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RPPR Final Report
as of 07-Mar-2022

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Proposal Number: 77825CHST1

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INVESTIGATOR(S):

Name: Ted Ohrn
Email: ted@a-t-w.com
Phone Number: 0000000000
Principal: Y

Organization: **Special Power Sources, LLC**

Address: 930 W Ely St, Alliance, OH 446011111

Country: USA

DUNS Number: 117239978

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Final Report for Period Beginning 01-Nov-2020 and Ending 31-Jan-2022

Title: Low Temperature P-SOFC 300W Power Source

Begin Performance Period: 01-Nov-2020

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Report Term: 0-Other

Submitted By: Cris DeBellis

Email: cris.debellis@spsources.com

Phone: (330) 806-2671

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STEM Degrees:

STEM Participants:

Major Goals: The objective of the project was to take the very promising results of intermediate temperature (350° to 600°C) proton-conducting solid oxide fuel cells (P-SOFCs) from lab scale results to larger, scalable cells toward the end goal of developing a high-power density generator. Results to date show great promise for various material sets based on P-SOFC technology, and show promise for fuel flexibility, long-term durability, inherent sulfur tolerance, and coking resistance.

Accomplishments: The project accomplished the following objectives:

- Development of processing for a stable large scale tubular P-SOFC with cell interconnections
- Testing of a single large-scale P-SOFC tube
- Development of a system concept and analysis of concept system performance
- Estimates of system weight produced

Training Opportunities: Nothing to Report

Results Dissemination: Nothing to Report

Honors and Awards: Nothing to Report

Protocol Activity Status:

Technology Transfer: Nothing to Report

PARTICIPANTS:

Participant Type: PD/PI

Participant: Ted Ohrn

Person Months Worked: 1.00

Funding Support:

Project Contribution:

National Academy Member: N

RPPR Final Report
as of 07-Mar-2022

Participant Type: Co-Investigator

Participant: Richard Goettler

Person Months Worked: 2.00

Project Contribution:

National Academy Member: N

Funding Support:

Participant Type: Other Professional

Participant: Mark Scotto

Person Months Worked: 1.00

Project Contribution:

National Academy Member: N

Funding Support:

Partners

Dr. Chuancheng Duan
Manhattan, KS USA

4

Dr. Duan, assistant professor at KSU, has 8+-year of technical expertise in the design, fabrication, and manufacturing of advanced materials, solid oxide fuel cells, and solid oxide electrolysis cells. Dr. Duan and co-workers have pioneered one of the state-of-the-art triple conducting cathodes, $\text{BaCo}_{0.4}\text{Fe}_{0.4}\text{Zr}_{0.1}\text{Y}_{0.1}\text{O}_{3-\delta}$. This work has led to one granted patent entitled "triple conducting cathode material for intermediate temperature protonic ceramic electrochemical devices". Additionally, his team has demonstrated world class P-SOFCs, cost-effective fuel cell manufacturing technology, and fuel-flexible and coking-tolerant P-SOFCs. His work has led to two granted patents, high-impact articles published in Nature, Science, and Nature Energy. He has also developed extensive experience and infrastructure to design and synthesize materials, manufacture and test oxygen-ion SOFCs. Dr. Duan has developed the cathode material which enables a superior power density of $>1 \text{ W cm}^{-2}$ at $<500 \text{ }^\circ\text{C}$.

I certify that the information in the report is complete and accurate:

Signature: Cris DeBellis

Signature Date: 3/3/22 3:49PM



Contract No. W911NF21P0005

Proposal No. A20B-T003-0002 entitled "Low Temperature P-SOFC 300W Power Source"

Contractor Special Power Sources, LLC (SPS)
930 W Ely St, Suite M1
Alliance, OH 44601-1500

Title **Low Temperature P-SOFC 300W Power Source**

Final Technical Report and Includes Progress in January Nov. 1st, 2020, to Jan. 31st, 2022

Contract Performance Period Nov. 1st, 2020, to Jan. 31st, 2022

Total Contract Amount \$ 166,406.21

Amount paid by DFAS to date \$ 138,671.85

Amount invoiced to date \$ 138,671.85

Employees working on project N/A

New employees placed on contract this month 0

**Principal Investigator
(Technical Point of Contact)**

A handwritten signature in blue ink that reads "Theodore R. Ohrn".

Ted Ohrn
Chief Technology Officer
ted@spsources.com
(330) 206-4839

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PROJECT SUMMARY

The objective of the project was to take the very promising results of intermediate temperature (350° to 600°C) proton-conducting solid oxide fuel cells (P-SOFCs) from lab scale results to larger, scalable cells toward the end goal of developing a high-power density generator. Results to date show great promise for various material sets based on P-SOFC technology, and show promise for fuel flexibility, long-term durability, inherent sulfur tolerance, and coking resistance. The project accomplished the following objectives:

- Development of processing for a stable large scale tubular P-SOFC with cell interconnections
- Testing of a single large-scale P-SOFC tube
- Development of a system concept and analysis of concept system performance
- Estimates of system weight produced

The project work became behind schedule because of late delivery of materials and difficulty processing tubes. As a result, SPS requested and received a total of 10 months no cost extension to the contract as shown in Figure 1. Due to ongoing difficulties producing stable tubes, the multi-tube test was not completed (milestone 4). An updated milestone table is shown below.

ID	Task Name	Resource	2020		2021										2022				
			Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar
1.0	Project Management	SPS					Extention 1		Extention 2		Extention 3								
	Milestone 1: Kickoff Meeting		◆																
	Milestone 6: Final Report Submitted																	◆	
2.0	Technology Transfer	KSU/SPS	[Green bar from Dec 2020 to Mar 2022]																
	Milestone 2: Single Tube Tested																	◆	
3.0	Interconnect Development	SPS/KSU			[Green bar from Jan 2021 to Apr 2021]														
	Milestone 3: Tube with Interconnect Produced																	◆	
4.0	Bundle Development	SPS			[Green bar from Mar 2021 to Mar 2022]														
	Milestone 4: Two or three tube test																		
5.0	Conceptual Design and TEA	SPS			[Green bar from Feb 2021 to Mar 2021]														
	Milestone 5: Conceptual rendering produced with weight and cost estimate																	◆	

Table 1 - Project Milestones

Milestone	Task	Milestone Title and Description	Date Completed
1	1	Kickoff Meeting	Complete
2	2	Single Tube Tested	Aug, 2021
3	3	Tube with Interconnect Produced	Aug, 2021
4	4	Two or three tube test	Incomplete
5	5	Conceptual rendering produced with weight and cost estimate	May, 2021
6	1	Final Report Submitted	Mar, 2022

PROJECT TASK DETAILS

This is the Final Technical Report for this project and includes progress in January.

