Novel Combined Heat and Power (CHP) System

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Novel Combined Heat and Power (CHP) System

Final Report

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Abstract

A comprehensive study investigating the integration of solid oxide fuel cells (SOFC) into a residential boiler has been completed. Material compatibility, combustion chamber characterization, thermal cycling abilities, long-term performance, and more factors related to the ability to generate electrical power directly from the hot exhaust gases present in heating, ventilation, and air conditioning (HVAC) systems have all been investigated in order to prove feasibility and begin development of commercial SOFC combined heat and power (CHP) systems. Testing was done with a combination of bench-top, lab-scale tests, real commercially available system analysis/integration, and theoretical analysis. Ultimately, the effectiveness of fully integrated SOFC CHP systems was shown and the remaining barriers toward full commercialization are minor, and plans exist for moving past those barriers.

Major achievements of this project include: development of a rich-burn, quick-mix, lean-burn (RQL) combustion chamber for testing flame-assisted fuel cells (FFCs), two comprehensive SOFC longevity tests, material investigation resulting in the development of high-power SOFCs, the initial development of a novel geometry micro tubular SOFC (mT-SOFC), a series of studies into the New York State CHP market, and an assessment of the economic feasibility of the proposed technology.

Keywords

Combined heat and power, cogeneration, solid oxide fuel cell, tubular solid oxide fuel cell, combustion, flame assisted fuel cell, microtubular solid oxide fuel cells

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Acronyms and Abbreviations

CHP	combined heat and power
SOFC	solid oxide fuel cell
FFC	flame assisted fuel cell
mT-SOFC	microtubular solid oxide fuel cell
IC-tSOFC	internal cathode tubular solid oxide fuel cell
RQL	rich-burn, quick-mix, lean-burn
Syngas	synthetic gas
COMER	Combustion and Energy Research
YSZ	yttria stabilized zirconia
SDC	samaria doped ceria
GDC	gamaria doped ceria
LSCF	lanthanum strontium cobalt ferrite
ICE	internal combustion engine
NiO	nickel oxide
OCV	open circuit voltage
SEM	scanning electron microscopy

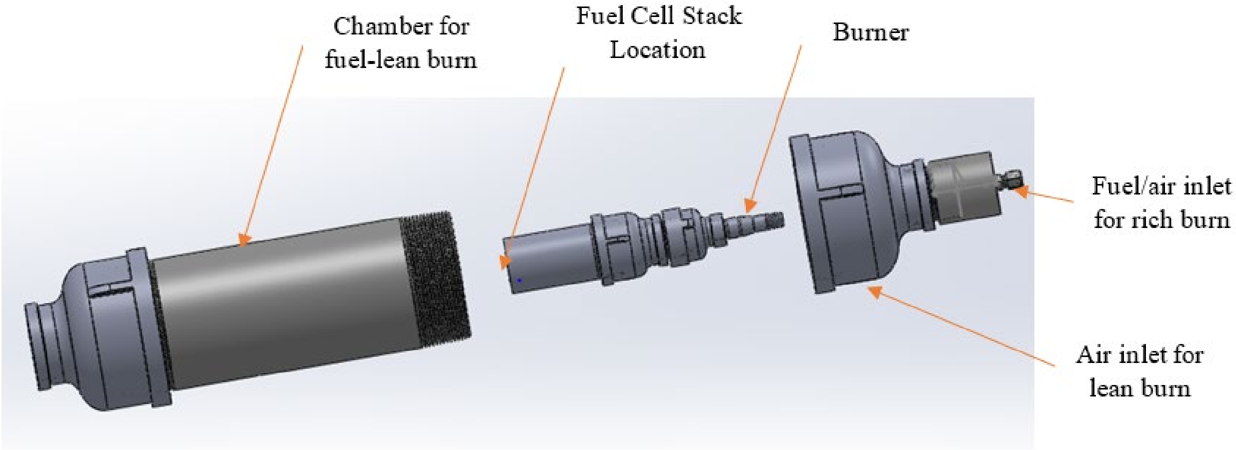
Executive Summary

In this work a novel combined heat and power (CHP) system was developed which directly integrates solid oxide fuel cells (SOFCs) into the combustion chamber of a residential boiler. CHP systems have seen increased interest because of the desire to reduce greenhouse gas emissions and overall energy usage (Knight and Ugursal 2005; d'Accadia 2003). SOFC based systems, however, have experienced limitations due to the separation of the heating, ventilation, and air conditioning (HVAC) system from the SOFC generator. The SOFC generator requires several additional balance of plant subsystems, including fuel processing and delivery and thermal management due to the high operating temperatures required for SOFC operation (Milcarek, Ahn, and Zhang 2017; Braun, Klein, and Reindl 2006). These energy consuming subsystems can be avoided by directly integrating the SOFC stack into the HVAC combustion chamber where the necessary fuel and temperatures are already present. To achieve this, the reliability of SOFCs in this environment must be studied and SOFCs that specifically meet the requirements of this application must be developed.

