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Emittance Measurements Relevant to a 250 W_t Class RTPV Generator for Space Exploration

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Abstract

A proposed 250 W_t Radioisotope Thermophotovoltaic (RTPV) power system for utilization in lunar exploration and the subsequent exploration of Mars is described. Details of emitter selection are outlined for use in a maintenance free power supply that is productive over a 14-year mission life. Thorough knowledge of a material's spectral emittance is essential for accurate modeling of the RTPV system. While sometimes treated as a surface effect, emittance involves radiation from within a material. This creates a complex thermal gradient which is a combination of conductive and radiative heat transfer mechanisms. Emittance data available in the literature is a valuable resource but it is particular to the test sample's physical characteristics and the test environment. Considerations for making spectral emittance measurements relevant to RTPV development are discussed. Measured spectral emittance data of refractory emitter materials is given. Planned measurement system modifications to improve relevance to the current project are presented.

Introduction

NASA and Creare Incorporated of Hanover, New Hampshire are currently engaged in a technology development program of an RTPV power system to be used in lunar exploration missions and the subsequent exploration of Mars. This effort follows prior work by Orbital Sciences Corporation (Ref. 1) and others. Table 1 contains performance details for both the beginning and end (B.O.M. and E.O.M.) of a 10-year mission life. Mass estimates are given for single and dual General Purpose Heat Source (GPHS) configurations. Figure 1 shows an exploded view of the configuration of interest with component parts labeled. The energy source for this configuration is a single GPHS containing plutonia fuel with a B.O.M. thermal output of 250 W.

The efficient conversion of emitted radiation is highly dependent on the temperature of the emitter. This is a combined effect of the T^4 increase in radiated power (Stefan-Boltzmann law) and a spectral shift towards higher energies as temperature increases (Wien's displacement law). To obtain the maximum efficiency the emitter temperature should be as high as possible. The planned operating temperature for the GPHS module is 1350 K. At this temperature the choice of materials that will not sublimate to cooler surfaces over long time periods is limited. It is desirable that the spectral power reaching the PV array is high for convertible photon energies, $E > E_g$, where E_g is the PV cell bandgap energy. However for the proposed power system, emitter spectral efficiency is secondary to low vapor pressure since evaporation of emitter material on to the cold PV array limits the lifetime of the system.

Emittance Measurement

Emittance involves radiation from within a material and so becomes more difficult to quantify as the thermal gradient through the material increases (Ref. 2). The emittance data available in the literature is particular to the test sample characteristics and the test environment. The surface quality, material and thermal gradient of the test article must be known to determine if the data can be appropriately applied to a model.

An opaque object's spectral reflectance when measured at an isotropic temperature can be used to determine spectral emittance by Kirchhoff's Law (Ref. 3), $\varepsilon_\lambda = \alpha_\lambda$ where ε_λ = spectral emittance, α_λ = spectral absorptance. For conservation of energy, $\alpha_\lambda + \rho_\lambda + \tau_\lambda = 1$ where ρ_λ = spectral reflectance and τ_λ = spectral transmittance. Therefore, since $\tau_\lambda = 0$ for an opaque object, $\varepsilon_\lambda = (1 - \rho_\lambda)$. This property is often considered intrinsic because the same material will exhibit the same spectral emittance regardless of thickness as long as it is opaque and of the same composition, temperature and surface geometry. However, if the temperature is not isotropic then the spectral emittance will depend on the temperature change through the material.

TABLE 1.—PERFORMANCE COMPARISON OF SINGLE AND DOUBLE GPHS CONVERTERS AT 15 AND 20 PERCENT EFFICIENCIES
[Mass estimates are conservative, engineering driven improvements are anticipated.]

	Dual GPHS[a]	Single GPHS	Notes
GPHS mass	3.212	1.606	kg
Converter mass	3.725	2.75	kg
Waste heat radiator mass	4.500	2.425	kg
Total mass	11.440	6.781	kg
Mass specific power at 15% η	6.56	5.53	W/kg
Mass specific power at 20% η	8.74	7.37	W/kg
Power output BOM at 15% η	75.00	37.50	W_e
Power output BOM at 20% η	100.00	50.00	W_e
Power output EOM at 15% η	60.04	30.02	W_e, with 0 material transfer, 10-year mission
Power output EOM at 20% η	80.06	40.03	W_e, with 0 material transfer, 10-year mission

[a]Dual GPHS data (Ref. 6).

