LNG tractors in the US.

A typical package delivery truck will be driven by the original purchaser until it is scrapped, approximately twenty years. During this time, fuel costs are the major component of operating costs.[17] Further, package delivery is a narrow margin business and minimizing fleet costs is a priority. Given these economic conditions and the proven use by UPS of more than 3,000 NGVs in 2016 the package delivery segment is without question a strong adopter of natural gas.

Range - Average daily ranges for package delivery vehicles vary by route, but an analysis of U.S. Census Bureau Vehicle Inventory and Use Survey (VIUS) data for similar vehicles suggests an average

[17] National Renewable Energy Laboratory. “UPS CNG Truck Fleet Final Results.” 2002. Fuel costs estimated as a percentage of total operating costs per mile based on scaling fuel prices given in the report to $3.00 per DGE.

daily range of 65 miles. Given the highly organized nature of the major package delivery firms regarding routes, these companies often have the flexibility to select routes that allow an alternative fuel vehicle to operate with a comfortable range margin, thereby customizing the fuel mix of their fleet and optimizing that mix to their delivery network's specific needs and requirements.

Base - Most package delivery vehicles are returned to fleet yards for fueling and maintenance. This environment is generally the most conducive to the introduction of new vehicles and fueling infrastructure.

Fueling Infrastructure - Most package delivery vehicles are fueled at the fleet yards as this provides the fleet with some ability to control fuel costs. Given proper route selection, most package delivery vehicles can operate from a single fueling location at the fleet yard. This model of fueling has allowed for rapid conversions of package delivery fleets to NGVs or other alternative fuel technologies.

Fuel Cost Sensitivity - Purchasing fuel constitutes a major cost of operating package delivery trucks, outstripping maintenance costs. Given the cost-sensitive nature of package delivery service, fleet operators in this segment are likely to strongly value the lower fuel costs associated with operating TEG units and/or NGVs in package delivery service.

Environmental Policies - All three major package delivery firms in the U.S. (FedEx, UPS, and the United States Postal Service) have adopted policies to reduce environmental impacts from their fleets, produce annual reports on their efforts, and purchase and demonstrate vehicles based on their environmental policies.

Heavy-Duty: Local and Regional Pickup and Delivery Trucks

As a high fuel use segment, local and regional pickup and delivery trucks can realize significant fuel cost benefits in switching to natural gas. Many fleets in this segment are reliant on publicly available fueling infrastructure.

Trucks with detachable trailers, known as semi-tractors, are the most common type of Class 7 and Class 8 trucks on the road. Semi-tractors, on average, also consume more fuel per vehicle than almost any other market segment. Approximately 65 percent of the miles traveled by these trucks are traveled with a daily range of 200 miles or less.

This market segment includes port trucks, food distribution trucks, and other short haul trucks. Natural gas trucks in this market can provide significant fuel cost reductions compared to diesel semi-trucks. Furthermore, their localized area of operation allows these trucks to rely on local fueling infrastructure.

Range - Most short-haul trucks operate from a fleet yard and are dispatched to move goods. Daily mileage generally increases with trip distances and fewer daily trips. Therefore, trucks that make numerous short trips, from a port terminal to a rail yard, for example, tend to have lower daily mileages due to the time spent loading and unloading cargo as well as the lower road speeds. Trucks performing regional haul operations, from a food distribution warehouse to a grocery store for example, tend to have higher mileages. On average, the short haul segment travels 200 miles per day or fewer. This range is achievable for natural gas trucks, particularly when using LNG, and will provide one or more days of fuel for many truck operators.

Base - Short-haul trucks are generally return-to-base operations, returning to a fleet yard at the end of each day. Depending on the size of the fleet and type of truck operator, employee, or owner-operator, the truck may or may not have access to fueling and maintenance at the fleet yard. For independent operators, their base location may change as they acquire new contracts.

Fueling Infrastructure - Because of the regional nature of their operation, short-haul trucks may rely on fueling infrastructure at their fleet yards or local public fueling stations. A recent example is the establishment of a large public fueling station and smaller fleet controlled fueling stations for approximately 800 LNG and CNG port trucks serving the ports of Los Angeles and Long Beach. Due to the variability in daily operations for many short haul trucks, access to both public and private fueling stations are important to most operators.

Fuel Cost Sensitivity - Short-haul trucks can consume more than 10,000 DGE of fuel per year, making fuel cost a major component of operating costs.

