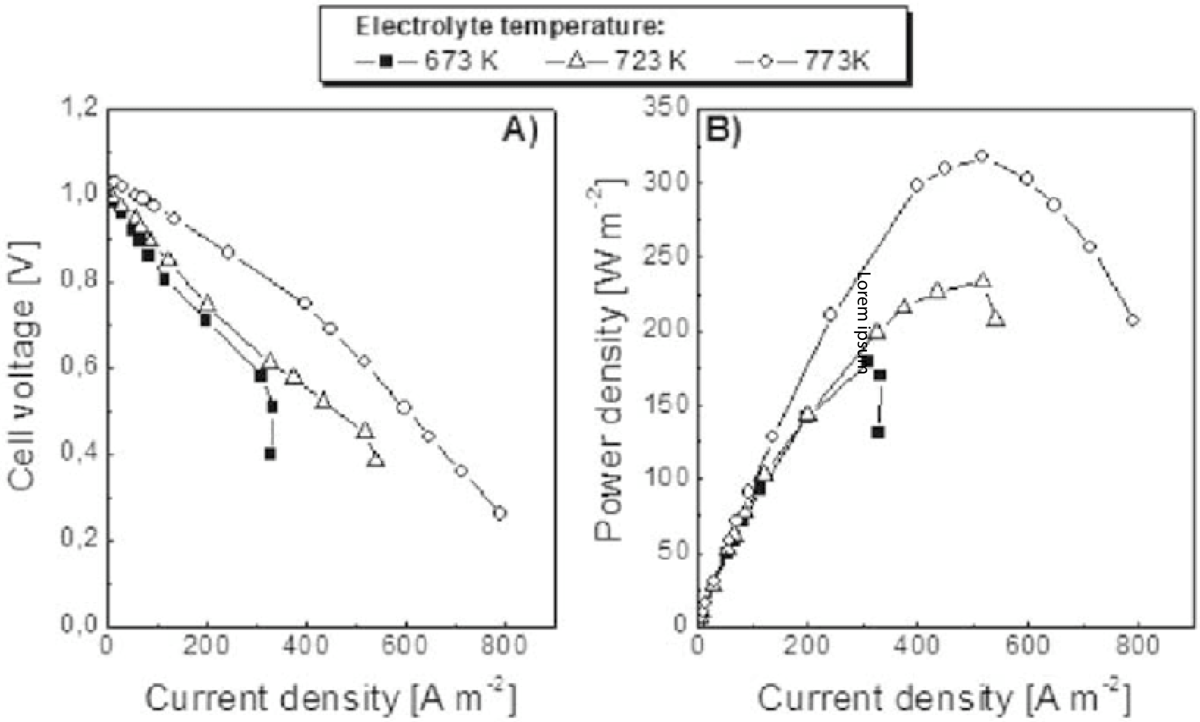
02C Performance of SOFCs

What are we interested in (intuitively)

- Does the voltage of the fuel cell change when current is drawn by a motor?
- How does the power delivered by the fuel cell change with the current?



The Units

Current is a fundamental performance measure of a battery or a fuel cell.

How do we scale the current from a laboratory experiment (a small cell) to a large cell or many cells connected in parallel?

- Cell is a stack of three sheets: the anode, the cathode and electrolytes. The current flows normal to the plane of the sheets. The performance of the cell is therefore prescribed in terms of the unit area of the plate.

The current flows across the thickness of the three-layer stack. Therefore, we normalize the current with the surface area of the sheet-pack and call it the current density. Therefore if I is the current in Amps, and the surface area is A in cm^2 then the current density, i is given by,

$i = \frac{I}{A}$ written in units of A(amps) cm^{-2} or mA cm^{-2}. (1)

What about the resistance:

$$R = \frac{\rho L}{A} \qquad (2)$$

where R is the resistance in Ω, ρ is specific resistivity in Ωcm, L is the length or the width through which the current is flowing (that is the thickness of the electrolyte), and A is the cross section through which the current is flowing.

From Ohm's Law:

$$V = RI \qquad (3)$$

where R is the resistance and I is the total current.

Substitute from Eq. (1)

$$V = RI = RiA = (RA)i \qquad (4)$$

where A the area of the plate surface and i is the current density.