Work began with a comprehensive investigation into the performance of SOFCs in combusted methane exhaust. A rich-burn, quick-mix, lean-burn (RQL) chamber (Figure ES-1) was constructed and consisted of two chambers separated by microtubular SOFCs (mT-SOFCs). In the first chamber methane was mixed with air at a high-equivalence ratio to obtain high concentrations of carbon monoxide and hydrogen, referred to as synthetic gas (syngas). This hot exhaust was routed through the inside of mT-SOFCs where it was then mixed with more air to ensure combustion of any remaining fuel. The chamber was used to examine temperature and species fluctuations as equivalence ratio in both chambers was adjusted (Milcarek and Ahn 2018b). Initial performance examinations were also done with the chamber identifying issues with sealing that would need to be remedied in future iterations. When progressing toward boiler integration, these environment characteristics would attempt to be matched as closely as possible to ensure satisfactory SOFC performance. Also using this chamber, an extensive thermal cycling test was performed in which the SOFC stack was put through 3000 cycles where the temperature was raised to 1200ºC and then lowered to 300ºC (Milcarek et al. 2018). Boilers turn on and off frequently depending on heating load and so the SOFC stack developed in this project must be able to withstand this cycling. Performance degradation was minimal with only a 6.88% drop in open circuit voltage (OCV) of the cells, indicating the stack's ability to withstand a lifetime of thermal cycling as desired.

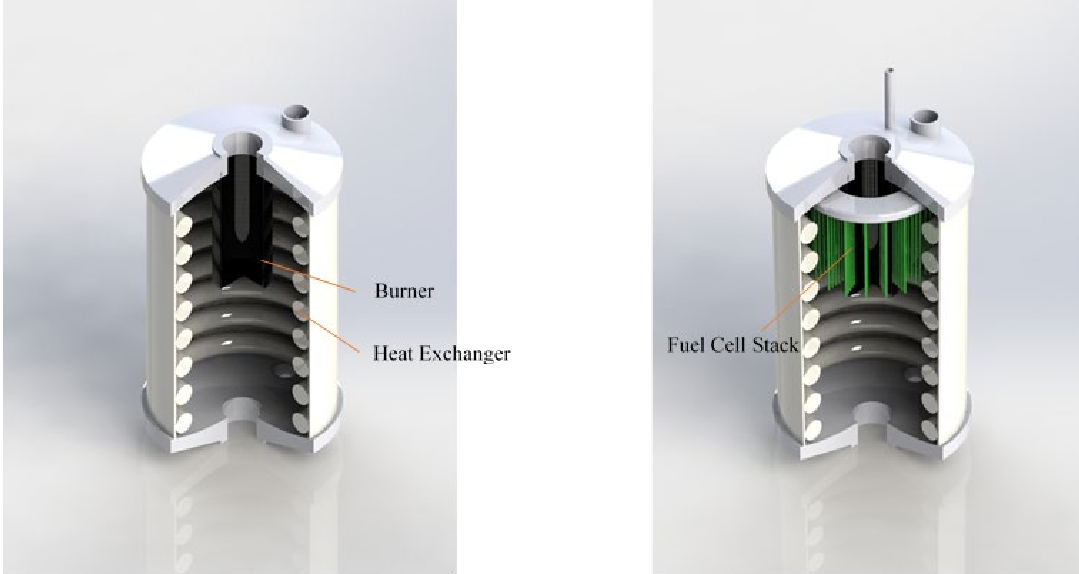
Finally, the chamber was used for a material study in which a buffer layer was added between the electrolyte and cathode of the cell. The buffer layer dramatically improved performance of SOFCs in the RQL chamber, increasing peak power density from 30 milliwatts/centimeter squared (mW/cm^2) to over 200 mW/cm^2. These cells in general also showed some of the highest performances of any SOFC tested in the COMER laboratory with peak power exceeding 1.57 W/cm^2 when using hydrogen as a fuel.

Figure ES-1. Diagram of Rich-Burn, Quick-Mix, Lean-Burn Chamber



The information gained from the RQL chamber was then applied to SOFC integration into a residential boiler. This process began by purchasing a modulating boiler of 20,000–50,000 British thermal units (Btu) in size from ECR International in Utica, NY. Boiler characterization tests were carried out and focused on obtaining temperature profiles and species concentrations as equivalence ratio was varied. It was found that syngas was generated at high-equivalence ratios as expected, proving the potential for SOFC operation in the boiler environment. The dimensions of the boiler were also taken for the development of SOFC stack. A model of the SOFC stack integrated into the boiler was developed (Figure ES-2).

Figure ES-2. Diagram of SOFC Stack Integrated into Residential Boiler



Although the boiler combustion chamber has the temperatures and fuel necessary for SOFC operation, mT-SOFCs are currently constructed in a way which requires the air accepting cathode surface to be on the outside of the tube, ultimately requiring fuel to be routed through the inside of the tube. This is a requirement that cannot be met without major alterations to the boiler, motivating the development of an internal cathode microtubular SOFC (IC-tSOFC) that has the anode surface on the outside of the tube, allowing for SOFC operation in the chamber without fuel rerouting needed. The geometry, however, causes stresses in the cell, which lead to cracking. At this time the defect has been unresolved, but work is continuing and functional IC-tSOFCs will be developed. Despite this issue, mT-SOFCs were tested in benchtop setups which replicated the boiler environment. When operating off model boiler exhaust, mT-SOFCs achieved peak power densities of over 350 mW/cm^2 and were shown to not degrade during long-term, 24-hour testing. Ultimately, this shows that the integration of SOFCs into a residential boiler can provide electrical power as intended without the need for a separate SOFC generator and the required complex subsystems. With finalization of the development of IC-tSOFCs, a prototype of the device can be produced illustrating the potential of this technology.

Finally, a market analysis, intellectual property (IP) landscape and competitive analysis was carried out to examine the economic viability of the technology. No preexisting technologies were found to be similar enough to cause issues when pursuing IP protection. Furthermore, it was found that the CHP market is growing in New York State and given the low cost of natural gas, adoption of this system is likely once development is finalized.

