“New Cathode Materials for Intermediate Temperature Solid Oxide Fuel Cells”
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Abstract

Operation of SOFCs at intermediate temperatures (500 – 800 °C) requires new combinations of electrolyte and electrode materials that will provide both rapid ion transport across the electrolyte and electrode - electrolyte interfaces and efficient electrocatalysis of the oxygen reduction and fuel oxidation reactions. This project concentrates on materials and issues associated with cathode performance that are known to become limiting factors as the operating temperature is reduced.

The specific objectives of the proposed research are to develop cathode materials that meet the electrode performance targets of 1.0 W/cm² at 0.7 V in combination with YSZ at 700 °C and with GDC, LSGM or bismuth oxide based electrolytes at 600 °C. The performance targets imply an area specific resistance of ~0.5 Ωcm² for the total cell. The research strategy is to investigate both established classes of materials and new candidates as cathodes, to determine fundamental performance parameters such as bulk diffusion, surface reactivity and interfacial transfer, and to couple these parameters to performance in single cell tests.

The initial choices for study are perovskite oxides based on Sr substituted LaFeO₃, where significant data in single cell tests exists at PNNL for cathodes on both YSZ and CSO/YSZ, and Ln₂NiO₄ compositions. A key component of the research strategy is to evaluate for each cathode material composition, the key performance parameters, including ionic and electronic conductivity, surface exchange rates, stability with respect to the specific electrolyte choice, and thermal expansion coefficients. Area specific resistances determined by ac impedance measurements for La₂NiO_{4+x} and Pr₂NiO_{4+x} on CGO are presented in this report. DC conductivity measurements on the P1 compositions La_{0.8}Sr_{0.2}FeO_{3-x} and La_{0.7}Sr_{0.3}FeO_{3-x} have been completed and studies of the surface chemistry by XPS continue. Processing conditions for the synthesis of (La,Sr)FeO₃ thin films by inter-diffusion of the component oxides have been determined. An ink jet process has been developed for preparing electrodes of different compositions.

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1. List of Graphical Materials

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- Figure 8. XRD pattern of an annealed 4-layer Sr/La/Sr/La thin film after heating in air at 500°C 113h and then 700°C for 10h.

Table 1 Thin film samples and annealing conditions

2. Introduction

The objectives of the project are to discover new oxide cathode materials that meet a performance target of 1.0 W/cm^2 at 0.7 V in combination with YSZ at 700°C and with CGO, LSGM electrolytes at 600°C . An ancillary objective of the project is to increase fundamental understanding of the intrinsic transport properties of mixed electronic ionic conducting oxides and oxide-oxide interfaces that can be used to accelerate further progress in the development of cost effective high performance solid oxide fuel cells. In Phase I, we are measuring the surface exchange rates, diffusion coefficients and interfacial transport for an initial set of perovskite related oxide materials. In Phase II we will synthesize and characterize new cathode materials and measure their kinetic parameters. The thermal and chemical compatibility with different electrolytes will be determined. Based on the results, a subset of the best materials will be selected for single cell tests. The phase III objectives are to evaluate the performance of the best materials identified in Phase I and II. The optimum electrode composition and microstructure will be determined and the longer term performance characteristics evaluated.

3. Executive Summary

The project began on October 1, 2003 and this is the fifth quarterly report. In the fourth period, we have evaluated the performance of $\text{Ln}_2\text{NiO}_{4+x}$, $\text{Ln} = \text{La, Pr}$, in symmetric cells. Reactivity studies indicated evidence for significant reaction and so the data were collected on gadolinia doped ceria electrolytes. The area specific resistances are low enough to warrant further studies. Samples (10g) have been sent to PNNL for further evaluation. We have measured the DC conductivity of two examples of P1 compositions $\text{La}_{0.7}\text{Sr}_{0.3}\text{FeO}_3$ and $\text{La}_{0.8}\text{Sr}_{0.2}\text{FeO}_3$ and continue to characterize the surface chemistry. With PNNL, we will extend the P1 compositions to include copper substituted samples. We have synthesized and started to characterize the P2 compositions $\text{LnBaCo}_2\text{O}_{5+\delta}$ ($\text{Ln} = \text{Pr}$ and Nd). We have continued to investigate synthesis conditions for $\text{LaFeO}_3 - \text{SrFeO}_{2.5}$ thin films. We have now demonstrated a processing approach to synthesize $\text{La}_{0.5}\text{Sr}_{0.5}\text{FeO}_3$ from the components and we will proceed with some further optimization and prepare a composition spread for measurements of the surface exchange. A commercial piezo-electric ink-jet printer has been modified to deposit patterned oxide layers on single crystal and ceramic substrates. The method will be used to generate patterns to test the roles of surfaces and phase boundaries (double and triple) in the activation and transport of oxygen by isotope methods.

