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MODELING AND SIMULATION TO SUPPORT PROTOTYPE DEVELOPMENT OF A WASTE THERMAL ENERGY HARVESTER

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THESIS

MODELING AND SIMULATION TO SUPPORT PROTOTYPE DEVELOPMENT OF A WASTE THERMAL ENERGY HARVESTER

by

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June 2019

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13. ABSTRACT (maximum 200 words)

The Navy and Marine Corps are studying ways to reduce their reliance on fossil fuels as a means to increase energy security and operational resilience. Many military systems reject waste heat into the environment; recovering this thermal energy for reuse could help to reduce overall reliance on fossil fuels. One technology that may effectively recycle waste heat as energy is the thermoelectric generator (TEG). This thesis uses a modeling and simulation (M&S)-based systems engineering approach to influence design of a TEG prototype system to gain insight into the feasibility of applying this technology to military systems. This research uses COMSOL and OrCAD’s PSpice to model a TEG array prototype system on the muffler of a portable generator, as a proxy for a naval system that releases waste heat. The results of the model informed the design and construction of a prototype system. The paper describes the testing of the prototype and compares the results of the prototype to the model. This thesis demonstrates the benefit of using modeling and simulation prior to design and construction. Finally, this research indicates that TEGs may have the potential to reduce the Navy and Marine Corps’ fossil fuel and energy dependence.

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MODELING AND SIMULATION TO SUPPORT PROTOTYPE DEVELOPMENT OF A WASTE THERMAL ENERGY HARVESTER

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Submitted in partial fulfillment of the
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ABSTRACT

The Navy and Marine Corps are studying ways to reduce their reliance on fossil fuels as a means to increase energy security and operational resilience. Many military systems reject waste heat into the environment; recovering this thermal energy for reuse could help to reduce overall reliance on fossil fuels. One technology that may effectively recycle waste heat as energy is the thermoelectric generator (TEG). This thesis uses a modeling and simulation (M&S)-based systems engineering approach to influence design of a TEG prototype system to gain insight into the feasibility of applying this technology to military systems. This research uses COMSOL and OrCAD’s PSpice to model a TEG array prototype system on the muffler of a portable generator, as a proxy for a naval system that releases waste heat. The results of the model informed the design and construction of a prototype system. The paper describes the testing of the prototype and compares the results of the prototype to the model. This thesis demonstrates the benefit of using modeling and simulation prior to design and construction. Finally, this research indicates that TEGs may have the potential to reduce the Navy and Marine Corps’ fossil fuel and energy dependence.

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LIST OF ACRONYMS AND ABBREVIATIONS

COTS	commercial-off-the-shelf
DoD	Department of Defense
FLIR	forward looking infrared
IR	infrared
MBSE	model-based systems engineering
SE	systems engineering
SECNAV	Secretary of the Navy
TEG	thermoelectric generator

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EXECUTIVE SUMMARY

“The Department of Defense provides the military forces needed to deter war and ensure our nation’s security” (Department of Defense [DoD] n.d.). To conduct successful missions, the Navy and Marine Corps must have access to energy to operate equipment and must have open lines of logistical communications. Energy is necessary for ships to launch and recover aircraft while underway, for supply convoys to support remote forward operating bases, and for a marine to operate a handheld radio. Energy reliance is a critical vulnerability that can be exploited by the adversary. Furthermore, ships, aircraft, and other tactical vehicles may operate in locations that attract the attention of the adversary, thus making the military susceptible to attack.

In 2009, the Secretary of the Navy (SECNAV) directed the Navy and Marine Corps to reduce their reliance on fossil fuels to improve energy security and energy efficiency (Paige 2009). To accomplish this, the Navy and Marine Corps are looking for methods to conserve energy, which will allow them to be less fuel dependent; this ultimately will improve operational endurance and resilience across military platforms (Pollman 2013). One path to reach these goals is to study energy generation methods that can be applied to systems already found on Navy and Marine Corps platforms. Some military systems, such as generators, turbines, communication server racks, and combat systems equipment, create heat that is rejected into the environment. Capturing some of this thermal energy and recycling it back into the system could be extremely beneficial, and would increase the range of these platforms. One possible method, examined in this report, is to recover this waste heat through the use of thermoelectric generators (TEG).

In this research, an initial prototype system was created that successfully reused waste heat to produce energy. The results of this thesis suggest that a TEG system may prove beneficial to military systems. Additional research is necessary to determine if it makes sense to use TEGs as an energy-generation method. Systems that may benefit from TEGs need to be identified and studied. Also, factors such as cost, efficiency, maintainability, and weight should be analyzed.

A thermoelectric generator is a stationary device comprised of different semiconductor metals, with designated hot and cold sides, which creates energy when it is exposed to a temperature difference. To create the temperature difference needed for the TEG to generate energy, the designated hot side of the TEG is placed onto a heat source, such as a turbine engine, and the cold side is in contact with a heat sink, such as a cooling water block. To determine if TEGs are an effective waste heat recovery method, a modeling and simulation (M&S)-based systems engineering approach was applied to design and test a prototype. This methodology helps to improve understanding of a system and can help an engineer design that system. COMSOL, a physics simulation software, was used to model the positioning of eight TEGs between the muffler of a gasoline-fueled portable generator and a water block connected to a water-cooling system. The results of the simulation revealed that the TEGs may have the capacity to recover the waste heat energy to reuse in the system. Next, PSpice, a circuit simulation software developed by OrCAD, modeled the TEGs in series and parallel arrangements to study power, voltage, and current output. The model verified that an all-series arrangement would produce the most power.

Using the results of the COMSOL and PSpice models, an initial prototype system with eight TEGs in series was designed and constructed using the muffler of a generator and water-cooling systems, as a heat source and heat sink, respectively. The prototype system was tested and compared to the results of the model. The model captured the trend of the prototype system, showing that modeling can indicate how systems operate in the real world. The results of the prototype system were put into the model to capture more accurately how the prototype system operates in a quantitative way. The updated model can be used to improve design for future TEG systems and be applied to equipment found on Navy and Marine Corps platforms.

This thesis presents this combination research method, which integrates M&S and prototype construction and testing, shared in two conference paper manuscripts. The first manuscript, “COMSOL Multiphysics Simulation of TEGs for Waste Thermal Energy Harvesting,” was presented by the author at the 2018 COMSOL Conference in Boston, Massachusetts (Howard et al. 2018). The second manuscript, “Modeling and Simulation Approach to Inform TEG Waste Heat Harvesting Prototype for Fossil Fuel Exhaust,” will be presented by the author at the International Conference on Energy Harvesting, Storage, and Transfer in Ottawa, Canada (Howard, Grbovic, and Pollman, forthcoming). The results of this thesis showed the initial TEG prototype system functions as it was designed and has the capability to reuse waste heat as a means to produce energy. This thesis captured the idea that modeling can improve the understanding of the system, show how a system will operate in the real world, and inform design of a system.

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I. INTRODUCTION

A. PURPOSE

Many military systems rely on fossil fuels to operate. These fossil fuels are transformed into power to operate the system and perform an intended function. Some of this energy is also released into the environment in the form of waste heat. This research was conducted to find ways to use a portion of this waste heat to reduce fossil fuels requirements in support of military operations. The purpose of this thesis is to study the effect of applying thermoelectric generators (TEG) to military systems to recover waste heat and transform it into electrical energy. The results gathered provide insight into the feasibility of using TEGs in military systems.

B. BACKGROUND AND MOTIVATION

In 2009, the Secretary of the Navy (SECNAV) set several goals to reduce the energy consumption of the Navy and Marine Corps, decrease the amount of petroleum consumed by commercial vehicles by 50%, and increase reliance on alternative energy sources by 40% (Paige 2009; Department of the Navy 2010). The end result of these goals is for the Navy and the Marine Corps to reach energy independence and energy security (Department of the Navy 2010). With the unstable price of oil and unknowns in getting fuel to deployed forces, it is deemed imperative that the military becomes more reliant on alternative energy sources.

As a result of the SECNAV’s goals, the Navy and Marine Corps are exploring ways to conserve energy to be less fuel dependent overall, thus improving operational endurance and resilience across military platforms. To accomplish its various missions, the Navy and Marine Corps must have the capability to keep its platforms, such as ships, aircraft, and tactical vehicles, underway for long periods of time, which increases their reliance on energy and creates a higher demand for fuel. There are limitations on how long and how far ships, aircraft, and tactical vehicles can travel before they run out of fuel. Finding ways to keep these platforms operational longer will help decrease this demand for fuel while ensuring the military’s mission success (Pollman 2013).