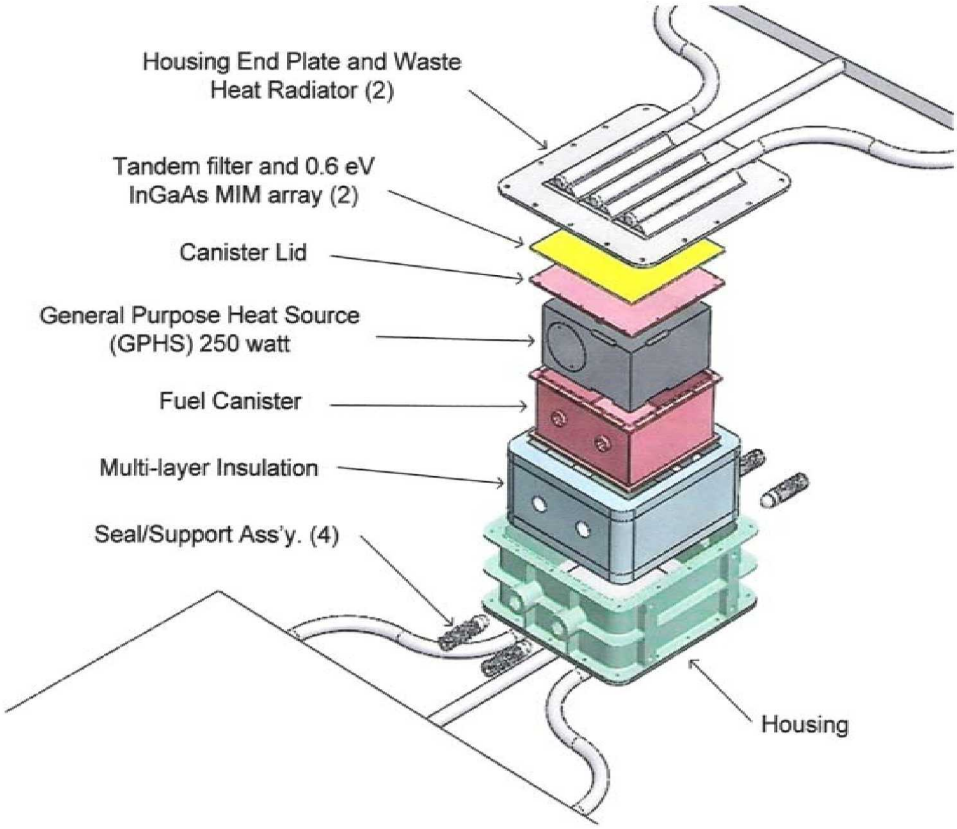

Figure 1.—Single GPHS power system, exploded view.

It would be a daunting task to equilibrate a sample at 1350 K and take an accurate reflectance measurement. Instead, a measurement is taken of the spectral emissive power originating from the hot sample and it is referenced to a calibrated blackbody. Figure 2 is a schematic of the Vacuums Emittance Measurement System (VEMS) at NASA, GRC. The system measures the normal spectral emittance, ε_n The following is the derivation for the formula used for VEMS data reduction. The spectral radiation flux per wavelength per unit area of an emitter of thickness d and the sample temperature T_s, measured by the instrument is $q_{ds}(\lambda, T_s)$. It is equal to $F\, e_S(\lambda, T_s)$, where F is a constant and $e_S(\lambda, T_s)$ is the spectral emissive power. Likewise $q_b(\lambda, T_b)$, the measured spectral radiation flux of the blackbody at temperature T_b is $F\, e_b(\lambda, T_b)$, where $e_b(\lambda, T_b)$ is the blackbody emissive power. Therefore, the constant $F = \dfrac{q_{db}(\lambda, T_b)}{e_b(\lambda, T_b)}$. Since spectral emittance is by definition the sample's spectral emissive power divided by blackbody emissive power for the same temperature, the result is the following:

