1. INTRODUCTION AND BACKGROUND

Thermal energy conversion and management is a core technology that can strongly affect energy efficiency advancement initiatives of numerous technologies, including wasted energy conversion transportation, energy conversion and industrial processes, including applications from restaurant ovens to refineries. The motivation for this research is the result of a critical need for new innovative high-power thermal energy conversion technologies to meet the demands for advanced recovery of waste heat recovery. The required procurement of new generation capacity presents opportunities for clean technologies to become an important part of the supply mix. ***The development of a unique made-in-Canada experimental platform to facilitate thermal energy conservation of a high volume manufacturable thermoelectric generators design is necessary for future development.***

A novel concept thermoelectric generator (TEG) currently under development by Thermal Electronics Corporation requires precise performance characterization to highlight key research and development priorities for the next phase research and collaboration with planned partner McMaster University. Thermal Electronics Corporation is therefore actively seeking the best characteristic mechanism to capitalize on the advanced design concept currently at its early prototype stage. This design deviates from the norm in TEG geometries and cannot be tested using standard thermal cooler facilities as is the case with some research labs entering the generator side of thermoelectrics. The proposed design and geometry facilitates automated manufacturing in in-line mixing, compression and sintering of the composite materials - a solution to the hand built devices currently imported from China. The development, however, has been impeded by lack of knowledge and understanding of energy recovery performance driving parameters such as material compositions, compact pressures, sintering temperature and times. Therefore, the overall objective of this phase of the planned collaboration between McMaster and Thermal Electronics Corporation is to design, develop and fabricate a characterization system and methodology to assess the thermal performance and identify underlying mechanisms of energy production of the novel design to advance the state-of-the-art in TEG towards main stream adoption of this green technology.

Thermoelectric generator relies on the Seebeck effect to convert heat directly into electricity (Rowe, 1995). They are solid state devices with no moving parts and are known to be extremely reliable in harsh thermal-mechanical environments. A thermoelectric generator produces electrical power from heat flow across a temperature gradient. As the heat flows, free charge carriers (electrons or holes) in the material are also driven to the cold end. The resulting voltage (V) is proportional to the temperature difference (ΔT) via the Seebeck coefficient, α, ($V = \alpha\Delta T$) (Rodríguez et al., 2009). By connecting an electron conducting (n-type) and hole conducting (p-type) material in series, a net voltage is produced that can be driven through a load. The interest in thermoelectrics for power generation applications has increased dramatically over the past decade as a result of recent advancements in thermoelectric materials (Sandoz-Rosadoi, & Stevens, 2009). TEG modules are typically based on bismuth telluride alloys (e.g. Bi_2Te_3) and are most efficient in temperature ranges from -20°C to 300°C (Rowe, 1995).

The largest challenge for wide scale TEC deployment is the number Bi_2Te_3 elements required to can generate sufficient power to drive electrical and mechanical devices and the current fabrication method. At the current stage of development TEG's are primarily made in China due to the challenges of automating the soldering and assembly process of the P-N junctions. ***Thermal Electronics Corporation has been developing a new method of assembling and integrating the P-N thermopile based on a new geometric configuration that is more accommodating to automated high volume manufacturing***. With minimal human interfacing it is a low cost design that can be manufactured in Canada as an alternative to the current Made-in-China solutions. In late 2009 Thermal Electronics fabricated the first prototype TEG in the new design, however due to the novel configuration performance testing has been relatively crude as existing test facilities originally developed for thermal electric cooling applications in the electronics industry are undersized and unsuitable for the design. At the infancy stage of its development performance characterization, the identification of key design parameters such as understanding the material composition and formulas, compression pressures, sintering temperatures and time periods, material compatibilities between the junctions and the isolator substrate material and interpretation of the differing mechanisms governing performance is required. The facility will be designed to achieve the high amperage targets of the novel design and will match industrial application inputs parameters to a precise and quantitative tool to allow experiments to be performed to understand the effects of temperature, thermal cycling, vibration effects, geometry, material, substrate coating and heat transfer surfaces on energy recovery and component life. The development of this facility is unique compared to the routine analysis currently performed in many labs who formerly studied Thermal Electric Coolers for electronics cooling.

