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**FEASIBILITY ASSESSMENT OF LOW TEMPERATURE
VOLTAIC ENERGY CONVERSION**

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ABSTRACT

An experimental and theoretical investigation of the feasibility of thermo voltaic (TV) power generation in the temperature range 800°C - 1000°C has been performed. In this concept, voltaic cells of Indium-Gallium-Arsenide (InGaAs) were employed to convert thermal radiation directly into electric power. The advantage of this concept over previous thermo photo voltaic concepts (TPV) is the reduced materials issues associated with a lower heat source temperature, and applicability to a wider range of fossil fuels.

A numerical model was constructed and used to analyze test data, demonstrating good agreement and understanding of process physics. The key functional parameters were found to be dark current coefficient and spectral efficiency. A conversion efficiency of 25% was measured at 900°C, with potential for 30% in optimized devices. The limiting issue for a practical TV power converter below 900°C is the required power density, which is a strong function of heat source temperature.

FEASIBILITY ASSESSMENT OF LOW TEMPERATURE VOLTAIC ENERGY CONVERSION

I. Introduction

The rapid progress being made in the design and fabrication technology of voltaic converters suggests application to lower temperature regimes where materials-related problems are more manageable, and where a wider range of fossil fuel heat sources may be employed. This paper addresses the feasibility of using voltaic cells to convert thermal radiation into electric power from temperatures as low as 800°C. Because of the low spectral content of visible light at these temperatures, the conversion process in this temperature range is referred to as **thermo voltaics (TV)**, rather than photo voltaic (PV) or thermo photo voltaics (TPV) as referred to in the literature^(1,2,3).

Figure 1 schematically describes the basic conversion process. An external energy source heats a static emitter which generates a thermal radiation spectrum. The thermal radiation is transmitted to voltaic cells which absorb the radiation and convert a fraction into useful electric power. Between the emitter and the voltaic cell is a spectral control device, with the function of minimizing the spectral content of below-bandgap (parasitic) thermal radiation reaching the voltaic cell. Generally there must be a partial vacuum between the emitter and the voltaic cell to minimize parasitic conduction and convection heat losses.

Previous similar work in the area of TPV^(4,5,6,7) has focused on temperatures > 1200°C, for use in solar concentration, or higher temperature fossil fuel systems. For heat source temperatures below 1000°C, achievable cell power density is much lower because of the strong temperature sensitivity of blackbody thermal emission (i.e. the Stefan-Boltzman T^4 functionality). With low heat input fluxes, output power density becomes a controlling factor in device design, necessitating the use of lower bandgaps (< 0.6 eV) than typically employed in TPV or PV. For a practical power generator to operate in this temperature regime, every effort must be made to maximize the photon flux above the bandgap, while minimizing the photon flux below the bandgap.

II. ANALYSIS RESULTS

Because of the need for lower bandgaps at lower temperatures, dark current levels are much higher, and play a greater role in limiting overall efficiency than in higher temperature applications (by limiting achievable output voltage). In addition, the fraction of blackbody thermal radiation above the bandgap is low under these conditions (< 10% at 900°C for a 0.6 eV bandgap). The low fraction of convertible thermal radiation magnifies the importance of high spectral control, i.e. the fraction of total energy absorbed by the voltaic cell that is above the bandgap must be high. Prior to analysis and experiment it was expected therefore that the key process parameters would be dark current and spectral efficiency.

Figure 2 shows predictions of efficiency and cell electric power density versus bandgap at 900°C. These calculations were performed with extrapolations of solar cell dark current correlations obtained from the National Renewable Energy Lab (NREL). Also implicit in the Figure 2 calculations is the assumption that below-bandgap energy is only 10% of the total thermal energy absorbed by the cell, i.e. a controlled thermal radiation source with 90% spectral efficiency is assumed. For the application of interest, an area electric power density $> 0.4 \text{ w/cm}^2$ was required, which necessitated a bandgap below 0.6 eV.

Figure 3 shows the sensitivity of efficiency and power density to the dark current coefficient. A factor of 10x in the dark current has approximately a 30% relative effect on efficiency and power density at a nominal bandgap of 0.6 eV. For nominal dark current values, efficiencies $> 25\%$ are predicted.

The sensitivity to spectral efficiency is shown in Figure 4, assuming a blackbody thermal emitter at 900°C. Varying the below-bandgap absorption fraction from 10% to 50% changes predicted conversion efficiency from 25% to 14%, demonstrating the strong sensitivity to the input thermal radiation spectrum and the importance of efficient spectral control. To achieve an overall efficiency goal of 20%, the spectral efficiency must be $> 70\%$.