$$\varepsilon_s(\lambda, T_s) \equiv \frac{e_s(\lambda, T_s)}{e_b(\lambda, T_s)} = \frac{q_{ds}(\lambda, T_s)}{F\, e_b(\lambda, T_s)} = \frac{q_{ds}(\lambda, T_s) e_b(\lambda, T_b)}{q_{db}(\lambda, T_b) e_b(\lambda, T_s)} \tag{2}$$

where (ref. 4)

$$e_b(\lambda, T_b) = \frac{2\pi h c_0^2}{\lambda^5 \left[\exp\left(\dfrac{h c_0}{\lambda k T_b} \right) - 1 \right]}$$

h Planck constant
c_0 the speed of light in a vacuum
k Boltzmann constant

Equation (1) assumes that the temperature of the sample is isotropic. Because of this there is a difficulty applying it to a thermally anisotropic sample.

Radiation that leaves the sample comes not only from the surface but from within the material. Thus, the emissive power and emittance depends on the temperature change across the material. This temperature is determined by the combined effects of thermal conduction and radiation. The temperature dependence is obtained from the solution of the following energy equation.

$$Q_{in} = -k_{th} \frac{dT}{dx} + Q_{rad(x)} \tag{2}$$

Where Q_{in} is the thermal power unit per unit area, k_{th} is the thermal conductivity and Q_{rad} is the total radiative power per unit area at position x. Equation (2) is solved for rare earth materials in Reference 5.

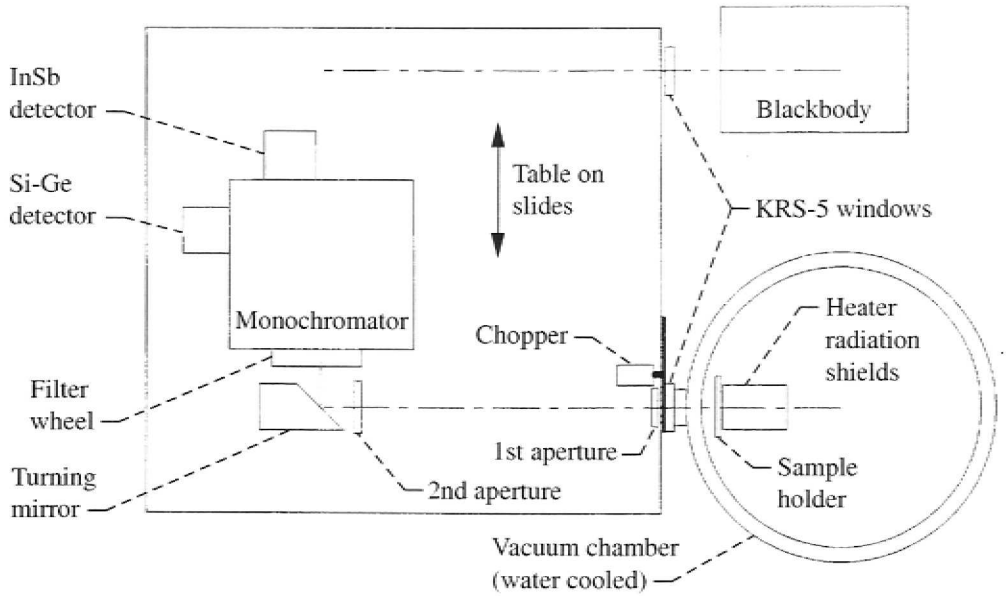

Figure 2.—Diagram of the Vacuum Emittance Measurement System (VEMS) at GRC.

Near the emitting surface the Q_{rad} term in Equation (2) will dominate and the temperature variation will be nonlinear. However, far from the surface the conduction term in Equation (2) dominates and the temperature variation will be linear.

