DESIGN AND FABRICATION OF SEGMENTED-IN-SERIES CELLS

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ABSTRACT

This paper describes design calculations for and experimental fabrication of patterned series-connected solid oxide fuel cells (SOFCs), i.e. the "segmented-in-series" configuration. Losses due to cell resistances, electrode ohmic resistances, interconnect resistance, and shunting by a weakly-conductive support material were considered in the calculation. For any given set of cell dimensions and characteristics, power density was maximized at an optimal cell length. Assuming typical SOFC materials and screen printed layer geometries, optimal cell lengths typically ranged from 1 to 3 mm. Shunting currents increased with decreasing cell lengths, but were found to have little effect on power density assuming partially-stabilized zirconia supports and temperatures ≤ 800°C. Screen printed 4-cell arrays with ceramic interconnects and active cell lengths of 1.1 mm were fabricated, and produced > 0.6 W/cm² at 800°C. However, OCV values were only ~ 0.7 V/cell due to porosity in the interconnect; this must be improved to realize good device performance.

INTRODUCTION

The "segmented-in-series" solid oxide fuel cell (SS-SOFC) design has often been implemented in a tubular configuration, with the cells delineated in bands around the tube, leading to the term "banded tubular" (1). Figure 1 shows schematically a cross-sectional view of this geometry. Recently, a similar design using flattened tubes instead of circular tubes has also been reported (2). Cell lengths were typically > 10 mm in both circular and flattened tube designs. In addition to the general advantages of tubes - seals are not required, and the interconnect is an integral layer rather than a separate piece - flattened tubes allow for higher packing density, thereby yielding higher power-to-volume ratios and facilitating the use of low-cost planar deposition methods such as screen printing.

General predictions regarding the performance of SS-SOFCs have been made based on modeling of the electrical, electrochemical, heat and mass transfer processes (3). In a recent paper, we suggested that SS-SOFCs could provide improved performance if the cell lengths were decreased below 10 mm, and demonstrated the fabrication of 1-2 mm long cells by screen printing (4). An estimate of the support shunting current was also...
given. However, neither of these papers considered in detail the limitations on SS-SOFC geometries imposed by practical processing methods, or made predictions concerning the optimal geometries and their expected performance.

In this paper, we present quantitative performance predictions for SS-SOFCs as a function of cell and interconnect geometry, support material, cell area-specific resistance, and electrode sheet resistance. Most of the calculations were done assuming ceramic layer fabrication by screen printing, where the minimum feature size is \( \approx 100 \mu m \). The results provide guidance regarding optimal SS-SOFC geometries and their expected power densities. We also present fabrication details and performance data for SS-SOFC arrays designed using the calculation.

**CALCULATION METHODS**

Two calculations were carried out. First, the electrode resistance losses across segmented-in-series cells and interconnects were calculated. Second, the shunting current between cells across the support was calculated. Cell dimensions were chosen to reflect the capabilities of screen printing, a commonly used SOFC fabrication method.

In terms of lateral print resolution, all lines and spaces were chosen to be at least 0.1 mm to reflect what is achievable with typical screen mesh counts (230 and 325), as well as visual pattern alignment. Layer thicknesses were also chosen to approximate typical results from printing with 230 or 325 mesh screens: a single printed layer is usually 15-20 \( \mu m \), while a double printed layer (dried between printings) is 30-40 \( \mu m \) thick.

**Resistance Loss Calculation**

The overall resistance of an array of identical cells, illustrated in Fig. 1b, was obtained by calculating the resistance of an individual repeat period (\( A \)) and multiplying by the number of cells. Component resistances \( R \) were calculated, for the most part, based on \( R = \rho_{\text{path}}/A \), where \( \rho \) is the component resistivity, \( l_{\text{path}} \) is the length of the current path, and \( A \) is the cross sectional area. The exception to this was the cell resistance \( R_{\text{cell}} \), in the portion of the device in Fig. 1a, where the calculation is complicated by the variation in cell current density with lateral position (\( x \)). The total resistance for each