4. Experimental

4.1 Characterization of K1 Compositions $\text{La}_x\text{Pr}_{2-x}\text{NiO}_{4+x}$ ($x = 2, 1.9, 1.2, 1.0, 0$).

The syntheses and compositional characterization of the K1 compositions in the series $\text{Ln}_2\text{NiO}_{4+x}$, $\text{Ln} = \text{La, Pr}$, have been described in previous report. The phase purity and lattice parameters were determined by powder X-ray diffraction. Thermo-gravimetric analyses were performed to determine the equilibrium oxygen non-stoichiometry. The diffusion coefficient and surface exchange rate were determined by electrical conductivity relaxation. Based on these results, we have evaluated the performance of the materials in

symmetric cells. Reactivity studies indicated evidence for significant reaction with YSZ and so the data were collected on gadolinia doped ceria electrolytes.

Gadolinia doped cerium oxide (CGO) containing 10 % gadolinia powder was purchased from Rhodia. The powder was cold isostatically pressed into pellets at 40,000 psi and sintered in air at 1350 °C for 10 h. The pellet density was greater than 95 % of the theoretical value. The electrode powders were made into ink, and used to fabricate symmetrical LNO/CGO/LNO cells with 1 cm² active area. The electrodes were sintered at 1000 °C in air for 2h. Gold gauze was used as the current collector on both electrodes. The symmetrical LNO/CGO/LNO cell and the Au gauzes were pressed together physically with spring loading. Electrochemical impedance spectra were obtained using a Solatron 1260 frequency response analyzer. The applied frequency ranges from 2MHz to 0.1 Hz.

4.2 Results of symmetric cell measurements

Typical impedance spectra obtained with a symmetrical cell under various oxygen partial pressures at 527 °C are shown in Figure 1. The intercepts with the real axis will be referred to $R_{electrolyte}$, which is independent of pO₂ in the high frequency region, and $R_{electrode}$ in the low frequency region. The low-frequency contribution whose amplitude depends on the oxygen partial pressure was attributed to the cathode reactions. The area specific resistance (ASR) is calculated as half the difference between the low and high frequency intercepts with the real axis (Figure 1). The ASR is then given by $ASR = (R_2 - R_1) \cdot S/2$, where R_2 and R_1 are low frequency intercept and high frequency intercept, respectively, and S is the geometrical surface area of the symmetrical cell.

Figure 1. Representative impedance spectra of the Pr₂NiO_{4+δ} electrochemical cell: Pr₂NiO_{4+δ}/CGO/ Pr₂NiO_{4+δ} (T= 527 °C).

The performance target for new oxide cathode materials is 1.0 W/cm² at 0.7 V in with GDC electrolytes at 600 °C. This translates to a total cell resistance of 0.5 Ω/cm². The measured

area specific resistance for the K1 cathodes $\text{La}_2\text{NiO}_{4+\delta}$ and $\text{Pr}_2\text{NiO}_{4+\delta}$ are shown in Figure 2.

Figure 2. Area Specific Resistance vs. Temperature for $\text{La}_2\text{NiO}_{4+\delta}$ and $\text{Pr}_2\text{NiO}_{4+\delta}$

The results for these non optimized electrodes are encouraging and suggest that with further optimization of the electrode structure may enable the target to be reached. This is also suggested by an estimate of the ASR based on the previously measured values of D and k . The results calculated at 700 C for an electrode with a surface area of $10,000 \text{ cm}^{-1}$, a particle size of $3 \mu\text{m}$, a porosity of 31% and a tortuosity of 1.16 are shown in Figure 3. The rectangle indicates approximately the range of values expected for the K1 oxides. Samples (10g) have been sent to PNNL for further evaluation.

Figure 3. Estimates of the ASR expected for different values of the diffusion and surface exchange coefficients. The rectangle illustrates the expected values for the K1 oxides.

The change in area specific resistance as a function of oxygen partial pressure can be represented by $1/ASR = 1/ASR^0 (pO_2)^m$. The exponent m is $0.27 \sim 0.31$ at $526^\circ\text{C} \leq T \leq 634^\circ\text{C}$ for LNO and PNO system as shown in Figure 4.