So now the relation between the voltage and the current density depends on RA, that is, the product of the resistance and the surface area of the three-layer stack.

RA has units of Ωcm^2 and it is called Ares Specific Resistance or ASR.

In a cell with an anode, a cathode and an electrolyte we have three ASRs connected in series:

(i) ASR of the anode/electrolyte interface

(ii) ASR of the electrolyte

(iii) ASR of the electrolyte/cathode interface.

The power density:

Power is the rate at which energy can be extracted from the fuel cell or a battery. It is equal to the product of the voltage and the current. Note that current has units of Amps that is Coulombe per second. Noting that the product of Yolts and Coulombs is equal to energy expressed in Joules, we have that the power, which is the rate of doing work, is given by

Power = Watts = Volts*I J s^{-1} (5)

Following the convention of normalizing the parameter with respect to the surface area of the stack, we write the power density as,

$$P_W = \frac{watts}{A} \quad \text{in units of W cm}^{-2} \qquad (6)$$

or we can write that

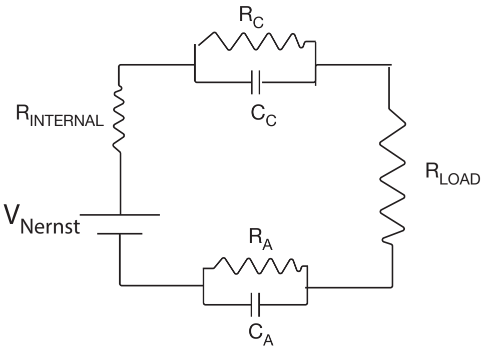
$$P_W = Vi \qquad (7)$$

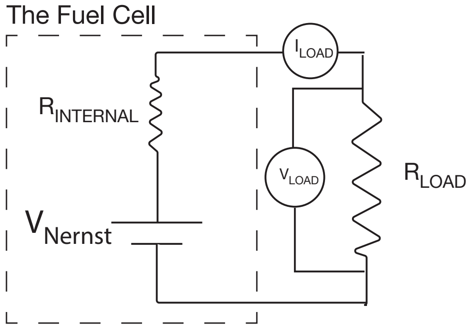
that is, the volts expressed across the load times the current density. Remember we are concerned with the power that is delivered to R_{LOAD}.

It is perhaps useful to remember that the goal of fuel cell performance it to achieve a power density of 1 W cm^{-2}, an easy number to remember. In reality the power density is less than 1 W cm^{-2}.

Explanation for the form of Voltage vs Current Density, and Power Density vs Current Density

The electrical performance of the cell is analyzed with a lumped equivalent circuit or simply as lumped-circuit. The simple form is given below.





In the above figure V_{Nernst} is the fundamental open circuit potential; it is determined from thermodynamic variables, such as the chemical potentials. The stack resistance, is an internal resistance of the cell, which is shown above as $R_{INTERNAL}$. The electrical load on the fuel cell, an electric motor for example, is represented as R_{LOAD}. The RC circuits represent the impedance of the anode/electrolyte and electrolyte/cathode interfaces.

For the present we neglect the interface impedances which simplified the circuit as shown on the right.

Measurement of the Internal Resistance

The internal resistance can be (at least approximately) estimated by measuring the change in voltage across the load when the current is increased (or decreased - this is a reversible phenomenon). For example consider the following analysis (Note the V_{NERNST} is now written more simply as V_N)