Refueling these craft is necessary but can be dangerous, especially in a tactical environment (Schwartz, Blakeley, and O'Rourke 2012). Slowing down an operation to refuel, or even bringing fuel to troops in a forward operating base, may attract the adversary (Kosowatz 2018). This reliance on energy forces vehicles to be tethered to a logistics train. This fuel source may not be readily available or operationally convenient.

Currently, there are no easy solutions to reduce the reliance on fossil fuels, and multiple energy generation methods need to be considered (Pollman and Gannon 2015). In particular, energy generation methods that can be applied to systems already found on ships, aircraft, tactical vehicles, and shore-based infrastructure need to be studied to find effective ways to reduce the reliance on fossil fuels. Military platforms must have viable options to create energy onboard to increase the time between refueling operations. Some systems found on military platforms create heat that is rejected to the environment, such as generators, turbines, communication server racks, and combat systems equipment. This thermal energy would be extremely beneficial if it could be captured and recycled back into a system, and thus increase the platform's range. One possible solution is the use of TEGs, which may benefit the military by recovering a portion of this heat and using it to generate electric current.

A thermoelectric generator is a device composed of different semiconductor materials that can harvest energy when a temperature difference is applied (Champier 2010). Champier explains that TEGs are stationary devices, meaning they have no moving parts and are noiseless while operating. Therefore, Champier adds, these devices require limited to no maintenance, which results in lower costs over their lifetime. Thermoelectric generators are scalable, with the potential to be applied to small systems, such as a handheld radio, or larger systems, such as an engine on an aircraft carrier (Priya and Inman 2009). This scalability and minimal maintenance requirements increases the range and variety of military systems that can employ them. However, the added weight can be substantial and counter these advantages.

C. METHODOLOGY

This thesis employs a combination of research methods: modeling and simulation (M&S)-based systems engineering and prototype construction and testing. Modeling and simulation are utilized to inform the design of a prototype TEG array device on the muffler of a portable power generator. This prototype simulates a military system that releases waste heat to its surroundings. The M&S approach helps in studying the TEG system performance prior to building the prototype. Prototype results validate and add more fidelity to the models. A working model can be scaled and used in later designs for military systems across the size, weight, and power spectrum. Modeling and simulation ensures design verification for future military system use, help engineers understand how design changes may impact the system, and provide a cheaper and more compressive way to explore the tradespace of systems across the Department of Defense (DoD) where TEGs can be applied (Friedenthal, Moore, and Steiner 2012).

Modeling and simulation of the prototype occurs through the use of COMSOL and OrCAD PSpice. COMSOL, a multiphysics finite element modeling software, is used to model the components of the expected prototype system to estimate the temperature difference across each TEG in the array. PSpice, a circuit simulation software, then uses the COMSOL estimated temperature differences to determine the most efficient TEG array configuration, series or parallel, to recover the maximum power from the muffler of the generator. The results of the modeling and simulation informs the design and construction of the initial prototype system. The thermoelectric generator prototype system is then tested. The prototype and the model outputs are compared to each other. This analysis reiterates the value in modeling and simulation and provides insight in the feasibility of applying TEGs to military systems.

D. PROBLEM STATEMENT

Supporting operational demands, military platforms and systems need to have the capability to operate for long periods of time. Current fleet technology is endurance-limited due to its reliance on fuel supply availability or battery life. Technology needs to be developed to conserve energy, and thereby increase the range of naval systems. Systems that reject waste heat into the environment have the potential for part of the discharge to be recycled back into the system, improving endurance. The Navy and Marine Corps need engineers and researchers to explore methods to recover this waste heat from its systems to better leverage operational energy.

E. RESEARCH QUESTIONS

1. Can a prototype, that demonstrates the application of a thermoelectric generator based on a modeling and simulation design, be created?
2. How effective is the model in predicting the behavior of the TEG array when testing the tabletop prototype?

F. THESIS OVERVIEW AND ORGANIZATION

This thesis builds on previous modeling and simulation research, which validated that thermoelectric generators may provide energy recovery for military systems (Moreno, Pollman, and Grbovic 2018, 2019). This work explored the concept that TEG modules are scalable whether connected in a series or parallel, allowing TEGs to be applied to a specific application in a model to influence early design of a military system (Moreno, Pollman, and Grbovic 2019).

In order to answer the two research questions posed above, this thesis is divided into four chapters. The first chapter, the introduction, provides the background, methodology, and research questions. The second chapter is a manuscript presented at the COMSOL Conference in Boston, Massachusetts on October 4, 2018, and details the modeling and simulation of a TEG array on top of a portable power generator (Howard et al. 2018). The third chapter is the manuscript that will be presented at the International Conference on Energy Harvesting, Storage, and Transfer in Ottawa, Canada on June 18–19, 2019 (Howard, Grbovic, and Pollman, forthcoming). This chapter explains the PSpice modeling of the TEG array in parallel and series configuration. The results of the PSpice modeling and first manuscript informed design of the prototype system. The manuscript describes the testing of the prototype and compares the results to that of the model. The final chapter concludes the thesis to include future work.

II. PAPER I: COMSOL MULTIPHYSICS SIMULATION OF TEGS FOR WASTE THERMAL ENERGY HARVESTING

This chapter was previously published as: Howard, Lauren, Daniel Tafone, Dragoslav Grbovic, and Anthony Pollman. 2018. “COMSOL Multiphysics Simulation of TEGs for Waste Thermal Energy Harvesting.” In *COMSOL Conference 2018 Proceedings*. https://www.comsol.com/conference2018/download-paper/66172.pdf.

A. [CHAPTER] ABSTRACT

The U.S. Navy relies on power to operate its systems effectively to complete missions worldwide. Many of these systems generate thermal energy, which is typically lost to the environment and not useful within the system. Capturing the energy that would otherwise be lost and recycling it in the system provides the opportunity to improve the system’s efficiency, reduce heat signatures, and decrease some cooling requirements. Thermoelectric Generators (TEGs), which create voltage when exposed to a temperature differential, have the potential to recover the waste heat from naval systems and recycle it back into the system. Modeling and simulation helps establish the feasibility of building a tabletop prototype, thus helping explore whether TEGs have the potential to increase the energy efficiency of military systems. The purpose of this study was to build a model in COMSOL to simulate a potential prototype system of a TEG array on the muffler of a portable generator. The model will help determine the temperature difference between the TEG sidings, as a measure of the array’s efficiency. COMSOL simulation showed that the average temperature difference between the TEG sidings was 37.52 degrees Celsius. COMSOL modeling effort’s output will inform design, construction, and testing of a tabletop TEG array energy harvesting prototype for employment on the generator exhaust. Prototype actual performance will be compared to COMSOL output to check the validity of the model, before using it to design a larger-scale version for actual shipboard deployment and testing.

B. INTRODUCTION

A fundamental step in systems engineering (SE) is to model a system prior to building a prototype. Modeling can improve understanding of a system and provide useful evaluation and feedback prior to the design and manufacturing of that system. This part of the SE process has become increasingly important in military acquisitions as it may lead to reduced cost and time in the design and construction of the system.

The military is implementing strategies to decrease greenhouse gas emissions, increase fuel efficiency, and rely more on alternative energy sources (Reinhardt and Toffel 2017). Military initiatives, such as the Great Green Fleet and Task Force Energy, have been established to explore ways to reduce the reliance on fossil fuels to promote a more efficient operational fleet. Exploring options to increase efficiency could greatly increase the operational battlespace by improving the range and endurance of military craft, such as ships and aircraft. This energy optimization would both reduce the adversary's ability to exploit the military's energy and fuel usage and also maximize lethal capabilities (Pollman 2013). Looking at ways to reduce the infrared (IR) signature of military systems may contribute to the operational resiliency. One method to increase efficiency is to recover heat and recycle it back into a system. Thermoelectric generators (TEGs) may have the capability to provide this function to Navy systems.

A thermoelectric generator is a passive device composed of two semiconductor metals that operate based on the Seebeck effect (Johnson, Choate, and Davidson 2008). One side of the TEG, designated as the hot side, is connected to a heat source. The other side is the cold side, which can be connected to the heat sink to provide heat dissipation. When the TEG is exposed to the heat source and sink, a voltage is created between the two metals. As the temperature difference occurs across the system, the TEG converts this difference into electrical energy. The greater the temperature difference, the more energy the TEG can create.