1 Introduction

The objective for this study was to produce a combined heat and power (CHP) system that integrated a solid oxide fuel cell (SOFC) stack directly into the combustion chamber of a residential boiler. The fuel cell stack would use the heat and exhaust gases already present in normal boiler operation to produce electricity. The electricity would then be used to power all system electronics, yielding a resilient, high-efficiency, and low-emission heating ventilation and air conditioning (HVAC) system.

Major achievements of this project include: development of a rich-burn, quick-mix, lean-burn (RQL) combustion chamber for testing flame-assisted fuel cells (FFCs) (Milcarek and Ahn 2018b), two comprehensive SOFC longevity tests (Milcarek et al. 2018), material investigation resulting in the development of high-power SOFC (Milcarek, Wang, Falkenstein-Smith, et al. 2016b; Milcarek, Wang, Garrett, et al. 2016), the initial development of a novel geometry micro tubular SOFC (mT-SOFC), a series of studies into the New York State CHP market (Milcarek, Ahn, and Zhang 2017), and an assessment of the economic feasibility of the proposed technology.

1.1 Combined Heat and Power

CHP systems are becoming increasingly common in both the residential and commercial sectors due to the possible increased efficiency and lower greenhouse gas emissions these systems offer (d'Accadia et al. 2003; Knight and Ugursal 2005). A variety of CHP configurations exist. Various combinations of heat pumps, geothermal systems, electrical heaters, and other alternative and traditional HVAC systems have been combined with a variety of power generator options including photovoltaics, internal combustion engines (ICEs), Stirling engines, and SOFCs. Most of these CHP options consist of two separate subsystems, the heater, and the power generator. In the case of photovoltaics, an exceptionally large system footprint is required, and they experience issues with variable power generation caused by changing weather; in the case of ICEs the system footprint is small but noise, low efficiency, and issues with reliability are common. SOFC based CHP systems have the potential to achieve these high efficiencies and reduced emissions, while also reducing noise and overall power usage (Milcarek, Ahn, and Zhang 2017). SOFC CHP systems with the current technologies consist of two separate systems, a heater and an SOFC generator that requires thermal management, fuel delivery/processing, power electronics, monitoring, and further stack subsystems (Hawkes and Leach 2005; Sorace, Gandiglio, and Santarelli 2017). This increases the overall system footprint, complexity, and limits the potential energy savings. If instead the SOFC generator is integrated directly into the

HVAC system, the thermal management and fuel delivery/processing subsystems can be eliminated, which has the potential to increase the overall system efficiency and avoids changes in typical HVAC system footprint. To commercialize the technology, it is necessary to confirm that SOFCs can operate effectively in the HVAC combustion chamber environment, and that they can withstand the thermal cycling and other possible modes of degradation.

1.2 Solid Oxide Fuel Cell Operation

The combustion of natural gas (mainly methane) produces heat and various exhaust species, which can include carbon dioxide, carbon monoxide, hydrogen, and water vapor. Under fuel-rich combustion, also known as partial oxidation, the amount of carbon monoxide and hydrogen formed is increased. These two species are highly effective SOFC fuels (Milcarek and Ahn 2019). The presence of these fuels combined with the high temperatures present provide conditions for successful SOFC operation and therefore power production. The COMER laboratory has extensively studied SOFCs operating off combustion exhaust, resulting in the development of flame assisted fuel cells (FFCs) (Milcarek and Ahn 2018a). Given that many HVAC systems operate by combusting natural gas there exists tremendous potential for the development of a fully integrated SOFC CHP technology where the SOFC stack is placed directly in the boiler combustion chamber. Research into material selection, stack configuration and sizing, exhaust species concentration, and combustion chamber temperature profiles must all be completed in order to fully develop this novel CHP system.

1.3 Biogas as System Fuel

Biofuels are attractive alternatives to fossil fuels. They offer the ability to reduce dependence on non-renewable resources, reduce destruction to the environment caused by fossil fuel extraction, and provide an economically desirable method for the reuse of agricultural and general biological waste (Ullah Khan et al. 2017). Biogas is also the product of anaerobic digestion (AD), a process commonly found in landfills, wastewater treatment plants, farms, and food manufacturers/breweries. Often, to dispose of this undesired gas, it is released directly into the atmosphere or combusted. This biogas consists mainly of methane, an extremely powerful greenhouse gas, which contributes to 18% of climate warming (Javadinejad, Eslamian, and Ostad-Ali-Askari 2019). A potentially less environmentally harmful method of biogas disposal is combustion, which converts the methane into mainly water vapor and carbon dioxide, a less powerful greenhouse gas. The energy released during combustion, however, is often not used efficiently, if at all.

Rather than releasing this methane into the atmosphere or combusting it, many systems are being developed to reuse this resource. Many HVAC systems already operate on natural gas, so they are well suited to operating on biogas (Alm et al. 2011; Forbes et al. 2016). There are contaminants which often need to be removed, but various low energy refinement processes are being developed to minimize the loss in overall efficiency this imposes (Žák et al. 2018). Ultimately, the use of biogas in HVAC systems can be an effective approach to mitigating climate change and environmental destruction.