![Cross sectional schematics of the SS-SOFC. Part (a) shows an individual cell with current flows indicated. Part (b) shows an overall view with dimensions labeled. Part (c) shows a closeup view of the shunting current calculation. Note: drawings are not to scale.](image-url)
repeat unit (of length \( \Lambda \)) also included electrode length in the gap between the active cell area and the interconnect, such that:

\[
R_A = R_{\text{CELL}} + \frac{\rho_{\text{ca}} \left( \frac{L_{\text{ca}} + L_I}{2} \right)}{t_{\text{ca}}w} + \frac{\rho_{\text{an}} \left( \frac{L_{\text{an}} + L_I}{2} \right)}{t_{\text{an}}w} + \frac{\rho_I}{L_Iw} \tag{1}
\]

where the dimensions are as given in Fig. 1b, \( \rho_{\text{ca}} \) is the cathode resistivity, \( \rho_{\text{an}} \) is the anode resistivity, \( \rho_I \) is the interconnect resistivity, and \( w \) is the cell width (into the plane of Fig. 1). The interconnect length was assumed small and the electrode resistivities were assumed small enough that the current density across the interconnector was uniform, allowing the use of the simple interconnect term in Eq. 1. The anode and cathode gap resistance terms were approximated simply by including half of the interconnect length in the electrode current paths. This does not introduce substantial error, given that this resistance is small relative to the other terms in Eq. 1. Maximum power density \( P \) was calculated using \( P = \frac{0.552}{R_{\text{cell}}A} \) where an open circuit voltage of 1.1 V was assumed.

The calculation of \( R_{\text{CELL}} \) accounted for the anode current decrease and the cathode current increase due to current traversing the electrolyte (Fig. 1a). The equations describing the current flow and voltage drops are given in Eqs. 2-4. The parameters are defined in the Appendix.

\[
dI_{an} = -dI_{ca} = -J_{el} L_{\text{CELL}} \, dx = -\frac{V_{OC} - (V_{ca} - V_{an})}{R_{ca/el} + R_{an/el} + R_{el}} L_{\text{CELL}} \, dx \tag{2}
\]

\[
dV_{an} = -I_{an} R = -I_{an} \frac{\rho_{an}}{L_{\text{CELL}} t_{an}} \, dx \tag{3}
\]

\[
dV_{ca} = -I_{ca} R = -I_{ca} \frac{\rho_{ca}}{L_{\text{CELL}} t_{ca}} \, dx \tag{4}
\]

Integration of these equations was performed in Matlab (5) by a simple iterative technique, setting a value for \( I_{an}(x=0)=I_{\text{CELL}} \) and varying \( V_{ca}(x=0) \) using a bisection algorithm until the boundary condition that \( I_{an}(x=L_{\text{CELL}})=0 \) was satisfied. The resulting values were used to give the resistance \( R_{\text{CELL}} = V_{ca}(x=L_{\text{CELL}})/I_{\text{CELL}} \) in Eq.1. The cell's operating voltage is defined as the difference between the cathode potential at \( x=L_{\text{CELL}} \) and the anode potential at \( x=0 \), \( V_{\text{an}}(x=0)=0 \), such that \( V_{\text{CELL}} = V_{ca}(x=L_{\text{CELL}}) \).

As a check of the present numerical calculation, total resistance values were compared with those obtained from the analytical expression given in Ref. 3, and the agreement was very good.

**Shunting Current Calculation**

This section describes the calculation of the current flowing between cells through a mildly conductive support, as illustrated in Fig. 1c. The goal was to provide a more accurate result than in previous work (4), where the crude assumption of a uniform field across the support was employed. Figure 1c shows a cross sectional schematic of two cells along with the assumed potential versus lateral position at the surface of the support.
(y=0). Since a typical Ni-YSZ anode is quite conductive, the potential gradient is entirely across the gap between anodes:

\[
V(x) = \begin{cases} 
\frac{V_o}{2} & \text{for } -L \leq x \leq -\frac{L_{G,an}}{2} \\
\frac{V_o}{L_{G,an}}x & \text{for } -\frac{L_{G,an}}{2} \leq x \leq \frac{L_{G,an}}{2} \\
\frac{V_o}{2} & \text{for } \frac{L_{G,an}}{2} \leq x \leq L 
\end{cases}
\]  

where \(V_o\) is the cell operating voltage. Since the potential was assumed not to vary in the \(z\) direction (perpendicular to the plane of the cross section pictured in Fig. 1c), it was approximated by a two-dimensional solution to Laplace's equation for a rectangular area:

\[
V(x, y) = \frac{A_0}{2} + \sum_n (A_n \cos \beta_n x + B_n \sin \beta_n x)(C_n e^{\beta_n y} + D_n e^{-\beta_n y})
\]

where the constants \(A_0, A_n, B_n,\) and \(\beta_n\) can be calculated using the case at \(y=0\) when \(Y_n = C_n e^{\beta_n y} + D_n e^{-\beta_n y} = 1:\n
\[
A_n = \frac{1}{L} \int_{-L}^{L} V(x) \cos \beta_n x \, dx \\
B_n = \frac{1}{L} \int_{-L}^{L} V(x) \sin \beta_n x \, dx \\
\beta_n = \frac{\pi n}{L}
\]

