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ADVANCED WASTE HEAT RECOVERY TECHNOLOGY BY THERMO-RADIATIVE CELL FOR NUCLEAR SPACE POWER APPLICATIONS

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In order to satisfy the long-lasting and high energy/power density requirements for NASA deep space exploration missions, Pu-238 has been identified as one of the most suitable radioisotope fuels for GPHS modules since the 1960s. The availability of Pu-238 is currently extremely limited. The limited availability suggests that efficiently using the heat generated by the GPHS is very important and critical for NASA space applications. However, the efficiency of the most widely used radioisotope thermoelectric generators is only about 6-8%, which means that a significant amount of energy is dissipated as waste heat via radiators such as metallic fins. In deep space, the extremely cold universe (3 K) provides a robust heat sink. Even for a heat source with a temperature below 373 K, the corresponding Carnot efficiency can be more than 99%. In this paper, we show a proof-of-concept demonstration of using a thermo-radiative cell, a new technology concept conceived in 2015, to convert heat to electricity. A reversed I-V characteristic between thermo-radiative cell and photovoltaic cell is also experimentally demonstrated for the first time. The predicted efficiency of thermo-radiative cells is significantly higher than thermoelectrics at peak power output, and can be even higher at reduced power output. Integrating thermo-radiative cells with radio-isotope heating units (high-grade heat) or radioisotope power system (RPS) radiators (low-grade waste heat) could provide a new way to significantly increase the energy efficiency of Pu-238 or other radioisotope fuels.

I. INTRODUCTION

Traditionally, there are two classes of thermal-to-electrical energy conversion systems: static and dynamic. The key benefit of static thermal-to-electrical energy conversion systems, like thermoelectrics, thermophoto-voltaics, and thermionics, is that no moving parts are involved in the system. Dynamic thermal-to-electrical energy conversion systems, like Stirling, Brayton and Rankine cycle engines, involve repetitive motion of moving parts containing various working fluids. The operation of these thermal-to-electrical energy conversion systems in deep space requires a high temperature heat source which is usually supplied by General Purpose Heat Source (GPHS) modules. In order to satisfy the long-lasting and high energy/power density requirements for the deep space exploration missions, Pu-238 has been identified as the most suitable radioisotope fuel for GPHS modules since the 1960s [1].

However, the bulk production of Pu-238 in the US was stopped in 1988. Although DOE is expected to be able to produce 1.5 kg Pu-238 per year by 2026 for NASA, there are still many uncertainties, and DOE is facing many challenges to meet this production goal. In addition, due to the highly technical nature of the Pu-238 production process and the long time required (~2 years) for technical staff training, the unit price of Pu-238 is very high, ~$8 million per kilogram [2,3]. NASA's budget can only support one radioisotope power system (RPS) mission every 4 years [3]. The extremely limited availability and high cost of Pu-238 suggest that efficiently using the heat generated by the GPHS is very important and critical for NASA space applications. However, the efficiency of multi-mission radioisotope thermoelectric generator, which is a thermoelectric RPS, is only about 6%. Even though the dynamic thermal-to-electrical energy conversion systems (e.g. Stirling RPS) can achieve 25% or even higher efficiency, there is still a significant amount of energy dissipated as wasted heat via radiators such as metallic fins. Harvesting energy from this waste heat not only improves the total energy utilization efficiency of GPHS, but also significantly reduces the mass of the required RPS.

For any thermodynamic energy conversion system, from ideal Carnot heat engine to photovoltaics, thermophotovoltaics, thermionics, or thermoelectrics, there must be a high temperature heat source and a low temperature heat sink. The heat source temperature ranges from 800-1200 K in thermoelectrics to near 5800 K in photovoltaics. The high temperature in these heat sources is necessary due to the relatively high temperature heat sinks (~300-500 K) used in these energy converters since larger temperature differences between the heat source and heat sink usually give higher energy conversion efficiency. In deep space, the extremely cold background temperature of around 3 K provides a robust heat sink. Even for a waste heat source with a temperature below 373 K, the corresponding Carnot efficiency can be more than 99%. Here we are imagining an energy converter that can convert part of the waste heat from the primary convertors to electricity and dump the rest of the waste heat into deep space by radiation (the only choice to reject heat in this deep space). Such a device belongs to the general emissive energy harvester (EEH) which was proposed by Byrnes et al. in 2014 [4]. The EEH is a device that has high emissivity in the "atmospheric window" at 8-13 μm and low emissivity for other wavelengths. Since the atmosphere is almost transparent for radiation wavelengths between 8 µm and 13 µm, the earth's surface temperature is 275-300 K and the outer space temperature is only 3 K, so the EEH (at the earth's ambient temperature) will emit far more thermal radiation than it receives from the outer space. The imbalance of the emitted and the absorbed thermal radiation can be converted into an imbalance of charge carrier motion in the EEH, i.e., generating electricity (Fig. 1).

