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A Survey of Sub-10W Thermoelectric Generators for Military Applications

Gisele Amow

Defence R&D Canada – Atlantic

Technical Memorandum

DRDC Atlantic TM 2009-217

January 2010

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Abstract

A literature survey and web-based search was undertaken to assess current state of the art thermoelectric devices for power generation in the sub-10W range to support the Advanced Soldier Adaptive Power (ASAP) Technology Demonstration Project currently underway at DRDC. Thermoelectric power generation can reduce logistical burdens of fuel transport, which can lead to lower costs and personnel risks on the battlefield. At present, overall thermal to electric efficiencies are low at 5-8%; however, steady advancements are being made in the development of novel materials and miniaturized device designs, which may one day enable their practical use.

Résumé

On a effectué un survol de la littérature et une recherche sur Internet pour évaluer l'état actuel de la technologie des dispositifs thermoélectriques utilisés pour la production d'électricité de puissance inférieure à 10 W à l'appui du projet de démonstration de la technologie des sources d'alimentation de pointe pour le soldat (ASAP) en cours d'exécution à RDDC. La production d'énergie thermoélectrique peut réduire le fardeau logistique de transport de carburant, ce qui peut donner lieu à des frais réduits et à des risques moindres pour le personnel sur le champ de bataille. À l'heure actuelle, l'efficacité globale de la conversion thermique-électrique est faible: 5-8 %. Cependant, on assiste à des progrès continuels dans le développement de nouveaux matériaux et de conceptions de dispositifs miniaturisés, qui peuvent un jour permettre l'utilisation pratique de ces dispositifs.

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Executive summary

A Survey of Sub-10W Thermoelectric Generators for Military Applications

G. Amow; DRDC Atlantic TM 2009-217; Defence R&D Canada – Atlantic; January 2010.

Introduction: The Canadian Forces is currently on a firm course towards the modernization of the soldier through the Integrated Soldier Systems Project (ISSP). Within this effort, power and energy play a key role in the 'system of systems' approach engendered within ISSP. In order to maintain battlefield superiority through technological advantages, the dismounted soldier of the future will carry with them a multitude of electronic devices, such as computers, personal radios, GPS, head up displays, all of which are intended to increase effectiveness, lethality and survivability. Such electronic devices will naturally increase the electric power demands from the already limited power sources largely available today as batteries. To mitigate these demands, the Advanced Soldier Adaptive Power (ASAP) Technology Demonstration Project, currently underway at DRDC, is targeted towards the reduction and optimization of the load carriage, as well as optimizing power source production and consumption through power management. Part of these efforts also involves the exploration of alternative power source technologies capable of delivering a sub-10W power output; a value defined within ASAP. One such technology, which is the focus of this report, is thermoelectric power generation, which utilizes a thermal gradient/flow to produce power.

Results: Thermoelectric power generation has the potential to reduce the logistical burden of fuel transport to and from the battlefield by taking advantage of converting heat into useable power through energy harvesting or waste heat recovery. The technology offers proven reliability, quietness, scalability and modularity. For the sub-10W power range, bulk thermoelectric modules are available commercially; however, their adoption for practical use is limited due to their overall low efficiencies. Advancements are being made in miniaturized thermoelectric devices, particularly those based on thin-films, which offer smaller footprints and, thus, higher power densities. It is clear that while thermoelectric modules are available commercially, their utilization requires very highly customized solutions, which begins with suitable material choices for the desired temperature range of operation, heat transfer to/from the device, and device design. Given these challenges, however, thermoelectric power generation remain a consideration for future requirements given the steady advancements being made and past historical successes as reliable power sources.

Significance: Thermoelectric power generation from energy harvesting and waste heat recovery, in particular, can enable more energy-efficient operations on a dispersed battlefield. It has the potential for reducing the logistical burdens of fuel transport to and around the battlefield, and in so doing, can reduce overall fuel costs and personnel risk during operations. Specific defence applications for thermoelectric power generation include, but are not limited to: portable power for battery recharging; remote power for telecommunications and unattended sensors; waste heat recovery from vehicles; powering autonomous microsystems/robotics; and portable/wearable soldier power.

Future plans: It is recommended that a watching brief on the development of thermoelectric materials and devices be maintained to monitor significant advancements in power generation; this is already being done through the Technical Cooperation Panel (TTCP MAT TP-8).