Task 2 Technology Transfer, Button-Cell to Single Tube

In this task, batches of powder were prepared by KSU and sent to SPS to begin trials on the formation of tubular cells following KSU protocols. Tubes were tested at SPS and compared to results obtained on button cells by KSU for similar formulations.

Results and Discussion

SPS pursued two substrate approaches toward the fabrication of tubular proton SOFCs. The initial approach was based on utilization of a NiO:BCZY support tube and a secondary approach utilizing a NiO:YSZ support was explored. The green support tubes were fabricated by wet bag iso-static pressing of spray dried powders.

NiO:BCZY support tube based P-SOFCs: Per recommendations from the KSU's background processing of button cells, a 60% NiO (by weight) and 40% BaCe_{0.4}Zr_{0.4}Y_{0.2}O_x (BCZY442) mixture of spray dried powder was procured for the tube fabrication. Electrical conductivity of the tube material was measured in the form of a pressed, sintered and reduced bar. The conductivity is plotted in Figure 2 for a bar having a residual porosity of about 25%.

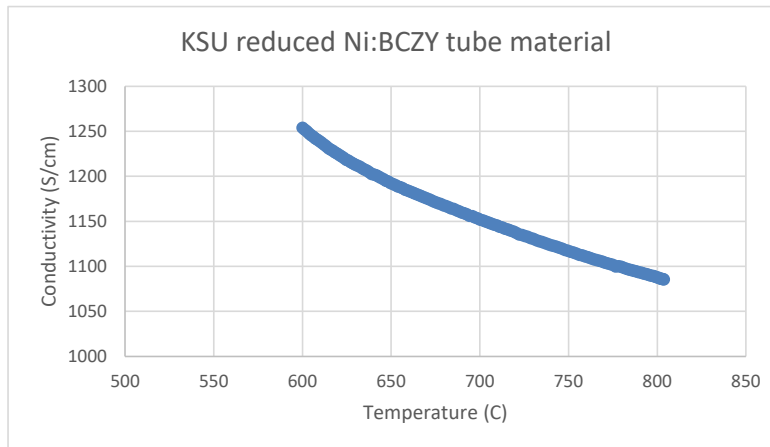


Figure 2 - Conductivity of a reduced sintered bar of 60NiO:40BCZY

Initially, a mandrel and mold were procured to press tubes that would sinter to ~15mm diameter, 0.75mm wall thickness and cut to 46 cm (standard tube length of SPS commercial tubes). The diameter and wall thickness was smaller than the SPS commercial SOFC tubes at 22 mm diameter and ~1.2mm wall thickness in order to minimize use of the NiO:BCZY powder. Challenges were experienced in removal of the initial sized P-SOFCs from the pressing mandrel, and as a result the resulting tubes were missing their closed end and had to be cut following sintering to less than the targeted 46 cm length. However, the tubes were adequate for initial sintering and reduction studies. Following pressing of the tubes, the active anode layer (also NiO:BCZY) and the BaCe_{0.4}Zr_{0.4}Y_{0.1}Yb_{0.1}O_x (BCZYb4411) was applied by ultrasonic spraying of slurries. The green tube plus anode and electrolyte layers were co-fired. As

shown by the microstructure of Figure 3, good densification was achieved for the BCZY:NiO tube and the BCZYYb electrolyte.

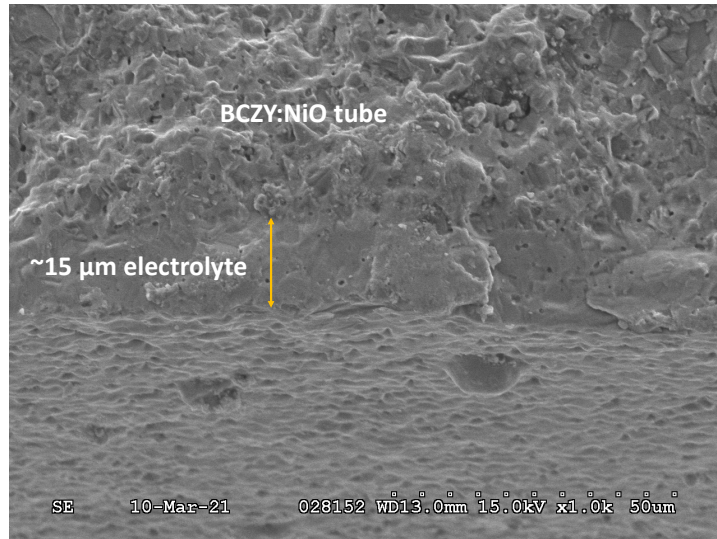


Figure 3 - Fractured cross section of proton SOFC fired to 1470C

Reduction trials to convert the tube and active anode to BCZY:Ni-metal and to introduce the porosity for gas transport was initially performed at standard temperatures and gas flows utilized for SPS Ni:YSZ tubes. This proved damaging to BCZY:Ni tube. KSU recommended the reduction procedure they utilize for small button cells based on lower temperatures and H₂/N₂ mixes versus the methane reformat mix typically used at SPS. The lower temperature and more moderate fuel concentrations recommended by KSU benefited the reduction process however the tubes were found to be fragile as repeated fracture of the tubes occurred during routine handling as shown in Figure 4.



Figure 4 - BCZY:NiO tube with interconnect bands overcoated with silver ink reduced in test rig under H₂/N₂ mixtures

NiO:YSZ support tube based P-SOFCs: To overcome the fragility of the reduced BCZY:Ni tubes SPS proceeded to investigate utilizing the baseline Special Power Sources' NiO:YSZ tube support and spraying on and co-firing with the tube the active proton BCZY:NiO anode and BCZYYb electrolyte. An additional benefit of this approach is that pore structure of the tube has been established for the Ni:YSZ to provide appropriate permeability for good electrochemical functionality and gaseous diffusion. The electrical conductivity of the Ni:YSZ at 600°C is ~ 2XXX S/cm versus the measured value of ~1250 S/cm for the Ni:BCZY tube.

