ENHANCING THE REDOX TOLERANCE OF ANODE SUPPORTED SOLID OXIDE FUEL CELLS BY MICROSTRUCTURAL MODIFICATION

D. Waldbillig, A. Wood, D. Ivey
1 Department of Chemical and Materials Engineering
University of Alberta, Edmonton, AB T6G 2G6, Canada
2 Versa Power Systems Ltd.
4852 52 St. SE, Calgary, AB T2B 3R2, Canada

ABSTRACT

The most commonly used solid oxide fuel cell (SOFC) anode material is a two phase, nickel and yttria stabilized zirconia (Ni/YSZ) cermet. During fuel cell operation, this material is exposed to a reducing environment and thus remains a cermet. However, the metallic component of the anode may reoxidize in a commercial SOFC system due to situations such as seal leakage, fuel supply interruption or system shutdown. The reduction and oxidation of nickel will result in large bulk volume changes, which may have a significant effect on the integrity of interfaces within a fuel cell and thus result in performance degradation. Following an initial study of the redox kinetics and dimensional changes after reduction and oxidation, as well as a baseline characterization of the electrochemical performance degradation and microstructural changes after redox cycling, two modifications to the anode microstructure were made in order to enhance cell redox tolerance. The Ni content of the AFL was functionally graded in order to produce an AFL layer with minimal expansion during oxidation near the electrolyte and good electronic conductivity and thermal expansion match near the anode substrate. An oxidation barrier layer was printed on the bottom of the cell in order to restrict the ability of oxygen to flow into the anode. Both types of microstructural modification significantly improved the cell redox tolerance compared with standard baseline redox tests.

INTRODUCTION

The most commonly used solid oxide fuel cell (SOFC) anode material is a two phase, nickel and yttria stabilized zirconia (Ni/YSZ) cermet. During fuel cell operation, this material is exposed to a reducing environment and thus remains a cermet. However, the metallic component of the anode may reoxidize in a commercial SOFC system due to situations such as seal leakage, fuel supply interruption or system shutdown. A reoxidized cell must be reduced prior to operation. Thus, cyclic reduction and oxidation (redox) of the anode is likely to occur during commercial SOFC operations. The reduction and oxidation of nickel will result in large bulk volume changes, which may have a significant effect on the integrity of interfaces within a fuel cell and thus result in performance degradation.
System redox solutions, such as the use of a reducing purge gas, are possible, but are cumbersome and expensive and so will likely not be feasible for small-scale SOFC systems. Another possible redox solution is to change the anode material to a substance that is less susceptible to oxidation, such as a ceramic oxide, metallic alloy, or noble metal. However, there are currently few alternative anode materials that exhibit equivalent performance to the state-of-the-art Ni/YSZ materials system and yet still meet the desired cost target. Thus, if the anode material remains unchanged and system redox solutions are deemed too expensive, the only remaining way to enhance SOFC redox tolerance is to modify the microstructure of the anode.

A few groups have published kinetic studies of the Ni/YSZ system or have looked at the change in anode dimensions after redox cycling (1,2,3,4,5). Three of these groups have also reported electrochemical results. Fouquet et al. noted that the polarization resistance of cells increased after redox cycling (2). Robert et al. indicated that serious electrolyte microcracking and performance degradation occurs after redox cycling due to anode substrate oxidation expansion (4). Lang et al. claim to have developed a fully redox tolerant cell fabricated by vacuum plasma spraying (5). Previous studies by this group have also measured the redox kinetics of the Ni/YSZ system and have characterized the change in anode dimensions after redox cycling (6). These studies indicated that the anode substrate does not expand during oxidation and thus should not be a source of redox induced degradation; however, the higher density anode functional layer (AFL) expands and cracks after redox cycling. Baseline studies of cell redox tolerance, through the characterization of the electrochemical performance degradation and microstructural changes that occur after redox cycling, have shown that the cell begins to degrade after redox cycles to a redox depth greater than 30% (1 hour oxidation) (7,8). Two main types of degradation may be designated: mechanical damage, of which the best example is fracture of the electrolyte caused by AFL expansion during oxidation and microstructural damage, which is much more difficult to characterize. The widely differing results reported in the literature likely indicate that redox tolerance measurements are extremely dependent on cell microstructure and testing conditions.