In Reference (2) the spectral emittance is defined in terms of the temperature of the back (high temperature) side of the emitter. The spectral emittance, assuming a linear temperature variation across the emitter, a large absorptance coefficient and small ΔT (the case for most metals) is approximated by the following expression.

$$\varepsilon(\lambda, T_b) = \left[1 - R(\lambda)\right] \exp\left[\mu_s \Delta T\right] \qquad (3)$$

Where R (λ) is the spectral reflectivity, μ_S the dimensionless photonic energy = $\dfrac{hc_0}{\lambda k T_s} = \dfrac{1.439 \times 10^7 \, (K \times nm)}{\lambda T_s}$ and ΔT = the dimensionless temperature difference = $\dfrac{T_b - T_f}{T_b}$, where T_b is the back side temperature and T_f is the front side temperature.

Figure 3 shows emittance data calculated using room temperature reflectance data for two tantalum samples of different surface roughnesses. The reflectance was measured using a Perkin-Elmer λ 950 dual beam spectrometer. Surface roughness accounts for the apparent difference in measured emittances. The smoother 0.4 mm sample has the lower emittance due to an increased reflectance. Note that this measurement is a total hemispherical measurement.

Figure 4 shows VEMS measurements in addition to the corresponding 1–R curve from Figure 3. This chart illustrates the difficulty of determining emittance using formula (1). Values are shown when calculated using both the cooler front surface

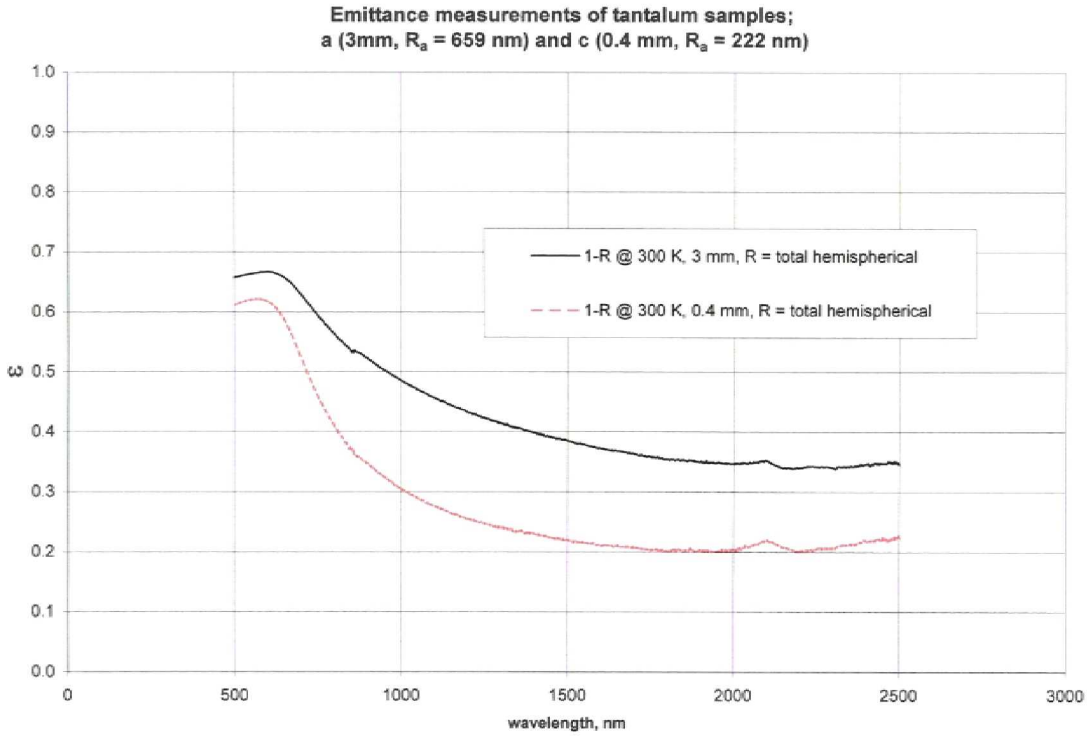

Figure 3.—ε= 1—R for two tantalum samples at 300 K, equilibrated temperature.