Since 1961, NASA has utilized radioisotope thermoelectric generators (RTEGs) in space to generate electricity for space systems (National Aeronautics and Space Administration 2013). Furthermore, thermoelectric systems have been applied to vehicles resulting in improvements to fuel efficiency and engine power (Liu et al. 2015; LaGrandeur et al. 2006). Even though thermoelectric devices are currently used for their waste heat recovery capabilities, the full potential and trade space has not yet been fully explored. Currently, many TEG systems can provide 2–5% energy efficiency. As technology improves, TEGs may be capable of creating 15% or greater efficiency (Johnson, Choate, and Davidson 2008). Through modeling, simulation, and prototyping, the feasibility and estimated efficiency of applying TEGs to naval systems can be determined prior to design of large-scale version for actual shipboard deployment and testing.

In this research, COMSOL utilized the Heat Transfer and AC/DC modules to analyze the potential temperature difference of a TEG array between a muffler and water block. In this trial of military applications, TEGs are applied to the small but vital systems such as portable gasoline generators. The wasted thermal energy released by the muffler can be recycled back into the system. This analysis will inform how to proceed on future prototypes.

C. USE OF COMSOL MULTIPHYSICS

1. Governing Equations

To determine the temperature difference across each TEG in the array, it is necessary to use both the heat transfer and AC/DC modules to account for heat transfer in fluids, laminar flow, electric current interfaces. The primary governing physics applied to the Heat Transfer module is shown in Equations 1 through 6. Equation 1 is the expression for heat transfer in fluids and Equation 2 describes the heat transfer in solids.

$$\rho C_{\rho}\mu \cdot \nabla T + \nabla \cdot q = Q + Q_{p} + Q_{vd} \tag{1}$$

$$\rho C_{\rho}\mu \cdot \nabla T + \rho \cdot q = Q + Q_{ted} \tag{2}$$

Conduction heat flux and convective heat flux are shown in Equations 3 and 4, respectively.

$$q = -\kappa \nabla T \tag{3}$$

$$q_{o} = h \cdot (T_{ext} - T) \tag{4}$$

Equation 5 represents laminar flow and Equation 6 is the continuity equation.

$$\rho(u\cdot\nabla)u=\nabla\cdot[-\rho+\mu(\nabla u+(\nabla u)^{T})-\frac{2}{3}\mu(\nabla\cdot u)I]+F \tag{5}$$

$$\nabla\cdot(\rho u)=0 \tag{6}$$

The primary governing physics applied to the AC/DC module using the Electric Currents interface is shown in Equations 7 through 9.

$$\nabla\cdot J=Q_j \tag{7}$$

$$J=\sigma E+J_e \tag{8}$$

$$E=-\nabla V \tag{9}$$

The following are the variable notations for Equations 1–9.

- C_p = heat capacity
- ρ = fluid density
- u = velocity of flow
- T = temperature
- Q = heat source
- Q_p = work due to change in pressure
- Q_{vd} = work due to viscous dissipation
- Q_{ted} = work due to thermoelastic damping
- P = fluid pressure
- μ = conductivity
- E = electric field
- V = electric potential

- J = current density
- J_e = external current density
- Q_J = current source

2. COMSOL Modules

The model designed in COMSOL uses the Heat Transfer module and AC/DC module. Specifically, the Heat Transfer module involved the Heat Transfer in Fluids interface and the Laminar Flow interface. The Laminar Flow interface simulated the movement of fluid, such as air being pushed through the muffler and water flowing through the water block. The Heat Transfer in Fluids interface identified the components of the system, both solids and fluids, as conductors of thermal energy and showed how heat will spread through them. Also, the Heat Transfer in Fluids interface assigned temperatures to various components, such as air entering the nozzle of the muffler.

Laminar Flow and Heat Transfer were joined together using multiphysics nonisothermal flow. This simulated the varying temperatures throughout the flow of water and air within the system.

The physics of the AC/DC module in conjunction with Heat Transfer were applied to the TEGs. Heat Transfer in Solids and Electric Currents interfaces were joined in multiphysics to create the thermoelectric effect and electromagnetic heating of the TEGs based on the known material and geometry.

The Heat Transfer module helped determine the temperature difference between the TEG sidings. Specifically, as a result of selecting Conjugate Heat Transfer, the two physics of Laminar Flow and Heat Transfer in Fluids were used throughout all simulations.

3. Component Material and Geometry

The model consists of three main components: the muffler as the heat source, TEG array, and water block as the heat sink. Two aluminum sidings, a platform and a plate, surround the TEG array, acting as a conductive material. Each components' dimensions are provided in Table 1.

Table 1. Model Component Dimensions

Component	X (m)	Y (m)	Z (m)
Muffler	0.39	0.195	0.23
TEG	0.056	0.056	0.0045
Water Block	0.23	0.23	0.0014
Aluminum Base Sheet	0.23	0.23	0.003
Aluminum Top Sheet	0.23	0.23	0.005

A commercial-off-the-shelf (COTS) gasoline powered generator provided the design and material composition of the muffler used in COMSOL. The muffler's material composition is carbon steel (email to author, June 20, 2018). The interior of the muffler is assumed to be hollow and modeled this way to simulate air flowing through it. The walls of the muffler are assumed to be 0.5 cm thick based on the measurements of the nozzle wall thickness. A top view and side view of the muffler geometry are displayed in Figure 1 and Figure 2, respectively.

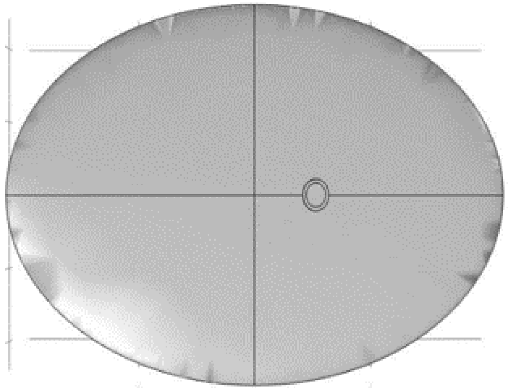

Figure 1. Muffler Top View Geometry

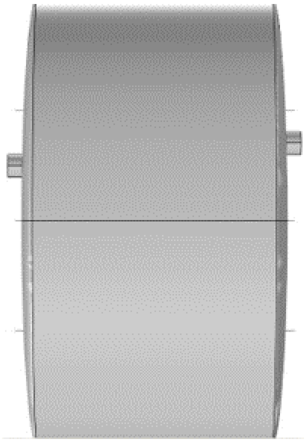

Figure 2. Muffler Side View Geometry

An aluminum base sheet was added to the muffler to provide a flat surface for the TEG array. The TEG array with the TEG’s “hot side” was assembled on the aluminum base sheet with an aluminum sheet on top of it.

An aluminum water block was constructed and placed on the top aluminum sheet for heat dissipation. Two nozzles were made to simulate a water-cooling system connected to the water block to provide constant cooling to the TEGs. The thinner aluminum walls of the water block’s interior forced the water from the cooling system to spread evenly throughout the block. The water block’s exterior and interior designs are displayed in Figure 3 and Figure 4.

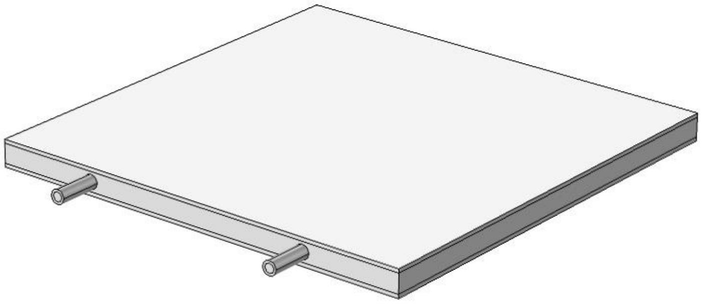

Figure 3. Water Block Exterior Design

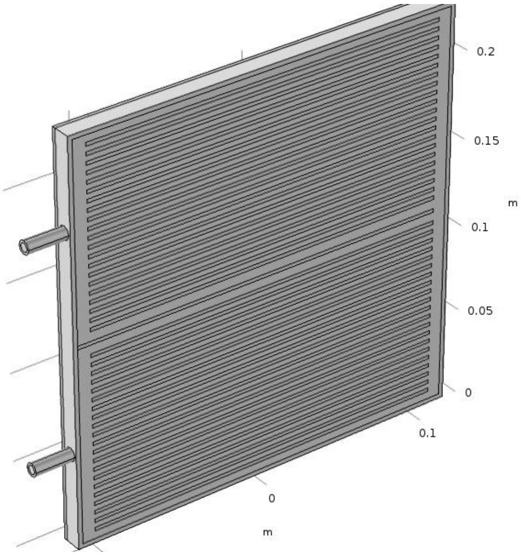

Figure 4. Water Block Interior Design

Each TEG in the TEG array was modeled based on a COTS TEG (TEGpro 2014). The TEG was disassembled as shown in Figure 5 to gather the structural details to design a more accurate internal representation.