After developing a baseline of cell redox tolerance, efforts have mainly focused on modifying the composition and microstructure of the AFL in order to minimize oxidation volume expansion and thus enhance cell redox tolerance. This study reports the results of two types of microstructural modifications made to enhance the cell redox tolerance and compares these results with the baseline results reported previously.

**BACKGROUND**

**Baseline Cells**

The baseline redox tolerance of TSC-2 cells produced at Versa Power Systems Ltd. (VPS), formerly Global Thermoelectric Inc., after standard redox tests at 750°C has been reported previously (8). Standard redox tests consisted of 6 oxidation cycles from 20 minutes (10% redox depth) to 360 minutes (180% redox depth) in length. Each oxidation cycle was followed by a four hour reduction in hydrogen. During the tests, the initial cell voltage was evaluated and compared to the voltage measured after redox cycling. A comparison of the cell voltage before and after redox cycling can be seen in Figure 1.
Cell performance decreased slightly after each redox cycle, but significant amounts of degradation did not occur until the 1 hour redox cycle (30% redox depth). The largest drop in performance occurred after the 4 hour redox cycle (120% redox depth), likely because this is the first redox cycle that fully oxidizes the cell. The average cumulative amount of voltage degradation, at 60 A (0.74 A/cm²) after the standard redox test, is $0.089 \pm 0.001 V$ or $10.8 \pm 0.1\%$.

![Figure 1. Baseline redox test results.](image)

A theoretical redox depth strategy was developed in order to better define the amount of oxidation that should occur. This analysis uses the amount of Ni within the cell and the flow rate of air to predict the amount of time it should take to oxidize the cell to a specific redox depth. The approach assumes an ideal situation in which all oxygen entering the anode chamber during the test is consumed oxidizing the nickel in the cell. In practice, the rate and amount of oxidation will depend on a number of factors including the gas flow rates, temperature, flow field configuration and other test specific factors. Therefore, some deviation from the theoretical redox depth predicted is expected. According to the redox depth approach, a redox time of approximately 200 minutes corresponds to a redox depth of 100%, i.e., complete oxidation.

During redox cycling the cell is unloaded and the voltage is monitored. The voltage response during oxidation can be used to validate cell redox depth calculations, since a voltage value of zero should indicate that the cell is mostly oxidized, i.e., there is no electrical connection between Ni/NiO particles. During baseline tests it took about 3.5 hours for the cell voltage to decrease to 0 V. This observation supports redox depth calculations that indicate that 100% redox depth should occur after approximately 200 minutes.

Gas chromatography (GC) of the anode outlet stream during oxidation can also be used to verify redox depth calculations. During baseline redox tests oxygen was not present in the anode exhaust until after approximately 2 hours of oxidation. After 2 hours, an oxygen concentration of about 1% $O_2$ was present in the outlet stream. The amount of
oxygen gradually increased until the oxygen content was about 20% after 6 hours. This indicates that the calculated time to redox depths greater than 60% (2 hours oxidation) will be slightly lower than the actual time, since some of the oxygen is exhausted in the outlet gas stream rather than being used up to oxidize the Ni in the cell.

**Graded AFL Cells**

Thermomechanical analysis (TMA) measures the change in sample displacement as a function of temperature, time, atmosphere, or applied force. TMA has been used previously to measure the dimensional changes that occur during reduction and oxidation for two types of NiO/YSZ ceramics, anode substrate samples and samples with microstructures similar to the AFL (6). The reduction/oxidation temperature and sample NiO content were varied during this study.