Sintering/co-firing studies at 1485°C were performed for the NiO:YSZ/NiO:BSZY anode/BCZYYb proton conducting electrolyte. Figure 5 is an example of a co-fired tube that is the standard size of Special Power Systems production SOFCs. Upon reduction of the tube under propane reformat compositions and dual environment for the tube, some delamination of the electrolyte was observed.

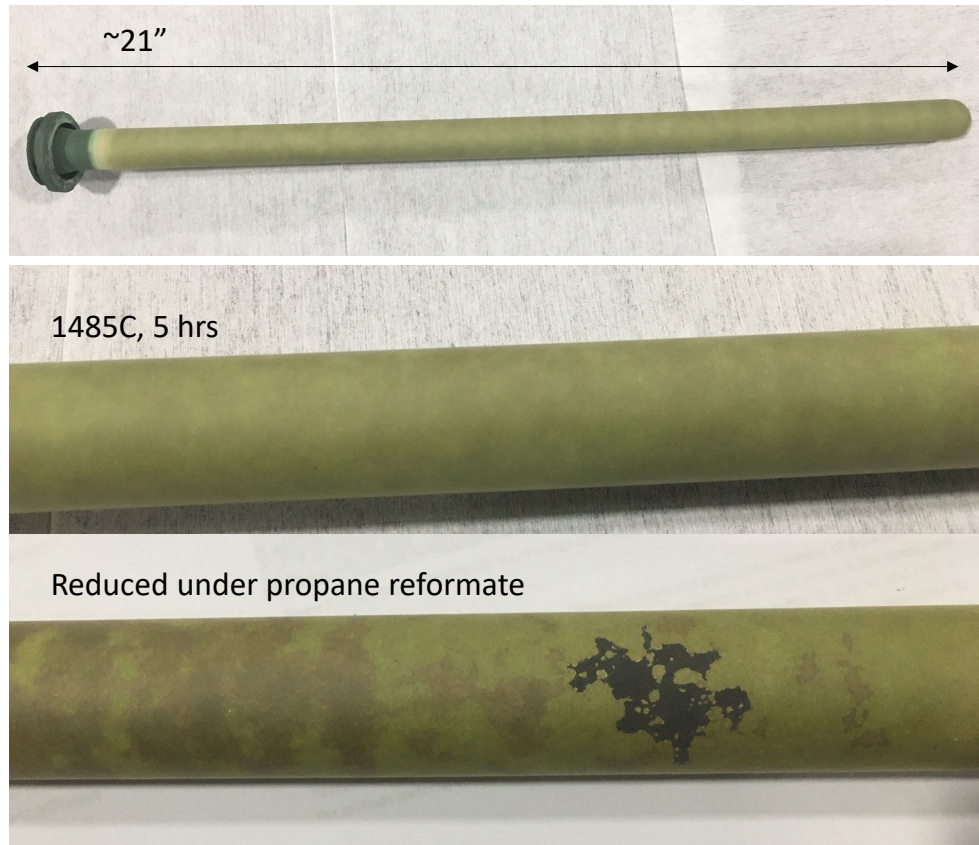
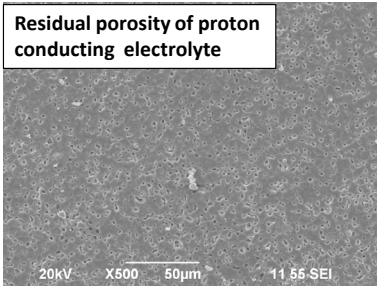


Figure 5 - Example of NiO:YSZ tube cofired with NiO:BCZY anode and BCZYb electrolyte

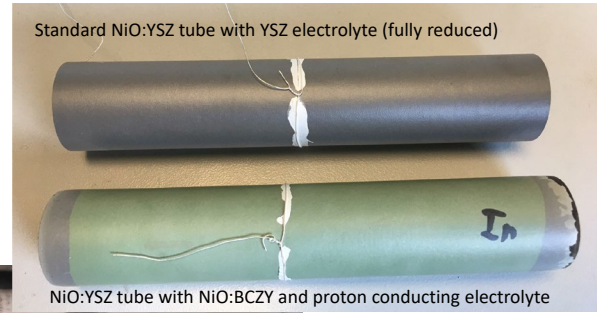
Further heat treatments up to 1535°C were performed on the tubes initially co-fired at 1485°C and resulted in improved sheen of the electrolyte surface, typically indicative of higher density. Figure 6 shows the results of reduction experiments performed for a NiO:YSZ tube with the proton conducting electrolyte, fired additional time at 1535°C. Reduction at 600°C under H₂/N₂ gas compositions achieved open circuit voltages of only ~0.5V. The reduction configuration and gas sealing was verified with a standard NiO:YSZ and YSZ electrolyte tube that exhibited the expected voltage of >1V. Microscopy revealed that the additional heat treatment to 1535°C still retained relatively high residual porosity within the proton conducting electrolyte adversely affecting the sealing and achieving an untestable fuel cell. It was concluded that additional development effort is required to achieve a proton conducting electrolyte powder with the required sintering kinetics and matched appropriately to the sintering characteristics of the NiO:YSZ support tube.



Configuration in test rig during reduction



Reduced Tubes



Ejector, fuel supply to tube

Figure 6 - Reduction of tube with proton conducting electrolyte versus standard YSZ electrolyte

Given the timeline of the project and the long lead time for the development of a new powder with the optimized composition, dopants/sintering aids and particle sizes it was determined to revisit the processing of tubes based on the NiO:BCZY support material. Improved structural integrity of the tube was addressed through a shift to a larger diameter tube with a thicker wall. (~22 mm sintered diameter and ~1.2mm wall as standard SPS tubes). In addition, literature reviews revealed the sensitivity of proton conducting electrolytes to oxygen partial pressure and temperature changes as a result of the chemical expansion of those compositions. Heating rates and gas compositions were better managed during the reduction process to improve integrity of the electrolyte. Initial reduction trials were performed with sections of small diameter processed NiO:BCZY tubes. As summarized in Figure 7, open circuit voltages of ~1V were achieved. The reduction cycle was rather prolonged (>50hr) to hit peak open circuit voltages.