2. RESEARCH METHODOLOGY, ACTIVITY SCHEDULE AND TECHNOLOGY TRANSFER

The proposed investigation will involve several simultaneous experimental and analytical studies towards the development of TEG characterization test facility that can accommodate standard and next generation TEG designs. The proposed design will undergo performance parameter testing by a 4th year thesis group once commissioning and validating of the testing facility is complete which is the final component of the 6 month project. The research program is comprised of three main Milestones as shown in Table 1

Table 1: Activity Schedule – dates are in months

Milestone	Description of Activities	Start Date	End Date
1: State of the Art of TEG characterization Test Facilities	Prepare a complete and detailed literature review of the current technologies for TEG characterization	1	1
2: Evaluation and Conception	Identify the temperature and geometrical constrains, required energy demands and level of precision required	1	1
	Complete design of the heating, cooling, mounting and data acquisition subsystems.	2	3
3: Design Fabrication, Commissioning and Validation	Order measurement equipment and test facility components	2	3
	Manufacture of the test facility and implementation of all the measuring devices.	3	4
	Commissioning the test facility and validate the experimental results	4	6
	Perform a comprehensive testing plan for the proposed TEG designs with different material formulations, sintering temperatures and other manufacturing and operating related parameters.	To be competed in undergraduate thesis project 2010-2011	

A state-of-the-art experimental design and performance characterization facility for emerging clean energy thermal energy conversion devices: Thermal Electric Generators – TEG's it the outcome.

The benefits of increased energy efficiency is a critical issue in Canada and the rest of the world due to depletion of natural resources and negative environmental effects of the by-products of energy generation. Recovery of waste heat energy using TEG devices is one of the most effective ways of increasing the availability of energy without adverse environmental effects and with no production of CO_2. ***This NSERC Engage project is envisioned as a first phase to long term research partnership between McMaster and Thermal Electronics Corporation to develop more advanced TEG designs.*** The integration TEG's as a device for energy recovery is a compliment to the ongoing research by the applicant including thermal storage and advanced combined heat and power systems. The next phases of the proposed partnership includes future design for manufacturing studies with the McMaster Manufacturing Research Institute (MMRI), and a collaborative project with a third party partner with significant thermal waste production challenges.

1.3 Project Objectives

While all commercially available thermoelectric generators come with specification and technical data on their performance this data is usually quite limited and not applicable to engineering situations (such as the open circuit voltage and the short circuit current). And the method used to obtain this data is under much debate as to its universal validity.
As such one of the main objectives of this project was to perform a precise characterization as the first step in a long-term program of collaborative research and development activities involving TEC and McMaster University. The overall objective of this first phase of collaboration between McMaster and the industry sponsor Thermal Electronics Corporation is to design, fabricate, and perform initial testing with an original characterization system and methodology, with the goal of assessing the thermal performance and identifying the underlying mechanisms of energy production for both the traditional flat and the new TEG design concept. The long-term goal of the collaborative R&D activity will be to advance the state-of-the-art in TEG technology, leading to the main stream commercial adoption of a technology that leads to a greater fuel utilisation efficiency, greenhouse-gas emission reduction and alternatives to fossil fuels for electric power.

2.0 Background

2.1 TEG Designs

Currently the commercial market for Thermoelectric Generators consists only of flat plate designs. The traditional flat plate design is quite simple but effective at harvesting the waste heat between two parallel surfaces. An image of the standard design of the TEG is included below.

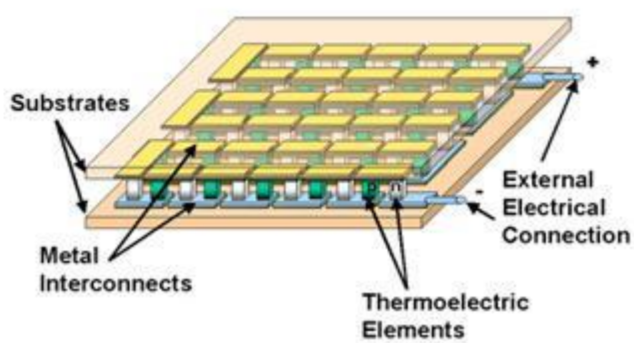

Figure 2.2 Traditional Commercial Flat-plate TEG

The TEG contains more than the two thermoelectric elements required for a simple thermocouple as the voltage generated is directly proportional to the number of thermoelectric couples. These couples are connected together electrically in series with electrical connectors, such as nickel coated copper or aluminium, such that their voltage simply sums together for a greater output. The electrical circuit is then encased in what is normally two sheets of ceramic to electrically insulate the thermocouples from whatever surfaces they are extracting heat from and to provide rigidity.

The circuit needs to be electrically insulated from the heated surfaces the use of ceramic is generally the case with thermoelectric coolers as it helps to maintain the generated temperature by providing a thermal resistance. In the design of thermoelectric generators however a more beneficial material would be that which is electrically insulating but thermally conductive as the bigger the temperature difference of the thermoelectric elements the higher the voltage created.