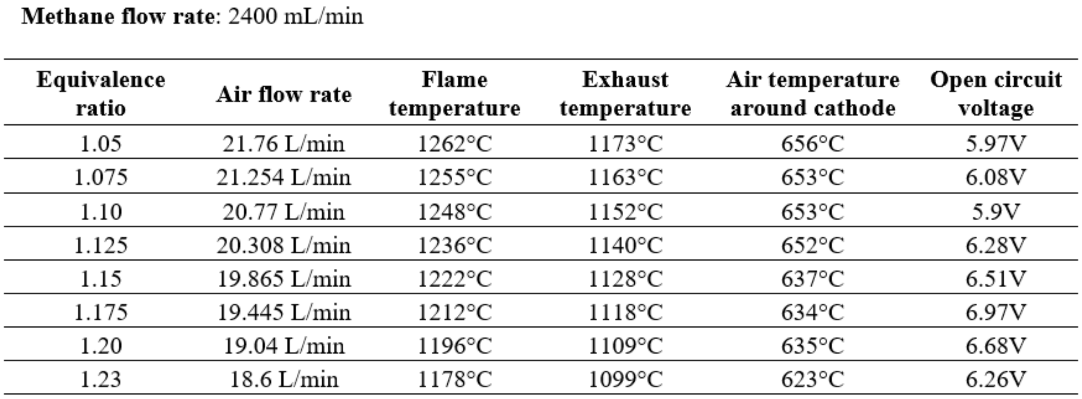
It is vital that the novel CHP system developed in this work is compatible with biogas. Previous work has shown that SOFCs can effectively operate with biogas and act as an efficient replacement for biogas burn off, especially within CHP systems which use both the biogas composition and the heat its combustion produces (Farhad, Hamdullahpur, and Yoo 2010). Like the method of biogas burn off, methane becomes carbon dioxide and water vapor, but the fuel cells act as a controlled combustor, oxidizing the fuel and generating electricity. This means methane disposal via SOFCs generates electricity as opposed to just wasted heat. SOFCs also act as higher efficiency biogas disposers than ICE based systems (Santarelli et al. 2012). This use of biogas combined with SOFCs allows the proposed SOFC stack within the boiler combustion chamber to act as an exhaust scrubber, removing extremely harmful greenhouse gases and toxic gases while producing electricity. This positive environmental effect positions the developed technology well to be adopted in an increasingly environmentally conscious HVAC field.

2 Flame Assisted Fuel Cell Performance

2.1 Development of Rich-Burn, Quick-Mix, Lean-Burn Chamber

The foundation of this project was based on the performance of SOFCs in the combustion chamber of the boiler. SOFCs require high temperatures to operate as well as a fuel-rich environment. The COMER laboratory has previously studied methane utilizing FFCs (Milcarek, Garrett, and Ahn 2016; Milcarek et al. 2019). However, for integration into a boiler, work needed to be continued with FFC performance in an actual combustion chamber. In order to investigate the performance of an SOFC stack in a methane combustion chamber, a model chamber was designed (Figure 1) and built and used for testing (Figure 2) (Milcarek et al. 2016; Milcarek, et al. 2016a). The RQL chamber allows for SOFC performance studies, including combustion gas performance analysis as well as thermal cycling testing. For FFC operation, fuel must first be burnt with mfigureinimal oxidant to allow for the generation of syngas, a highly effective SOFC fuel consisting of hydrogen and carbon monoxide. The RQL chamber offered a unique opportunity to study the effects of fuel equivalence ratio on the production of syngas as well as the direct impact on the performance of the SOFCs. For testing, the fuel equivalence ratio could be precisely adjusted, and temperature could be monitored very accurately using a series of thermocouples (six thermocouples in the chamber and two immediately next to ignition zone). After eliminating leakage issues, performance characteristics were able to be obtained for a variety of equivalence ratios. This data is summarized in Table 1. The temperatures within this chamber are well within the zone of typical SOFC operation and the stack voltage is within the expected range (Singhal 2000). The air temperature at the cathode however is lower than optimal for lanthanum strontium manganite (LSM), which is the cathode material typically used with an yttria stabilized zirconia (YSZ) electrolyte. This issue will be addressed in the material selection section. Figure 3 shows the power and polarization curves of the stack. The highly turbulent nature as well as minor leakage contributed to flaming around the fuel cells causing the instability in these plots. Power is also much lower than would be desired, most likely due to the same issues with turbulence around the cells.

Table 1. Performance of Fuel Cell Stack in Model Combustion Chamber at Different Equivalence Ratios



Methane flow rate: 2400 mL/min

Equivalence ratio	Air flow rate	Flame temperature	Exhaust temperature	Air temperature around cathode	Open circuit voltage
1.05	21.76 L/min	1262°C	1173°C	656°C	5.97V
1.075	21.254 L/min	1255°C	1163°C	653°C	6.08V
1.10	20.77 L/min	1248°C	1152°C	653°C	5.9V
1.125	20.308 L/min	1236°C	1140°C	652°C	6.28V
1.15	19.865 L/min	1222°C	1128°C	637°C	6.51V
1.175	19.445 L/min	1212°C	1118°C	634°C	6.97V
1.20	19.04 L/min	1196°C	1109°C	635°C	6.68V
1.23	18.6 L/min	1178°C	1099°C	623°C	6.26V