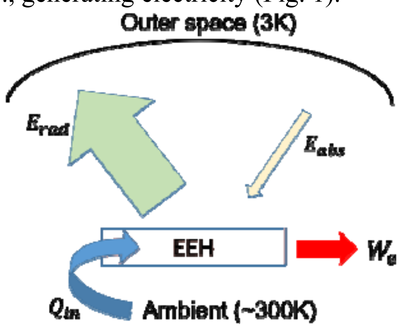

Fig. 1. Principle of emissive energy harvester (EEH).

Based on the general EEH idea, Strandberg [5] proposed a new technology concept, termed the thermo-radiative (TR) cell, to convert heat into electricity and reject the unused heat via thermal radiation. The thermo-radiative cell is essentially made of semiconductor P-N junctions and operated at an elevated temperature (325 K to 475 K, or even higher temperature depends on the accessible waste heat source temperature) compared to its surroundings (3-150 K in cold universe). It is well-known that P-N junctions are widely used in photovoltaic (PV) cells to convert solar radiation energy to electric power. In a photovoltaic cell, since the solar surface temperature is much higher than the cell temperature, more photons are absorbed by the PV cell than emitted by the PV cell. In a thermo-radiative cell, the surrounding temperature is lower than the cell temperature, thus the generated voltage has an opposite sign to the photovoltaic cell. When the device is connected with a load, the current direction in the thermo-radiative cell is also opposite to that of a photovoltaic cell (Fig. 2).

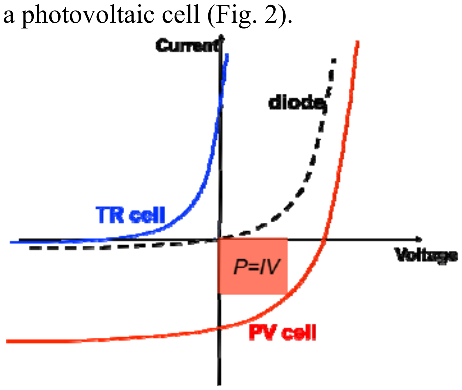

Fig. 2. The voltage and current directions in PV and TR cells are opposite. Both can generate power (P=IV <0).

II. THEORETICAL PREDICTION OF THERMO-RADIATIVE CELL PERFORMANCE

Power density and energy efficiency are the two most important parameters for any power generation devices. For deep space applications, the heat sink temperature can vary from 3 K (when the TR cell faces the deep space) to 100-150 K (when the TR cell faces some cold planets or their satellites). The power density of the thermo-radiative cell increases with the heat source temperature. The efficiency of the thermo-radiative cell varies with the cell voltage or the power density. The efficiency of the thermo-radiative cell can be analyzed by the principle of detailed balance [6-8], which was used to derive the famous Shockley-Queisser limit for photovoltaic cell.

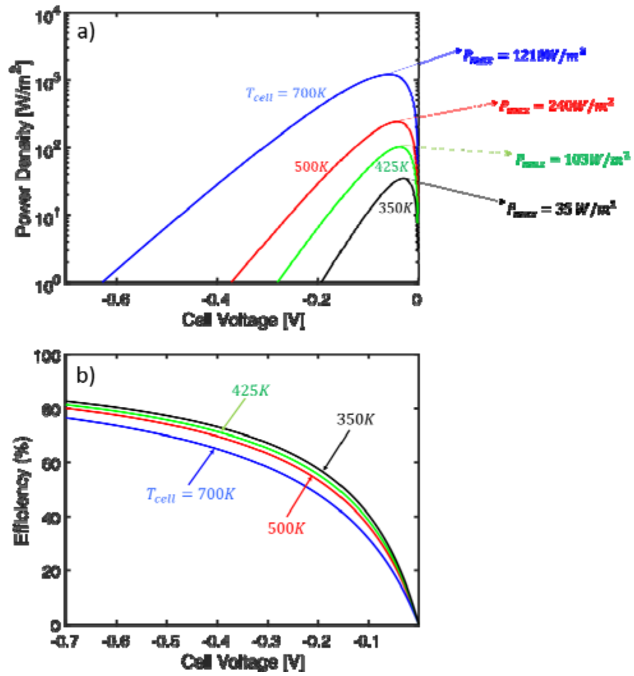

Fig. 3. (a) Power density and (b) Efficiency of the TR cell as a function of cell voltage at different temperatures.