Figure 5. Side by Side View of TEG Exterior and Interior

To simulate the real TEG, the model was designed with 22 rows of bismuth telluride pellets with 11 pairs in each. Each pellet was 1.5 mm x 1.5 mm x 1.5 mm. Aluminum plates were constructed on the top and bottom of the pellets. Figure 6 shows one row of this internal design.

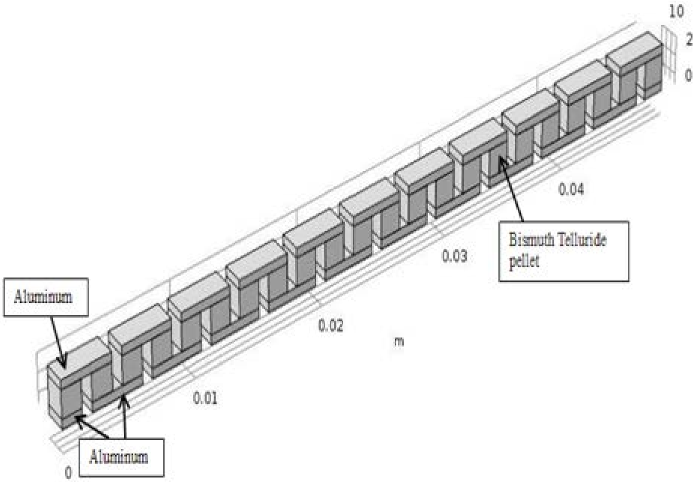

Figure 6. Complex Internal TEG Design

The COTS TEG was designed with silicone based adhesive. This was simulated by adding hollow boxes of 3.5 mm by 2.5 mm of silicone internally throughout the TEG to serve as insulation.

A simplified TEG was constructed in COMSOL to compare computation time and thermal conduction. This TEG had the same external dimensions and same volume of materials. The materials were inserted into two 23 mm by 23 mm blocks centered in the TEG. Figure 7 and Figure 8 display the complex TEG design and simplified TEG design, respectively.

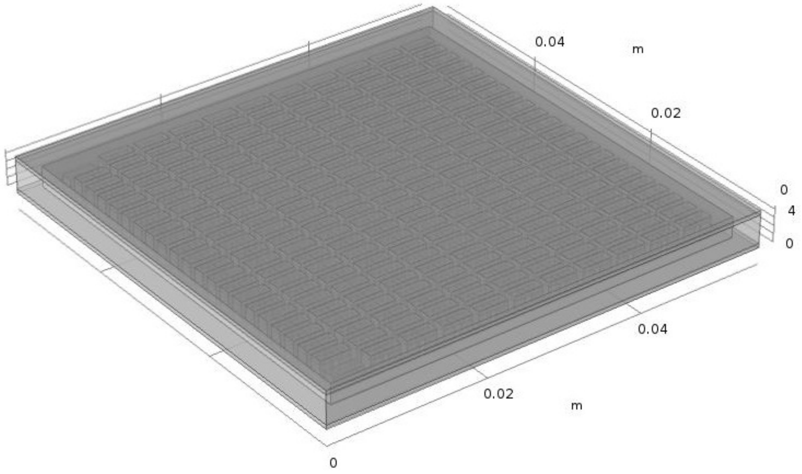

Figure 7. Complex TEG Design

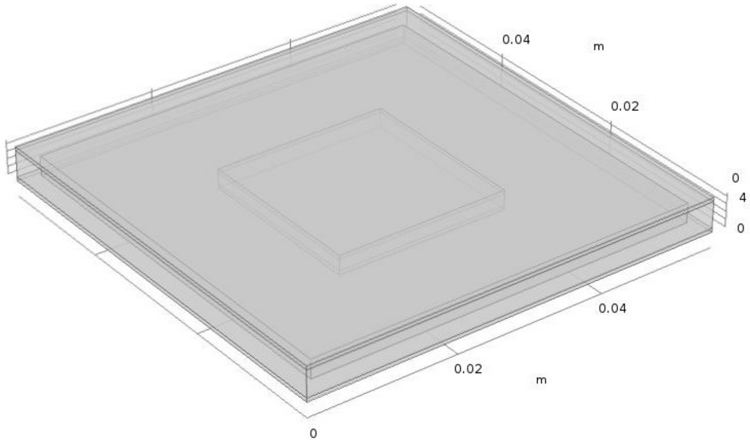

Figure 8. Simplified TEG Design

4. TEG Model Comparison

To compare models, the Heat Transfer module simulated placing the TEG in a block of air at ambient temperature, then heating one side of the TEG at 20°C intervals from 100–180°C. Measuring the temperature of the opposite side showed how heat transferred though the TEG. Results are displayed in Table 2 verifying that there was no difference in thermal conduction between TEGs constructed of the same material but with complex or simplified designs. However, computation time was nine times faster for the simplified design at three seconds per simulation compared to the complex design at 27 seconds. Based on this performance, the simplified TEG design was utilized in the overall system design.

Table 2. TEG Comparison

Temperature Input (°C)	**Complex TEG Temperature (°C)**	**Simplified TEG Temperature (°C)**
100.00	373.04	373.04
120.00	393.00	393.01
140.00	412.97	412.97
160.00	432.93	432.92
180.00	452.88	452.88

5. TEG Array Design

In the model, eight simplified TEGs were closely spaced on the aluminum plate directly on top of the muffler as displayed in Figure 9. Having a small gap between the TEGs in the array has been found to provide the maximum amount of thermal energy produced by the muffler to be absorbed by the TEGs (Moreno, Pollman, and Grbovic 2018).

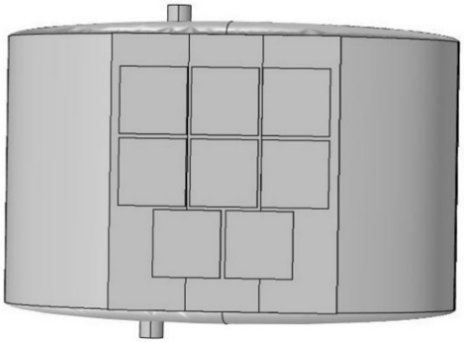

Figure 9. Designed TEG Array on Aluminum Base Plate of Muffler

6. Boundary Conditions

Boundary conditions were applied to the muffler and the water block. A forward looking infrared (FLIR) camera helped determine the inflow temperature and average surface temperature of the muffler by capturing images after the generator operated for 10 minutes at steady state. Analyzing the FLIR images determined that the inflow temperature entering the nozzle of the muffler was approximately 406°C. This condition was inputted into the Heat Transfer of Fluids interface. The average surface temperature of the muffler was 258°C. Through reverse engineering, the inlet flow rate in the Lamar Flow interface was adjusted until the muffler matched 258°C, resulting in an inlet flow rate of 0.0117 m^3/s. The FLIR image and the COMSOL image of the muffler's average surface temperature is displayed in Figure 10 and Figure 11, respectively.