Figure 1. Schematic of Model Combustion Chamber

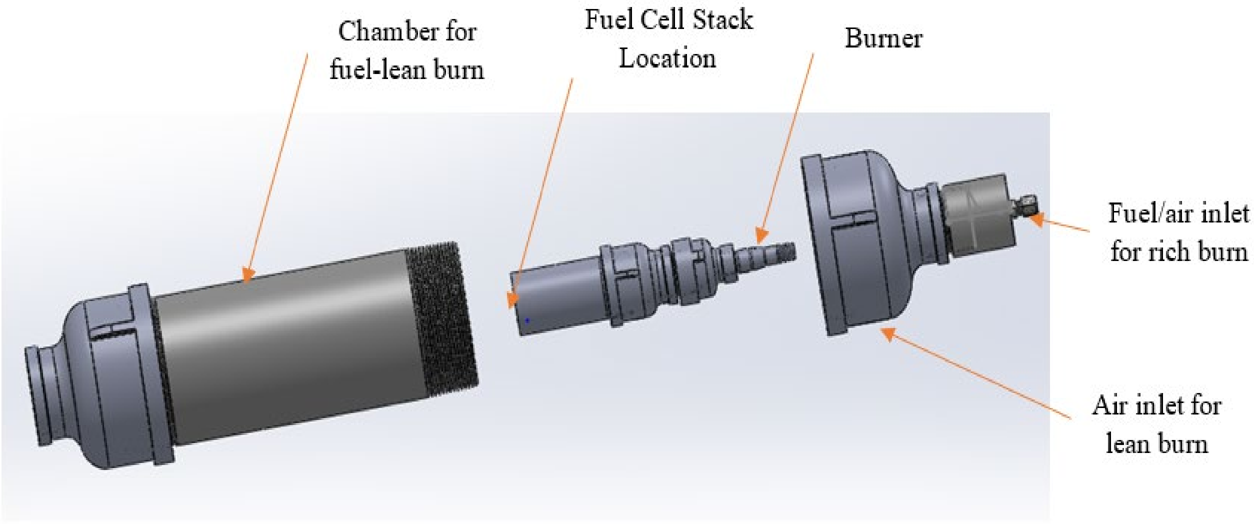


Figure 2. Model Combustion Chamber with Thermocouples Visible

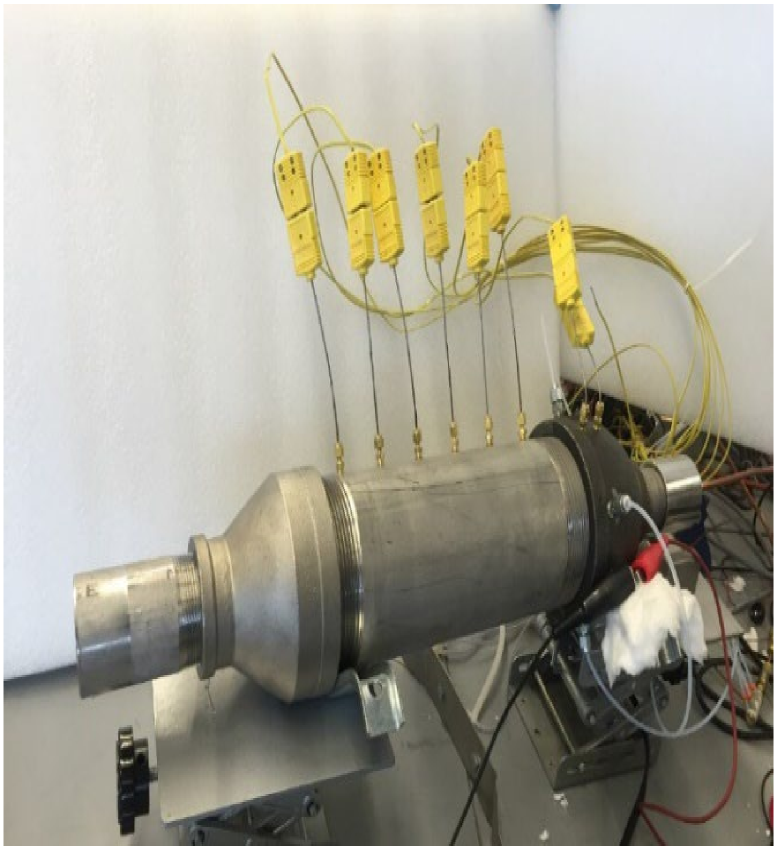
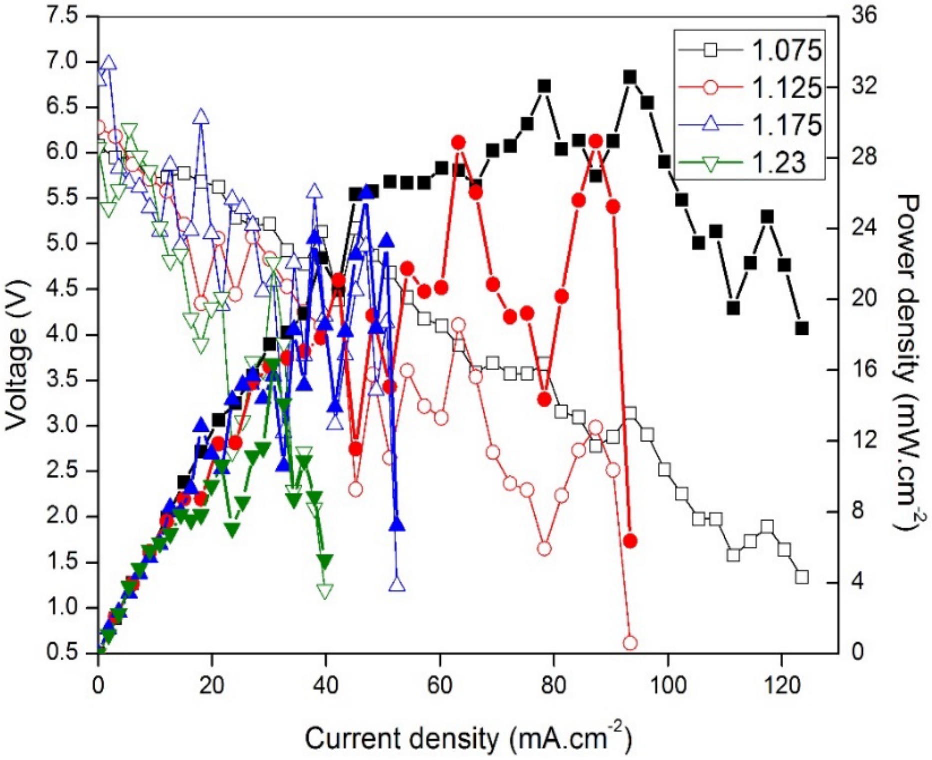