It was found that the dimensions of anode substrate samples did not change during oxidation or reduction while AFL sample dimensions remained constant during reduction, but the samples expanded and cracked after oxidation. These observations indicate that the expansion of the AFL during oxidation is likely to be one cause of redox induced cell degradation, while the anode substrate seems to be unaffected by redox cycling. During TMA testing it was observed that AFL samples with more than 30wt% NiO and less than 57wt% NiO, expanded less than standard 57wt% NiO samples during oxidation. This indicates that if the amount of Ni in the AFL is reduced, less oxidation expansion might occur and thus cell redox tolerance may be increased.

The knowledge gained from the TMA studies can be used to modify the AFL microstructure to enhance redox tolerance; however, the functional requirements of the AFL still need to be considered in order to maintain good cell performance. The amount of Ni in the AFL must be high enough to ensure that the AFL has sufficient electronic conductivity, triple phase boundary length and porosity, but should be as low as possible in order to minimize the amount of oxidation volume expansion. In order to best satisfy these conflicting requirements, the Ni content in the AFL can be functionally graded so that the Ni content is high near the anode substrate to provide good electronic conductivity and thermal expansion match with the anode substrate and lower near the electrolyte to minimize the amount of AFL expansion during oxidation and to better match electrolyte thermal expansion.

**Oxidation Barrier Cells**

Another strategy to increase cell redox tolerance is to restrict the flow of oxygen into the anode by the addition of an oxidation barrier layer to the bottom of the cell. Since there must be good flow of fuel into the anode during regular operating conditions, this barrier layer must be porous in reducing conditions.

The AFL has a much finer microstructure and smaller pores than the anode substrate. In oxidizing conditions, a layer with the same microstructure as the AFL located on the bottom of the cell will rapidly oxidize due to the fine microstructure and become very dense due to volume expansion upon oxidation filling the small pores. This dense layer may restrict the amount of air that can flow into the anode and thus act as an oxidation barrier. In reducing conditions, the bottom layer will be quite porous and therefore will
not interfere with cell operation. Thus this barrier layer should enhance the redox
tolerance of the cell by reducing the rate at which oxygen penetrates into the cell.

EXPERIMENTAL PROCEDURE

Fuel Cell Preparation

Versa Power Systems Ltd.'s (VPS's) standard TSC-2 cell manufacturing process was
used to fabricate the anode supported SOFC samples. This process is made up of three
major unit operations: tape casting, screen printing and co-firing. A thick anode
substrate support layer is produced via a single layer tape cast process. After the tape is
dried the anode functional layer, electrolyte and cathode layers are screen printed onto
each green (unfired) anode substrate piece. The final processing step involves one-step
cofiring of all cell components. This action combines binder burnout, high temperature
cosintering and cooling into a single firing step. The details of the cell manufacturing
process have been reported previously (8).

Graded AFL cells were prepared using VPS's standard TSC-2 procedure, except a
modified paste was used for the second anode functional layer. All samples had a two
layer AFL structure with the first layer (next to the anode substrate) consisting of a 57
wt% NiO paste and the second layer (next to the electrolyte) consisting of a paste
containing a lower amount of NiO. The total thickness of the graded anode functional
layer was approximately the same as a regular cell. A backscattered electron (BSE) SEM
image of a reduced cell with a graded AFL is shown in Figure 2. Three types of samples
were fabricated: samples with a NiO content of 40 wt% in the second anode functional
layer, samples with a NiO content of 45 wt% and samples with a NiO content of 50 wt%.

Oxidation barrier cells were prepared using VPS's standard TSC-2 procedure; however,
before the cell was co-fired, an additional oxidation barrier layer was printed on the
bottom of the cell. A low magnification BSE SEM image showing a fuel cell with an
oxidation barrier layer, is given in Figure 3. Two types of samples were prepared: one
sample had an oxidation barrier with exactly the same composition (57 wt% NiO) and
microstructure as the AFL, the other sample had a higher Ni content (75 wt% NiO)
oxidation barrier layer in order to provide a more porous reduced layer and a more dense
oxidized layer. The oxidation barrier layer was about 20 µm thick after firing.
Electrochemical Testing Methods

The single cell testing facilities at VPS were used for all redox tests. Standard TSC-2 10x10 cm (81 cm² active area) production cells with stainless steel test jigs, cross flow fuel (H₂) and oxidant (air) delivery and the same seals and current collection as used in VPS’s SOFC stacks were used for all tests. This testing setup provided a commercially realistic testing configuration, as no precious metal contact materials or current collectors were used, and no special furnace or sealing configurations were required. Power densities as high as 1.4 W/cm² have been achieved previously at 0.7 V and 750°C using this testing configuration (9).