Environmental Policies - Some large fleets are adopting policies to reduce environmental impacts, and some shippers are beginning to request lower-impact cargo transportation. However, many short haul trucks are owned by small, independent operators that do not typically make purchase decisions based on environmental considerations.

Technology and Market Compatibility: The regional delivery trucks are somewhat likely to adopt a TWHR system. This is a case-by-case market to determine if the technology is appropriate and the cost-benefit is present.

Mid to long range or varied routes delivery fleets: lower adoption of CNG

Regarding mid to long range delivery fleets or those who have varied routes, adoption of CNG or other alternative fueled vehicles is typically substantially lower than the short-range defined-route fleets. The reason for this is higher infrastructure costs associated with fueling stations as well as the added impact and planning required to counteract range anxiety for alternative fuel technologies. However, the longer the routes that these vehicles cover, the more likely it is that a technology such as TEG, which can deliver fuel efficiency within the existing fuel mix (e.g. diesel or gasoline), would be attractive to members of the industry.

c. Other Dedicated Fleets: Movers, Tankers, Dump Trucks and other specialized vehicles

There are numerous dedicated fleets that make use of heavy-duty trucks for a variety of purposes. Those include but are not limited to moving vans, tanker trucks, dump trucks and many specialized fleet activities from utility maintenance to mining and logging. The dedicated fleets are based around some common conditions such as continuous or near continuous operations and dedicated routes. While these dedicated fleets have a percentage of market share, the rollup can complete a business case by addressing similar types of operations with dedicated fleets.

Technology and Market Compatibility: The non-refuse dedicated fleets are somewhat likely to adopt a TWHR system. This is a case-by-case market that will require an individualized determination whether the technology is appropriate, and the cost-benefit calculation is favorable.

d. Long-Haul Trucking:

Theoretically, liquefied natural gas (LNG) infrastructure would be preferable within the long-haul trucking segment, due to the higher energy density of LNG, allowing for greater range within a similar envelope and weight parameters for fuel tanks. However, with the market today, liquefied natural gas is not gaining the market share that had been expected given its technical attributes. The additional costs and complexity involved with LNG infrastructure and fueling have not been offset by the lower costs of natural gas relative to diesel, especially in today's lower-price diesel environment.

Many market observers and analysts have said that if (perhaps when) the price of diesel climbs significantly, consideration of an adoption of natural gas infrastructure in the long-haul trucking market will likely be re-examined, but for now in today's relatively low diesel price environment, the higher upfront costs and infrastructure investments associated with natural gas vehicles are offsetting the operational cost benefits that the technology provides.

Technology and Market Compatibility: The long-haul trucking is a market segment that is highly likely to adopt a TWHR system.

e. Rental

The rental market for compressed natural gas or other alternative fuel vehicles has been subdued in recent years due to relatively cheap prices for traditional fuels. Ryder currently has a fleet of approximately 1,000 CNG trucks available for rent. Since diesel prices dropped in recent years usage has been so-so due to less economic incentive to save fuel costs with natural gas. This is especially true for the rental market where uses of trucks is for short periods and the low differential between CNG and diesel prices means that the cost of convenience becomes an issue in market adoption.

Technology and Market Compatibility: Rental fleets are somewhat likely to adopt a TWHR system. This is a case-by-case market to determine if the technology is appropriate and the cost-benefit calculation is favorable.

Market Issues to Consider:

1. Fueling Stations

Installation of fueling stations is a significant challenge and the expense involved in setting up the infrastructure to support compressed natural gas and/or liquefied natural gas transportation systems is a significant portion of the cost involved in conversion to these technologies. For obvious reasons, fueling stations are easier to set up for short haul, defined route delivery systems with a common maintenance or central depot facility. Segments of the sector that fit this profile include bus transit systems, refuse/municipal solid waste fleets, and local delivery fleets.

2. Training for First Responders

Natural gas (methane) is flammable; however, it only burns within a narrow range when mixed with air in a ratio of between 5 and 15 percent. Natural gas is odorless, colorless and tasteless. Natural gas is lighter than air, so it rises and diffuses into the atmosphere when released. Natural gas has unique hazards not found in gasoline and diesel fuel: Natural gas is in a gaseous state at normal temperatures and pressures. To be stored efficiently, it must be stored under high pressure (3600 psi) in a compressed natural gas (CNG) system or at an extremely low (cryogenic) temperature (-220°F to -212°F / -140°C to -136°C) in liquid form as liquefied natural gas (LNG). Due to those characteristics first responders and staff where CNG is used must have specialized training. Some of the issues for example are: for gaseous cylinders, do not apply water with a fire because the PRD (pressure release device) will not work, and for LNG, gloves and shields should be worn to prevent frostbite. The issue of training first responders and employers what do with CNG/LNG when there is a fire must be addressed when doing assessments.