In order to solve for the constants \(C_n\) and \(D_n,\) two boundary conditions were used:

\[
\begin{align*}
\text{at } y = 0, & \quad Y_n = 1 \quad [13] \\
\text{at } y = -t_s, & \quad \frac{dy_n}{dy} = 0 \quad [14]
\end{align*}
\]

The first boundary condition assures that potential profile will match Eqs. 5-7 at \(y=0,\) while the latter condition expresses that no current can flow in the \(y\) direction at the free surface of the support. The calculation was carried out over four complete cells, and the potential variation taken between the central two cells in order to eliminate edge effects.

The expression for the potential profile was then differentiated according to the expression

\[
J = -\nabla V / \rho_s 
\]

in order to find the approximate current density between the two cells (7). The expression is applicable to weakly-conductive ohmic materials with isotropic dielectric properties, where localized charges do not affect the potential gradient.

RESULTS AND DISCUSSION

Resistance Loss Calculation

In this section, the calculated voltage and current distributions across SS-SOFCs are described for cells where one electrode has a significantly smaller sheet resistance than the other. The asymmetrical electrodes reflect a common situation in actual SOFCs, in which the Ni-based anode is more conductive than the perovskite cathode. For Ni-based anodes a sheet resistance of 0.5 $\Omega \text{cm}^{-1}$ is used, based on a thickness of 20 $\mu$m and a resistivity of $1 \times 10^{-3} \Omega \text{cm}$ (8), as previously reported for porous Ni-YSZ in a 55:45 volume ratio (4). For perovskite cathode materials such as (La,Sr)MnO$_3$ (LSM), a sheet resistance of 10 $\Omega \text{cm}^{-1}$ is used, based on a resistivity of $0.02 \Omega \text{cm}$ and a 20 $\mu$m layer thickness. For simplicity, the individual cells are assumed to follow ohmic behavior, and the cell area-specific resistance (ASR) $R_{AS} = R_{cel} + R_{an} + R_{el}$ value was 0.5 $\Omega \text{cm}^2$ unless otherwise specified.

These calculations were done for sheet resistance values of 0.5 $\Omega \text{cm}^{-1}$ for the anode (e.g. Ni-YSZ), with 10 $\Omega \text{cm}^{-1}$ or 30 $\Omega \text{cm}^{-1}$ for the cathode, the latter expected for ~20 $\mu$m thick LSM or La$_{0.6}$Sr$_{0.4}$Co$_{0.2}$Fe$_{0.8}$O$_3$ (LSCF) layers taking porosity into consideration (9). All electrode potential profiles and electrolyte current densities were calculated for cells operating at maximum power, i.e. with $V_{CELL} = V_{el}(x=L_{CELL}) = 0.55$ V. Figure 2 illustrates the electrode potential (a) and electrolyte current density (b) versus position across a cell at maximum power output. The anode potential was essentially constant. The cathode potential did vary substantially with position. For the cathode sheet resistance of 30 $\Omega \text{cm}^{-1}$, the cathode potential dropped ~0.3 V, as compared to ~0.15 V for the lower cathode sheet resistance. As shown in Fig. 2b, the electrolyte current for the high sheet resistance case was smaller than the low resistance case near $x = 0$ mm, as expected.
because the voltage was closer to \( V_{OC} \) (Fig. 2a). The electrolyte current variation was larger for the higher cathode sheet resistance.