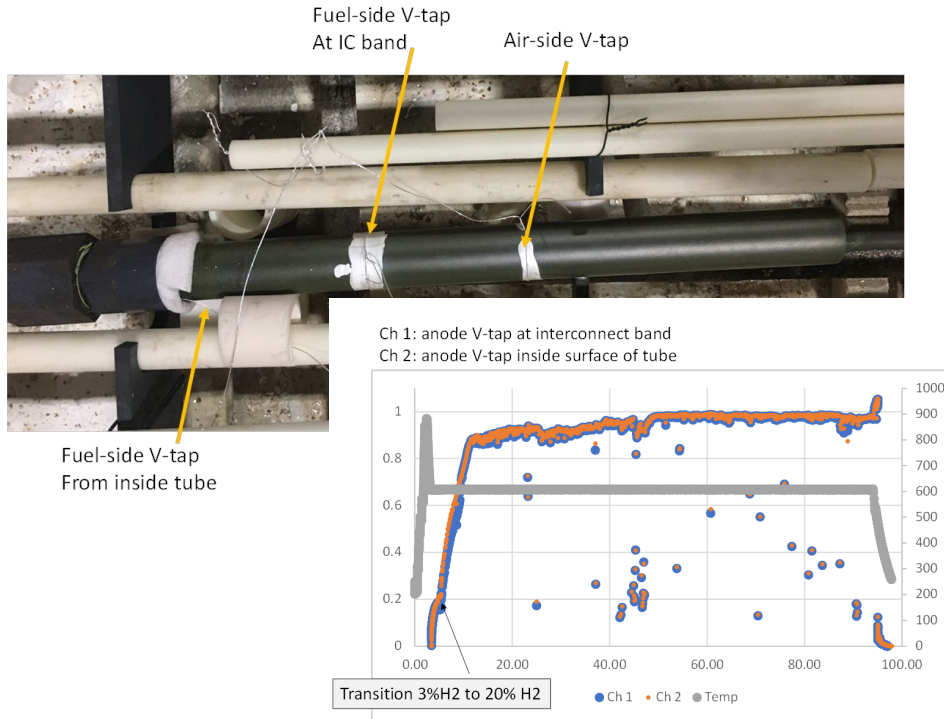


Figure 7 - Improved reduction of NiO:BCZY tube with proton conducting electrolyte

Cathode Recommendation by KSU: KSU provided button cell performance data for two cathodes (Figure 8) listed below. The ASR for the button cells were ~ 0.34 ohm-cm² tested at 600°C on low fuel utilization of hydrogen. It should be noted that KSU utilized a low firing temperature of 900°C for the cathode processing resulting in a very active (minimally sintered) cathode.

- $\text{PrBa}_{0.5}\text{Sr}_{0.5}\text{Co}_{1.5}\text{Fe}_{0.5}\text{O}_{5+\delta}$ (PBSCF)
- Composite of $\text{BaCo}_{0.4}\text{Fe}_{0.4}\text{Zr}_{0.1}\text{Y}_{0.1}\text{O}_x$ (BCFZY) and $\text{BaCe}_{0.4}\text{Zr}_{0.4}\text{Y}_{0.1}\text{Yb}_{0.1}\text{O}_x$ (BCZYYb4411)

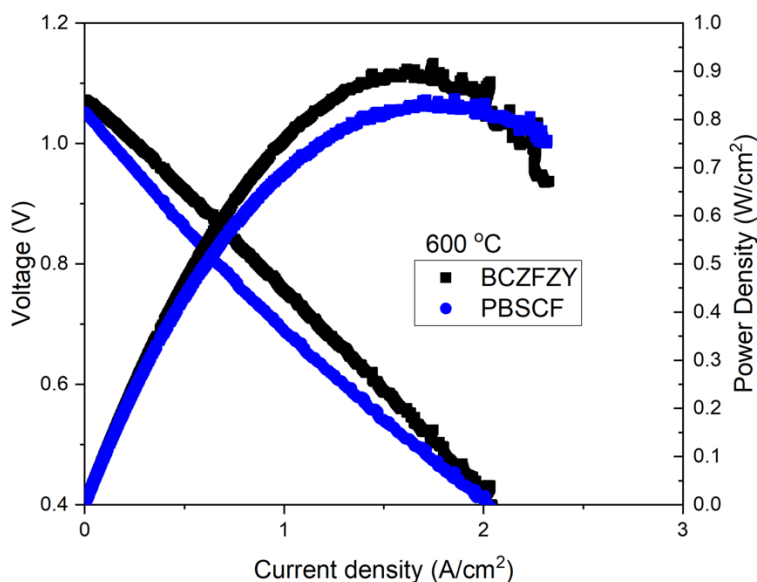


Figure 8 - Button cell comparison of recommended cathodes

The initial cathode utilized for full scale cell fabrication was $\text{PrBa}_{0.5}\text{Sr}_{0.5}\text{Co}_{1.5}\text{Fe}_{0.5}\text{O}_{5+\delta}$. Various firing temperatures from 900°C up to 1150°C . Higher firing temperatures were required for the full-scale tubes to achieve adequate adhesion strength of the cathode to the electrolyte. Even with the 1150°C firing temperature, SPS was unable to reliably screen print the silver cathode-side current collecting mesh pattern without avoiding delamination of the cathode layer. Cause of this is combination of degree of sintering to the electrolyte and the high thermal expansion of the cathode.

Task 3 Interconnect Development

In this task, SPS and KSU explored utilizing interconnect (IC) bands to connect to the anode side of the fuel cell. This effort was led by SPS to determine if existing options for the SOFC materials (plasma sprayed and screen-printed options) are compatible and have sufficient conductivity for this application. Other potential materials will be explored by KSU.

Results and Discussion

The interconnect material utilized in SPS' commercial SOFC cells is a plasma sprayed chromite applied at four interconnect locations along the 46cm tube. These interconnections allow the electrical connection between adjacent tubes in a SOFC stack/bundle, and the chromite is chemically stable with the underlying YSZ electrolyte and NiO:YSZ tube support material. KSU performed experiments to probe the compatibility of the chromite with the BCZYb4411 electrolyte material. The interconnect band powder was mixed with the BCZYb4411 electrolyte powder and ball mill for 2 hours. The x-ray diffraction (XRD) of both pristine, as-milled powder and after treatment in ambient air at 600°C for 48 hours, and at 1400°C for 10 hours was performed. Figure 9 shows the XRD patterns before and after treatment. Some additional peaks are present after the thermal treatments, especially after 1400°C exposure (a temperature condition experienced during the processing steps). These results indicate the potential of the IC band and the proton electrolyte materials reacting to form interphases of high electrical resistance.