Figure 4. The variation of the ASR with oxygen partial pressure at different temperatures.

4.3 DC Conductivity of Perovskite Compositions P1, $\text{La}_{1-x}\text{Sr}_x\text{FeO}_3$, $x = 0.2, 0.3$

The synthesis and characterization of $\text{La}_{0.7}\text{Sr}_{0.3}\text{FeO}_3$ and $\text{La}_{0.8}\text{Sr}_{0.2}\text{FeO}_3$ (LSFO) were described in the previous report. Pressed pellets of the four compounds were sintered and cut into bars for Dc conductivity measurements using the procedure described previously.

Figure 5. DC conductivity of $\text{La}_{1-x}\text{Sr}_x\text{FeO}_3$, $x = 0.2, 0.3$ in 100% oxygen.

The results are similar to other perovskite systems. The conductivity on increasing temperature shows Arrhenius behavior followed by a decrease as oxygen is lost from the sample on heating. The conductivity at $x = 0.3$ is somewhat higher than at $x = 0.2$.

In discussions with PNNL (Pete Rieke), we have started to synthesize $\text{La}_{1-x}\text{Sr}_x\text{FeO}_3$ with part of the Fe replaced by Cu. Samples of these compositions will also be provided to us by PNNL for conductivity relaxation and stoichiometry measurements.

4.4 Synthesis and characterization of P2 compositions $\text{LnBaCo}_2\text{O}_{5+\delta}$ (Ln = Pr and Nd)

In recent years, many oxide materials containing Mn, Fe, Co and Ni have been studied for use as cathode materials at intermediate operating temperatures. For the most part, these compositions can be represented by $(\text{La},\text{Sr})(\text{B},\text{B}')\text{O}_{3-x}$ where $\text{B},\text{B}' = \text{Mn}, \text{Fe}, \text{Co}$ and Ni . A characteristic feature of these compounds is that the A site and B site cations are disordered. Disorder can be prevented by appropriate choice of the cation combinations. To induce A site order, requires increasing the size difference between the two cations for example in Pr,Ba as distinct from La,Sr. A typical consequence of the A site order is that the oxygen vacancies also occupy specific sites as shown in Figure 5. In the specific example is the oxygen-deficient perovskite, $\text{LnBaCo}_2\text{O}_{5+\delta}$ (Ln = Pr and Nd). The oxygen content can be as high as $\delta = 0.7$ for samples synthesized in air.

Figure 6. The structure of $\text{LnBaCo}_2\text{O}_{5+x}$; the purple and silver spheres represent the barium and lanthanide cations, the square pyramidal coordination of cobalt ions is shown in blue, and the partially occupied oxygen ion sites as orange spheres.

We have chosen this structure type as our second class of perovskite compositions (P2). In the initial studies $\text{LnBaCo}_2\text{O}_{5+\delta}$ (Ln = Pr and Nd) compounds were synthesized via a citrate precursor method. Stoichiometric amounts of Pr_6O_{11} (Alfa 99.99 %) and $\text{Nd}(\text{NO}_3)_3$, and cobalt nitrates (Aldrich, 99.99 %), were dissolved in dilute nitric acid. Ethylene glycol (EM science >98 %) and citric acid (Aldrich, 99.5 %) were added to the solution. This

mixture was covered and stirred at 150 °C until the solution began to foam and formed a dry resin. Further heating at 300 °C and then 600 °C for 24 h periods decomposed the dry foam containing residual organic components. The final mixture was pressed into a 1-inch diameter die followed by cold isostatic pressing (CIP). The pellet was sintered in air at 1100 °C for 12 h and then cooled down slowly in nitrogen. Finally a rectangular shape bar ($16.0 \times 2.4 \times 1.7$ mm), was cut for DC conductivity and ECR measurements. The DC conductivity was measured by the 4-probe technique. The total conductivity in the range of $25\text{ °C} \leq T \leq 400\text{ °C}$ is $\sim 400 - 600$ S/cm in air. As the temperature increases the conductivity begins to decrease around 150 °C due to the loss of interstitial oxygen atoms from the lattice.

Figure 7. DC conductivity data for $\text{PrBaCo}_2\text{O}_{5+\delta}$ at different oxygen partial pressures

Electrical conductivity relaxation and further characterization studies of this system are in progress.