Sommaire

A Survey of Sub-10W Thermoelectric Generators for Military Applications

G. Amow; DRDC Atlantic TM 2009-217; R & D pour la défense Canada – Atlantique; Janvier 2010.

Introduction : Les Forces canadiennes se sont nettement engagées vers la modernisation du soldat au moyen du projet d'équipement intégré du soldat (PEIS). Dans le cadre de cet effort, l'alimentation et l'énergie jouent un rôle clé dans l'approche du « système de systèmes » engendré au sein du PEIS. Afin de maintenir la supériorité sur le champ de bataille grâce aux avantages technologiques, le soldat débarqué de l'avenir doit porter sur lui une multitude de dispositifs électroniques, tels que des ordinateurs, des postes radio personnels, un récepteur GPS et des affichages tête haute, qui servent tous à augmenter l'efficacité, la létalité et la capacité de survie. Évidemment, ces dispositifs électroniques augmenteront la demande en énergie électrique des sources d'alimentation déjà limitées grandement disponibles aujourd'hui sous la forme de batteries. Pour freiner cette demande, le projet de démonstration de la technologie des sources d'alimentation de pointe pour le soldat (ASAP), en cours d'exécution à RDDC, vise la réduction et l'optimisation de l'alimentation de la charge, ainsi que l'optimisation de la production et de la consommation de l'énergie au moyen de la gestion de l'énergie. Ces efforts comprennent l'exploration de technologies de sources d'alimentation de remplacement capables de fournir une puissance de sortie inférieure à 10 W, valeur définie dans le projet ASAP. Une de ces technologies, qui fait l'objet principal du présent rapport, est la production d'énergie thermoélectrique, qui exploite un gradient/écoulement thermique pour produire de l'énergie électrique.

Résultats : La production d'énergie thermoélectrique a le potentiel de réduire le fardeau logistique de transport de carburant en direction et en provenance du champ de bataille en mettant en valeur la conversion de chaleur en énergie utilisable grâce à la collecte de l'énergie ou à la récupération de la chaleur. La technologie offre une fiabilité éprouvée, le silence, l'échelonnabilité et la modularité. Pour une puissance inférieure à 10 W, des modules thermoélectriques en vrac sont disponibles dans le commerce; toutefois, leur adoption à des fins pratiques est limitée à cause de leur faible rendement global. Il y a des progrès en cours au niveau des dispositifs thermoélectriques miniaturisés, notamment ceux qui sont basés sur les couches minces et qui présentent un encombrement moindre, donc, de plus grandes densités de puissance. Il est clair que, bien que des modules thermoélectriques soient disponibles dans le commerce, leur utilisation exige des solutions fortement personnalisées, qui commencent par le choix de matériaux convenant à la plage de température de fonctionnement voulue, le transfert thermique en direction et en provenance du dispositif et la conception du dispositif. Malgré ces défis, la production d'énergie thermoélectrique demeure une considération pour les exigences futures, compte tenu des progrès continuels réalisés et des utilisations réussies en tant que sources d'alimentation fiables.

Portée : La production d'énergie thermoélectrique, notamment à partir de la collecte d'énergie et de la récupération de chaleur, peut donner lieu à des opérations plus éconergétiques sur un champ de bataille dispersé. Elle a le potentiel de réduire le fardeau logistique de transport de carburant en

direction et à l'intérieur du champ de bataille, ce qui permet de réduire le coût global du carburant et d'atténuer le risque pour le personnel pendant les opérations. Des applications, propres à la défense, de la production d'énergie thermoélectrique comprennent, sans toutefois s'y limiter : source d'alimentation portable pour la recharge des batteries; source d'alimentation éloignée pour les télécommunications et les capteurs sans surveillance; récupération de la chaleur de véhicules; alimentation de microsystèmes/robots autonomes; et source d'énergie portable pour le soldat.

Recherches futures : Il est recommandé d'exercer un mandat de surveillance sur le développement de matériaux et dispositifs thermoélectriques pour suivre les progrès importants de la production d'énergie électrique; cela ce fait déjà par l'intermédiaire du Technical Cooperation Panel (TTCP Mat TP-8).

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Acknowledgements

The author acknowledges support from the Advanced Soldier Adaptive Power (ASAP) Technology Demonstration Project.

1 Introduction

1.1 Background

The Canadian Forces is currently on a firm course towards the modernization of the solider through the Integrated Soldier Systems Project (ISSP). Within this effort, power and energy play a key role in the 'system of systems' approach engendered within ISSP. In order to maintain battlefield superiority through technological advantages, the dismounted soldier of the future will carry with them a multitude of electronic devices, such as computers, personal radios, GPS, head up displays, all of which are intended to increase effectiveness, lethality and survivability. Such electronic devices will naturally increase the electric power demands from the already limited power sources largely available today as batteries. To mitigate these demands, the Advanced Soldier Adaptive Power (ASAP) Technology Demonstration Project, currently underway at DRDC, is targeted towards the reduction and optimization of the load carriage, as well as optimizing power source production and consumption through power management. Part of these efforts also involves the exploration alternative power source technologies capable of delivering a sub-10W power output; a value defined within ASAP. One such technology, which is the focus of this report, is thermoelectric power generation, which utilizes a thermal gradient/flow to produce power.