3. Capitalization

The costs of capitalization remain an important part of the conversation relative to natural gas vehicle adoption and conversion and the broader marketplace. Market analysts report that there is typically an up charge of $40,000 to $50,000 per vehicle for NG trucks vs. diesel trucks with similar specifications. Per ACT Research, looking at the cost of fuel over a typical operational lifetime for long-haul vehicle, diesel typically wins the cost-benefit analysis at $3 or less per gallon of diesel.

Furthermore, Hi-Z's H cost-benefit analysis for long-haul trucking estimated an installation cost of between $3,000 and $5,000 per unit for a thermo-electric generator installed on a heavy-duty truck. This would add an additional 10% to the up charge for conversion to a CNG truck for the installation of a TEG system.

Also, it is worth noting that there seems to be a limited resale market for compressed natural gas trucks. Market analysis indicates that there are a few relationships where local logistics facilities will buy batches of used CNG trucks, but a broader and deeper resale market (along the lines of what is available in traditional diesel trucks) has yet to emerge.

4. Maintenance

While it is evident there are major cost savings over the life a vehicle using CNG, it cannot be ignored that there are upfront costs for maintenance. Those include training, equipment and revised maintenance schedules. The good news is that the paper studies match real-world data and those cost factors are well understood. There is no real debate on how to calculate net savings within any type of fuel used, however, many different models are used to calculate when comparing differently fueled vehicle such as CNG, LNG, diesel and electric. This is compounded when comparing vehicles used for different purposes such as trucking, busing or waste collection. This appears to be an issue with institutional users for school buses or solid waste disposal. There is no real issue but when doing a market assessment, however, one must be aware there are increased upfront costs for maintenance of CNG vehicles.

5. Emissions Compliance

Natural gas vehicles do provide notable benefits in terms of emissions compliance, as natural gas burns cleaner and with fewer particulates compared to traditional diesel fuels. According to the US Department of Energy (DOE), conversion to natural gas reduces greenhouse gas emissions in trucks from 6 to 11 percent versus gasoline or diesel. According to the Alternative Fuels Data Center of the US DOE Energy Efficiency and Renewable Energy Office, the U.S. Environmental Protection Agency (EPA) requires all fuels and vehicle types to meet increasingly lower, near zero, thresholds for tailpipe emissions of air pollutants and particulate matter. However, most conventional systems require additional emissions control technologies to meet the requirements, whereas natural gas vehicles typically do not need additional emissions control technologies. NGVs continue to provide life cycle emissions benefits—especially when replacing older conventional vehicles or when considering life cycle emissions. However, unless these emission improvement benefits are monetized in some way, the additional upfront cost of natural gas vehicles can serve as a disincentive for adoption by the broader transport community.

Synopsis of Key Insights

The trucking market is highly segmented by vehicle weight, fuel type, applications and hours of operation. Due to that segmentation, the markets for a TWHR system within the trucking sector are also segmented. Some are perfect fits such as heavy-duty refuse trucks while others are not. In general, for cost, efficiency and policy reasons there are large sectors where a TWHR system is appropriate. The following chart is a representation of these different market segments.

Domestic Market Assessment for Thermoelectric Waste Heat Recovery System for Trucks

Highly Likely Adopter	**Somewhat Likely Adopter**	**Unlikely Adopter**
New, heavy-duty, diesel and LNG trucks	< 5-year old, CNG tractor trucks for long-haul operations	Used, heavy-duty trucks
Heavy-duty, refuse trucks	Regional delivery trucks	
Long-haul trucks	Non-refuse dedicated fleets	Short-haul trucks with limited hours of operation
	Rental fleets	

The next step in this effort is to identify specific market sectors that are worthy of further investigation. The unique nature of the thermal electric generation technology means that individual opportunities or market "niches" exist, but that the cost-benefit calculations and dynamics that drive customer behavior within those specific applications must be assessed to achieve a proper picture of the market opportunity. One aspect of the heavy-duty truck market is the predominance of fleets in certain segments of the market, allowing a targeted outreach to owners of numerous vehicles as opposed to a myriad of individual owner/operators. This phenomenon is even more pronounced in local, state or federal government fleets.