For comparison, the same calculation was carried out for \( L_{CELL} = 10 \text{ mm} \) (not shown). The overall dependence was similar to that in Fig. 2, although the potential gradients and the increase in current density at large \( x \) were more pronounced. For both cathode sheet resistance values, the electrolyte current density increased from \(<100 \text{ mA cm}^{-2}\) at \( x=0 \) to \(\approx900 \text{ mA cm}^{-2}\) at \( x=10 \text{ mm} \). Most of the current travels through the anode and crosses the electrolyte at large \( x \) in order to avoid a long current path across the more resistive cathode. For both values of \( L_{CELL} \), the high cathode sheet resistance prevents substantial current flow except within \( \approx 2 \text{ mm} \) of the interconnect for both the 2 and 10 mm cells. These results show that: a) smaller cell lengths result in more uniform current distributions and higher average electrolyte current densities, primarily due to the shorter electrode lateral current paths, and b) higher sheet resistances require the use of smaller cell lengths to minimize ohmic losses.

In this section, we illustrate the impact of electrode resistance losses on overall performance. Figure 3 shows the maximum power density (MPD) versus active cell length \( L_{CELL} \) for an anode sheet resistance of \( 0.5 \Omega \square^{-1} \), a cathode sheet resistance of \( 10 \Omega \square^{-1} \), and \( R_{AS} = 1.0, 0.5, 0.3, \) and \( 0.2 \Omega \text{ cm}^{2} \). MPD values were calculated using the full surface area of the array and included losses due to the interconnect and inactive portions of the electrodes (Eq. 1). Interconnect resistivity and thickness were \( 1 \Omega \text{ cm} \) and \( 20 \mu \text{m} \), respectively. Referring to Fig. 1, the surface can be divided into active cell length \( (L_{CELL}) \) and interconnect/gap length \( (L_i + L_{G,an} + L_{G,cath}) \). We have assumed interconnect/gap lengths that took screen printing limitations into consideration. Two cases are considered here. First, lengths were assumed that are relatively easy to achieve, i.e. \( L_{G,an} = L_{G,cath} = L_i = 0.25 \text{ mm} \). Second, we chose lengths near the limits of screen printing, i.e. \( L_{G,an} = L_{G,cath} = L_i = 0.1 \text{ mm} \).

Figure 3 shows MPD curves for the two cases, each showing an optimal MPD for each \( R_{AS} \) value. Indicated in the figures are the values of \( L_{CELL} \) corresponding to the optimal MPDs. Also shown on these figures is the fraction of the surface that is active cell area. The maximum occurs at active area fractions from \( \approx 0.5 \) to 0.8. The maximum is a result of the increasingly prominent effects of electrode resistance with increasing \( L_{CELL} \), combined with the decreasing fraction of active cell area with decreasing \( L_{CELL} \).
Decreasing the gap/interconnect lengths allows narrower cells while maintaining a reasonably high active cell fractional area. Thus, the maximum power densities were higher and optimal cell lengths smaller for the smaller gap/interconnect lengths shown in Fig. 3b. Note that for the smaller gap/interconnect lengths, the electrode lengths are decreased, decreasing that resistance, but the narrower interconnect has a higher resistance. Finally, note that the cell length corresponding to the power density maximum can be increased by decreasing cathode sheet resistance. For example, for $R_{AS}=0.5 \ \Omega \ \text{cm}^2$, decreasing from 10 to 1 $\Omega$/square (i.e. increasing the thickness from $\approx 20$ to 200 $\mu$m) increases the optimal cell width from $\approx 1.5$ mm to $\approx 2.5$ mm.

Resistance losses in the interconnect region can also influence overall cell performance. Because of the relatively high resistivity of typical ceramic interconnect materials, this can be an important effect. To demonstrate the effect of the interconnect length on array performance, the array's optimum MPD and the optimum active cell length are plotted versus interconnect length in Fig. 4. $R_{AS}$ was assumed to be 0.5 $\Omega \ \text{cm}^2$ and the electrode gap lengths were kept constant at $L_{GS,CN}=L_{GS,NN}=0.25$ mm. With those parameters, an interconnect length of 0.1 mm and an associated active cell length of 1.35 mm gave the highest MPD. Larger interconnect lengths resulted in lower MPDs due to the smaller fraction of active cell area. Decreasing the length below 0.1 mm also lowered MPDs because of the increasing interconnect resistance.

While the power densities predicted above are generally lower than reported for planar SOFCs, a couple of qualifying issues should be considered. First, SS-SOFC power densities calculated here include interconnector and current collection losses, such that they should be compared with planar SOFC stack results, rather than single cells. Second, the calculated power densities include both cell and interconnect areas.