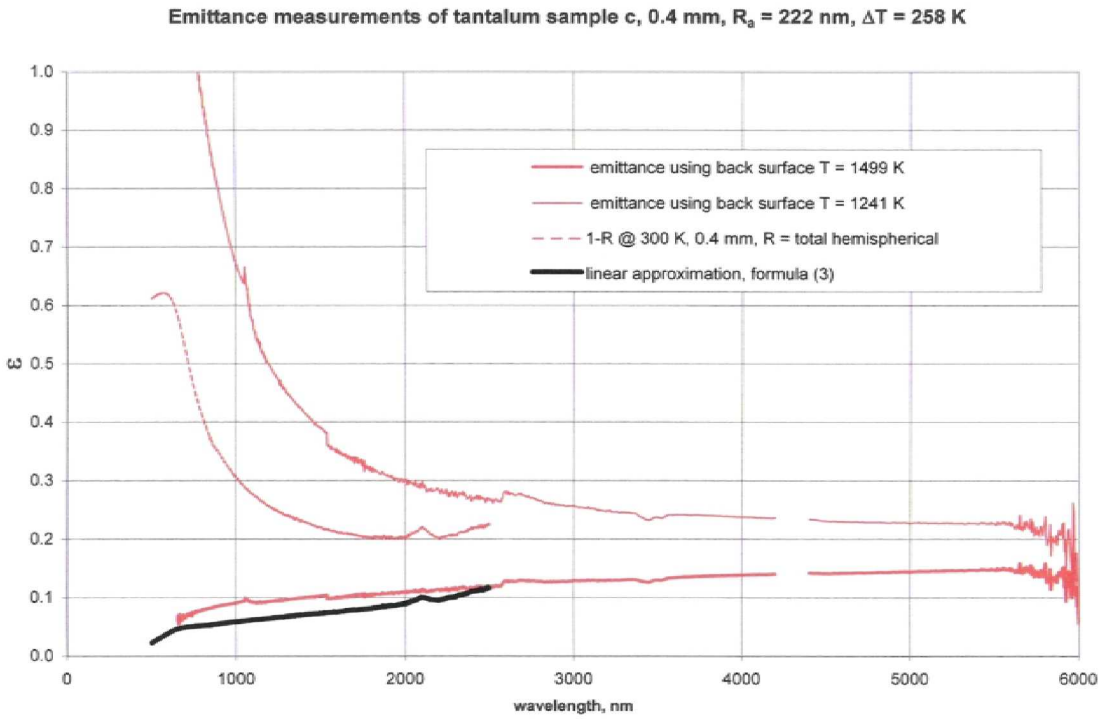

Figure 4.—Emittance data for 0.4-mm-thick tantalum sample, ΔT = 258 K.