Thermoelectric generators are proven reliable long-term power sources. They are scalable, modular, have low noise signatures with no moving parts and can produce continuous and predictable power outputs. They have a well-known history of being used for deep space missions and remote terrestrial weather stations [1] where radioisotopes are used to provide the 'hot side' temperature required for operation through radioactive decay. For practical military operations, however, the thermal gradient can be provided by: (i) direct fuel combustion whose sole intent is to produce the heat to power the thermoelectric generator; (ii) energy harvesting; and (iii) waste heat recovery. The distinction is made here between energy harvesting, where the thermal gradient is relatively small (tens of degrees or less), such as heat from the human body or other low grade sources (electronics), and waste heat recovery in which the thermal gradient is much larger and of higher grade (hundreds of degrees), such as from automotive catalytic converters and exhausts, gensets and solar thermal. Thermoelectric power generation from energy harvesting and waste heat recovery, in particular, can enable more energy-efficient operations on a dispersed battlefield. It has the potential for reducing the logistical burdens of fuel transport to and around the battlefield, and in so doing, can reduce overall fuel costs and personnel risk during operations.

1.2 Military Uses for Thermoelectric Devices

Thermoelectric devices are already being used for military and solider applications, specifically for cooling, such as night vision binoculars [2]. This is made possible by the Peltier effect, which results in cooling when an applied voltage is provided [1, 3]. For power generation applications, many opportunities exist, such as portable power for battery recharging, remote power for telecommunications and unattended sensors, waste heat recovery from vehicles, powering autonomous microsystems/robotics and portable/wearable soldier power to name a few. There has been a strong interest in employing thermoelectric generators for power generation in this context over the last two decades. For example, the US Navy has and continues to invest heavily in the development of thermoelectric power generators [4]. The US Department of Defense has also investigated the feasibility of energy harvesting from soldiers as a means to provide power for battery recharging as well as field heaters for kitchens[5, 6], More recently, these efforts have also included the participation by the US Department of Energy to develop a 1.6kW thermoelectric power system for portable soldier power [7].

1.3 Scope of Report

For this report, a literature and web-based search of thermoelectric devices suitable for power generation in the sub-10W range was undertaken. Section 1 of this report provides the background and relevance of thermoelectric devices for defence applications while Section 2 describes the underlying scientific principles of power generation from thermoelectric generators including device design and limitations. Section 3 describes commercial state of the art thermoelectric modules for power generation in the sub-10W range. Finally, Section 4 provides a summary and conclusions of this report.

2 Thermoelectric Concepts

2.1 Fundamental Principles

Thermoelectric generators produce electric power from a thermal gradient based on the Seebeck effect [1, 3]. When heat flows in a conductive material, the charge carriers in the material are also carried along, which results in a potential difference between the ends of the material. Based on this phenomenon, a thermoelectric generator can be constructed by connecting the hot ends of two dissimilar conductors (thermoelements) to form a hot junction and by connecting a load to the cold end of the two materials as shown in **Fig. 1**. Such devices require no fuel; only a temperature differential is needed to produce a finite power output.

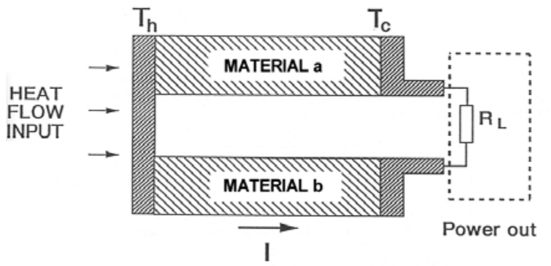

Figure 1 Illustration of a thermocouple as a power generator[1].

The maximum thermal-to-electric conversion efficiency of a thermoelectric generator is the product of the Carnot efficiency and a materials factor dependent on the dimensionless thermoelectric figure-of-merit, ZT:

$$\eta_{\max} = \frac{T_{hot} - T_{cold}\sqrt{1+ZT} - 1}{T_{hot}\sqrt{1 + ZT + \frac{T_{cold}}{T_{hot}}}}$$

ZT is a combination of three material transport properties of n-type and p-type thermoelements and the absolute operating temperature (T).

$$ZT = S^2\sigma/k$$

where S is the thermopower (μV/K), σ is the electrical conductivity (S/m) and *k* the thermal conductivity ($Wm^{-1}K^{-1}$). In practice, the efficiencies of thermoelectric devices are very low at ~ 5-8%. To improve upon this, significant efforts are being made to improve ZT with novel materials design in the temperature range of interest, optimizing heat transfer to/from the thermoelectric devices and device design.

2.2 Thermoelectric Materials

Today's commercial state of the art thermoelectric materials are based on bismuth telluride, Bi_2Te_3, which has ZT ~1. In principle, ZT has no upper limit and theoretical models have shown that it is possible to derive materials with ZT values of 10 [8]. For power generation applications, thermoelectric modules based on bismuth telluride and related compounds have a limited temperature range of operation before materials degradation set in. Since power generation scales with increased thermal gradient, alternative materials have been developed with higher temperature tolerances than bismuth telluride such as those based on tellurium-silver-germanium-antimony (TAGS) and lead-silver-antimony-tellurium (LAST) compounds [9, 10].