**Shunting Current Calculation**

In order to provide an example of the shunting current expected in a typical SS-SOFC, we have assumed PSZ supports, which are convenient for SS-SOFCs because of the good chemical stability and thermal expansion match with SOFC materials. Resistivity values for dense PSZ range from $\approx 1300$-$220 \ \Omega \ \text{cm}$ between 575-1000°C, respectively (10).

**Figure 4. Maximum power density and optimum active cell length versus interconnect length for interconnect thickness of 20 $\mu$m and resistivity of 1 $\Omega \ \text{cm}$.**
These values were corrected to account for the typical porosity of 30-40 vol% (4). Since PSZ is ionically conductive and the Ni-YSZ electrodes are electronically conductive, current flow through the support requires electrochemical reactions at each of the interfaces (Fig. 1c), resulting in an associated polarization resistance. This resistance is neglected in the present calculation since its value may vary greatly depending on exact electrode composition and structure. Thus, the shunting current values given below must be regarded as upper limits.

The net substrate current $I_{\text{shunt}}$ was obtained by integrating the current in Eq. 15 over the thickness of the support at the midpoint between the two cells:

$$I_{\text{shunt}} = \int \int J(x=0) \, dz \, dy = \int \int (-\nabla V(x=0)/\rho_S) \, dz \, dy = -\left(\frac{w}{\rho_S}\int \frac{dV}{dx}\bigg|_{x=0}\right) \, dy$$  \[16\]

Note that since $dV/dy = dV/dz = Q$ at the midpoint by symmetry, $V_F = dV/dx$. The shunting current increases gradually with decreasing gap length. The present results are for one specific support thickness; in general, the shunting current will increase with increasing support thickness.

Figure 5 shows the ratio of $I_{\text{shunt}}$ to $I_{\text{CELL}}$ as a function of $L_{\text{CELL}}$, assuming an operating temperature of 800°C. $L_{G,in}$ was taken to be 0.25 mm and cell power output data were the same as those used in the $R_{As}=0.5$ Ω cm$^2$ series in Fig. 3. At $L_{\text{CELL}} \approx 6$ mm, the ratio goes through a minimum value of about 0.026 due to the increasing cell current. Below $L_{\text{CELL}} \approx 1$ mm, $I_{\text{shunt}}/I_{\text{CELL}} > 0.05$. As $L_{\text{CELL}}$ approaches 10 mm, the ratio rises slightly because the long current path has a detrimental effect on cell performance.

Figure 6 shows the predicted shunting current assuming $L_{G,in} = 0.4$ mm, $L_{\text{CELL}} = 1.8$ mm, and $w = 8.5$ mm. The current increases with increasing cell operating temperature. The highest value was 8.2 mA at 1000°C, whereas the lowest value was 1.4 mA at 600°C. At the expected operating temperature of 800°C (a resistivity of 752 Ω cm after correction for porosity), the shunting current was calculated to be 4.3 mA, translating to at most a 5-6% degradation in maximum power density when considering the performance data given in Fig. 3. Thus, it appears that the support shunting current is a minor loss for reasonable cell dimensions and operating conditions.

An experimental check of the calculation results was obtained by making resistance measurements (in humidified hydrogen) across an array of four Ni-YSZ anodes printed onto the surface of a porous PSZ substrate. The dimensions were the same as those used
in the calculation described above. The measured current, shown in Fig. 6, increased with increasing temperature, like the calculation result, but at a faster rate. While the reason for the difference in slope is not known, there was reasonable agreement between the magnitudes of the measured and predicted shunting currents. Note that the measured values are lower than the predicted values at lower temperatures; this may be due to the effect of polarization resistance, which was not considered in the calculation. Also plotted are shunting current values calculated assuming a uniform electric field across the array repeat period $A$ and an operating voltage of 0.55 V, as mentioned in our previous paper (4). This method produced shunting current values at least a factor of 10 less than those calculated using the present method. These results illustrate the importance of operating temperature on the shunting current, originating from the temperature dependence of the PSZ resistivity. Lower temperatures are clearly desirable to minimize shunting current, assuming that the cell current does not decrease too much at the lower temperature.

**Experimental Results**

To demonstrate the fabrication and performance of the patterned arrays, 4-cell arrays were fabricated by screen printing on die-pressed PSZ pellets and tested in humidified hydrogen. Ni-YSZ was the anode, YSZ was used as the electrolyte layer and a LaCrO$_3$-based ceramic material was used as the interconnect. After co-firing at ~1350°C, an LSCF-Ce$_{0.9}$Gd$_{0.1}$O$_2$ (GDC) composite layer and a pure LSCF layer were printed for the cathode. They were then fired at a lower temperature.