Figure 3. Power and Polarization Curves of Fuel Cell Stack at Varying Equivalence Ratios in Model Combustion Chamber



2.2 Thermal Cycling

Boilers and HVAC systems in general are not steady-state operating systems. They cycle frequently based off occupancy, ambient temperature/weather, and building envelope. The sealants that are used for SOFCs as well as the cell itself are intended for steady operation where fuel, oxidant, and temperature remain approximately constant. The performance of a fuel cell operating through thousands of thermal cycles has not been studied extensively and most research has been limited to dual chamber (planar) fuel cells which require large amounts of sealant. In addition, these studies have not exceeded 300 total cycles which is significantly less than the expected number of cycles the SOFCs in the CHP system would undergo in their lifetime. As such, mT-SOFCs were put through 3,010 thermal cycles reaching ~1000°C and cooling to ~300°C to replicate the expected thermal stress cycle (Milcarek et al. 2018). The cycle characteristics are shown in Figure 4. It was found that after cycling, cell degradation was minimal. Due to the minimal use of sealant afforded by the geometry of the mT-SOFCs as well as the resilience of the high-temperature ceramic SOFC materials used, change in stack voltage was less than 7% (Table 2), and the power performance of the cells increased after cycling (Figure 5). These results indicate fuel cells placed within the boiler combustion chamber would be able to withstand the highly variable environment without facing any issues with cell fracture, sealant rupture, or material degradation. The cells also did not face issues with carbon coking. Despite being in a high-temperature environment with a large number of carbonaceous species, carbon deposition on the anode was minimal. A layer of carbon was visible on the anode surface, but performance as well as scanning electron microscopy images revealed that the anode remained porous and performance was not impacted.

Figure 4. Thermal Cycling Temperature Profile

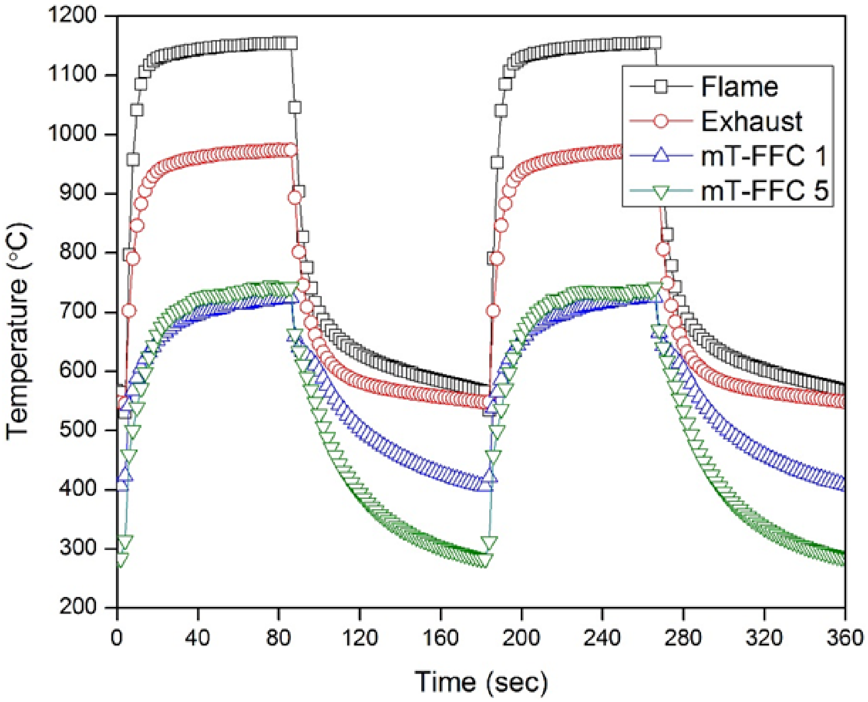
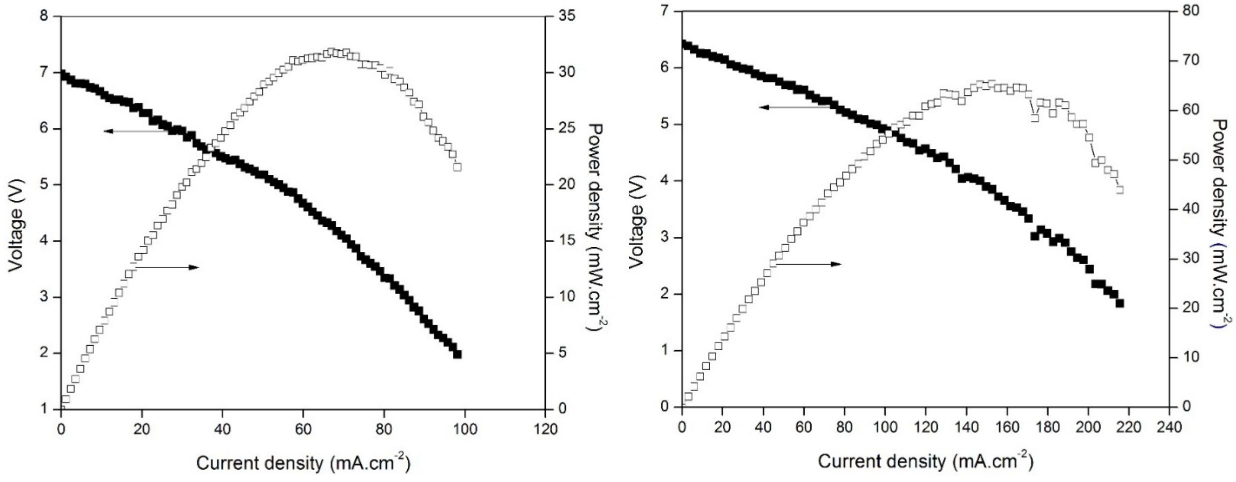