Significant efforts have also gone into designing novel materials with high ZT values; however, the highly interdependent nature of S, σ and *k* makes this a very challenging goal. Recent developments of new thermoelectric materials is being assisted through the development of new synthetic techniques such as nanostructured thin-films, quantum dot superlattices, and 1-D composites. Such new initiatives have resulted in substantial progress with ZT values as high as 2-3 being reported [11], [12], [13].

2.3 Heat Exchangers

To maximize the benefits of thermoelectric conversion, device and system losses must be minimized. For a given temperature differential, the waste heat flux density is inversely proportional to the thickness of the thermoelectric elements. Scaling thermoelectric converter devices down to very small dimensions means operating with very large heat fluxes, in the hundreds of W/cm^2. However, typical heat flux densities are usually 1-40W/cm^2, which means that it is quite difficult to minimize thermal losses for thermoelements much smaller than 5 mm to 10 mm in thickness. This situation is exacerbated where a high temperature differential is in waste heat recovery processes as most waste heat gas streams can contaminate, degrade, and corrode the surfaces of heat exchangers. For waste heat recovery applications, it is preferable when possible to design cold-side heat exchangers to operate with a liquid as the heat exchange medium. Liquids have thermal conductivities and capacities an order of magnitude higher than that of gases, which allows the cold-side heat exchanger to use proven technologies and operate as low in temperature as possible.

2.4 Thermoelectric Devices

Thermoelectric devices can be divided broadly into two categories: those based on large bulk material devices and miniature devices; the latter recently being made possible by advancements in thin-film deposition techniques and nanostructure materials development.

2.4.1 Bulk Material Devices

Generally, thermoelectric devices are made up of individual thermoelements (n-type and p-type), which are connected electrically in series but are thermally parallel to each other, see **Fig. 2.** Commercially, there are two types of thermoelectric modules available, shown in **Fig. 3**. Type A

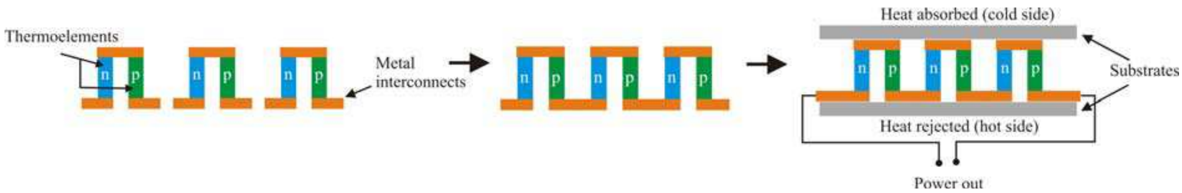

Figure 2 Illustration of thermoelectric generator module

was designed originally for cooling applications where there is significant inter-thermoelement separation. In this type of module, the n- and p-type thermoelements are connected in series by highly conducting metal strips, which are sandwiched between thermally conducting but electrically insulating plates. These have been shown to be useful for power generation at or near room temperature [14]. In the second variation, called Type B here, which is designed for power generation (for larger thermal gradients), the module is densely constructed with very small inter-thermoelement separation. In this case, the conducting metal strips are not insulated and the module cannot be attached directly to electrical conductors such as an aluminum heat sink.

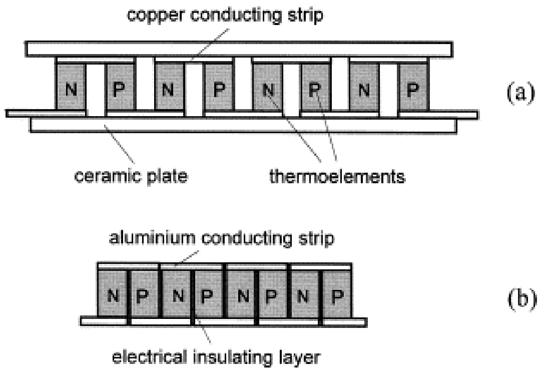

Figure 3 Schematic diagrams of thermoelectric modules. (a) Type A and (b) Type B configuration

For any given thermoelectric material, there is a maximum figure of merit that can be achieved at a specific temperature. Consequently, over a given temperature range, the majority of the thermoelement material operates below its potential maximum performance. To overcome this, several strategies can be undertaken to maximize its efficiency over a wider temperature range. For example, *functionally graded* materials can be used where the materials are prepared with varying carrier concentrations along the length of the thermoelement; this optimizes the figure of merit at each point along the operating temperature gradient supplied. Such functionally graded materials can be prepared by the Bridgman method, which is used to grow ingots from a molten solid [15] and has been successfully used to prepare p-type bismuth telluride and related materials [16]. The preparation of n-type materials by this method, however, is not useful since the thermoelectric properties along the length of the pulled ingot vary insignificantly.

In such a case, *segmentation and cascading* strategies may be used. In *segmentation*, two or more materials, each with their own figure of merit optimized for a different temperature range and are joined (segmented) together, see **Fig. 4.** Doing this ensures that the each segmented material operates within their most efficient temperature range. In practice, however, choosing thermoelectric materials that are compatible with each other presents a significant challenge in increasing the device efficiency and much consideration must be undertaken to ensure optimized matching [17, 18].