Assuming a thermo-radiative cell with a bandgap 0.1 eV, its output power density and efficiency at different temperatures are calculated and shown in Fig. 3. The peak power density ranges from several tens of Watts per square meter (at 350 K) to over one thousand Watts per square meter (at 700 K) (Fig. 3a). For thermo-radiative cells operating at 500 K (near the low-grade waste heat upper limit), the generated electrical power density is on the same order of magnitude as photovoltaic cells. When the cell temperature reaches 700 K (medium-grade waste heat), the generated power density is several times higher than the state-of-the-art power density achieved in photovoltaic cells. The generated electricity could be used to supply power for the power electronics on spacecraft. Although the thermo-radiative cell efficiency increases with the magnitude of the cell voltage (Fig. 3b), the power density generated at those very large efficiency ranges (e.g., >50%) is low, except when the thermo-radiative cell is operated at relatively higher temperature (e.g., 700 K). Therefore, the efficiency near those peak power outputs is more useful (10%-35%). For low-grade waste heat recovery, the efficiency at peak power output is above 12%, which is significantly higher than the 6-8% efficiency of state-of-the-art thermoelectric RPS.

III. EXPERIMENTAL DEMONSTRATION

III.A. Thermo-Radiative Cell System Setup

For NASA space applications, the extremely cold universe (3 K) will serve as the heat sink for the TR cell energy conversion process. However, achieving such low temperature is difficult and requires expensive equipment. For terrestrial proof-of-concept demonstration, liquid nitrogen-based heat sink is chosen to mimic the cold universe. The radiation power from a black surface is proportional to the 4th power of temperature. For a heat sink at either 77 K or 3 K and a thermo-radiative cell at a temperature of low-grade waste heat, the net outgoing radiation (emitted minus absorbed) power from the TR cell surface is almost same for both cases. Therefore, it is accurate enough to mimic the cold universe heat sink with liquid nitrogen-base cryogenic system. The TR cell is kept near room temperature or mildly heated to a temperature corresponding to the typical low-grade waste heat temperature (less than 100°C).

The thermo-radiative cell performs best with low bandgap semiconductors. There are a few good semi-conductor candidates that are commercially available and suitable for working as thermo-radiative cells for low-grade waste heat recovery. These candidates are InSb, $Hg_{1-x}Cd_xTe$, and $InAs_{1-x}Sb_x$, with appropriate x. Usually semiconductor bandgap decreases with temperature. Therefore, for high temperature operation, there are more semiconductor choices (e.g., InAs). HgCdTe commercial photodiode has been selected as the thermo-radiative cell in this demonstration, due to its wide tunable bandgap range and commercial availability.

The HgCdTe photodiode we used is covered with an immersion lens, so that the field of view (FOV) can be controlled. We placed a planar cold plate (liquid nitrogen cooled) at a finite distance from the cell and ensure that cold plate surface completely covers the FOV of the HgCdTe thermo-radiative cell. The cold plate is made of aluminum with embedded copper tubes. Liquid nitrogen flows through the copper tubes to maintain the aluminum plate surface at low temperature. The surface temperature is adjustable from room temperature down to around 77 K. The surface temperature is controlled by the flow rate of the liquid nitrogen in the copper tube. An ultra-black foil is covered on the top surface of the cold plate. It aims to minimize the reflections from the environment to the thermo-radiative cell since it has very low reflectance from visible light to long-wavelength infrared (LWIR).

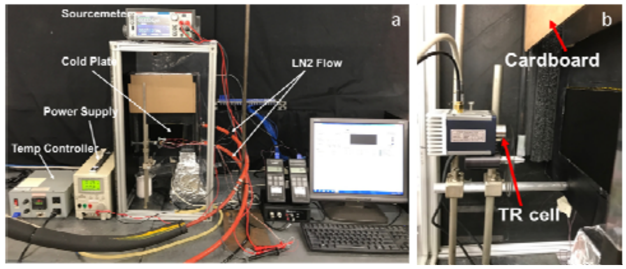

Fig. 4. (a) Experimental setup. (b) Side view of TR cell.

Fig. 4 shows the integrated thermo-radiative cell measure-ment system. During the measurements, a cardboard sheet is controlled manually to block/unblock the view of the thermo-radiative cell. The system is placed in a chamber during the measurement which is flowed with dry nitrogen gas to maintain a positive pressure and reduced humidity inside, which could avoid the water vapor in the ambient entering into the chamber as well as minimize the condensation on the cold plate.

III.B. TR Cell ON/OFF Response Demonstration

Initially, the cell and the cold plate are both at ambient temperature. At this point, there should be zero net radiation from the thermo-radiative cell to the cold plate. The measured output electrical signal of the thermo-radiative cell is almost zero as expected. As we continuously decrease the cold plate surface temperature by controlling the liquid nitrogen flow rate, the output electrical signal continuously increases. If we use cardboard to suddenly block the view of the cell to the cold plate, we observed that the electrical signal suddenly drops to zero. This is because the cardboard and the thermo-radiative cell are at the same temperature. In other words, the thermo-radiative cell changes from the "ON" state when it faces to the low temperature cold plate, to the "OFF" state when it suddenly faces to the ambient temperature cardboard. This ON/OFF response is clearly showed in Fig. 5.