The difficulty in achieving a fully dense BCZYYb electrolyte co-fired with the NiO:YSZ tubes as described under Task 2 meant that an interconnect material compatible with the NiO:BCZY support material was necessary. Two approaches were considered as summarized in Figure 10. Option 1 continues to utilize the standard plasma sprayed chromite interconnection but with a barrier layer co-fired with the NiO:BCZY support tube and BCZYYb electrolyte. The barrier layer is compatible with the chromite and the tube support materials. Option 2 utilizes a silver interconnection applied using commercial inks and firing to temperature sufficient to densify the silver to provide a suitable gas seal between the fuel and air sides of the cell.

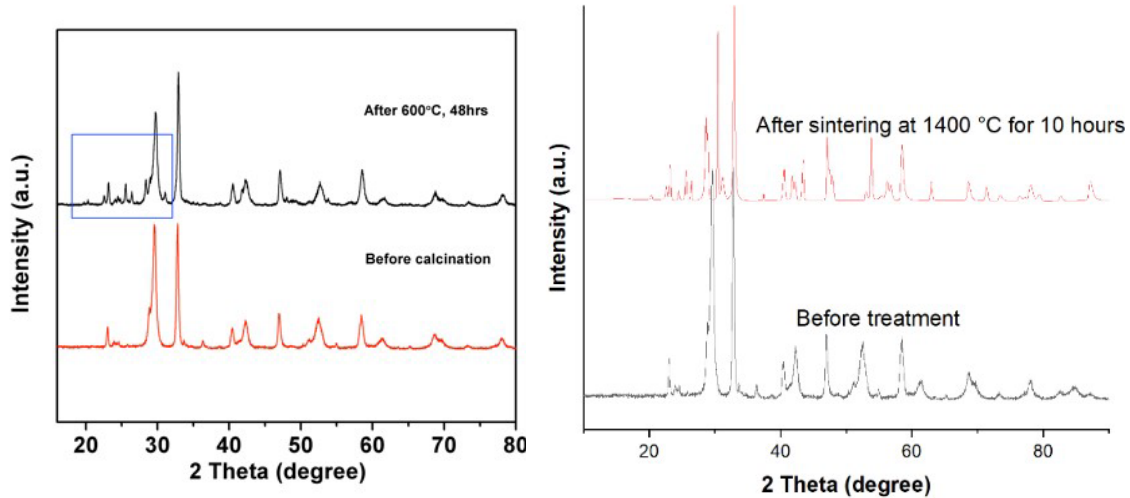


Figure 9 - XRD patterns of the mixed IC band material and electrolyte powder, and the composite powder after treatment at 600 °C for 48 hours (left). At 1400 °C for 10 hours (right).

Option 2 was selected for emphasis during Phase 1 for the purpose of demonstrating the proton conducting electrolyte on a large format tube configuration given the more extended time required to develop and optimize the barrier layers for interconnect approach Option 1. Figure 11 shows the open circuit voltage (OCV) achieved for a full size (45 cm long, 2.2 cm diameter) standard tube with silver interconnect bands processed and heat treated as required for a NiO:BCZY tube. The tube was reduced under H₂/N₂ conditions at 600°C required for proton conducting tube material sets. An OCV of ~0.98V was achieved. On post-test inspection, the tube exhibited a high leakage per the SPS standard qualification test. But the tube leakage was in specification after cutting out an end section of tube with one suspect quality interconnect band indicating some variability in the quality of these initial silver interconnect bands. Overall, Option 2 was a viable approach for demonstrating the electrochemical performance of a commercial scale, geometry proton conducting tube.