Cell performance was measured by conducting current-voltage (I-V) curve tests. During these tests, high fuel and air flows were used and the current was stepped slowly from 0 A to 60 A (0.74 A/cm²). Tests were performed at 750°C using humidified H₂ fuel.

Redox Cycling

Single cells were redox cycled at 750°C. After measuring the baseline current-voltage response and operating the cell under steady-state current load, the cell was unloaded and then was slowly oxidized by blowing a low flow rate of air (0.12 SLPM) across the anode. The low air flow rate simulates a worst case scenario of the condition in which the fuel supply is interrupted and air leaks into the anode cavity. Oxidation cycles 20 minutes (10% redox depth), 40 minutes (20% redox depth), 60 minutes (30%), 120 minutes (60%), 240 minutes (120%, i.e., excess air flow) and 360 minutes (180%, i.e., excess air flow) in length were performed during the redox tests. After oxidation, the cell was reduced in hydrogen and current-voltage curves were measured in order to determine the amount of degradation caused by the redox cycles.

The validity of the redox depth approach was verified using two methods: by observing the behaviour of the cell voltage during oxidation, i.e., the length of time required for the voltage to decrease to a value of 0 V, and by measuring the amount of oxygen in the fuel outlet stream during oxidation, using gas chromatography.

Scanning Electron Microscopy (SEM)

Scanning electron microscopy was used to characterize the microstructure of the baseline and modified cells. All SEM images were taken using a LEO 1450 variable pressure...
SEM operating at 15 kV with an Oxford Instruments ultra thin window (UTW) energy-dispersive x-ray (EDX) spectrometer. Samples were examined in the SEM as fresh fractures after a thin gold coating was applied to minimize charging effects.

RESULTS

Graded AFL Cells

The initial performance of the three types of graded AFL samples (40, 45 and 50 wt% NiO) was measured and then the cells were redox cycled. These results were compared with the baseline redox test results. The initial performance of graded AFL cells with a composition of 45 or 50 wt% NiO was stable and equivalent to standard cells. Cells with 40 wt% graded AFL had good initial performance, but this performance rapidly degraded. The performance of 40 wt% NiO graded AFL cells stabilized and dramatically improved after the 2 hour redox cycle.

The cumulative percent voltage degradation for baseline and graded AFL cells at 60A (0.74 A/cm²) after multiple redox cycles is shown in Figure 4. Baseline samples degraded slightly after each redox cycle. After the standard 6 cycle redox test, the baseline cell voltages had degraded by an average of 10.8% (0.089 V). The voltage of cells with a 45% or 50% graded AFL increased slightly after short redox cycles (< 60 minutes oxidation, 30% redox depth) and then began to degrade after longer redox cycles. After the standard redox test, cell voltage for 45% graded AFL cells had degraded by 7.8% (0.062 V) while cells with a 50% graded AFL had degraded by 9.7% (0.078 V). Cells with a 40% graded AFL initially had very rapid voltage degradation rates and then had a sudden increase in performance after the 2 hour redox cycle. After the standard redox test 40% graded AFL cells had degraded only 5.9% (0.049 V). After a standard redox test all graded AFL samples had better redox tolerance than standard cells.

Figure 4. Summary of the cumulative percent degradation for baseline and graded AFL cells at 60A (0.74 A/cm²) after multiple redox cycles.
During oxidation, the voltage decrease of graded AFL cells followed the same trend as baseline redox cycled cells. The cell voltage decreased to 0 V after approximately 3.5 hours.