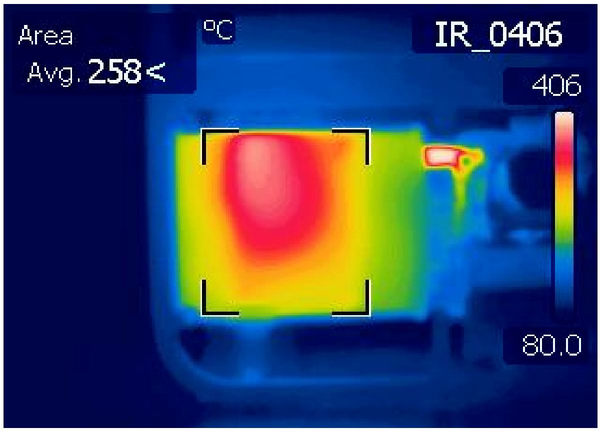

Figure 10. FLIR Image of Muffler's Average Surface Temperature

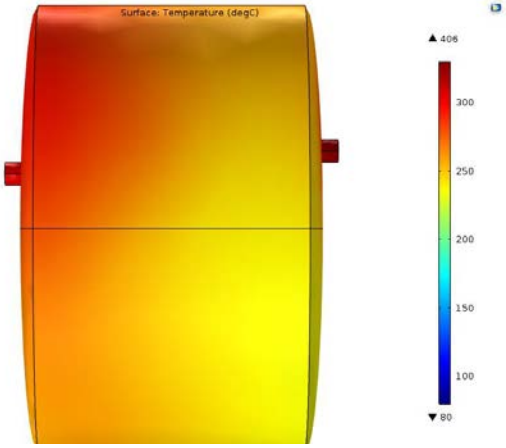

Figure 11. COMSOL Image of Muffler’s Average Surface Temperature

The inflow in the Heat Transfer of Fluids interface was set to simulate a cooling system chiller with a water temperature of 19°C and pressure 60 Psi. This simulated the pressure and temperature of the water leaving the cooling system and entering the water block. The cooling system’s inlet flow rate into the water block for the Laminar Flow interface was 0.00014 m3/s (BV Thermal Systems n.d.).

D. SIMULATION RESULTS

All of the systems’ components with their individual physics already applied were compiled together to form the entire system. The system was meshed and the model was run with the resulting simulation displayed in Figure 12 and the hot and cold temperature of each TEG was measured as shown in Table 3.

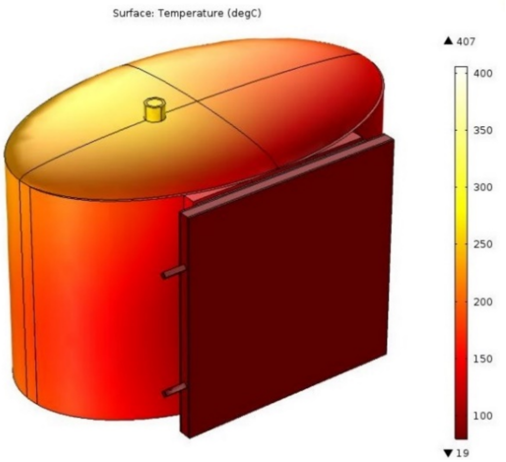

Figure 12. Final System Surface Temperature Distribution

Table 3. Simulation Temperature Results of TEG Array Using 5 mm Aluminum Plate

TEG	**Hot Side Temperature (°C)**	**Cold Side Temperature (°C)**	**Temperature Difference (°C)**
1	89.26	37.47	51.79
2	70.68	34.26	36.42
3	71.01	34.27	36.74
4	77.27	34.94	42.33
5	58.50	31.06	27.44
6	62.30	31.35	30.95
7	67.82	33.58	34.24
8	60.24	30.99	29.25
Average Temperature Difference			36.15

Another simulation was performed in which the aluminum plate width between the TEG array and the water block was reduced from 5mm to 3mm to determine if the temperature difference across the TEGs would change. Table 4 shows the results of this simulation.

Table 4. Simulation Temperature Results of TEG Array Using 3 mm Aluminum Plate

TEG	**Hot Side Temperature (°C)**	**Cold Side Temperature (°C)**	**Temperature Difference (°C)**
1	91.00	39.51	51.48
2	72.74	36.18	36.56
3	72.87	35.83	37.04
4	79.61	36.93	42.68
5	61.52	33.09	28.43
6	66.30	33.45	32.84
7	74.65	36.32	38.37
8	66.29	33.53	32.76
Average Temperature Difference			37.52

By decreasing the width of the plate, the average temperature difference increased from 36.15°C to 37.52°C.

E. FUTURE WORK

Future work includes comparing the COMSOL model output to a tabletop prototype in order to validate the COMSOL model. Additional modeling could be done, such as applying the temperature differences across each TEG determined by COMSOL to PSPICE to predict the voltage and amperage produced by each TEG and TEG array. This work will influence the design and allow for a TEG array to be built to a specific requirement. Future modeling of the TEG design includes determining the most efficient parallel and series combinations of the TEG array to support the specified requirement. This initial tabletop prototype will provide insight in the applicability of a TEG array as a proof-of-concept system in military applications.

Further research includes investigating the ability of a COTS TEG to reduce the IR signature. If proved practical, this could be beneficial to military systems. Reducing the heat signature of engines in military systems such as aircrafts and tanks, would increase platform survivability.

F. CONCLUSION

COMSOL helped study the temperature difference between the sidings of each TEG by simulating an array of eight TEGs on the muffler of a portable generator. Through simulation, COMSOL verified the physical characteristics of the TEG, water block, and muffler to their physical counterparts. Two simulations were run in which COMSOL determined the hot and cold side temperature for each TEG. In the first simulation, the average temperature difference with a 5.0 mm aluminum plate between the water block and array was 36.15°C. This increased to 37.52°C in the second simulation with a 3.0 mm plate. These findings will be utilized in further modeling, design, and construction of a TEG array prototype.

III. PAPER II: MODELING AND SIMULATION APPROACH TO INFORM WASTE HEAT HARVESTING PROTOTYPE FOR FOSSIL FUEL EXHAUST

This chapter has been accepted for publication by International ASET Inc. and is forthcoming: Howard, Lauren, Dragoslav Grbovic, and Anthony. Pollman. Forthcoming. “Modeling and Simulation Approach to Inform Waste Heat Harvesting Prototype for Fossil Fuel Exhaust.” In *International Conference on Energy Harvesting, Storage, and Transfer 2019.* www.international-aset.com.

A. [CHAPTER] ABSTRACT

Many military systems produce thermal energy as a by-product. Generally, this so-called waste heat is lost to the surroundings. Capturing the waste heat and putting it to beneficial use could increase the efficiency of military systems, while having the added benefit of reducing thermal signatures. This paper outlines the application of modeling and simulation to estimate the usable electric power produced by a thermoelectric generator (TEG) array on the exhaust muffler of a small fossil fuel generator. The simulation results informed design, construction, and testing of an initial prototype. Key prototype test variables were temperature difference, load resistance, and electric current. The results of the experiment were compared to and used to update the initial model. This small-scale effort provides initial insight into the efficacy of applying thermoelectric generators to military systems. Future work will explore larger arrays, as well as detailed investigation of the tradespace to identify promising equipment or applications, and inform capability and acquisitions requirements.

B. INTRODUCTION

The purpose of this research is to model a waste heat energy recovery system using thermoelectric generators (TEGs) on the muffler of a portable generator, and then use modeling and simulation to predict how a prototype TEG system will perform under certain conditions. Comparing measurements from an experimental prototype system to the model allows for validation of the model while also providing new information to improve the model for future use. Having a validated performance model could be used to support feasibility and trade-off analysis during the design of future military systems that might employ waste energy recovery.

C. BACKGROUND

The military relies on energy at sea to conduct operations such as fueling aircraft, launching missiles, and providing logistical resources to sailors. Implementing energy efficiency and optimization methods will reduce refueling at sea operations as well as increase the overall longevity of military platforms. This operational energy is critical to mission success, but runs the risk of increasing susceptibility to an enemy that is capable of exploiting energy usage (Pollman 2013). The Department of Defense is researching different methods to reduce reliance on fossil fuels to increase the efficiency of military forces (Schwarts, Blakelye, and O’Rourke 2012). Thermoelectric generators may help to provide the military this capability as these devices can capture wasted heat and recycle it back into military systems.

1. Thermoelectric Generators

A thermoelectric generator is comprised of two different semiconductor metals, p-type and n-type (LeBlanc 2014). A TEG operates by the Peltier and the Seebeck effects. In the Peltier effect, heat is absorbed at the junction of the two metals when an electrical current flows through the device (Lineykin and Ben-Yaakov 2007). The Seebeck effect describes the phenomenon of subjecting a TEG to a temperature difference, causing the dissimilar semi-conductor metals to induce a voltage, thus creating usable energy.