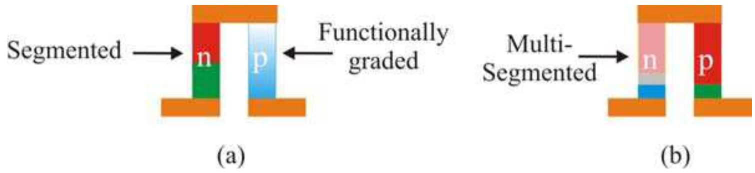

Figure 4 (a) Functionally graded and segmented and (b) multi-segmented

The compatibility issues associated with segmenting can be avoided with the use of cascading thermoelectric generators. Cascading is a well-known technique for maximizing cooling potential by widening the temperature range across the device; however, it can also be used for power generation. While this is known to achieve higher efficiencies, it is more challenging to implement than segmentation. In practice, cascading occurs when multiple modules are stacked onto each other in a pyramidal or piggy-back manner; see **Fig. 5(a).** The first module of the 'cascade' serves as a low temperature heat sink for the second module and so on, thus widening the maximum temperature range. Alternatively, an integrated design [18] is shown in **Fig. 4 (b).**

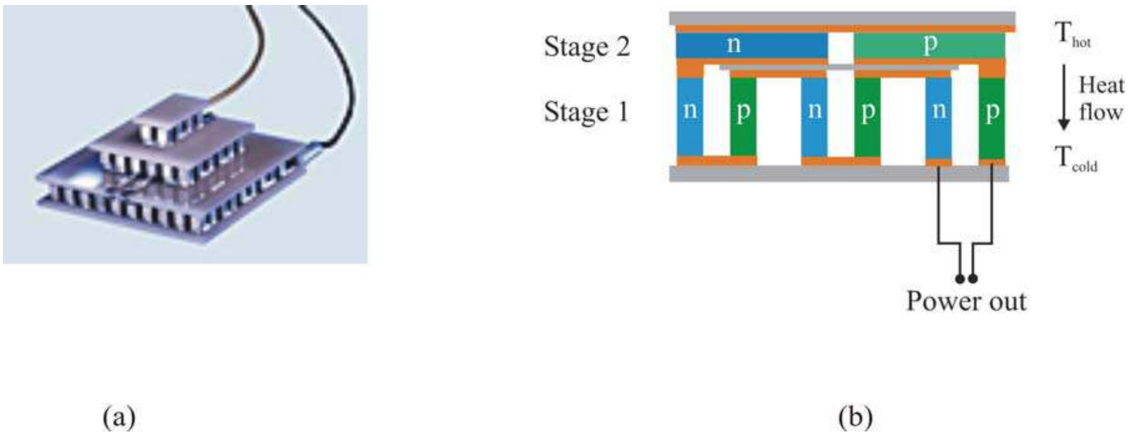

Figure 5 Cascaded thermoelectric devices (a) piggy back and (b) integrated design

2.4.2 Miniature Thermoelectric Devices

Compared to the large bulk thermoelectric modules, thin-film thermoelectric devices for power generation operate over much smaller power ranges from µW to mW and are suited for miniaturization. Such small devices can take advantage of harvesting energy from waste heat generated from natural sources, e.g. human body heat, and have been demonstrated with the realization of a thermoelectric watch by Seiko in 1998 [19]. Up until this point, watches powered by solar energy or by kinetic energy drawn from the motion of the arm had already been developed and commercialized. It was only through advancements made in the miniaturization of the thermoelements by electromachining that it became possible to fabricate a miniature thermoelectric generator. To provide an effective temperature difference to the thermoelectric device used in the watch, the back lid of the watch received heat from the user's arm as the hot-side while the case emitted heat efficiently from the back lid as the low-temperature end with a temperature difference of ~1 - 3 ^{o}C, which generated ~ 1.5 μW of power.

Since then, the emergence of small thermoelectric devices has been further advanced by thin film deposition techniques such as chemical vapour deposition and sputtering. These techniques have yielded superlattices, which are highly anisotropic in nature, with high ZT-values of ~3 due to quantum size effects[11]. In addition to these high ZT materials, the manner in which these thin-films are integrated into the device influences the overall efficiency. In the case of polycrystalline anisotropic materials, the average Z values along each direction of the converter are the same due to the random orientation of each crystallite. Therefore, in the final device, the temperature gradient can be applied parallel or perpendicular relative to the substrate without efficiency losses due to already averaged ZT values, see **Fig. 6(a)**. Above average ZT-values can be maximized by depositing highly anisotropic crystalline material in specific orientations relative to the substrate. Consequently, one can obtain either *cross-* or *in-plane* designs. In the *cross*-plane design, the high ZT direction is considered to be perpendicular to the substrate while for the *in*-plane design, the high ZT direction is parallel to the substrate. As such, the application of the thermal gradient becomes very specific; the external temperature gradient must be perpendicular or parallel to the high ZT direction to achieve optimum device performance, see **Fig. 6(b) and (c).** Compared to bulk materials, cross-plane thin film devices require very high heat flux densities to generate significant temperature differentials, while in-plane thin film devices are extremely sensitive to thermal shorting from supporting substrates and insulation packaging.