Images of an as prepared (oxidized) and a reduced cell with a graded AFL are shown in Figure 5 and Figure 6. The AFL 2 layer has a lower NiO content in order to decrease the amount of layer expansion during oxidation. The layer looks slightly less porous in the reduced condition, which is to be expected since much of the AFL porosity is caused by the porosity induced when NiO is reduced.

![Figure 5. BSE SEM image of an as prepared cell with a functionally graded AFL.](image1)

![Figure 6. BSE SEM image of a reduced cell with a functionally graded AFL.](image2)

**Oxidation Barrier Cells**

The initial performance of cells with an oxidation barrier was measured and then the cells were redox cycled. The initial performance of oxidation barrier cells was stable and equivalent to standard cells. The oxidation barrier layer did not appear to impede the flow of fuel to the anode during operation as no diffusional limitations were seen during testing, even at current densities greater than 1 A/cm².

The cumulative percent voltage degradation for oxidation barrier samples compared to baseline samples at 60A (0.74 A/cm²) against time, after multiple redox cycles, is shown in Figure 7. After a standard 6 cycle redox test, baseline cell voltages degraded by an average of 10.8% (0.089 V). Cells with a 57% oxidation barrier degraded by an average of 8.8% (0.073 V) after a standard redox test, while cells with a 75% oxidation barrier degraded by 8.4% (0.068 V). Oxidation barrier cells had significantly reduced amounts of degradation for short (less than 60 minutes) and intermediate (120 to 240 minutes) oxidation cycles compared to baseline redox tests. Although cells with oxidation barriers containing a higher amount of NiO (75 wt%) had better redox tolerance than 57% oxidation barrier cells, all oxidation barrier samples had better redox tolerance than baseline cells after a standard redox test.

The voltage behaviour during oxidation also supports the hypothesis that cells with an oxidation barrier should have better redox tolerance. Typically the cell voltage reaches 0 V after approximately 3.5 hours of oxidation; however, it takes more than 6 hours for a cell with an oxidation barrier to reach 0 V. This data strongly supports the idea that the oxidation barrier reduces the rate at which oxygen penetrates into the anode.
GC analysis during oxidation showed that oxygen appeared in the anode outlet much faster for cells with an oxidation barrier compared with baseline cells. Approximately 1% oxygen was seen in the anode outlet after about 2 hours of oxidation for baseline redox tests, while it took only 30 to 60 minutes for oxygen to be present in the anode outlet during oxidation barrier redox tests. This result again confirms that the oxidation barrier blocks oxygen from penetrating into the anode under oxidizing conditions.

Figure 7. Summary of the cumulative percent degradation for baseline and oxidation barrier cells at 60A (0.74 A/cm²) after multiple redox cycles.

Figure 8 to Figure 11 show cross sectional views of oxidation barrier layers in the as prepared (oxidized), reduced and reoxidized conditions. In the images, the light grey areas are YSZ, the darker grey particles are Ni or NiO and the black areas are pores. It can be seen that the Ni/NiO particles in the anode substrate are much coarser than those particles in the oxidation barrier layer. The difference in porosity between the as prepared, reduced and reoxidized samples is also readily apparent in the figures.

Figure 8. Cross sectional BSE SEM image of an as prepared 57wt% NiO oxidation barrier.

Figure 9. Cross sectional BSE SEM image of a reduced 57wt% NiO oxidation barrier.
Figure 10. Cross sectional BSE SEM image of a reoxidized 57wt% NiO oxidation barrier.

Figure 11. Cross sectional BSE SEM image of a reoxidized 75wt% NiO oxidation barrier.

Figure 12 to Figure 15 show BSE SEM images of the surface of oxidation barrier layers. In the images, the light grey areas are YSZ, the darker grey particles are Ni or NiO and the black areas are pores. The reduced barrier layers appear to be much more porous than reoxidized layers, which is to be expected since most of the layer porosity is created when NiO is reduced. The 75wt% oxidation barrier layers look much more porous in the reduced state and much more dense when reoxidized. This indicates that these layers should be better at blocking the penetration of oxygen into the anode during oxidation. None of the oxidation barriers appears to be fully dense after reoxidation which indicates that none of the barriers will completely prevent the penetration of oxygen into the anode.
DISCUSSION

Graded AFL Cells

All the graded AFL samples (40, 45 and 50wt% NiO) had improved redox tolerance when compared with the baseline redox tolerance characterized for standard cells.