This design flaw belays a serious deficiency to the market in general which is that the vast majority of flat plate TEGs on the market at the moment are simply thermoelectric coolers marketed as the generators. As such they do not address the inherent problems with TEGs which have to deal with much higher temperatures than the average cooler. These problems present serious difficulties to the design of thermoelectric generators. Thermal expansion of the components can cause stress on the elements causing them to fracture and break. The solder used in electrically connecting the elements and connectors melts under the applied high temperatures experienced by a TEG.

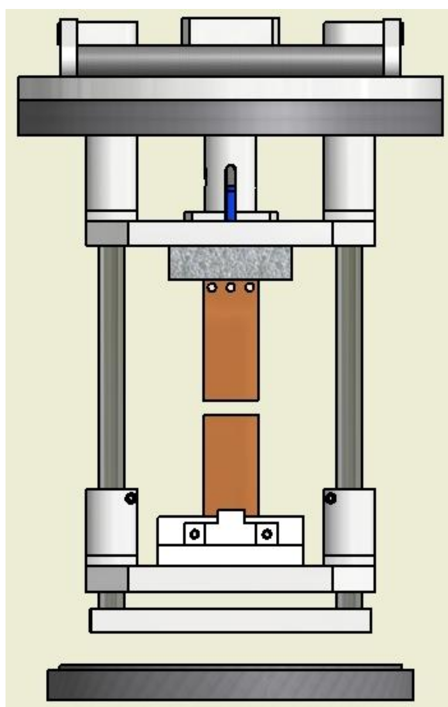

Figure 3.1: Flat-plate TEG testing apparatus (Steel cylinder not shown for clarity)

REFERENCES

D.M. Rowe, Handbook of thermoelectrics, CRC Press, 1995

A. Rodríguez, J.G. Vián, D. Astrain, and A. Martínez, "Study of thermoelectric systems applied to electric power generation", Energy Conversion and Management, 50, 1236-1243, 2009

E. Sandoz-Rosadoi and R. Stevens, "Experimental Characterization of Thermoelectric Modules and Comparison with Theoretical Models for Power Generation", Journal of Electronic Materials Special Issue Paper DOI: 10.1007/s11664-009-0744-0, 2009

BUDGET JUSTIFICATION

1) Salaries and Benefits

The funding requested here will be used to support two undergraduate summer students and a current M.A.Sc. graduate students to supervise the undergrad students on a part-time basis. The Engage project described is related to my current students project in general terms of thermal management and energy conversion and the opportunity for Kevin to supervise an undergrad will be a valuable experience. Details of the salary are outlined in Table A. Salary provisions for Technical Assistance in the selection and programming support of the data acquisition system components and machining of the test section and fixturing has also been included.

Table A

	Name	Degree	Salary May 1- Aug 31,
Student I	Undergraduate	B.A.Sc.	
Student II	Undergraduate		
Student III	Kevin Ng	M.A.Sc.	
Student III and IV*	Undergraduate	B.A.Sc.	
Technician Assistance			
a)Total Proposed - Students			

*It is proposed that the project will continue beyond the duration of the Engage project timeframe as an undergraduate 4th year capstone project for two students, potentially Student 1 as a continuation of the Engage to the TEG performance characterization studies.

2) Equipment, Materials & TEG's

The experimental investigation will be based on the design and analysis of the students. A comprehensive survey of TEC and TEG characterization facilities will be conducted and the design facility will be built and qualified over the course of the project. The proposed experimental facility will be a versatile test apparatus capable of accurate control and measurement of thermal loads and electrical outputs for a known clamping pressure to capture the contact resistance. Tables B show the proposed budget for Equipment, TEG's and required Materials and Supplies.

Table B

Equipment purchase	Description	Cost
	Isothermal Test Fixture	
	Thermocouples	
	Data acquisition system	
	Electrical components: servo, load cell, power measurement, electrical box and safety equip (E-stop)	
	Cartridge Heaters	
	Variac	
	Chiller, cooling fans	
	Programmable Controllers	
	Heat Spreaders	
	Housing and Mounting System	
	EQUIPMENT TOTAL	
Materials and Supplies	Conductive Paste	
	Heat Flux Sensors	
	Miscellaneous Office and Lab Supplies/Consumables	
	MATERIAL TOTAL	

3) Travel

Travel to and from McMaster to Thermal Electric Corporation, Aurora, Ontario, including car rental and accommodations for two students is estimated to cost **$xxxx** over the course of the project.