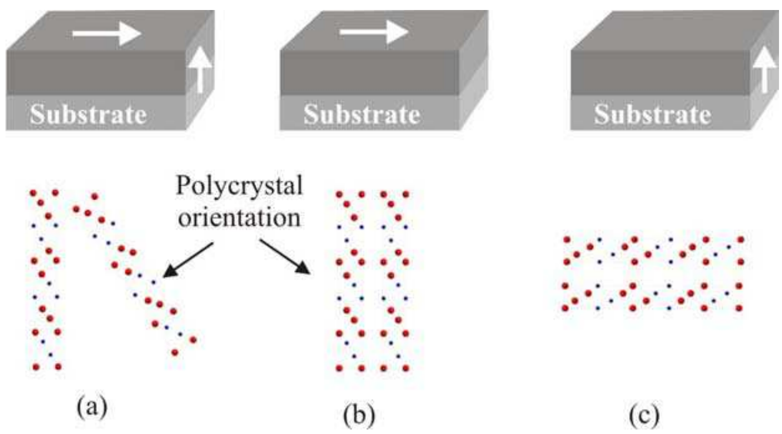

Figure 6 Illustration of (a) polycrystalline materials oriented randomly; highly oriented crystalline materials with high Z direction oriented (b) parallel and (c) perpendicular to the substrate. Arrows indicate temperature gradient direction.

3 Commercially Available Generators State of the Art

3.1 Bulk Materials Devices

There are literally dozens of companies, which provide thermoelectric modules for cooling applications, while few offer power generating thermoelectric modules. Modules tend to be large and thick and are generally based on or are related to bismuth telluride, which constrains them to a relatively narrow thermal gradient of a couple hundred degrees or less.

3.1.1 Hi-Z Technologies

Founded in 1988, Hi-Z is a small research and development-oriented thermoelectric company, which designs, develops, manufactures, and markets bulk material thermoelectric modules and generator systems. In 2002, Hi-Z were developing thermoelectric generators (from 300 mW to 20W) with combustion heat sources for the US Army, TACOM-ARDEC, for battery replacement in the field and for powering lightweight portable battery chargers. Their modules range in size from mW to multiple kW in power output. Hi-Z uses a patented egg-crate design for their modules, which provides insulated spaces for a large number of n- and p-type thermoelements, see **Fig. 7**. The absence of gaps in the walls of the spaces virtually removes the possibility of interwall shorts between the elements. Their smaller power generating modules (2.5 W to 13 W) are summarized in **Table 1** [20]**.**

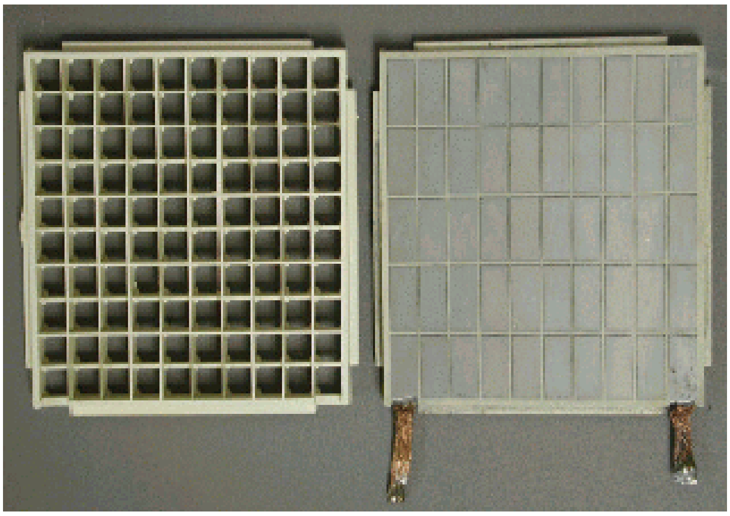

Figure 7 Hi-Z egg-crate thermoeletric module design

Table 1 Technical Specifications of Hi-Z thermoelectric modules for power generation.