Cells with an AFL containing 40wt% NiO had unexpected redox behaviour. These cells had very rapid initial degradation rates and then had a drastic performance improvement after the 2 hour redox cycle (60% redox depth). This change in behaviour was quite unexpected, but was seen during all redox tests of 40% graded AFL cells. This phenomenon may have been caused by an enhancement in the connectivity of the Ni particle network, which improved the electronic conductivity of the AFL. Since the Ni content in the AFL was quite low, it might actually be too low to provide stable initial performance. When the Ni in the AFL was oxidized, it likely expanded into the porosity present in the AFL and may have come into better contact with the surrounding Ni particles. Upon reduction, the Ni particles may have maintained some of this enhanced contact, which improved the performance after redox cycling. On average, grading the AFL with 40wt% NiO enhanced the redox tolerance of the cell by about 46%, compared with the baseline cell tolerance after a standard redox test. However, the initial unstable performance means that higher Ni contents are likely necessary to ensure stable performance.

Cells with graded AFLs with NiO contents of 45 and 50wt% also had enhanced redox tolerance compared with baseline cells and exhibited a slight rise in performance after the 20, 40 and 60 minute redox cycles (10%, 20% and 30% redox depth). This performance increase may have been caused by a slight enhancement in the anode contact or microstructure after short redox cycles. On average, grading the AFL with 45wt% NiO enhanced the redox tolerance of the cell by about 28% and grading the AFL with 50wt% NiO enhanced the redox tolerance of the cell by about 10% compared with the baseline cell tolerance after a standard redox test.

During oxidation, the cell voltage for graded AFL cells followed the same trend as standard cells and took about 3.5 hours to reach 0 V which supports theoretical redox depth calculations.

Oxidation Barrier Cells

All of the oxidation barrier cells also had improved redox tolerance when compared with the baseline tolerance characterized for standard cells, especially for intermediate redox times (1 to 4 hours). Redox degradation was decreased by between 18 and 22% for cells with an oxidation barrier compared with the baseline cell degradation after a standard redox test. After shorter redox tests, the redox tolerance is vastly superior for oxidation barrier cells versus standard cells. For cells with a 57wt% NiO oxidation barrier, redox tolerance increased by 37% after a 4 hour redox cycle while cells with a 75wt% NiO oxidation barrier had their redox tolerance increased by 66% compared with standard cells. This improvement in redox tolerance is likely due to a lowering of the rate that oxygen penetrates into the anode. However, since oxygen is not completely prevented from entering the cell by this barrier, oxidation barriers are less effective at enhancing
cell redox tolerance for longer redox times (> 6 hours) and would therefore have to be used as part of an overall system strategy to solve redox degradation.

Both the cell voltage response during oxidation and GC testing supported the observation that the oxidation barrier reduced the ability of air to penetrate into the anode under oxidizing conditions compared with standard cells. The addition of an oxidation barrier almost doubled the length of time that it took for the cell voltage during oxidation to reach 0 V and oxygen was seen in the anode outlet gas 60 to 90 minutes earlier than standard cells. Both of these observations support the hypothesis that the oxidation barrier inhibits the flow of air into the anode during oxidation.

CONCLUSIONS

As long as Ni/YSZ cerments are used as SOFC anodes, the cyclic reduction and oxidation (redox) of the Ni component will be an issue that will have a significant effect on cell performance and lifetime. This study is built on previous work, which indicated that the AFL expanded during oxidation and thus was likely one of the primary causes of redox induced degradation. In order to improve cell redox tolerance two types of anode microstructural modifications were made: the nickel content in the anode functional layer (AFL) was functionally graded and an oxidation barrier layer was added to the bottom of the cell.