RELATIONSHIP TO OTHER RESEARCH SUPPORT CURRENTLY HELD AND APPLIED FOR:

Agency	Type	Subject	Date of Award	Dura-tion	Relationship
McMaster University	Start-Up Funds,	Sustainable Energy Technology Development (*Cotton*)	07 (N)	1	There is no conceptual or budgetary relation.
NSERC	Discovery	Development of Electrohydrodynamic Two-Phase Heat Exchanger and Thermal Management Technologies (*Cotton*)	08 (N)	5	There is no conceptual or budgetary relation.
NSERC	RTI - Category 1	High Speed Particle Image Velocimetry (PIV) System (*Ziada and 5 others*)	08 (N)	1	There is no conceptual or budgetary relation.
NSERC	RTI - Category 1	Hot Oil Temperature Control Unit for Characterization of Thermal Management Systems and Devices *(Ching and 3 others)*	08 (N)	1	There is no conceptual or budgetary relation.
OCE	INTERAC	Energy Mediator (Hydrolyser™) Thermal Storage System(TOS) Blueprint (*Cotton*)	08 (N)	1	There is no conceptual or budgetary relation.
OCE	INTERAC	Two-Phase Thermal Mngmt. Device Opportunities for Porous Foams (*Cotton*)	08 (N)	1	There is no conceptual or budgetary relation.
OCE	Connections	Design of a Test Facility to Investigate Impact of Bypass on HVAC Filter Cleaning and Energy Efficiency (*Cotton*)	08 (N)	1	There is no conceptual or budgetary relation.
CFI	LOF	Thermal Energy Recovery & Management Testing Platform (*Cotton*)	09 (N)	1	There is no conceptual or budgetary relation.
NSERC	Collaborative Research and Development Grant	Flow Accelerated Corrosion in Piping Components under Single and Two Phase Flow Conditions *(Ching and Cotton)*	09(N)	2	There is no conceptual or budgetary relation.
Union Gas Limited	Grant	Union-Gas-Enersmart Partnership in Research and Education (*Chidiac and 3 others*)	09(N)	2	There is no conceptual or budgetary relation.
NSERC *applied for*	RTI - Category 1	Dynamic Two-Phase Flow Pattern and Void Fraction Measurement System (*Cotton and 3 others*)	NA	1	There is no conceptual or budgetary relation.
NSERC *applied for*	RTI - Category 1	A High Frequency High Voltage Generation System (*Ching and 4 others*)	NA	1	There is no conceptual or budgetary relation.
NSERC *applied for*	RTI - Category 1	Laser Doppler Velocimetry (LDV) System (*Ziada and 3 others*)	NA	1	There is no conceptual or budgetary relation.

SUMMARY OF PROPOSAL

Thermal energy conversion and management is a core technology that can strongly affect energy efficiency advancement initiatives of numerous technologies, including wasted energy conversion transportation, energy conversion and industrial processes, including applications from restaurant ovens to refineries. The motivation for this research is the result of a critical need for new innovative high-power thermal energy conversion technologies to meet the demands for advanced recovery of waste heat recovery. The required procurement of new generation capacity presents opportunities for clean technologies to become an important part of the supply mix. ***The development of a unique made-in-Canada experimental platform to facilitate thermal energy conservation of a high volume manufacturable thermoelectric generators design is necessary for future development.***

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COMPANY PROFILE

Thermal Electronics Corp. (Gerard Campeau)

Thermal Electronics Corp., located in **Peterborough, Ontario**, develops, designs, and manufactures Thermo Electric Peltier and Seebeck based appliances and components for food service, medical, and industrial applications. A Canadian Company involved with Thermoelectric Devices and products for the past 19 years. It has always been our intention to develop products and technology that meet certain market niches and we have been very successful with that approach. Our main business has been in the commercial food service equipment market. In the last 4 years and though still immature we have seen a shift in our industry. The shift has been to commercialize waste heat and power generation using (TEG) Thermoelectric power generators to produce electricity. Not, only has this shift been appearing in the domestic market but internationally as well. We export 70% of our products to the USA, Central America and Europe. Building on this base, we see the growth of our company evolving into a manufacturer of high value alternative power products. The future growth of our company is in small to medium size Thermoelectric Power Devices (100W to 5 KW).

As world energy prices escalate, alternative power sources and technologies are starting to show buoyancy in the market place. Our marketing as well as our list of clients continues to be skewed towards power generation. We believe that companies have been positioning themselves to become dominant players in the renewable power and power conservation market. In 2000 our small company began looking at Thermoelectric Generators and understood then the potential of the technology to be integrated into main stream devices and equipment was a matter of finding a method to manufacture these devices at a reduced cost. Thermoelectric device design has not changed in 50 years and is still being manufactured using a design that was focused on cooling not power generation. In anticipation we began the research and development of a unique design that could be mass-produced, focused on power generation, and be manufactured using full-automation. After years of prototyping and design change, we have a lab scale device that can be commercialized and produced using Full-Automation.