A heat source and heat sink can provide the resources to create the required temperature difference. A TEG has a designated hot side and cold side. The hot side is subjected to a heat source, such as a gas turbine found in a ship, and the cold side of the TEG connects to a heat sink, such as sea water. With a greater temperature differential, the TEG module can generate more energy. The material composition of the TEGs affects the temperature difference. Semiconductor materials that have higher-rated temperatures have the potential to produce more voltage (Montecucco, Siviter, and Knox 2014). The TEG’s voltage, current, and internal resistance changes as the temperature difference changes.

Multiple TEGs can be applied at one time to produce power, and the number required depends on the application. For example, in an automotive study, 72 TEG modules were applied to a heat pipe as a means to replace the radiator. This resulted in producing 28 W at idle and 75 W at 80 km/hr (Baatar and Kim 2011). Thermoelectric generator modules in an array can be arranged in parallel, in series, or in combination to produce the most efficient amount of power for their application. In an ideal environment, each TEG is exposed to the same temperature differential, resulting in each TEG creating the same output voltage (Montecucco, Siviter, and Knox 2014). However, most situations are not ideal, and particular system geometries can cause each module to experience different temperatures, and therefore different voltages and internal resistances, across the array (Montecucco, Siviter, and Knox 2014).

2. Role of Modeling and Simulation

Model-based systems engineering (MBSE) is an informative tool that can be used to study a system prior to applying it to real-world use. In MBSE, engineers utilize models "to support system requirements, design, analysis, verification, and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases" (International Council on Systems Engineering 2007, 15). Models can represent theory and concepts that have the potential to be applied to real-world applications (Friedenthal, Moore, and Steiner 2012). The application of modeling provides insights into how a system will function.

This research expanded on MBSE by the addition of simulation. This methodology, known as modeling and simulation (M&S)-based systems engineering, incorporates executing the model to understand how the system operates in a dynamic environment (Gianni, D'Ambrogio, and Tolk 2015). This provides the engineer and stakeholder numerical analysis as a means to evaluate the system (Gianni, D'Ambrogio, and Tolk 2015). By studying the system in a simulated operational environment, the engineer is able to identify issues earlier in the developmental process leading to reduced risk, reduced cost, and enhanced system performance (Gianni, D'Ambrogio, and Tolk 2015). Having an understanding of how a system will operate prior to building a prototype helps to inform design, ultimately aiding in defining operational and performance requirements (SEBoK n.d.).

Once the prototype is tested, its performance data can be compared to validate the model. New information gained from the prototype can be integrated into the model, helping to improve conceptual understanding and design of the system. This loop of modeling and refining the prototype helps to mitigate unexpected behaviors in a system and refine requirements. Applying the insight gained in testing the prototype to a future model will provide validity for when the model is scaled for future production of the system.

D. METHODOLOGY

The overall methodology followed in this research was to construct thermal and electrical models of a prototype TEG array system, measure performance of individual TEGs to be used in constructing an experimental prototype, and then use measured and estimated parameters to predict the performance of the prototype. Measurements of the actual TEG prototype's performance were then compared to the initial modeling predictions to validate and adjust modeling parameters.

1. Thermal Modeling

This research expands on previous research that utilized COMSOL Multiphysics software to model a future prototype TEG system (Howard et al. 2018). The system consisted of an array of eight simulated TEGs between a muffler operating at steady state and a water block. The physical geometry of the experimental prototype's actual TEG modules, muffler, and the water-cooling system utilized in this research were input into COMSOL to determine the estimated temperature difference between the TEG sidings. Results are displayed in Table 5. The simulation data indicated the TEGs are capable of recycling a portion of the muffler's wasted thermal energy back into the system. The predicted temperature differences will be applied to additional electronic circuit modeling to determine the optimum series or parallel arrangement of the array, thus predicting the voltage and power output capabilities.

Table 5. Simulation Temperature Results of TEG Array. Source: Howard et al. (2018).

TEG	**Hot Side Temperature (°C)**	**Cold Side Temperature (°C)**	**Temperature Difference (°C)**
1	91.00	39.51	51.48
2	72.74	36.18	36.56
3	72.87	35.83	37.04
4	79.61	36.93	42.68
5	61.52	33.09	28.43
6	66.30	33.45	32.84
7	74.65	36.32	38.37
8	66.29	33.53	32.76
Average Temperature Difference			37.52

2. Thermoelectric Generator Performance Characterization

An experimental setup was designed to characterize the TEG module to determine its performance parameters, as shown in Figure 13. To collect data, a hot plate was used as the heat source. A water cooler pumping water into a water block simulated a heat sink. The TEG was placed between two aluminum spacer plates with cutouts to allow for insertion of thermocouples, used to measure the temperature difference across the module. The water block sat on the top aluminum spacer plate, and the entire system rested on a hot plate. A clamp held the system together.

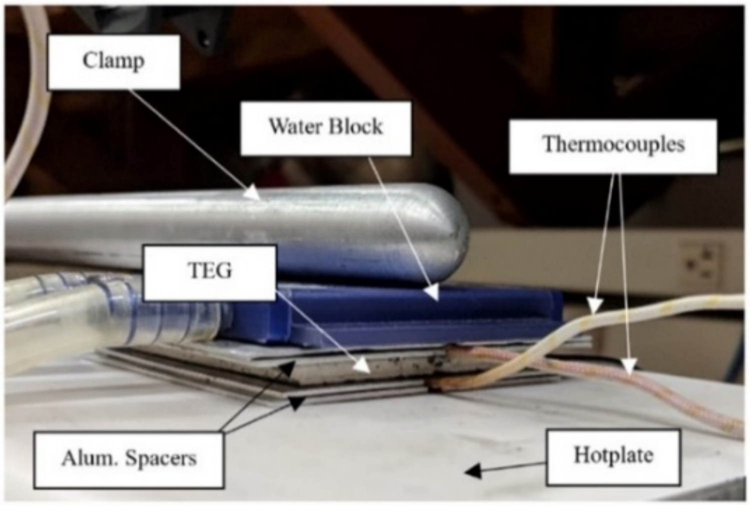

Figure 13. Experimental Apparatus of Characterization. Source: Moreno, Pollman, and Grbovic (2018).

Data was collected over a temperature a range of 180°C to 250°C at 10°C intervals. The temperature range was selected based on the heat profiles near the portable generator's muffler. The TEG was placed in a simple circuit and three different load resistors were used—1 Ω, 2.5 Ω, and 3 Ω. Three sets of data were collected using a multimeter for each resistor. In each data set, the following data was collected five times at each temperature increment: voltage across the resistance load (V_{load}), measured voltage in an open circuit (V_{oc}), short circuit voltage (I_{sc}), current across resistance load (I_{load}), and temperature difference (T_{diff})

The data collected was averaged for each parameter and empirical mathematical models developed using linear regression. These models reflected the aggregate open circuit voltage as well as the internal equivalent resistance (R_{eq}) of the TEG module. Equation 10 represents the temperature-dependent open circuit voltage equation and Equation 11 is the temperature-dependent internal TEG resistance determined through the Thévenin Theorem.

$$v_{oc} = 0.0187T_{diff} - 0.0051 \tag{10}$$

$$\mathrm{R}_{eq} = 0.0078T_{diff} + 2.1829 \tag{11}$$

3. Thermoelectric Generator Array Performance Prediction

The array of eight TEGs needs to be connected to produce a combined voltage. The temperature differences displayed in Table 1 were applied to several models in a circuit simulation software, OrCAD PSpice, to analyze current, voltage, and power output. Two models were developed in PSpice to simulate the TEG arrays: eight modules in series and eight modules in parallel. The temperature differences from Table 5 were applied to Equation 10 and Equation 11 to simulate each TEG's expected voltage and internal resistance, as shown in Table 6. These calculations predict how the temperature of the air moving through the muffler and the temperature of water circulating through the water block affects each TEG module's voltage and equivalent resistance. Figure 14 shows the PSpice graphical model of the all series arrangement of eight TEG modules. Each TEG is represented by the predicted voltage and internal resistance displayed in Table 6.