	HZ-2	HZ-9	HZ-14	HZ-20
Electrical Properties (As a generator)				
Power** (W)	2.5	9	13	19
Load Voltage (V)	3.3	3.28	1.65	2.38
Internal Resistance (Ω)	4.0	1.15	0.15	0.3
Current (A)	0.8	2.9	8	8
Open Circuit Voltage (V)	6.53	6.5	3.5	5.0
Efficiency (%)	4.5	4.5	4.5	4.5
Thermal Properties				
Design hot Side T (^oC)	230	230	230	230
Design cold Side T (^oC)	30	30	30	30
Max. continuous T (^oC)	250	250	250	250
Min. continuous T (^oC)	-	-		
Max. intermittent T (^oC)	400	400	400	400
Thermal Conductivity* ($Wcm^{-1}K^{-1}$)	0.024	0.018	0.024	0.024
Heat Flux (Wcm^{-2})*	9.54	5.52	9.54	9.54
Physical Properties				
Width x Length (cm)	2.9	6.27	6.27	7.5
Thickness (cm)	.508	0.651	0.508	0.508
Weight (g)	13.5	105	82	115
Compressive Yield Stress (MPa)	20	70	70	70
Number of Active couples	97	97	49	71

*At design temperatures; ** At matched load

3.1.2 Tellurex

Tellurex is considered to be the world's leading manufacturer of high performance thermoelectric modules for solid-state cooling and electric power generation with their patented Z-Max© module. This company is involved in a partnership of universities and the Office of Naval Research to develop super-efficient nanomaterials for thermoelectric applications. Their smaller power generating modules range from ~ 1W to 7W, see **Table 2** [21].

3.1.3 Marlow Industries

Marlow Industries is also a large producer of thermoelectric modules and value-added systems for the aerospace, defence, medical, industrial, automotive, power generation and telecommunications markets. Their power generating modules range from ~3W-6W, see **Table 3** [22].

Table 2 Technical Specifications of Tellurex thermoelectric modules for power generation.

Product No.	Length (mm)	Width (mm)	Height (mm)	Max Temp (°C)	T-hot (°C)	T-cold (°C)	Power @ ΔT 100(°C)	V(dc)
G2-30-0313	30	30	3.3	260	150	50	1.3	2.6
G1-34-0315	34	31	3.3	175	150	50	1.5	2.8
G2-35-0315	35	35	3.85	260	150	50	1.5	2.6
G1-40-0322	40	40	3.7	175	150	50	2.25	2.8
G2-40-0313	40	40	4	260	150	50	1.3	2.6
G2-40-0329	40	40	3.5	260	150	50	2.9	2.6
G1-44-0333	44	40	3.2	175	150	50	3.3	2.8
G1-54-0557	54	49	3.2	175	150	50	5.7	4.8
G2-56-0352	56	56	5.1	260	150	50	5.2	2.6
G2-56-0375	56	56	4.3	260	150	50	7.5	2.6
G2-56-0570	56	56	4	260	150	50	7	5

Table 3 Technical Specifications of Marlow thermoelectric modules for power generation.

Product No.	Width (mm)	Length (mm)	Height (mm)	Max. Temp (°C)	T-hot (°C)	T-cold (°C)	P (W)	V_{OC} (V)
TG-12-4-01L	29.97	34.04	3.43	250	230	50	4.05	9.45
TG 12-6-01L	40.13	44.70	4.01	250	230	50.0	6.16	9.51
TG 12-8-01L	40.13	44.70	3.63	250	230	50.0	7.95	9.43
TG 12-2.5-1L	29.97	34.04	4.04	250	230	50.0	2.71	9.56

3.2 Miniature Thermoelectric Devices

Compared to the bulk materials device manufacturers, there are essentially three companies involved in the development of miniature thermoelectric devices. They are considered to be relatively young companies, still early in the research and development of miniature devices although Nextreme Thermal Solutions offer their products commercially.

3.2.1 Nextreme Thermal Solutions

Nextreme designs and manufactures micro-scale thermal and power management products that overcome thermal and power constraints in electronics for applications in support of products for the telecomunications, consumer, test and measurement, industrial, automotive and government/aerospace markets. The company has patented thin-film embedded cooling technology and power generation capabilities that have been incorporated into the widely accepted copper pillar bumping process used in high-volume electronic packaging [23].

Nextreme has a unique advantage over other thermoelectric device manufacturers in that its devices use extremely thin (~5-15 µm) thermoelectric materials. These small values allows for exceptionally high heat fluxes and low thermal resistances. As a result, commercially, Nextreme has produced a high power density thermoelectric generator with a very thin, lightweight form factor producing >90mW at ΔT of 70°C and >260mW at ΔT of 120°C. With modules measuring ~ 1.6mm x 3.2mm, the TEG has an output power density of ~ 5W/cm^2.

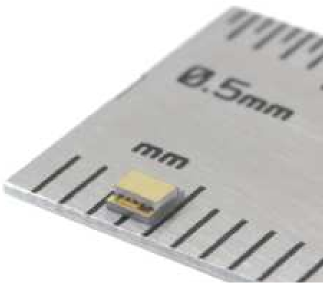

Figure 8 Image of Nextreme Power Generation module eTEG HV14.

3.2.2 Micr^{O}pelt GmbH

Micr^{O}pelt GmbH started as a project of Infineon Technologies AG in cooperation with the Fraunhofer Institute for Physical measurement Techniques (Fraunhofer IPM) in Freiburg (Germany). Micr^{O}pelt utilizes planar technologies with silicon wafer substrates. Their targeted markets are: chip spot cooling, biomedical, HVAC (heating, ventilation and cooling), fibre optics and energy harvesting for low power applications [24].