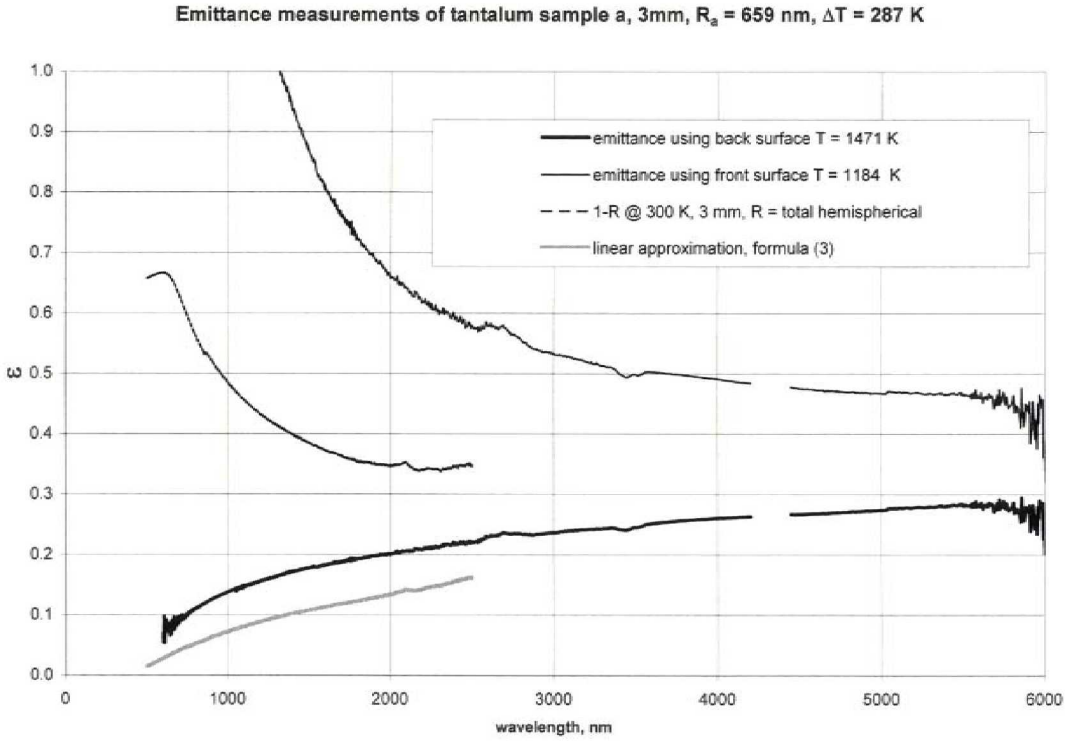

Figure 5.—Emittance data for 3-mm-thick tantalum sample, ΔT = 287 K.

temperature (top curve) and hot back surface temperature (heavy curve). Temperature measurements were made using 0.005 in. diameter C type tungsten/tungsten-rhenium thermocouples. Contact of the thermocouples to the sample was confirmed electrically by a continuity measurement between the front and back thermocouples. The back surface temperature is not appropriate because even though the metal is closest to this temperature through most of the emitter, radiative cooling dominates near the surface where the emittance takes place. The front surface temperature is an obviously inappropriate value because it produces emittances in excess of one. All emittance occurs in a thickness of approximately one micron, as can be demonstrated by the non-transmitting nature of a film of that thickness. Despite this small dimension, the outer most atoms of the metal are sufficiently cooled by radiation that they do not well represent the temperature through the emitting region. The bottom curve shown is the approximation of emittance using a linear temperature gradient only (formula 3). This curve is in fairly good agreement with emittance calculated using the back surface temperature.

Figure 5 shows the emittance data for the 3 mm thick sample. Of note is the greater difference between the emittance based on T_f and the emittance based on T_b. This corresponds to the greater ΔT across the sample. Also notice that the formula (3) approximation does not agree with the back temperature as well as with the thinner sample.

Measurement Modifications

In the optical cavity of a TPV converter, radiation is reflected back to the emitter from the filter-PV array. This radiation will heat the front surface of the emitter and thus reduce the thermal gradient across the emitter. To approximate the conditions that exist in the optical cavity of a TPV system, the VEMS facility is being modified. The objective is to measure the spectral radiation flux of the test sample through an aperture in a chilled plate, which approximates the filter-PV array. A highly polished, gold plated surface facing the emitter would reflect energy back to the sample, thereby raising the front surface temperature and lowering the ΔT across the sample. The modified instrument would be able to generate spectral radiation flux data, q_s, for a given material, ΔT and surface geometry, thereby approximating operational conditions for a configuration of interest.

Summary

A brief description is given of the goals of the NASA/ Creare RTPV power system development program.

Methods to determine the spectral emittance of system materials in order to model system energy flow are presented.

While emittance measurements are straight forward in thermally isotropic materials, it is difficult when a significant thermal gradient exists through the material of interest. Emittance occurs within a region near the radiating surface that has a severe thermal gradient created by locally dominate radiative heat transfer. Methods dependant on a single temperature value are therefore insufficient. A definition of an emittance must include the temperature variation through the material. A method to reduce temperature gradients is proposed. The spectral radiation flux of the sample, $q_S(\lambda, T)$, is measured through a plate that reflects energy back to the test sample. Thus the thermal gradient can be controlled to the anticipated RTPV conditions while $q_S(\lambda, T)$ is determined. This measurement can be achieved on a 1 to 2 day cycle time in the VEMS facility. This allows for the possibility of rapid emitter optimization.

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