5. Combinatorial Approach to Measurement of Transport Parameters.

5.1 Ink jet printing of oxide patterns (University of Toronto):

A commercial piezo-electric ink-jet printer (3 color + black) has been modified to deposit patterned oxide layers on single crystal and ceramic substrates. The method will be used to generate patterns to test the roles of surfaces and phase boundaries (double and triple) in the activation and transport of oxygen by isotope methods. The composition of the printed pattern is governed by a custom-written printer driver which was written from scratch to avoid the color correction that is normally done by commercial printer drivers. Also the printer feed mechanism was also modified to allow flat, thin solid samples to be fed through the paper path.

Recently the research has been focused on optimization of the deposition system for the combinatorial samples, using inorganic solutions plus polyethylene glycol (PEG) to optimize the drying of the printed specimen. The printed samples are then dried and

calcined. Initial problems of nozzle clogging were solved by optimization of the PEG concentration. The initial materials involved the printing of (Gd + Ce) solutions onto single crystal (100) YSZ specimens. Specimens with a programmed variation in the Gd/Ce ratio have been prepared. These samples are currently being characterized by SEM, ToFSIMS, and XPS at a variety of annealing conditions.

Infusion with O-18 labelled oxygen followed by ToFSIMS mapping of the infused oxygen will be attempted on these initial samples. Eventually, the printing of perovskites on these and thin film samples prepared at the University of Houston will begin to reveal the details of oxygen activation on possible cathode materials.

5.2 Laser Deposition of (La,Sr)FeO_{3-x} Samples:

Perovskite and perovskite - related oxides are noteworthy for their tolerance of a very wide range of compositions. This is an advantage in that variations in composition can be used to simultaneously optimize several important properties such as surface exchange rate, diffusion coefficient, thermal expansion, and substrate reactivity. The disadvantage is that the matrix of possible compositions is very large and serial evaluation of properties is time consuming. Consequently, we have decided to adopt a combinatorial approach whereby many compositions can be screened for one or more properties using a single specimen. As a first step, we are investigating compositions in the LaFeO₃ – SrFeO_{2.5} system which have been shown recently to be of interest as cathode materials for intermediate temperature operation. Eventually, we plan to expand the scope to include four different oxide components. We will use the two oxide component system to develop the technique and the processing conditions needed to prepare samples.

At this point we have prepared a number of different film geometries with 2, 4, and 8 layers in sequences starting with either LaFeO₃ or SrFeO_{2.5} as the first layer deposited on the substrate using pulsed laser deposition (PLD). The deposition method was described in previous reports. All films were deposited at ambient temperature and subsequently annealed at two different temperatures as indicated in the summary table below (Table 1). The total film thickness was ~3000 Å in each case. The samples were analyzed by X-ray diffraction after annealing and then depth profiled using SIMS and a gallium ion source to determine the extent of inter-diffusion.

The most successful processing conditions to date were obtained for a 4-layer film, SrFeO_{2.5}/LaFeO₃/ SrFeO_{2.5}/LaFeO₃/LaAlO₃ (Sr/La/Sr/La/LaO) (#8 in Table 1). For inter-diffusion, the film was heated at 504 °C for 113 h and then 703 °C for 10 h in flowing oxygen. The annealing temperature was increased relative to the earlier experiments from 380 °C to 500 °C to accelerate the inter-diffusion process. This temperature is above the crystallization temperature of SrFeO_{2.5} (400 °C) but below the crystallization temperature of LaFeO₃ (600 °C).

The XRD pattern of the annealed film is shown in Figure 1. The film has some orientation with respect to the substrate as indicated by the two large La_{0.5}Sr_{0.5}FeO₃ peaks at 22.7 (001) and 46.4° (002). The peak at 27.2 ° is possibly from LaFeAl₁₁O₁₉ formed by reaction

between the LaFeO_3 layer and the LaAlO_3 substrate. The small peaks at $32.4\text{--}32.8^\circ$ and 39.9° are most likely due to (110) and (111) reflections from other film orientations.