Table 2. Cell Performance Changes due to Thermal Cycling

Initial	6.98 V
Final	6.5 V
Change	0.48 V
Percentage change	6.88%
Voltage degradation	0.016 V per 100 cycles

Figure 5. Stack Performance before Thermal Cycling (left), Stack Performance after Thermal Cycling (right)

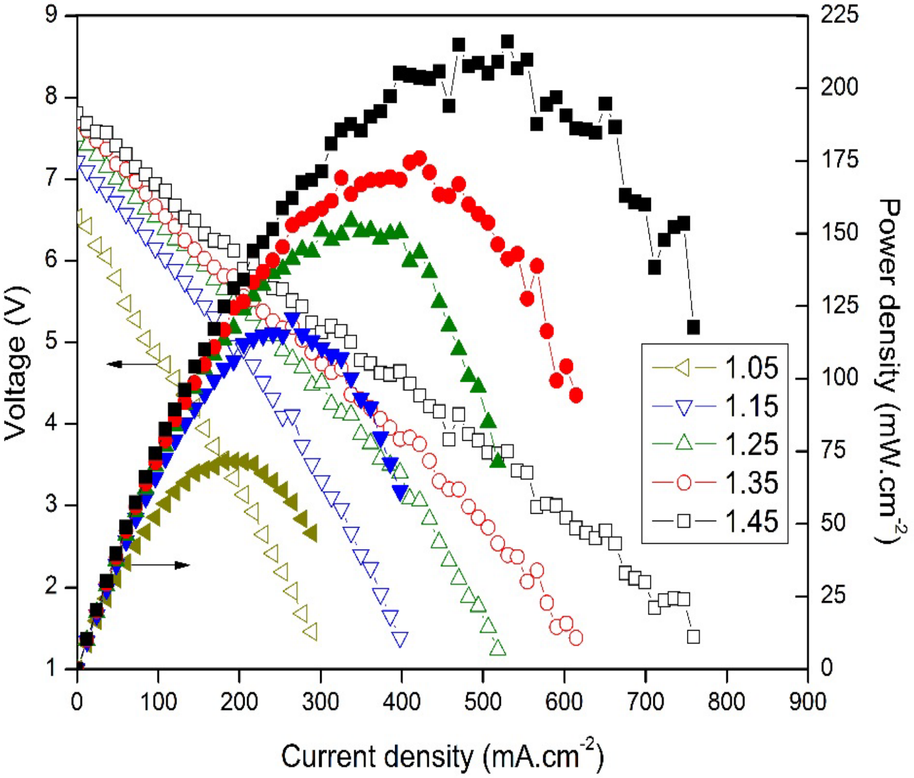


2.3 New Material Investigation and Application

As previously stated, the temperature the cathode is exposed to is lower than optimal for an LSM cathode. The power performance of the fuel cells within the RQL chamber was also lower than expected and poses issues with potential commercialization of the CHP system. Only the fuel mixture is heated by combustion, the air delivered to the cathode must be heated by other means contributing to this low temperature. Rather than attempting to develop a system to preheat the cathode air sufficiently incurring large parasitic losses with the overall CHP system, it is better to choose a cathode material which operates efficiently at the cathode air temperatures. By finding materials optimized to the environment of the combustion chamber, the COMER lab was able to increase performance of FFCs significantly (Milcarek, Wang, Falkenstein-Smith, et al. 2016b; Milcarek, Wang, Garrett, et al. 2016). Another material that is more applicable to this environment is lanthanum strontium cobalt ferrite (LSCF) (Mai et al. 2005; Suzuki et al. 2008; Duan et al. 2006; Wang et al. 2008; Chen et al. 2013; Li et al. 2013; Shi et al. 2012). Unlike LSM, however, LSCF is not directly compatible with an YSZ electrolyte (Shi et al. 2012; Li et al. 2013). At the temperatures seen in the combustion chamber, as well as the temperatures occurring during sintering, cobalt containing cathodes react with YSZ forming an insulative barrier layer between the YSZ and LSCF preventing fuel cell operation. These issues can be remedied, however. Two options exist, the first is to use a gadolinium-doped ceria (GDC) buffer layer to prevent YSZ-LSCF reaction, and the second is to use an electrolyte that does not react with

LSCF (Mai et al. 2005). Given the operating temperatures of the fuel cell observed within the RQL chamber, as well as during boiler characterization testing, it is most desirable to use a NiO anode, a YSZ electrolyte, and LSCF cathode. As a result, for the CHP system it is best to use option one and add a GDC buffer layer as protection against any solid-state reactions.