Cells with functionally graded AFL had a lower amount of Ni near the electrolyte in order to decrease the amount of oxidation induced volume expansion, and a higher Ni content near the anode substrate in order to provide good electronic conductivity and thermal expansion match. Cells with 40, 45 and 50 wt% NiO graded AFL were fabricated and all cell types had improved redox tolerance when compared with the baseline redox tests. Cells with a 40% graded AFL had their redox tolerance enhanced by 46%, grading the AFL with 45 wt% NiO enhanced cell redox tolerance by about 28% and 50% graded AFL cells had their redox tolerance enhanced by about 10% compared with the baseline cells after standard redox tests. However, the initially unstable performance of 40% graded AFL cells means that NiO contents higher than 40% are likely necessary in order to ensure stable performance.

A layer with a fine microstructure similar to the AFL was printed on the bottom surface of the anode substrate in order to serve as an oxidation barrier layer. In reducing conditions, the layer is porous in order to allow normal cell operation while in oxidizing conditions the layer rapidly oxidizes and densifies in order to restrict the rate that oxygen penetrates into the cell. The amount of redox degradation for cells with an oxidation barrier was decreased by between 18 and 22% compared with the baseline cell degradation after standard redox tests (6 redox cycles). The redox tolerance for oxidation barrier cells was significantly improved for shorter redox cycles (up to 4 hours in length). For cells with a 57 wt% NiO oxidation barrier, redox tolerance was increased by 37% after a 4 hour redox cycle while cells with a 75wt% NiO oxidation barrier had their redox tolerance increased by 66% compared with standard cells after a 4 hour redox cycle. This improvement in redox tolerance for oxidation barrier cells is likely due to a reduction in the rate that oxygen penetrates into the anode, which increases the amount of time it takes to reach a certain redox depth.
ACKNOWLEDGEMENTS

The authors would like to thank Versa Power Systems Ltd. for providing samples, access to testing facilities and funding. The Alberta Energy Research Institute (AERI) Core University Research in Sustainable Energy (COURSE) program and the Natural Sciences and Engineering Research Council (NSERC) of Canada are also acknowledged for providing financial assistance. Finally, the authors would like to thank Tahir Joia, Dale Steedman and Murray Tilleman for their assistance.

REFERENCES

1. N. Tikekar, T. Armstrong, A. Virkar, in SOFC VIII, S.C. Singhal and M. Dokiya, Editors, PV2003-07, p. 670, The Electrochemical Society Proceedings Series, Pennington, NJ, (2003).
2. D. Fouquet, A. C. Muller, A. Weber, E. Ivers-Tiffee, Ionics, 8, 103-108 (2003).
3. G. Stathis, D. Simwonis, F. Tietz, A. Moropoulou, A. Naoumides, Journal of Materials Research, 17, 951 (2002).
4. G. Robert, A. Kaiser, E. Batawi, in Sixth European Solid Oxide Fuel Cell Forum Proceedings, M. Mogensen, Editor, p. 193, European Fuel Cell Forum, Oberrohrdorf, Switzerland (2004).
5. M. Lang, T. Franco, M. Johnson, G. Schiller, P. Szabo, in Sixth European Solid Oxide Fuel Cell Forum Proceedings, M. Mogensen, Editor, p. 877, European Fuel Cell Forum, Oberrohrdorf, Switzerland (2004).
6. D. Waldbillig, A. Wood, D. Ivey, Solid State Ionics, accepted for publication, (2005).
7. D. Waldbillig, A. He, D. Ivey, in Towards a Greener World, Conference Proceedings, Hydrogen and Fuel Cells Conference and Trade Show, p. 174, Vancouver, Canada (2003).
8. D. Waldbillig, A. Wood, D. Ivey, J. Power Sources, accepted for publication, (2005).
9. E. Tang, F. Martell, R. Brulé, K. Marcotte, B. Borglum, in SOFC VIII, S. C. Singhal and M. Dokiya, Editors, PV2003-07, p. 935, The Electrochemical Society Proceedings Series, Pennington, NJ, (2003).