Table 1 Thin film samples and annealing conditions

	XRD	SIMS	Sample	layers	1 st annealing		2 nd annealing	
					T & t	Atm.	T & t	Atm.
1	√	x	$\text{SrFeO}_{2.5}/\text{LaFeO}_3/\text{LAO}$	2	380°C, 110h	O_2	714 °C, 8h	O_2
2	√	√	$\text{LaFeO}_3/\text{SrFeO}_{2.5}/\text{LAO}$	2	380°C, 110h	O_2	714 °C, 8h	O_2
3	√	√	$\text{LaFeO}_3/\text{SrFeO}_{2.5}/\text{LAO}$	2	350 °C, 50 h	O_2	703 °C, 15h	O_2
4	√	√	$\text{LaFeO}_3/\text{SrFeO}_{2.5}/\text{LAO}$	2	350 °C, 167 h	O_2	703 °C, 15h	O_2
5	√	√	$\text{LaFeO}_3/\text{SrFeO}_{2.5}/\text{LAO}$	4	350 °C, 171 h	O_2	703 °C, 10h	O_2
6	√	√	$\text{SrFeO}_{2.5}/\text{LaFeO}_3/\text{LAO}$	2	350 °C, 171 h	O_2	703 °C, 10h	O_2
7	√	√	$\text{SrFeO}_{2.5}/\text{LaFeO}_3/\text{LAO}$	2	504 °C, 113 h	O_2	703 °C, 10h	O_2
8	√	√	$\text{SrFeO}_{2.5}/\text{LaFeO}_3/\text{LAO}$	4	504 °C, 113 h	O_2	703 °C, 10h	O_2
9	√	√	$\text{SrFeO}_{2.5}/\text{LaFeO}_3/\text{LAO}$	8	504 °C, 278 h	air	703 °C, 10h	air
10	√	x	$\text{SrFeO}_{2.5}/\text{LaFeO}_3/\text{LAO}$	8	504 °C, 278 h	air	703 °C, 10h	air
11	√	x	$\text{SrFeO}_{2.5}/\text{LaFeO}_3/\text{LAO}$	4	504 °C, 278 h	air	703 °C, 10h	air
12	√	x	$\text{SrFeO}_{2.5}/\text{LaFeO}_3/\text{LAO}$	4	504 °C, 278 h	air	703 °C, 10h	air
13	√	x	$\text{SrFeO}_{2.5}/\text{LaFeO}_3/\text{LAO}$	2	504 °C, 278 h	air	703 °C, 10h	air

Figure 8. XRD pattern of an annealed 4-layer Sr/La/Sr/La thin film after heating in air at 500 °C 113h and then 700 °C for 10h.

The SIMS data are consistent with the X-ray result and indicate substantial though not quite complete inter-diffusion. Having now demonstrated a processing approach to synthesize $\text{La}_{0.5}\text{Sr}_{0.5}\text{FeO}_3$ from the components, we will proceed with some further optimization and then prepare a composition spread for measurements of the surface exchange.

Other film work: In discussions with Peter Rieke at PNNL, we propose to investigate isotope exchange on samples of $\text{La}_{0.7}\text{Sr}_{0.3}\text{Cu}_{0.2}\text{Fe}_{0.8}\text{O}_{3-x}$, a promising cathode composition.

We have prepared a target (2.5 cm in diameter and .7 cm thick) of this material for thin film deposition.

6. Conclusions

We have evaluated the performance of $\text{Ln}_2\text{NiO}_{4+x}$, $\text{Ln} = \text{La, Pr}$, in symmetric cells. Reactivity studies indicated evidence for significant reaction and so the data were collected on gadolinia doped ceria electrolytes. The area specific resistances are low enough to warrant further studies. Samples (10g) have been sent to PNNL for further evaluation. We have measured the DC conductivity of two examples of P1 compositions $\text{La}_{0.7}\text{Sr}_{0.3}\text{FeO}_3$ and $\text{La}_{0.8}\text{Sr}_{0.2}\text{FeO}_3$ and continue to characterize the surface chemistry. With PNNL, we will extend the P1 compositions to include copper substituted samples. We have synthesized and started to characterize the P2 compositions $\text{LnBaCo}_2\text{O}_{5+\delta}$ ($\text{Ln} = \text{Pr}$ and Nd). We have continued to investigate synthesis conditions for $\text{LaFeO}_3 - \text{SrFeO}_{2.5}$ thin films and have now demonstrated a processing approach to synthesize $\text{La}_{0.5}\text{Sr}_{0.5}\text{FeO}_3$ from the components. We will proceed with some further optimization and prepare a composition spread for measurements of the surface exchange. A commercial piezo-electric ink-jet printer has been modified to deposit patterned oxide layers on single crystal and ceramic substrates. The method will be used to generate patterns to test the roles of surfaces and phase boundaries (double and triple) in the activation and transport of oxygen by isotope methods.

