

Emissivities and Thermal Characterization of Components for AMTEC Cells

M.A. Ryan, A. Kisor, R.M. Williams, B. Jeffries-Nakamura, M.L. Underwood, and D. O'Connor
Jet Propulsion Laboratory, California Institute of Technology, Pasadena CA 91109

Understanding the thermal characteristics of the various components and materials in an alkali metal thermal-to-electric converter (AMTEC) cell is necessary for optimizing performance of such a cell. Thermal models have been developed and used to good advantage [Underwood, *et al.*, 1990; Sutor, *et al.*, 1992], but those models have, until now, been descriptive of the thermal characteristics of components of cells, rather than used to make decisions concerning materials and construction. Extensive experimental data on the thermal characteristics have not previously been available for use in those models. With the measurement of emissivities of several components of an AMTEC cell, data are now available for use in models, and such data may be used to determine optimum materials and device construction. The emissivities of components of the electrode, current collection network, solid electrolyte, and heat shields of AMTEC cells have been measured in the temperature range 900-1200 K, both in vacuum and in sodium atmosphere using optical pyrometry.

Measured emissivities were used to determine electrode temperature both at open circuit and during current flow in an operating AMTEC cell. Direct measurement of the electrode operating temperature makes it possible to calculate the temperature at the reaction site while a cell is operating; a reliable, direct measurement of this temperature has not previously been made. Direct measurement of the electrode operating temperature has also made it possible to calculate an upper and lower bound for the thermal conductivity of β -alumina at AMTEC operating temperature.

Experimental

Emissivities

The optical emissivities, ϵ , of components of AMTEC cells were measured in vacuum and in sodium atmosphere. Pieces of bare β -alumina solid electrolyte (BASE), of BASE with

Pt/W electrode, of BASE with electrode and molybdenum mesh and wire current collecting network, and of molybdenum foil used as a heat shield material were mounted on a cylindrical cartridge heater in a vacuum chamber equipped with a window. In addition to the materials to be measured, a piece of Mo foil and a piece of β -alumina painted with zirconia black-body paint (making the painted material a grey body with $\epsilon = .99$) in the temperature range of interest) were mounted in the chamber. A cylinder painted with zirconia paint and with a narrow slit exposing the samples to the window was wrapped around the samples. This cylinder kept radiation from the heated samples from reflecting from the walls of the vacuum chamber and returning to the samples. The experimental set-up is shown in Figure 1.

Thermocouples were mounted on each sample, including the painted reference materials, so that the thermocouple tips were in contact with the material but out of the field of view of the pyrometer telescope. In the case of ceramic (BASE), electrodes on BASE) materials, the thermocouples were mounted in shallow trenches cut into the material; for the metal foil, the thermocouple was tied on to the foil with Mo wire behind the tip and the tip bent down to make contact with the foil.

Temperatures and emissivities were measured using a Mikron model M90H digital infrared thermometer (optical pyrometer). The spectral range of this instrument is .78-1.06 μm . The radiation blocking effect of the window was measured by setting the pyrometer emissivity to .95 and measuring the difference in temperature between the thermocouple and the pyrometer. Emissivities of the materials of interest were then measured by scanning emissivities with the pyrometer until the temperature reading on the pyrometer matched the temperature measured by the thermocouple attached to that sample. The emissivity was then adjusted for window absorption. Emissivities were measured for all samples in the temperature range 850-1200 K.