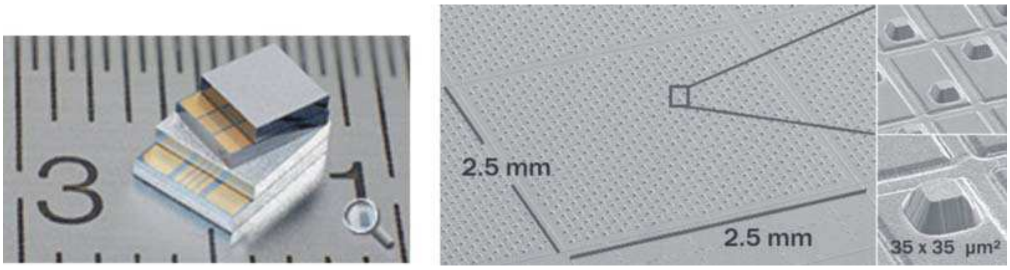

Figure 9 Microfabricated thermoelectric elements showing thermoelectric legs on Si wafer (right).

Unlike the rest of the thermoelectric device manufacturers, Micr^{O}pelt has gone a step ahead to develop some novel products for power generation such as the TE-Power Bolt, TE-Power Clamp and TE-Power Ring. These products highlight some novel applications for thermoelectric power generation and are available as evaluation kits at this time.

The TE-Power Bolt is intended for use as a remote power supply for wireless and remote sensors, data loggers and other low power devices, see **Fig. 10**. A few mW of continuous power can be made available from many warm or hot surfaces of industrial machinery or process equipment.

Figure 10 TE-Power Bolt from Micr^{O}pelt.

Micr^{O}pelt's TE-Power Clamp was designed to attach to the flow and return pipes of any radiator. Since these two pipes have a temperature difference by design they represent a reliable thermal power harvesting source (as long as in operation), see **Fig. 11.** The clamp produces `18mW @ 4.5 V with a temperature gradient of 70^{o}C. Finally, the TE-Power Ring is a battery-less maintenance-free wireless bearing conditioning monitoring system. The Power Ring converts the bearing's friction heat (or any other waste heat) into electrical energy to supply a wireless sensor node.

Figure 11 TE-Power Clamp (left) and Ring (right) from Micr^{O}pelt.

4 Summary and Conclusions

This Technical Memorandum provides an overview of thermoelectric devices for military and solider power applications and their state of development in support of the ASAP Technology Demonstration Project. Thermoelectric power generation has the potential to reduce the logistical burden of fuel transport to and from the battlefield by taking advantage of converting heat into useable power through energy harvesting or waste heat recovery. The technology offers proven reliability, quietness, scalability and modularity. The vast majority of commercial thermoelectric devices are used primarily for cooling applications; however, significant efforts in power generation are being made in the realms of materials and design development. For the sub-10W power range, bulk thermoelectric modules are available commercially. While the technology readiness levels of such thermoelectric modules are high (TRL 9), their adoption for practical use have been limited due to their overall low efficiencies. Advancements are being made in miniaturized thermoelectric devices, particularly those based on thin-films, which offer smaller footprints and, thus, higher power densities. However, their technology readiness levels are lower (TRL 5-6) than their bulk material counterparts. Furthermore, it is clear that while thermoelectric modules are available commercially, their utilization requires very highly customized solutions, which begins with suitable material choices for the desired temperature range of operation, heat transfer to/from the device, and device design. Given these challenges, however, thermoelectric power generation remain a consideration for future requirements given the steady advancements being made and past historical successes as reliable power sources.

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A literature survey and web-based search was undertaken to assess current state of the art thermoelectric devices for power generation in the sub-10W range to support of the Advanced Soldier Adaptive Power Technology Demonstration Project currently underway at DRDC. Thermoelectric power generation can afford reduced logistical burdens of fuel transport, which can lead to lower costs and personnel risks on the battlefield. At present, overall thermal to electric efficiencies are low at 5-8%, however, steady advancements are being made in the development of novel materials and miniaturized device designs, which may one day enable their practical use.

On a effectué un survol de la littérature et une recherche sur Internet pour évaluer l'état actuel de la technologie des dispositifs thermoélectriques utilisés pour la production d'électricité de puissance inférieure à 10 W à l'appui du projet de démonstration de la technologie des sources d'alimentation de pointe pour le soldat (ASAP) en cours d'exécution à RDDC. La production d'énergie thermoélectrique peut réduire le fardeau logistique de transport de carburant, ce qui peut donner lieu à des frais réduits et à des risques moindres pour le personnel sur le champ de bataille. À l'heure actuelle, l'efficacité globale de la conversion thermique-électrique est faible : 5-8 %. Cependant, on assiste à des progrès continuels dans le développement de nouveaux matériaux et de conceptions de dispositifs miniaturisés, qui peuvent un jour permettre l'utilisation pratique de ces dispositifs.

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