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8 List of Acronyms and Abbreviations

CGO	Cerium Gadolinium Oxide
ECR	Electrical Conductivity Relaxation
EPMA	Electron Probe MicroAnalysis
GDC	Gadolinia Doped Ceria (see CGO)
LSGM	Lanthanum Strontium Magnesium Gallate
PLD	Pulsed Laser Deposition
TGA	Thermogravimetric Analysis
YSZ	Yttria Stabilized Zirconia
IEDP	Isotope Exchange and Depth Profiling

9. Milestones and Scope of Work

The project is divided into three phases that will overlap as shown in the timelines below

Months	1-3	4-6	7-9	10-12
Year1		Phase I		
Year 2		Phase II	Phase II	
Year 3		Phase II	Phase III	
		Phase III		

Phase I: The Phase I objectives are to complete the characterization of a set of perovskite materials for which performance data already exists at PNNL. We will then measure the relevant kinetic parameters. The comparison the real performance data with the fundamental kinetic parameters will be used to guide materials selection in Phase II.

Phase II: The Phase II objectives of the project are to synthesize and characterize new cathode materials and to measure their kinetic parameters. The thermal and chemical compatibility with different electrolytes will be determined. Based on these results, a subset of the best materials will be selected for single cell tests. Some additional compositions will be synthesized if indicated by the single cell test data.

Phase III: The phase three objectives are to evaluate the performance of the best materials identified in Phase I and II. The optimum electrode composition and microstructure will be determined and longer term performance characteristics evaluated.

Updated Milestones for Year 1

The updated milestones reflect two program adjustments since the original submission. The first is that we have started work on the K1 compositions ahead of the P1 compositions. The latter have been moved into the second half of the first year. The second is that in order to accelerate the thin film materials selection work we have decided to adopt a combinatorial approach which will permit the simultaneous synthesis of many compositions.

PHASE I

- Task 1.0 Four modified perovskite oxide compositions (**P1**) selected by UH and PNNL will be synthesized and characterized by X-ray diffraction (XRD) and electron microprobe analysis (EMPA) (Months 6-9) **completed**
- Task 2.0 The chemical compatibility with YSZ and CGO electrolytes will be determined (Months 6-9) **completed**
- Task 3.0 The temperature dependence of the dc conductivity and stoichiometry will be determined in air for the **P1** compositions. (Months 6-9) **in progress**
- Task 4.0 The diffusion coefficients and surface exchange rates will be measured by electrical conductivity relaxation (Months 6-12) **in progress**
- Task 5.1 Thin films of perovskite compositions will be synthesized by PLD using a combinatorial approach. (Months 3-9) **in progress**
- Task 5.2 Electrode-electrolyte interfaces will be characterized for thin films of cathode materials by AC impedance spectroscopy (Months 9-12)
- Task 6.0 Electrode-electrolyte interfaces will be characterized for thin films of cathode materials by IEDP (9-12)

PHASE II

- Task 1.0 Four modified perovskite oxide compositions (**P2**) will be synthesized and characterized by XRD and EMPA (Months 9-12) **in progress**
- Task 1.1 Two A_2BO_4 compositions (**K1**) will be synthesized and characterized by XRD and EMPA. (Months 1-4) **completed**
- Task 1.2 Three additional A_2BO_4 compositions (**K2**) will be synthesized and characterized by XRD and EMPA. (Months 6-9) **completed**
- Task 2.0 The chemical compatibility with YSZ, CGO and LSGM electrolytes will be determined for **P2** (Month 12)
- Task 2.1 The chemical compatibility with YSZ, CGO and LSGM electrolytes will be determined for **K1** (Month 7) **completed for YSZ and CGO**
- Task 2.2 The chemical compatibility with YSZ, CGO and LSGM electrolytes will be determined for **K2** (Month 9) **completed for YSZ and CGO**
- Task 3.0 The dc conductivity and stoichiometry will be determined in air for the **K1** compositions that have chemical compatibility. (Months 4-6) **completed**
- Task 4.0 The diffusion coefficients and surface exchange rates will be measured by electrical conductivity relaxation for the **K1** materials evaluated in Task 3 (Months 6-12). **completed**

- Task 4.1 K1 samples will be characterized in symmetric cells by AC impedance spectroscopy (Months 6-9) to confirm the measured values of k_{ex} .
completed
- Task 5.0 Electrode-electrolyte interfaces will be characterized for thin films of cathode materials selected from Task 4.0 by AC impedance spectroscopy (Months 10-33).
- Task 6.0 Electrode-electrolyte interfaces will be characterized for thin films of cathode materials selected from Task 4.0 by IEDP (Months 10-33)
- Task 7.0 Results from Tasks 4.0, 5.0, and 6.0 will be used as they become available to select cathode electrolyte combinations for single cell tests (Months 10-33).