Emissivities were measured in vacuum. The measurements were repeated in sodium

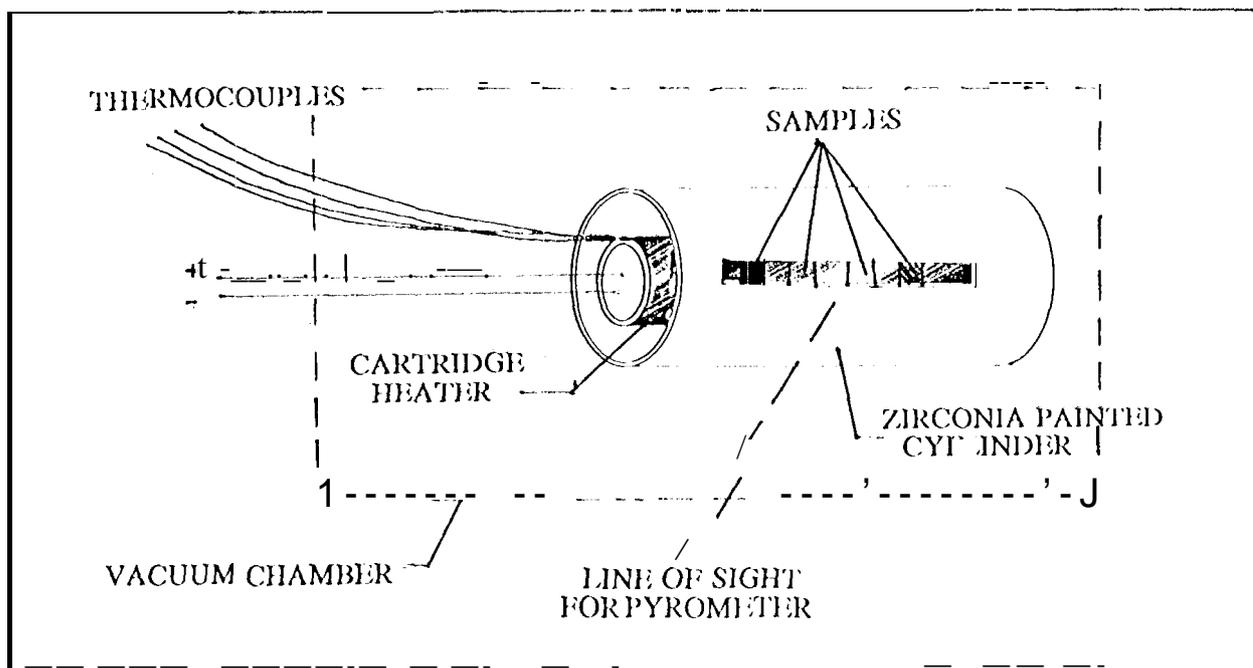


Figure 1: The experimental set-up for measuring emissivity in vacuum and in sodium atmosphere,

atmosphere by providing a source of sodium vapor in the chamber.

AMTEC Electrode Operating Temperature

The temperature of a Pt₃W AMTEC electrode was measured during operation of an AMTEC cell. The cell chamber was equipped with a shuttered window and a hole in the heat shield surrounding the BASE/electrode assembly. Temperature was measured by setting the optical pyrometer to the determined emissivity and reading the temperature. Electrode temperature was measured at open circuit and while current-voltage curves were run. The temperature of the electrode plus the current collection network was measured with the Mikron infrared thermometer. The temperature of the electrode alone was measured with a Pyro [disappearing filament optics] pyrometer ($\lambda = 0.65 \mu\text{m}$) by locating the filament over a section of electrode not covered by the current collecting mesh,

Results

The measured emissivities are shown in Figures 2 and 3. It was found that the emissivity of molybdenum mesh and foil drop after being held for several minutes at ~ 1000 K, apparently because of the loss of the surface oxide layer. The emissivity is then reproducible as temperature is either increased

or decreased. Previously reported values for molybdenum are .40 - .46 at 1100-1200 K in vacuum [Wall, *et al.* 1993; Makino, *et al.*, 1983]; emissivities of .41 - .50 were measured on Mo foil in these experiments, but after several minutes at 1000 K, the emissivity fell rapidly and settled around 0.3.

The emissivity of β -alumina is very close to 1 over the temperature range 900 - 1200 K. The emissivity of Pt₃W electrode is around .4 at 1000 K and rises with increasing temperature. The most interesting measurement is the emissivity of the Pt₃W electrode with Mo mesh and tic wires. As temperature is increased, the emissivity of the electrode increases until it reaches a maximum -.95 at 1100 K. The electrode plus mesh acts more and more as a black body as temperature increases.

Sodium atmosphere has little or no effect on the emissivity of the electrode plus current collecting network; the emissivity of molybdenum foil is somewhat lowered as a result of exposure to sodium vapor.