Table 6. Predicted Voltage and Internal Resistance across Each TEG Module

TEG	**V_{oc} (V)**	**R_{eq} (Ω)**
1	0.958	2.584
2	0.679	2.468
3	0.688	2.472
4	0.793	2.516
5	0.527	2.405
6	0.609	2.439
7	0.712	2.482
8	0.696	2.438

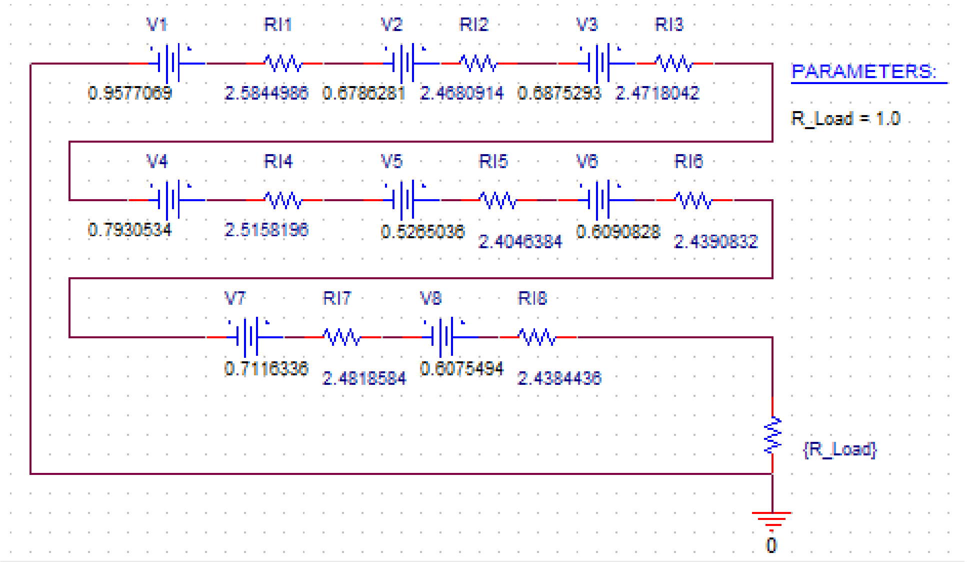

Figure 14. Thermoelectric Generator Module in Series

A simulation was run to determine the open circuit voltage for each circuit. For the series arrangement and the parallel arrangement, the V_{oc} was determined to be 5.57 V and 0.46 V, respectively. For each arrangement, the resistance load was changed in PSpice from 1 to 55 Ω at 1.0 Ω increments to determine when peak power occurs for each model. Table 7 displays peak power for each arrangement to include the resistance load as it occurred and the resulting V_{load} and I_{load}.

Table 7. PSpice Simulation Results for Peak Power

	TEG Arrangement	
Parameter	**Series**	**Parallel**
Resistance Load (Ω)	20.00	1.00
V_{load} (V)	2.79	0.35
I_{load} (A)	0.14	0.35
Peak Power (W)	0.39	0.12

For prototype testing, the arrangement producing the most voltage, all series, was utilized as it shows the potential to harvest more energy. The prototype's open circuit voltage, voltage across the resistance load, and the current across the resistance load were compared to the PSpice model outputs.

4. Prototype Construction and Measurements

The initial prototype system is composed of an aluminum base plate that conforms to the muffler, eight TEG modules connected in series using electrical cap connectors, and an aluminum water block. This entire system sits on top of a muffler of a portable generator and is held together with two hose clamps. The aluminum base plate acts as a flat surface to hold the TEG array. The hot side of the TEGs in the array touches the aluminum base plate, which sits directly on the muffler acting as the heat source. The cold side of the TEGs touch the water block, acting as the heat sink. The water block is connected to a circulating refrigeration unit to provide cooling to the TEG system. The aluminum base plate and the side of the water block touching the surface of the TEGs each have grooves that allow for space to add thermocouples, which measure the temperature difference across each TEG. Figure 15 shows this TEG prototype system mounted to the muffler of the generator.

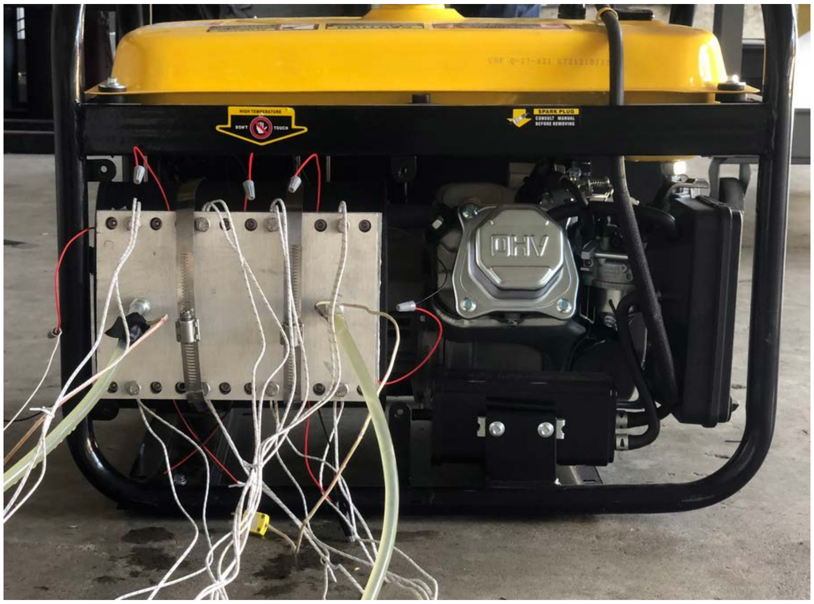

Figure 15. Thermoelectric Generator Waste Heat Harvesting Prototype Mounted to Muffler of Generator

Five sets of data were collected. For each data set, the generator ran for 10 minutes to reach steady state operations prior to collecting data. In each data set, the hot and cold side temperatures of each TEG were collected using a thermocouple meter. A multimeter was used to measure the V_{oc} of the TEG array circuit as well as the V_{load} and I_{load}. To measure the V_{load} and I_{load}, the circuit was connected to several resistors—1 Ω, 10 Ω, 20 Ω, 33 Ω, 47 Ω, and 55 Ω. By using multiple resistors, the peak power of the system was determined.

E. RESULTS AND COMPARISON TO MODEL

Excel was used to determine the average for each data parameter collected. Table 8 represents the average hot and cold side temperature for each TEG as well as the T_{diff} across each module.

Table 8. Average Experimental Temperature Results of the TEG Array

TEG	Hot Side Temperature (°C)	Cold Side Temperature (°C)	Temperature Difference (°C)
1	74.42	17.56	53.86 ± 1.45
2	81.52	20.20	61.32 ± 0.40
3	89.08	22.64	66.44 ± 2.23
4	88.42	22.06	66.36 ± 3.36
5	70.34	19.10	51.24 ± 2.25
6	76.20	18.26	57.94 ± 3.03
7	84.58	20.20	64.38 ± 2.03
8	83.38	20.86	62.52 ± 2.04

Note. Experimental error analysis was applied to the average temperature difference for TEG in the array.

The experimental average open circuit voltage for the prototype was determined to be 10.11 volts. The average V_{load}, I_{load}, and power for each resistance load is shown in Table 9.

Table 9. Average Experimental Voltage, Current, and Power Across the Resistance Load

Resistance Load (Ω)	V_{load} **(V)**	I_{load} **(A)**	**Power (Watts)**
1.00	0.471 ± 0.043	0.481 ± 0.028	0.226 ± 0.033
10.00	3.002 ± 0.187	0.304 ± 0.021	0.913 ± 0.120
20.00	4.658 ± 0.248	0.233 ± 0.010	1.084 ± 0.102
33.00	5.874 ± 0.235	0.180 ± 0.009	1.058 ± 0.090
47.00	6.640 ± 0.352	0.141 ± 0.007	0.936 ± 0.094
55.00	6.842 ± 0.367	0.135 ± 0.006	0.926 ± 0.087

Note Experimental error analysis was applied to the average temperature difference for TEG in the array.

Table 8 and Table 9 display the experimental error for each parameter that was measured. As the key measurement tools, the multimeter and thermocouples may have contributed to the source of error. Results may have been more precise if more than five sets of data were collected and if each set of data was collected simultaneously. The data sets were not collected within the same day to allow for proper startup and shutdown of the generator. While this allowed for each set to be collected after the generator reached steady state, this means variations in the outside temperature may have influenced the temperature difference across each TEG. The performance of the TEGs may degrade after each use as well. These dynamic factors may have affected the overall accuracy of the experimental results.