Figure 7 shows a typical I-V plot recorded from one such array tested in air and humidified hydrogen at 800°C. The active area per cell was 0.11 cm$^2$. An ASR of ~0.22 Ω cm$^2$ was measured using AC impedance analysis. The rather low OCV of ~0.7 V per cell was at least partially due to porosity in the interconnect layer, which was observed with a scanning electron microscope (SEM).

In ongoing work, larger arrays are being prepared by screen printing on both sides of porous, closed-ended PSZ tubes prepared by gelcasting. Figure 8 shows an example of a 5 cm x 6 cm tube with 17 cells. Testing of such tubes is currently ongoing.
SUMMARY AND CONCLUSIONS

Calculations were done to predict a) the electrical behavior of segmented-in-series SOFCs based on their geometry and components’ sheet resistances, and b) the shunting current flowing between cells through the porous substrate. Calculations were made using array geometries reflecting the capabilities of screen printing and conductivities typical of SOFC materials. For a gap length of 0.25 mm and an assumed operating temperature of 800°C, the shunting current through the substrate was estimated to be ≤ 6% of typical cell currents. For area specific cell resistances of 0.2, 0.3, 0.5, and 1.0 Ω cm², the optimum maximum power densities occurred from 1.05-1.9 cm for \( L_{G,an} = L_{G,ca} = L_I = 0.25 \text{ mm} \) and 0.8-1.45 cm for \( L_{G,an} = L_{G,ca} = L_I = 0.1 \text{ mm} \). The calculations can be used to design and optimize SS-SOFCs for a given materials set, operating condition, and processing technique. For typical SOFC materials and layer thicknesses typically obtained by screen printing, reducing the active cell length from 10 mm to 1-3 mm should result in a significant improvement in power density.

Screen printed 4-cell arrays with ceramic interconnects and active cell lengths close to those calculated to be optimal produced as much as 0.6 W/cm² at 800°C, with a measured initial ASR of 0.22 Ω cm². The low OCV of 0.7 V was most likely caused by porosity in the ceramic interconnect – this is the major area that needs to be improved to realize high quality devices.

APPENDIX—DEFINITIONS FOR SYMBOLS

| Symbol | Meaning |
|--------|---------|
| \( d_{ln} \) | Change in anode current in length element \( dx \) |
| \( d_{lc} \) | Change in cathode current in length element \( dx \) |
| \( dV_{an} \) | Voltage drop across anode in length element \( dx \) |
| \( dV_{ca} \) | Voltage drop across cathode in length element \( dx \) |
| \( i_{an} \) | Current flowing through anode |
| \( i_{ca} \) | Current flowing through cathode |
| \( I_{CELL} \) | Cell current |
| \( I_{shunt} \) | Shunting current |
| \( I_{el} \) | Flux of electrons through electrolyte |
| \( L \) | Repeat period of array |
| \( L_{cell} \) | Anode length plus half of anode gap length |
| \( L_{G,an} \) | Gap length between anodes |
| \( L_{G,ca} \) | Gap length between cathodes |
| \( L_I \) | Length of interconnect |
| \( \rho_{an} \) | Resistivity of anode |
| \( \rho_{ca} \) | Resistivity of cathode |
| \( R_{as} \) | Area specific resistance of cell (excluding electrodes), \( R_{el}R_{as}+R_{wa} \) |
| \( R_{el} \) | Resistance of cathode/electrolyte interface |
| \( t_{el} \) | Thickness of electrolyte |
| \( t_{an} \) | Thickness of anode |
| \( t_{ca} \) | Thickness of cathode |
| \( t_I \) | Electrolyte thickness |
| \( t_I \) | Interconnect thickness |
| \( t_s \) | Substrate thickness |
| \( V_{an} \) | Voltage of anode (relative to 0) |
| \( V_{ca} \) | Voltage of cathode (relative to 0) |
| \( V_O \) | Cell operating voltage |
| \( V_{OC} \) | Open circuit voltage of cell |
| \( w \) | Cell width |
| \( x \) | Position along cell width |
| \( y \) | Distance from substrate surface |
| \( z \) | Direction perpendicular to xy plane |

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