Using the measured emissivities, the operating temperature of a Pt₃W electrode in an AMTEC cell was measured pyrometrically. Using an infrared thermometer, the operating temperature of the electrode plus current collecting network was measured and compared with the temperature measured in the sodium pool on the high pressure side of the BASE. The temperature of the electrode plus current

collecting network was monitored while taking a current-voltage curve. Temperature was measured after it had reached a steady-state value during operation. The rate of decrease of electrode temperature during operation corresponded closely to the fall in the temperature of the sodium pool, as shown in Figure 4.

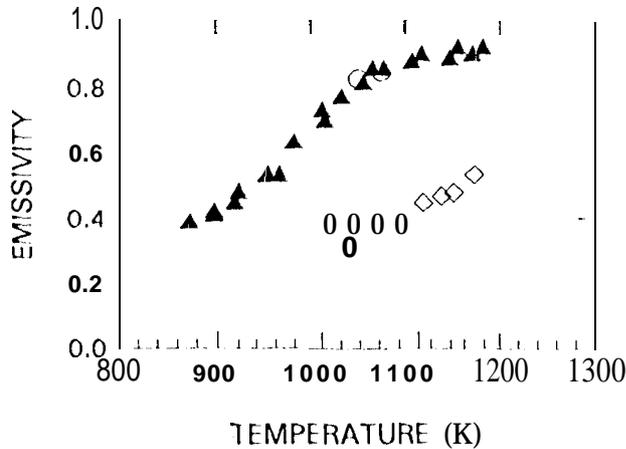


Figure 2: The measured emissivities for PtW electrode in sodium vapor (O) and PtW electrode with MO mesh and tie wires in vacuum (A) and in sodium atmosphere (O).

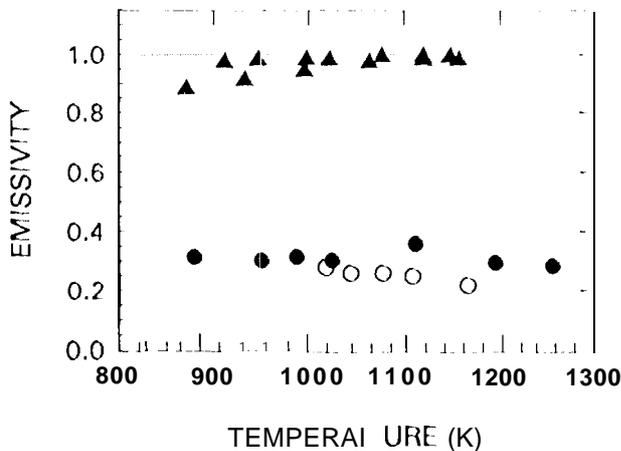


Figure 3: The measured emissivity of β -alumina solid electrolyte in vacuum (A) and of molybdenum foil in vacuum (●) and in sodium atmosphere (O).

The temperature of the reaction zone is the temperature of particular interest for analysis of the thermal characteristics of an AMTEC cell. The temperature of the electrode surface was

measured using a disappearing filament pyrometer. The emissivity of the electrode surface was taken to be .95, the maximum ϵ reached by the electrode + mesh assembly, as shown in Figure 2.

The thermal conductivity, K_{th} , of BASF was then calculated from the measured electrode surface temperature, assuming the thermal resistance of the $1 \mu\text{m}$ thick electrode to be negligible. The values calculated, $K_{th} = 1.5 \text{ W/mK}$ at 1143 K and $K_{th} = 1.2 \text{ W/mK}$ at 1163 K, compare favorably with reported values of 3.0 W/mK at 300 K and 2.9 W/mK at 680 K [May, 1978].

The temperature of the reaction zone during AMTEC operation, T_{el} , may be calculated using a value of $1-2 \text{ W/mK}$ for K_{th} when the sodium pool temperature T_{Na} is known, using the relation

$$T_{el} = T_{Na} - (W_{th} \cdot \delta / I A_{el} \cdot K_{th})$$

where T is temperature in K, W_{th} is the thermal input power in Watts, A_{el} the total electrode area in m^2 , and δ the electrolyte thickness in meters.