The average experimental temperature differences collected from the prototype was applied back to the PSpice model. This was used to update the model to more accurately reflect the real-world system as well as help to improve design when arranging modules in a series, parallel, or combination on the muffler, depending on the purpose of the TEG array. Applying the updated temperature differences to the all series PSpice model resulted in a closer representation of the prototype results. Figure 16 displays power plotted against resistance for the initial PSpice model results, the average experimental power data with its experimental error, and the updated PSpice model data with the average experimental temperature difference applied.

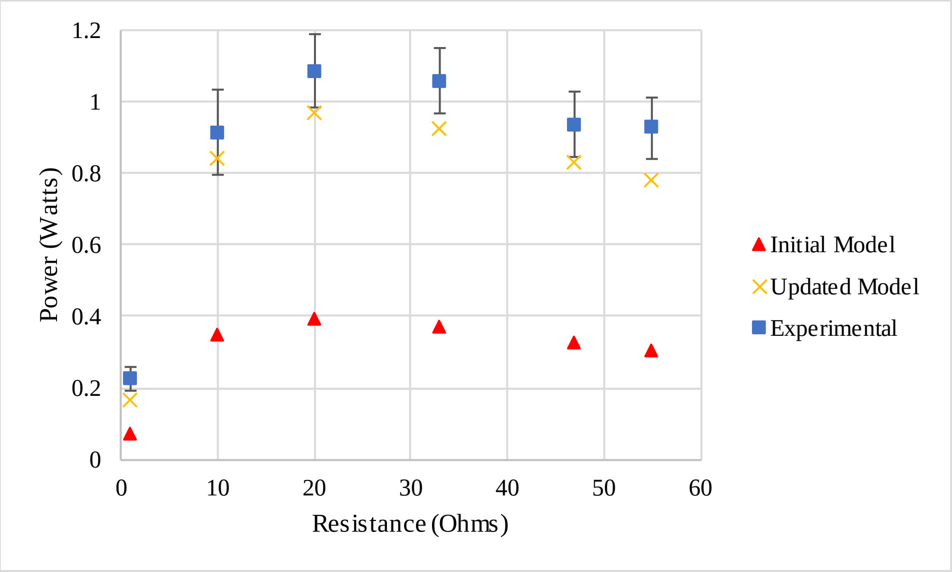

Figure 16. PSpice versus Average Prototype Collected Experimental Data

F. CONCLUSIONS

Overall, the hot side temperature was higher and the cold side was colder in the prototype when compared to the model. The V_{oc}, V_{load}, and power of the circuit were higher when compared to the model output. This corresponds to the TEGs in the prototype being exposed to a greater temperature difference. Both the model and the prototype showed an increasing voltage with increasing resistance. Also, the prototype exhibited peak power at approximately 20 ohms, as did the model.

In the model that predicted the hot and cold side temperatures of each TEG, the muffler was assumed to be hollow and software was applied to vary the temperature and movement of the water through the water block as well as the air moving through the muffler. The muffler and water block used in prototype testing have internal geometry that is more complex than in the model. This affects the movement and temperature of the air in the muffler and water in the water block. The temperature of the water and air in the actual system may have different variations than that simulated by computer software. With these assumptions and parameters applied to the model, it did not accurately portray every aspect of the system in a real-world environment. However, it did capture the trend of the system.

This paper presented a modeling and simulation approach by depicting the modeling of a TEG system prior to building and testing a prototype system. Modeling a TEG system on a muffler of a generator increased the understanding of how a TEG system operates. This knowledge was used to build an actual system for testing. A prototype system of eight TEGs on top of a muffler of a generator was built based off the insights provided by the model. The system was tested, and its experimental data was compared to that of the model. Even though the model did not accurately capture the prototype's experimental data, it did capture the trend of how the system operates in the real world. This research reinforces the idea that modeling and simulation can represent concepts that occur in the real world.

G. FUTURE WORK

Future work includes applying the results of the prototype to additional modeling to create a higher fidelity model. Applying the results from this research will help to model and build a system for a defined requirement. For example, additional models can be created to simulate shipboard systems to further predict the practicality in applying TEGs to recover waste heat. Military systems that could benefit from the application of TEGs need to be identified. This also includes conducting an analysis of alternatives for which heat sources/sinks would provide most benefit for the TEG to produce energy. From there, the architecture needs to be explored to determine which systems benefit from the greatest efficiency while exploring other factors such as cost, weight, reliability, and maintainability.

Off-ship military systems may benefit from the application of TEGs. For example, systems such as a tactical vehicles or aircraft also lose waste heat to the environment. Models and prototypes need to be explored to determine the application of TEGs in different environments to help increase the military's energy efficiency. Finally, it is important to consider the tradespace of applying TEGs to reduce the infrared signature in military systems. Reducing heat signatures in military systems that emit waste thermal energy could reduce the adversaries' ability to detect and target those systems, thus increasing the survivability of military platforms.

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IV. CONCLUSION

This thesis used a modeling and simulation (M&S)-based systems engineering approach to inform design, manufacturing, and testing of a TEG waste heat harvesting system. This approach supported the idea that M&S can show how a system functions in the real world. The TEG array design was tested via M&S until the results indicated that a given prototype design could create energy. The working model informed design, construction, and testing of a prototype system for waste heat harvesting from a muffler. The prototype system successfully demonstrated that TEGs can use waste heat from a muffler to generate adequate electrical energy to be useful in military applications. While the model did not quantitatively capture the observed prototype behavior in a precise way, it did qualitatively show how the system operates. This successful proof of concept indicates that TEGs could be a possible energy generation method for DoD applications.

A. SYSTEMS ENGINEERING CONCLUSION

This thesis showed the benefit of following a systems engineering methodology. The model was designed and adjustments were made until it produced working results. The modeling and simulation process provided the basis for creating the prototype. Modeling the system prior to design and manufacturing reiterates that modeling and simulation can provide cost-savings to the life cycle of the project while also advancing the understanding of TEGs. Modeling helped streamline the process in creating a successful first prototype system, as opposed to building several prototypes until one worked. Modeling the system revealed how the TEGs would perform depending on the arrangement, parallel or series, while interacting with the muffler and water-cooling systems. This knowledge helped produce the actual TEG-array system.

Systems engineering is an iterative process. The results of the prototype system were applied back to the model to create a higher fidelity model, improving its performance to better match the real world. This higher quality model can now be used in future work to serve as the baseline model. The model can then be reused and adjusted to serve specific requirements. As more data is gathered, it can be applied to the model to create an even more enhanced model while providing traceability, design verification, and future requirements validation for the lifetime of the project (Friedenthal, Moore, and Steiner 2009). The research showed that TEGs could be a promising contribution to reducing the military’s fuel and energy dependence, and should be further studied to identify the full breadth of potential benefits and uses, as well as the tradeoffs.

B. FUTURE WORK

Systems within the Navy and Marine Corps that generate waste heat need to be identified. The baseline model can be reused and modified to simulate those systems to estimate the effectiveness of TEGs in recovering waste heat and turning it into electrical energy. Thermoelectric generators have the capability to produce more power when the heat source and heat sink create a greater temperature difference across the modules. Different heat sink devices need to be studied with the identified military system that generates waste heat. This will help determine how to produce the most efficient amount of energy.

With those identified systems, an analysis needs to be conducted to determine if it makes sense to use TEGs as an energy conservation or operational endurance method. Factors such as cost, additional weight of applying TEGs and a cooling system, maintainability of the system, and predicted efficiency of the system needs to be looked at as whole. This analysis can then be brought to the decision maker when examining all the factors to aid in determining the feasibility of applying TEGs to systems within the military.

The initial prototype system was tested with a water-cooling system in a temperate climate. The Navy and Marine Corps operate in different environments around the world. TEGs need to be tested in different environments to determine if these devices operate more or less effectively in different locations.

DoD installations abroad are starting to integrate batteries as an energy storage source and as a way to provide a continuous power supply (Kosowatz 2018). Thermoelectric generators may have the capability to transferring recovered energy into a battery, and this potential application when considering efficiency needs to be investigated.

Systems that generate thermal energy pose operational risks to the military. Adversaries exist that can identify high value targets using sensors that see thermal energy and use this capability negatively against the United States. Applying TEGs to a heat source may reduce its heat signature by a significant amount. Thermoelectric generators may help improve the combat capability of military forces and increase the survivability of equipment and personnel.

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