III. EXPERIMENTAL RESULTS

The voltaic cells employed in these experiments were developed by NREL, and the details of design are considered proprietary at this time, as is the specific spectral control technology. The cells have a grid coverage (shadow loss) of approximately 15%, and an active power producing area of $.075 \text{ cm}^2$ per cell. Measurements were taken with both single cells and multiple-connected cells with similar results, i.e. little cell-to-cell, or cell coupling variation.

Reported efficiencies are calculated as the ratio of delivered electric power density to absorbed thermal radiation flux. Input thermal flux measurements were obtained with a calibrated pyroelectric radiometer. Output power was determined from cell current/voltage (IV) output traces obtained by varying the load resistance to find the maximum power point. The technique of using output to input flux ratios to calculate efficiency ignores the conduction and convection losses that would be present in an actual generator environment, and neglects reflection effects (less than 5% effects for both above-bandgap and below-bandgap wavelengths). These efficiencies represent the upper bound on achievable generator efficiency.

Figure 5 presents a series of measured InGaAs cell IV curves for varying emitter temperature, with voltaic cell temperatures held below 30°C. As pointed out previously, the key feasibility issue with low-bandgap cells was considered to be voltage generation. From the data in Figure 5 the achieved voltage factors (open circuit voltage divided by cell bandgap) are ~ 0.5, agreeing closely with predictions. It is to be noted that the maximum achievable voltage is thermodynamically limited to the Carnot efficiency times the cell bandgap⁽⁸⁾, which would be 0.48 volts for a 0.6 eV bandgap with heat source temperature at 900°C. These initial InGaAs cells therefore achieved roughly 62% of the maximum theoretical voltage.

Comparison of input power to output current indicates an integral quantum efficiency of approximately 80%, which is a high value considering the unoptimized nature of these initial cells. Initial cell fabrication runs were made without detailed knowledge of optical absorption properties, and subsequent cells would be expected to have improved quantum efficiency.

Figure 6 summarizes measured efficiency and power density versus "effective" emitter temperature, which is defined in terms of the photon flux impinging on the voltaic cell. For example, a quoted temperature of 900°C corresponds to a photon flux equal to that at the surface of a blackbody emitter with emissivity of 1.0 at 900°C. Emissivities lower than 1.0, and/or converter geometries that reduce the view factor, can lower the effective photon flux and temperature, reducing efficiency and power density.

Figure 6 presents measured overall conversion efficiencies versus emitter temperature. The measured spectral efficiency for these experimental conditions was approximately 94%. Measured conversion efficiencies ranged from 22.8% at 777°C, to 26.0% at 1054°C, in good agreement with analytical predictions. Also demonstrated in Figure 6 is the strong sensitivity of output electric power density to emitter temperature, as expected. The required power density of 0.4 W/cm² appears achievable at 900°C or higher.

SUMMARY

Analytical and experimental evaluation of voltaic energy conversion indicates that conversion efficiencies $> 20\%$, and electric power densities $> 0.4 \text{ w/cm}^2$ are achievable at emitter temperatures below 900 C . There appears to be growth potential in this area, given the unoptimized nature of the voltaic materials used, either by improvement in the quantum efficiency, or reduction in the dark current. Practical power generation application would involve additional losses due to convection, conduction, and generator geometric effects, that will reduce achievable efficiency and power density.

Lower temperatures offer a practical advantage for many applications because of reduced materials related issues (emitter vapor pressure, thermal stress, corrosion etc.), and because of the increased range of fossil fuels that can be employed. The limiting issue for practical voltaic converters below 900°C is the required power density, which is a strong function of temperature. The specific application will determine the minimum practical emitter temperature.

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FIGURE 1

Thermo Voltaic Concept

FIGURE 2
Predicted 900°C Voltaic Cell Performance
(Spectral Efficiency = 90%)

FIGURE 3
Predicted TV Performance Versus Dark Current
(Bandgap = 0.6 eV)

FIGURE 4

Predicted TV Performance Sensitivity To Spectral Control
(Bandgap = 0.6 eV)

FIGURE 5
Measured IV Characteristics For InGaAs Cells
(Bandgap = 0.6 eV)

FIGURE 6

Measured Efficiency And Power Density vs Emitter Temperature
(Bandgap = 0.6 eV)

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