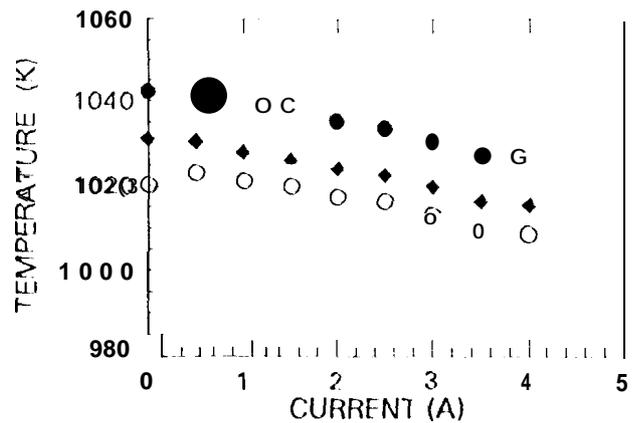


Figure 4: The measured temperature of the sodium pool (●), the electrode + mesh assembly (O), and the electrode surface (+) during current flow in an AMTEC cell.

Discussion

The sharp increase of emissivity of the electrode plus current collecting mesh as the temperature increased was one of the more surprising results of this study. This increase in emissivity is attributed to the presence of the mesh. As the temperature of the entire assembly increased, the mesh acted as walls to create a hole, and each square in the mesh acted as an individual black body. This behavior made it possible to measure the electrode surface temperature directly, using a disappearing filament pyrometer and considering the electrode surface surrounded by mesh walls at $T > 1100$ K to be a grey body with $\epsilon = .95$

The emissivity of Mo foil is slightly lower in sodium atmosphere than in vacuum; this difference may be attributed to the corrosive effect of hot sodium vapor on Mo. The sodium vapor removes any trace of oxide layer which remains on the surface, and the emissivity measured is that of the unoxidized material. The same effect should occur with a metal foil at high temperature in vacuum over a longer time period; the sodium vapor accelerates the removal of the oxide layer.

The temperature of the reaction zone is ~ 15 K lower than the temperature of the sodium pool. This difference, which is caused by the thermal resistance of the BAS11, will change slightly the values of cell operation parameters previously reported from this laboratory, but the differences will be small. Future calculations will take into account the difference in temperature between the sodium pool and the operating electrode.

As shown in Figure 4, the rate of change in temperature caused by current flow is similar for the sodium pool (on the high pressure side of the BAS11) and for the electrode (on the low pressure side of the BAS11). The electrode surface temperature may be calculated from the thermal conductivity, as described above. Thus, it is not necessary to instrument an AMT113C tube on the low pressure (electrode) side to monitor the temperature of the reaction if the temperature inside the tube and behind the site of interest can be more easily measured.

The temperature of the electrode on an operating AMT113C tube will not reflect the reaction site temperature if it is measured with a thermocouple in contact with the mesh and/or tic wires. The mesh and tic wires are cooler than the electrode, because they reject heat and

because the mesh squares form black bodies which retain heat at the electrode surface. A thermocouple in contact with both the surface and the mesh will measure an intermediate temperature.

Further work to characterize the thermal conductivity, K_b , of BAS11 more accurately and over a larger temperature range is underway, including direct measurement of K_b of sodium (Y-alumina ceramic).

Acknowledgements

The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. The work was supported by NASA and by the Department of Energy - Advanced Industrial Concepts Division.

References

- Makino, T.; Kinoshita H.; Kunitomo, T.; *Fourth Japan Symp. on Thermophysical Prop.*, 1983, 13.
- May, G. J.; *J. Power Sources*, 1978, 3, 1.
- Suitor, J. W.; Williams, R. M.; Underwood M.L.; Ryan, M. A.; Jeffries-Nakamura, B.; O'Connor, D.; in *Proc. 27th IECEC*; Bland, T., Ed., SAE, Warrendale PA, 1992; Vol 6.
- Underwood M.L.; O'Connor, I I.; Williams, R. M.; Jeffries-Nakamura, B.; Ryan, M. A.; Bankston, C.); in *Proc. 25th IECEC*, Nelson, P. A., Ed.; AIChE, New York, 1990; Vol. 5.
- Wall, R. N.; Bosch, D. R.; Jacobson, H. I.; *J. Materials Eng.*, in press.