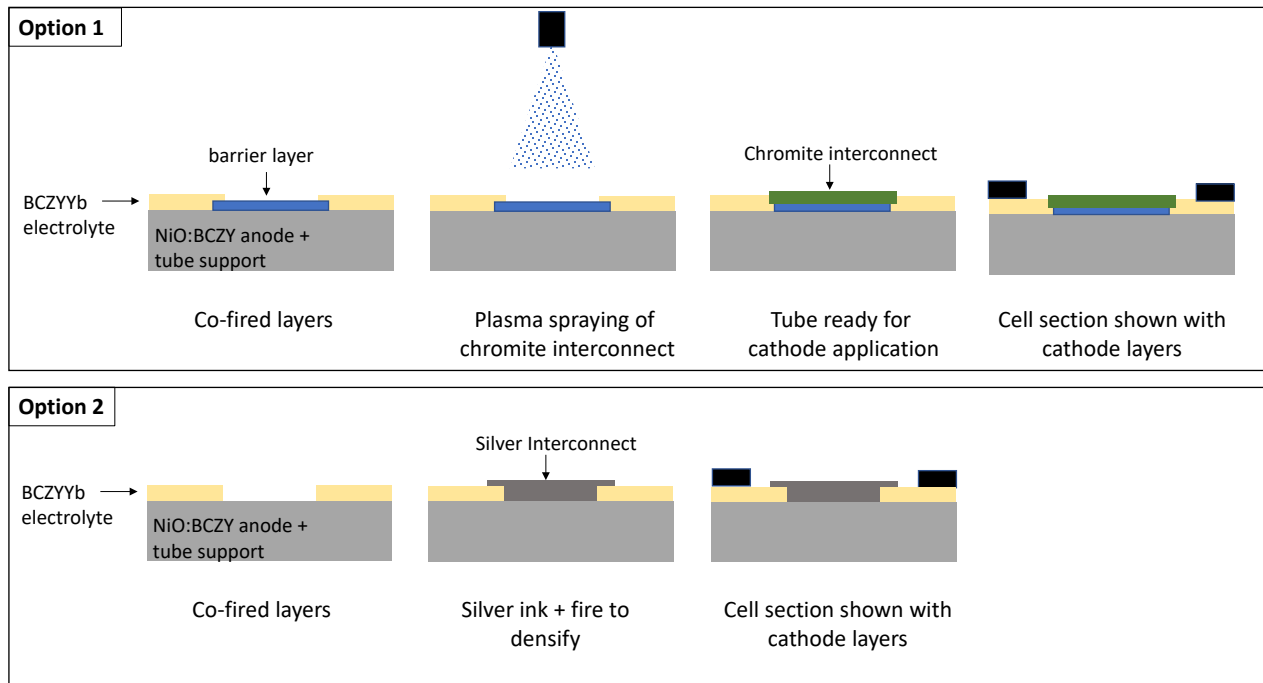


Figure 10 - Options for anode-to-cathode interconnect materials

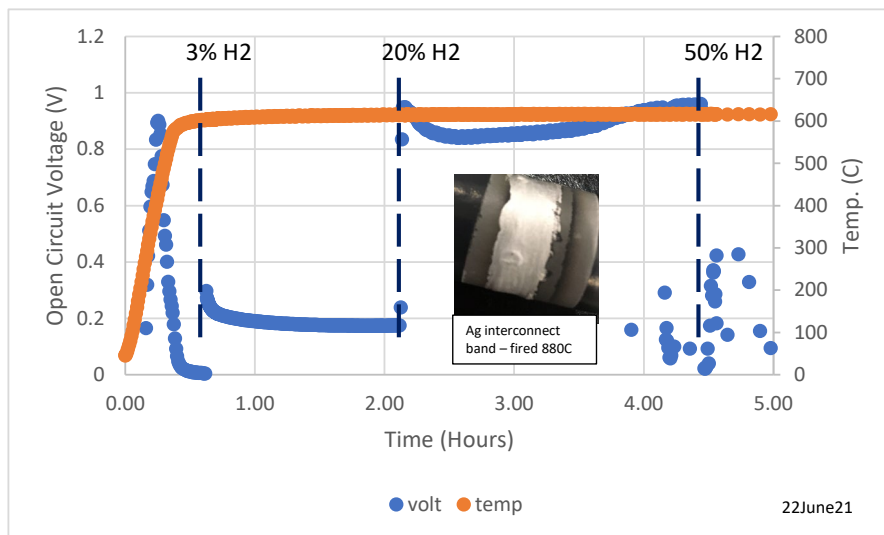


Figure 11 - Initial demonstration and OCV of a tube having silver interconnections for low-temp (~600°C) proton conducting SOFC

Task 4 Bundle Development

The intent was to demonstrate the interconnection between tubes with at least 2 cells. Because of difficulties producing stable tubes, this task was not completed. The capability to connect tubes is inherently demonstrated by the method of testing which utilizes interconnections exactly as would be done in a bundle.

Results and Discussion

Figure 12 shows a P-SOFC tube constructed of the NiO:BCZY support and anode and BCZYYb electrolyte and combined with the silver interconnection, and at various stages of fabrication in preparation for electro-chemical testing. This commercially relevant P-SOFC single cell has an active area of $> 150 \text{ cm}^2$.

Sintered tube with fired cathode



Application of interconnect band



Application of cathode current collection

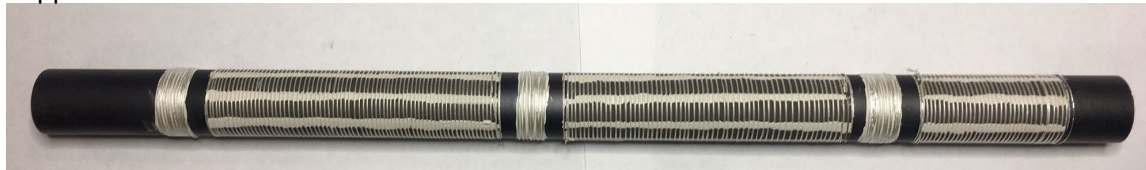


Figure 12 - Progression of tubular P-SOFC processing through cathode-side current collection

The cathode applied for the cells fabricated is $\text{PrBa}_{0.5}\text{Sr}_{0.5}\text{Co}_{1.5}\text{Fe}_{0.5}\text{O}_{5+\delta}$.

Being standard diameter tubes, the cells are readily able to be tested in the established testing rigs utilized at SPS for quality assurance, performance, and short-term durability testing. The installation of a P-SOFC is documented in Figure 13. The performance of the tubular P-SOFC at 600°C , shown in Figure 14 was measured as an area specific resistance of 1.4 ohm-cm^2 and a peak power density of 0.146 W/cm^2 . A single tubular P-SOFC cell delivered a peak power of 22 W . The open circuit voltage of $\sim 0.91\text{V}$ was low attributed to leakage at the interconnect band and tube/electrolyte defects upon reduction. The interconnect band for these Phase 1 tubes is a sintered silver film versus a plasma sprayed chromite used on SPS standard NiO:YSZ tubes. The area specific resistance is high compared to values of 1.05 ohm-cm^2 measured at the button cell level for a cathode fired similarly at 1150°C . Additional resistance for the full-scale tubular P-SOFC is expected given the in-plane conductance paths for a tubular cell, current distribution variations, the interconnection losses and gas diffusional resistance losses arising from the denser substrate structure utilized than for button cells.