There are several prospective market entry points for the thermo-electric generation technology to gain a foothold in the North American trucking market, with room to expand to other corners of the globe. With additional engagement of potential customers within specific segments of the trucking industry and a higher profile for the types of solutions that the technology can provide, thermo-electric generation systems have an opportunity to grow into a substantial new market in the coming years.

III. Insights and Next Steps Based upon Market and Customer Outreach

Over the course of the TEG demonstration project, Energy Florida and the other project partners talked with several partners, including the engineering, maintenance and procurement teams at LYNX, and a few trucking operators to glean information regarding their tolerance for risk and willingness to consider adoption and implementation of an innovative fuel-saving technology such as the TEG systems demonstrated during this project.

Through these conversations, the team gleaned a few key insights, particularly into the mindset and procedures of major transit authorities regarding procurement of new technology or new features associated with the fuel efficiency of their bus fleet(s).

The feedback from the transit agencies we engaged is that the primary consideration for most transit agencies in looking at new technology installed on buses is whether that technology has any prospective impact on the warranties that the OEMs provide for their buses.

For a technology such at the TEG to successfully enter and be accepted by the transit market at scale, having an agreement with the relevant bus manufacturers to enable and support the technology is key because most transit system operators do not want to risk violating the warranties for their equipment by including unauthorized add-ons and aftermarket components or systems.

Most transit systems try to buy technology as an integrated solution, with supporting assistance from the manufacturer(s) of their vehicles. For example, the LYNX team prefers information on fuel efficiency improvements incorporated into the design and maintenance documents provided by the OEM. Transit systems do not want to have a bus sitting out of service because something has broken and there is a disagreement between the transit system and the OEM over who is responsible for payment for repair of that component. Anything that is aftermarket has the potential to complicate maintenance conversations with OEMs.

If the technology is offered by the OEM, that's a very straightforward conversation at the transit agency level. Transit agencies are interested in what the OEM says capability is and can deliver and will hold the OEM to those representations. For OEMs, TEG could be part of an option package.

Lynx does consider retrofitting devices onto buses, but only if the return on investment is very strong and there is some connection/engagement with the original manufacturer to provide some support.

Outside of working with an OEM, the path to market in the transit community will be much tougher. Regarding any technology to be implemented in a transit agency fleet - if an agency needs to do something "special"/out of the ordinary to coordinate with the OEM to support a technology, that quickly becomes a major issue against adoption of the technology from a transit agency's perspective.

Regarding the procurement and selection process for transit buses:

Transit authority money is split into two buckets: capital expenditures and operating funds.

Capital expenditures are harder to come by, typically comes through grants from the Federal government for equipment. Operating funds are primarily local dollars - transit authorities also have some state dollars for operating and funding from fares, advertising, and other revenue sources.

If a technology such as the TEG promises to cut annual operating expenditures significantly – local transit authorities may very well expend additional capital expenditure dollars (e.g. pay more up front for a bus) to effect operating savings over time. Price differences of a few thousand dollars (in the range of what a commercial TEG system are expected to cost/add to the price of a vehicle once the product is being produced at scale) can be overcome if the operational performance/efficiency benefits and payback period for those investments in terms of reduced operational costs can be defined and quantified, and that evidence is compelling. Transit authorities generally look for the liability to rest with the OEM in terms of components breaking or major repairs, and having a component supported by the OEM goes a long way to helping its inclusion in a specifications sheet for a procurement of new equipment.

Transit authorities are especially interested in anything that will reduce wear & tear on an engine. For example, several transit authorities we talked with are looking at some components that automatically lubricate themselves within an engine to reduce the need for oil (as well as the negative impacts of oil leaks). Lynx and other transit authorities are also always looking for systems that provide no additional burden on their drivers. There are already a lot of distractions and issues on the road and the transit agencies don't want their drivers having to handle additional duties related to the technology if possible.