$$V_N = I(R_I + R_L)$$
$$V_L = IR_L = V_N - IR_I \qquad (8)$$

Now normalizing with respect to the surface area of the cell-stack

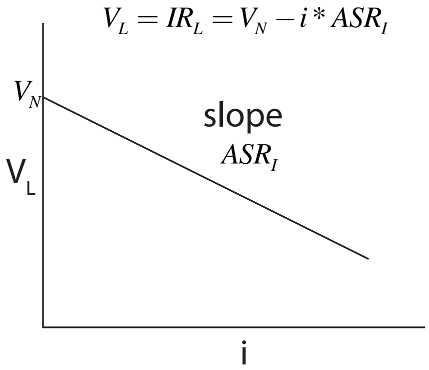
$$V_L == V_N - \frac{I}{A}(R_I A)$$

$$V_L = V_N - i * ASR_I \qquad (9)$$

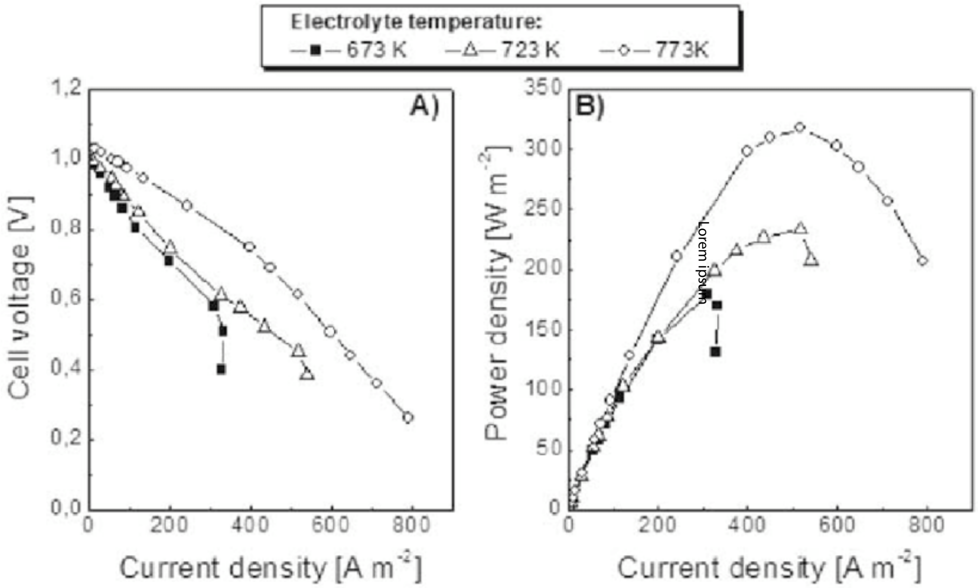
We remind ourselves *i* is the current density (A/cm^2), V_N is the Nernst Potential, and V_L is the cell voltage. Our objective is to measure the internal resistance of the cell ASR_I.

As shown in the schematic on the right, applying Eq. (8) we see that the slope of the cell voltage plotted against the current density gives internal ASR.

An example from real experiments is given on the next page (repeated from the figure at the start of this chapter. You can see that the data have a reasonable fit to a straight line. Two points to note: (i) The data deviate somewhat from the expected straight-line behavior - shown on the right. This deviation arises from the interface impedances both at the anode and that the cathode-electrolyte interface. The second point is that the



slope, that is the internal resistance, is seen to decrease as the temperature is increased. The conductivity of the electrolyte depends on the conduction of oxygen ions, which is related to the diffusion coefficient of oxygen ions. Higher temperature increases the diffusivity and thus reduces the interface ASR.



Therefore, like the description of the temperature dependence of diffusion coefficient the specific conductivity of the electrolyte can be written as

$$\sigma = \sigma_o \exp(-\frac{Q}{RT}) \qquad (10)$$

As an exercise let us calculate the ASR of the interface (ASR_I) from the figure on the left at 773 K. The slope is given by

$$ASR_I = \frac{\Delta V(volts)}{i(Acm^{-2})} = \frac{0.8V}{800*10^{-4}Acm^{-2}} = 10 \ \Omega\text{cm}^2$$

This is a typical value for the internal resistance of the cell.

Description of the Power Density

The data, shown in the figure just above, shows a peak in the power density at approximately 55 mA cm^{-2} at 773 K (1 A m^{-2} = 0.1 mA cm^{-2})

Now let us analyze the position of the peak.

$$P_W = V*i \text{ units are Wcm}^{-2}$$

$$\begin{aligned}
&P_W = V_L * i \\
&V_L = V_N - i * ASR_I \\
&P_W = (V_N - i * ASR_I) * i = V_N i - i^2 ASR_I \qquad (11) \\
&\text{to find the maximum in P}_W \\
&\frac{dP_W}{di} = 0 \\
&V_N - 2 i_{\max} ASR_I = 0 \\
&i_{\max} = \frac{V_N}{2ASR_I}
\end{aligned}$$

Substituting for the Nernst Potential and the value for ASR_I calculated just above we obtain $i_{\max} \approx 50\,mAcm^{-2}$ which agrees with the position of the maximum in the data for the poer density.