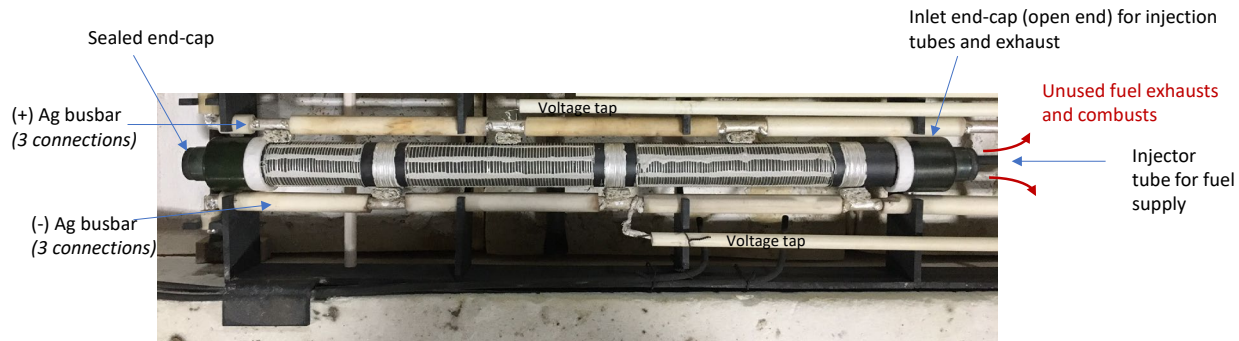


Figure 13 - Example of P-SOFC tube installed in test fixture

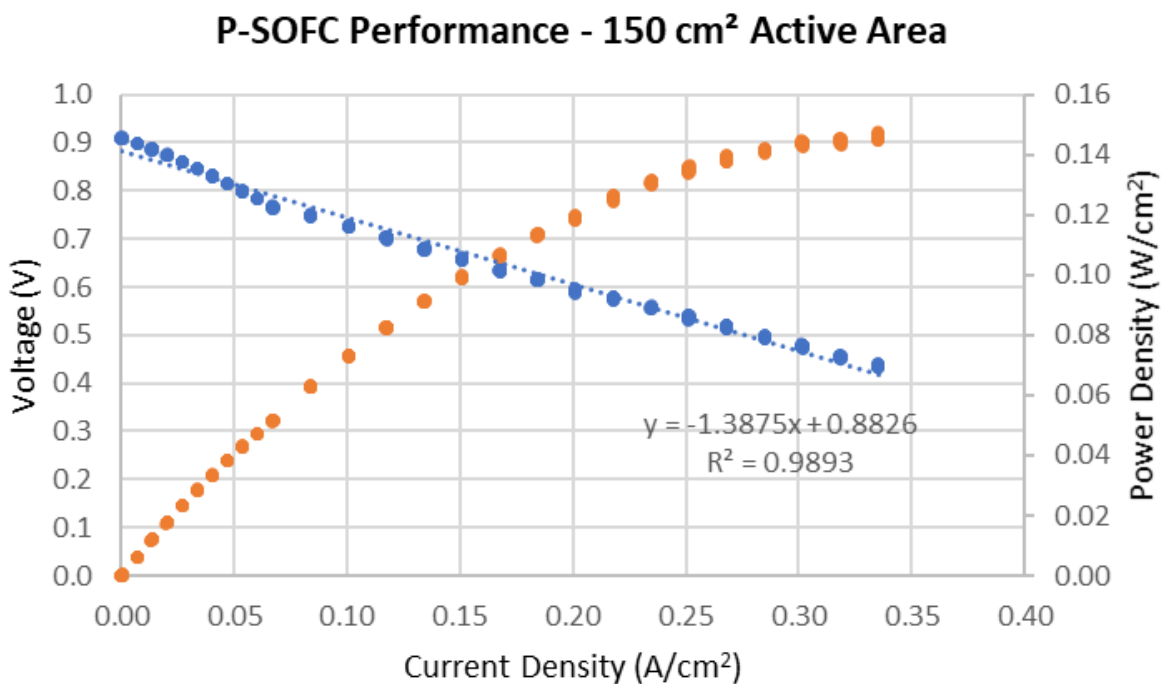


Figure 14 - Tubular P-SOFC e-chem performance V-I plot (PBSCF cathode, 1150C firing)

A different cell with the PFBCF cathode exhibited similar ASR at that shown in Figure 15, but voltage collapsed at ~ 0.15 A/cm². As shown in Figure 15, the tube had multiple cracks on cooling, and various degrees of cracking was observed on all NiO:BCZY substrate based P-SOFCs tested under this project. The excessive cracking is attributed to the chemical expansion characteristics of the barium cerium-zirconate material. A single tubular cell was fabricated with the newly identified BaCo_{0.4}Fe_{0.4}Zr_{0.1}Y_{0.1}O_x (BCFZY) and BaCe_{0.4}Zr_{0.4}Y_{0.1}Yb_{0.1}O_x (BCZYYb4411) cathode. However, the ASR was measured as substantially higher than that obtained for the PBSCF cathode, both cathodes fired at 1150°C. Follow-on work is required to understand the cause of the higher ASR for the BCFZY:BCZYYb cathode.



Figure 15 - Representative tube cracks following reduction and electrochemical testing.

The single tubes that were tested were electrically connected to the bus bar of the test rig in an identical manner as tubes are bundled together in a multiple tube stack configuration. Because of budget and program time limitations, multiple tubes were not actually tested in a bundle configuration.

The main conclusion from the processing experience and testing results was that the preferred design for the P-SOFC is that based on the NiO:YSZ support tube. That approach would provide a structurally robust support tube. Materials development is required to achieve sufficient electrolyte density upon cofiring with the support tube and underlying active anode layer. (See G. Hudish et. Al., “Chemical expansion in $\text{BaZr}_{0.9-x}\text{Ce}_x\text{Y}_{0.1}\text{O}_{3-\delta}$ ($x=0$ and 0.2) upon hydration determined by high-temperature X-ray diffraction”, J. Am Ceram Soc., 2018;101:1298-1309.)

Task 5 System Conceptual Design and Modelling

A system concept is developed for a small compact portable SPS power-generation unit that uses PSOFC technology. The “P” in PSOFC is for proton exchange where hydrogen is transported through the electrolyte membrane to the cathode side rather than traditional SOFC where oxygen is transported to the anode side. Therefore, in order to promote reforming of fuel on the anode side without carbon formation, steam must be added as part of the fuel feed for a system that uses PSOFC technology. The current proposed solution employs a small store of glycol solution to provide the required steam. Although this approach adds some weight, there are several performance advantages when comparing this technology (PSOFC) to SOFC that yield a net weight benefit for the system.

Steam reforming is endothermic or heat absorbing leading to significant process advantages. The heat absorbed can be used to control fuel cell temperature and may be better suited for PSOFC technology since one of the intents behind their use is to operate at lower temperature which has other operational advantages not discussed here. The absorbed heat is turned into chemical energy that yields input power or heating value that is higher than the original fuel feed. Conversely, SOFC technology typically uses air to make hydrogen in a process known as partial oxidation that does the opposite, lowers the input power of the fuel feed in proportion to the amount of air used, typically 15-20%. The disadvantage of steam reforming is that it requires steam which could lead to additional process unit operations to recover the required energy to make the steam. However, SPS proposes what it believes is a relatively

simple approach to achieve internal steam reforming in the small portable unit proposed, which is the subject of the phase 1 work performed for the Army.

Other operational factors that improve performance for PSOFC compared to SOFC are a higher reversible voltage of the fuel cell. Reversible voltage (V_{rev}) indicates the thermodynamic performance potential of the cell which is a function of temperature, pressure, and composition at the active cell surface. PSOFC conditions lead to a relatively high reactant H_2 concentration, and a relatively low reactant steam concentration that yield a relatively high V_{rev} .

Area specific resistance is the other main factor related to performance. A cell with a low resistance design improves performance in terms of power output and efficiency. It is experimentally observed that ASR always decreases with increasing temperature which favors the higher temperature SOFC approach. However, it is believed that PSOFC can overcome the trend of increased ASR with lower temperature due to its unique material set that promotes low resistance at low temperature, and by yielding operating conditions that increase the minimum required ASR to meet the targeted performance.