The commercialization team received feedback that regarding a system like a thermoelectric generator, transit authorities are looking for a device that can fit within the existing envelope of the bus and its engine compartment. Along these lines, it came to our attention that over the course of the demonstration project, there was significant concern raised within LYNX about the size of the TEG prototype, but several members of LYNX's engineering team successfully made the case that prototypes are nearly always 4 to 5 times larger than final production units once all testing, adjustments and design improvements have been made. It was made clear that a unit that had the profile of the existing TEG prototype unit demonstrated during this project would not be sale-able for the transit market in most cases without some significant modifications/reduction of its overall footprint and form factor(s).

Regarding integration of add-on technologies such as the TEG with the maintenance function at transit authorities: LYNX's Maintenance group indicated that it would like a system similar to the TEG to be able to provide a read-out so that the team can know quickly if it is working or not on a regular basis, as well as some readout providing metrics showing performance over time relative to projections and in order to identify anomalies or potential breakdowns within the unit's function.

Maintenance and operational cost considerations are a very important part of the procurement and selection process. From the maintenance perspective, in reference to any new technology package such as the TEG, the transit agency's procurement committee is usually very interested in finding out what the agency needs to do with a specific system. Typical questions include: How often does the unit/technology need to be serviced (how many times per year)? Does it need a new filter/component installed? How often? What is involved in maintaining a system?

The more modular a system is in terms of maintenance, the better from the transit customer's perspective. Oftentimes, the transit authority will like to swap systems in and out if it's possible to do that, the maintenance team will look at the unit with an issue while the new one is out running with the bus. This reduces downtime and allows greater flexibility with the fleet and leads to an inventory of spare units being held on-site for contingency purposes. Transit authorities typically prefer to do as much maintenance in-house as possible. Although they will send out specific components for repair if they are too complex, they prefer to request support & training from the OEM to allow them to keep that maintenance process in-house and make purchase decisions for new technologies in line with this approach.

In terms of current energy efficiency systems, most transit authorities are looking at other types of drivetrains such as compressed natural gas or electric buses as opposed to improvements to current diesel engine platforms.

Time in service/uptime is extraordinarily important for transit authorities and school fleets. Transit agencies typically have 20% downtime for their equipment at any given time - certainly don't want to increase that, if it's possible to find ways to improve that rate of downtime even better.

Buses need to always be in service, and a significant downside in consideration of electric buses is the availability of electricity in times of disasters or recovery from disasters such as hurricanes. This is also true of compressed natural gas – transit authorities need to have guaranteed availability of the fuel to provide resilience in disaster situations. Improving the energy efficiency of a fuel source that's broadly and easily available (e.g. diesel) is a big plus for a TEG system. The TEG, if successfully demonstrated, is meeting a definitive need within the public transit community.

The commercialization project team looked at several sources in an attempt to identify key benefits and potential cost considerations that could have an impact on the implementation of Thermal Electric Generation systems. With the assistance of Hi-Z, the technology development firm supporting the design and assembly of the TEG unit for the project, conducted an initial cost-benefit analysis based on the original design parameters for the TEG unit envisioned in this effort (e.g. a 2,000-watt system).

This analysis included an estimate of $5,000 price for a final manufactured TEG unit with a 2,000-watt capacity that could be retrofitted onto a long-haul truck or transit bus. Under these parameters, it was assumed that a diesel fueled long-haul truck averaging 125,000 miles per year would save approximately 2.4% of its fuel costs in using a TEG generator to supplement the electric loads generated by its alternator. Given a cost of fuel of $2.65/gallon for diesel from spring 2017, the investment in a TEG system would pay back in just under 4 years (3.7 years to be exact). If the current retail cost for diesel (as of August/September 2018) of $3.20 /gallon is assumed, the TEG unit would pay for itself in just over 3 years (3.1 years).

This is roughly in line with the analysis of the FSEC data analysis team that reviewed the results of the TEG that was installed and demonstrated on the transit bus at LYNX in Orlando, and that calculated an estimated fuel efficiency improvement of approximately 1% for the bus based upon the empirical data on the electricity generated by the TEG unit that was collected over the course of the demonstration at LYNX.

Ultimately the TEG unit as designed, assembled and installed on the transit bus had a rated capacity of slightly over 1,000 watts, which was demonstrated to operate at its designed capacity during the initial testing of the unit on the bus at the Kennedy Space Center. Ultimately, due to the operational profile of the bus while servicing its normal assigned routes during the live demonstration phase of the project, the average observed generation of electricity in day-to-day operations was closer to 400 watts. Therefore, the estimated 1% improvement in bus fuel efficiency from a TEG unit typically generating between 400 and 500 watts at an alternator acceptance factor of about ½ highlighted in the analysis by FSEC is consistent with (if not a bit higher than) the estimate of a 2.4% fuel efficiency improvement for a TEG unit with a rated capacity of 2,000 watts that is operated in an environment much more likely to approach the designed capacity of the system (e.g. longer period of consistent operation at higher engine & exhaust temperatures).