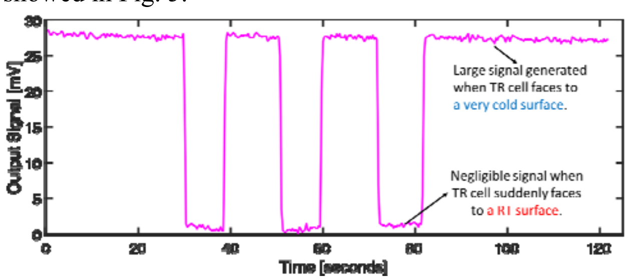

Fig. 5. A measurement curve when the cold plate is at -50C and the TR cell is at ambient temperature.

III.C. TR Cell I-V Characteristic Demonstration

We compared the I-V curves of the cell under three different conditions. Under the first condition, the cell is in thermal equilibrium with the ambient. In this case, the I-V curve passes through the origin point, i.e., when the bias V=0, the current I=0 (the blue curves in Fig. 6). The cell shows the standard p-n junction behavior under dark condition. As we heated up the cell and controlled the plate to the cryogenic temperature, the cell works in the thermo-radiative cell mode. The I-V curve moves upwards from the thermal equilibrium curve, i.e., when the bias V = 0, the short-circuit current is positive (the black curves in Fig. 6). When we kept the cell at ambient temperature and heated up the plate temperature, the cell works in the (thermo-)photovoltaic mode. The I-V curve moves downwards from the thermal equilibrium curve, i.e., when the bias V = 0, the short-circuit current is negative (the red curves in Fig. 6).

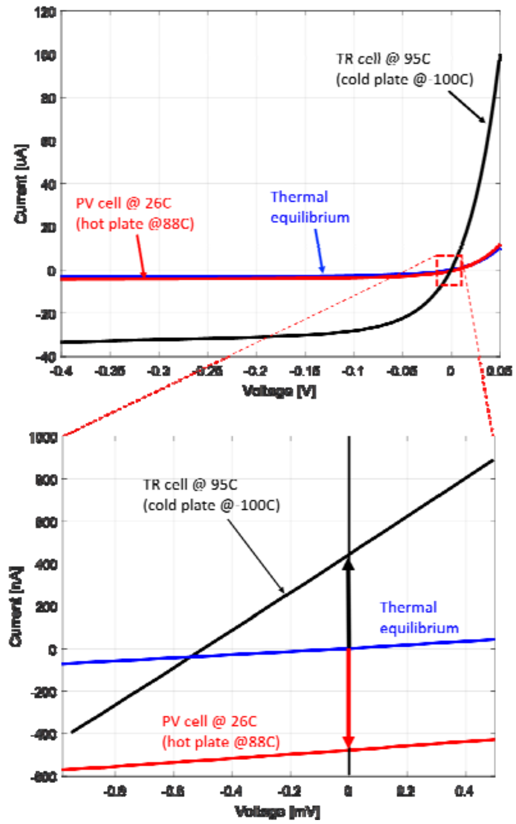

Fig. 6. I-V measurement of the cell under three conditions: PV mode, TR mode, and thermal equilibrium.

To the best of our knowledge, this is the first experimental demonstration of the reversed current-voltage characteristics between a thermo-radiative cell and a photovoltaic cell. The demonstration clearly indicates the feasibility of using thermo-radiative cells for power generation. For example, we can integrate thermo-radiative cells with RPS radiators to harvest the low-grade waste heat, i.e., providing additional electric power for RPS.

IV. CONCLUSIONS

In summary, thermo-radiative cell is a new waste heat recovery technology that is extremely suitable for space power applications. Usually it is difficult to harvest energy from low-grade waste heat since the temperature difference between the terrestrial ambient and low-grade waste heat is small, and the heat dissipation at low temperature is more difficult. However, in deep space, since thermo-radiative cell can easily make use of the cold universe as the heat sink (3 K to 150 K), it makes low-grade waste heat recovery much easier. In addition, it is passive with no moving parts, and does not require maintenance. It could potentially serve as an easy add-on to the radiator panels without changing the current RPS design. The predicted efficiency of thermo-radiative cells is significantly higher than thermoelectrics at peak power output, and can be even higher at reduced power output. Integrating thermo-radiative cells with radioisotope heating units or radioisotope power system radiators could provide a new way to increase the energy efficiency of Pu-238 or other radioisotope fuels. To the best of our knowledge, the reverse current-voltage characteristics between thermo-radiative cell and photovoltaic cell are experimentally demonstrated for the first time.

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