Modelling Results

The modelling results presented below compare performance for SOFC and PSOFC for the same thermal input and fuel cell surface (i.e. number of standard size SPS tubes). Fuel cell current density and fuel utilization as defined is roughly the same between cases. The calculations show power density 50% higher at 45% efficiency versus ~30% efficiency for SOFC. The explanation for this is given below.

Figure 16 below shows the PSOFC steam reforming conditions that yield the high V_{rev} values. Steam reforming yields an incoming H_2 concentration over 42%. In addition, PSOFC takes hydrogen away from the anode as it reacts. This induces the water gas shift to produce more hydrogen to maintain its equilibrium as H_2 is consumed. This tends to sustain H_2 at high concentration levels as the reactions proceed. The model calculations show that the H_2 concentrations remains above 30% until the backend of the cell surface where it starts to drop off more rapidly. In addition, high levels of steam, a fuel cell product, reduces V_{rev} . With PSOFC the pertinent steam levels for the calculation of reversible voltage are on the cathode side, and are relatively low due to dilution in air, the carrier gas. The steam contents on the air side peak around 3%. Therefore, the reversible voltage is very high, in part due to the lower temperature operation typical of PSOFC, but also due to this composition effect.

For comparison to PSOFC, the typical SOFC CPOX propane conditions are shown in Table 2. The standard SOFC system requires propane CPOX typically operating at an O/C ratio of 1.2 and requiring an external CPOX reactor to reform the gas. Propane CPOX yields an inlet mole% H_2 of ~27%. The required minimum ASR for the given level of performance shown can be much higher for PSOFC which will help to offset the tendency for ASR to increase with decreasing operating temperature. Given the operating advantages of PSOFC using steam reforming, it is believed this technology can easily overcome the inherent disadvantage of lower operating temperature with respect to its impact on ASR yielding improved power output and higher efficiency operation for a given active cell surface area.

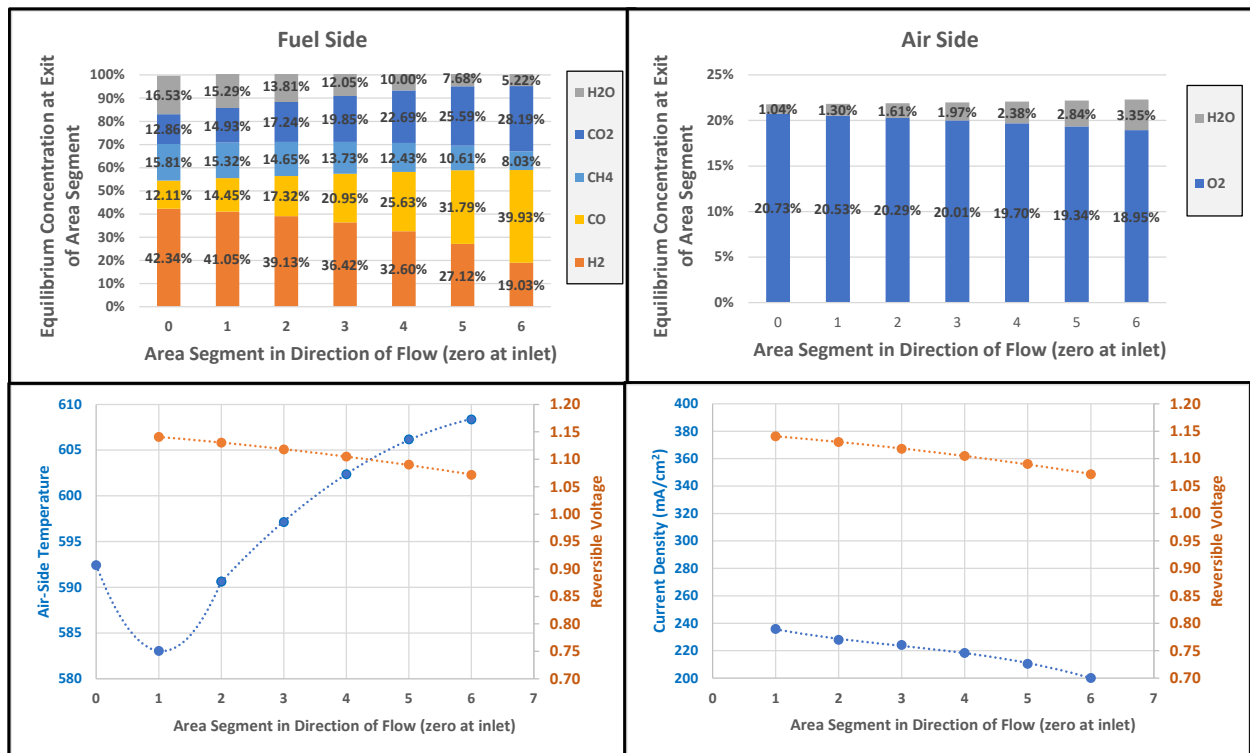


Figure 16 - SPS modelling showing FC profile results for composition, temperature, and current density.

Table 2 - Comparison of modelled PSOFC with Steam Reforming with typical output for propane CPOX

Parameter	units	PSOFC w/ Steam Ref.	SOFC w/ CPOX
Operating Temperature	°C	600	750
Fuel Power Input,	watts (fuel LHV * fuel flow)	1000	1000
After Reforming	watts	1170	810
Fuel Cell Power	watts	450	300
FC Fuel Utilization	% (FC heat / power in)	53	52
V _{rev}	volts	1.1	0.95
V _{op}	volts	0.8	0.75
Current Density	amps/cm ²	0.22	0.22
Required ASR	ohm-cm ²	1.38	0.86

System Weight Trade-off

PSOFC requires steam reforming that necessitates the use of a stored water supply which has the inherent disadvantage of added system weight. A practical means of providing water would be as an

ethylene glycol solution which would avoid the issue of freezing in any field application. Figure 17 shows a gallon of antifreeze to be blended with a 2-pound supply of propane. This mixture is calculated to provide about 30 hours of mission operation per the modelling results presented above. The added weight of the ethylene glycol is about 8.5 lbs. assuming the added weight of a liquid micropump to inject it into the system is roughly offset by that of an air blower required for the standard SOFC CPOX approach. Therefore, given the increases power density of PSOFC, for total system weights (with the ethylene glycol excluded) of 17 lbs. or greater, the PSOFC approach should yield reduced weight in terms of power density if the ASR targets predicted by the model can be achieved. It is expected that the system weight will be significantly greater than 17 lbs.



Figure 17 - Proposed fuel-side reactant supply for approximately 30 hours of operation at 45% efficiency