IV. Market Data – North American Bus and Truck Manufacturers

Given the feedback received from transit agencies for the bus market, and the findings of the market research report regarding the importance of working with the OEMs in the bus market and small volume specialty vehicle manufacturers in the heavy-duty truck market, the TEG commercialization team led by Energy Florida compiled a list of all the relevant manufacturers in North America in these industry sectors. Using the Thomas Registry, NAICS codes and including “conversion” and “modification” in the definition of manufacturing, Energy Florida compiled data in three ways to obtain a very good view of the overall market; metaphorically the ocean. By using the Thomas Registry and NAICS codes specific for buses and trucks, allowed us to capture specific uses and types of truck and buses, again metaphorically the different types of fish in the “ocean.” While we did not capture every single use or type, we did cast a wide enough net to ensure an adequate sample of the market. Here are some insights from that exercise:

Buses:

Our initial analysis identified 59 bus manufacturers, including major manufacturers as well as companies that provide conversions and modifications for buses. Among the major manufacturers in North America, there are several manufacturers who specialize in specific segments of the truck market, including Gillig and New Flyer (transit buses), Blue Bird & Thomas Built (school buses), Mercedes-Benz USA, and Freightliner (shuttle buses). There are also prominent electric vehicle bus makers including Proterra and BYD. A majority of the 59 North American companies involved in bus manufacturing and distribution that are easily identified are parts/component suppliers or bus distributors/resellers. A list of the bus manufacturers identified in North America is available in Appendix 1.

Overall, the market players seem to be well-established, as the overwhelming majority of the bus manufacturing companies listed are more than 20 years old. These companies are spread geographically across the United States and Canada:

AL:	**2**	**MB:**	**1**	**OH:**	**3**
AR:	**1**	**MD:**	**2**	**OR:**	**1**
CA:	**8**	**ME:**	**1**	**QC:**	**1**
GA:	**1**	**MI:**	**2**	**TN:**	**1**
IA:	**2**	**MO:**	**3**	**TX:**	**6**
IL:	**2**	**NC:**	**3**	**VA:**	**1**
IN:	**6**	**NJ:**	**2**	**WA:**	**2**
KS:	**3**	**NV:**	**1**		
KY:	**2**	**NY:**	**2**	**Total:**	**59**

Approximately 25% of these bus manufacturers and distributors export to countries outside of North America.

Approximately 26% are large employers with more than 500 employees and 10 reporting more than 1,000 employees

This data reflects a highly stable market with well-established customers both domestic and foreign.

Assessment of North American truck manufacturers

NAICS Code 336211 – Motor Vehicle Body Manufacturing:

Definition of NAICS Code 336211: This U.S. industry comprises establishments primarily engaged in manufacturing truck and bus bodies and cabs and automobile bodies. The products made may be sold separately or may be assembled on purchased chassis and sold as complete vehicles.

317 companies have been identified across the country that meet the NAICS Code 336211 definition. A list of these companies is included in Appendix 2.

The breakdown of these companies' areas of specialization are as follows:

Automobile Wreckers (Mfr) = 19	Buses-Bodies (Mfr) = 16
Truck & Bus Bodies (Mfr) = 280	Truck Sleepers (Mfr) = 2

These also appear to be highly stable and established manufacturers.

Other Truck Manufacturing (Specialty Vehicle Manufacturing):

268 companies were identified that produce vehicles such as armored cars, crane, drilling equipment, car/truck haulers, tankers, unique equipment and many more. These may be considered niche markets but collectively they are a large segment of the transportation industry. An overwhelming majority of these companies are 30 years old or more, again highlighting the stability and established nature of this business. Approximately 27% of these specialty manufacturers report exports to countries outside of North America.

Each of these companies have their particular "niche" markets within the broader context of the specialty vehicle manufacturing industry and depending on the particular "niches" that are deemed most promising for application of the TEG technology, there are specific manufacturers to engage within each of those sub-segments of the market.

V. Other Market Opportunities

Commercial Marine Applications

The marine (commercial boating) market has emerged as a strong candidate market for the TEG technology. This is due to the operational profile of many commercial fishing or shipping operations, where ship engines are run constantly, leading to high engine operating and exhaust temperatures, and fuel efficiency makes a big difference in operational costs. Combined with readily available access to a major heat sink (the body of water upon which the craft is operating) and source of coolant, the potential for a major impact on fuel efficiency and an accelerated payback period for an investment in thermal-electric generation technology promises to provide a great platform for commercialization and adoption of thermal electric technology if it can be adequately demonstrated in an analogous application. Initial cost-benefit estimates indicate that a thermal electric generation system may be able to pay for itself within a matter of months in a commercial marine application, which makes the marine market among the most promising market segments for an "early adopter" outreach strategy. In addition, the additional weight or bulk of a thermal-electric conversion system may not be such a big issue within the commercial marine context, as opposed to on a truck or transit bus where both space (volume) and weight of ancillary systems comes at a premium. Because of this analysis, the TEG project partners have begun to explore the commercial marine market segment as a potential alternative or parallel path to commercialization of the thermal waste heat recovery technology demonstrated during this initial project.

Of note, a Swedish shipping conglomerate (Stena AG) released a request for information regarding potential waste heat recovery technologies that the firm might be able to test or implement on its shipping fleet. The TEG project partners have reached out and engaged the company regarding that opportunity, and others that may arise to implement this technology within the commercial marine industry. In a similar vein, opportunities could arise through the Office of Naval Research to pursue further investigations regarding marine applications, as these technologies could be equally well applied to the Navy's fleet to improve fuel efficiency and reduce operational costs over time.

Static Power/Heat Sources

A market segment worth further exploration is the potential adaptation of this technology to support stationary distributed power installations, especially those that are operated on a continuous basis for power generation or combined cooling, heat and power purposes. Thermal electric generation systems such as those demonstrated during this project could help to improve the efficiency of these power generation units by providing a supplemental tranche of power generation in addition to the unit's rated capacity based upon conversion of waste heat from the combustion process. The thermal electric modules could act as a type of combined-cycle operation for smaller, distributed units in which a full heat recovery steam generator process is too large or cumbersome to implement. This would help to raise the overall operational efficiency of these distributed power installations and help to save potentially significant quantities of fuel over the operation lifetime of these facilities. The exhaust temperatures and operational parameters for distributed co-generation facilities vary widely, so this market would also likely require its own demonstration project (or projects) to demonstrate the effectiveness and technical potential of waste heat recovery systems for supporting a cleaner and more efficient electric co-generation infrastructure. Such a demonstration could also help to determine what types of installations (both scale and operational profile) would be most likely to benefit from making use of the thermal electric generation technologies demonstrated in the BEERD TEG diesel-fueled transit bus demonstration project.

VI. Conclusion

New technology often leads to greater efficiency and return on investment. Companies that adopt new technology such as the TEG unit, will be leading their respective industries with a competitive advantage.

New technologies like the TEG unit should be adopted or integrated by existing market players rather than being supplanted by new market entrants. This dynamic may be evolving with the introduction of electric vehicle technology (and over time, the implementation of autonomous or "driverless" operations), at the current juncture the transit market and trucking market represent solid candidates for new technologies to be applied.

The team had numerous discussions with multiple transit authorities in various regions and the number one priority was to have a return on investment that is less than five years and ideally less than two and half years for any technology. Once a base-line manufacturing price is established and there is documented power generation - fuel efficiency data to support a TEG unit purchase, this would make a value proposition that one transit official said, "go ahead" decision to purchase. The greater the efficiency the easier it is to reach the "go ahead" decision. It is the combination of fuel efficiency and price that makes the "pay-for-itself" point sooner than later.

Moving forward, the development team needs to extend the TEG unit proof of concept to include integration with the electrical systems of host vehicles and begin to refine the elements of the TEG unit to meet the form factors and functions most desired by the target market and their respective return on investment strategies.

This report noted several potential market segments well beyond the transit bus sector where the TEG unit technology will have an impact on improving fuel efficiency and reducing emissions. The development team has established promising initial results from this demonstration that can be used to provide a starting point for conversations with stakeholders in multiple industries.

It is evident that the development team has a clear goal for the TEG unit technology package to establish a price point, with performance and sales volume that closes the business case for prospective manufacturers and distributors of these systems in the years to come. There are several viable markets justifying further development of that technology.

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