Figure 6. Stack Performance in the RQL Chamber with SDC Buffer Layer at Fuel Equivalence Ratios of 1.05-1.45



In the COMER, the use of a buffer layer with mT-SOFCs had not been studied previously. Standard tubular fuel cell manufacturing techniques, however, made this addition extremely simple. After dip-coating of the YSZ electrolyte, the cell was dipped in the samaria doped ceria (SDC) buffer layer. As a result of this addition, cell performance increased significantly as shown in Figure 6. Without the buffer layer, stack performance in the RQL chamber did not exceed 40 mW/cm^2. With the buffer layer added performance increased to over 200 mW/cm^2. This increase by more than 500% shows it is possible for the CHP system to be economically feasible. Additionally, testing in the COMER of similar cells operating in hydrogen showed peak powers of up to 2 W/cm^2 (Milcarek, Wang, Garrett, et al. 2016), a very high performance in the field of SOFCs. These results indicate performance issues seen up to this point were almost entirely due to suboptimal material selection. As long as the correct materials are used, performance of the SOFC stack should be sufficient to prove economic viability of the CHP system. Real cell performance in combustion chambers and with model boiler exhaust have shown some developments and growth with this specific application is necessary to realize the full potential demonstrated in the material selection tests.

3 Solid Oxide Fuel Cell Stack Integration into Boiler

To allow for SOFC power production, the initial combustion process must be at a high-equivalence ratio to promote the formation of syngas. In the RQL chamber this could be easily adjusted, but in the final integration into a boiler, a balance between optimal SOFC operation conditions and optimal boiler performance must be sought. To investigate this balance, characterization of a purchased residential boiler was done. The flow rate of air coming from the boiler pump was adjusted to fluctuate the equivalence ratio and then both temperature profiles and exhaust species concentrations were taken. Operation of SOFCs within the conditions was then analyzed to ensure success of the final application.

3.1 Boiler Characterization

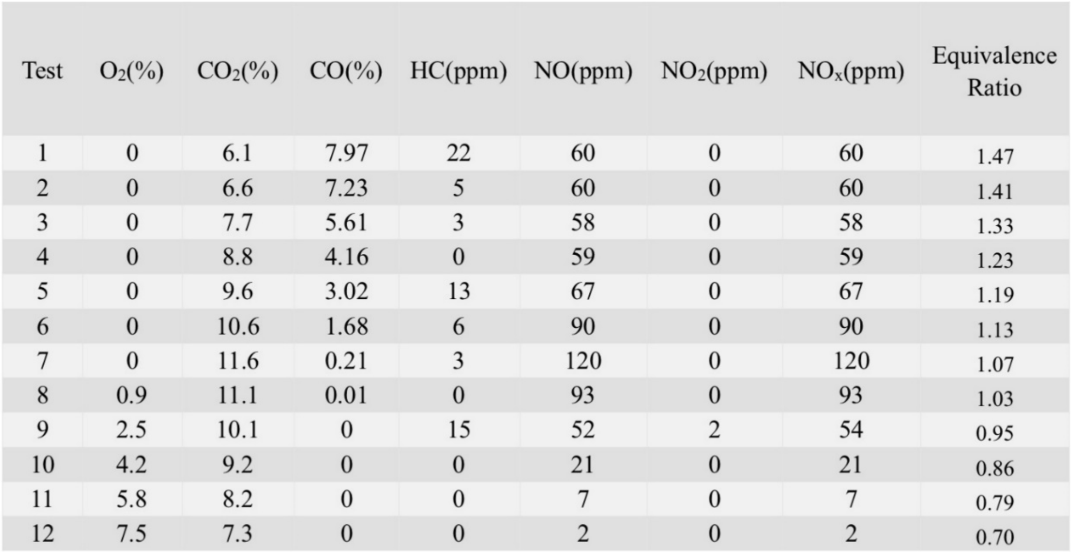
A gas fired hot water heating boiler from ECR International in Utica, NY (model: UBSSC-050) was selected for this project. The chosen boiler could modulate up to a maximum of 50,000 Btu/hr which satisfied the minimum size requirement. The boiler could be fueled by either natural gas or liquefied petroleum gas. Natural gas was used as the fuel in this study. The boiler consisted of a radial combustion chamber, a heat exchanger assembly, and a boiler control module, all of which made this boiler a good representative of a typical domestic boiler. Also, the design of the combustion system and the physical dimension of the heat exchanger were sufficient for fuel cell integration.

Figure 7. Residential Boiler Installed at Syracuse Center of Excellence in Environmental and Energy Systems (SyracuseCoE) with Dummy Heating Load

After the specified boiler was installed and all the pipes and electric lines were successfully connected (Figure 7), an initial baseline test was conducted to determine the boiler's performance and ensure every system inside of the boiler worked properly. This baseline test was conducted with various objectives including gas input capacity range check, heating capacity check, air flow rate control, inlet and outlet water temperature measurement, emission gas temperature measurement, and emission gas composition detection.

The boiler was tested under a wide range of operating conditions within its input capacity range. Since the boiler had a programmable electronic controller and a user interface module, the test was conducted under the control of the user module, feedback status and all the measurements were obtained constantly from the interface module monitor. All measurements were confirmed with the use of a gas flow meter, thermocouple, and gas analyzer device. The initial test was performed under the default temperature set point of 76°C, and the central heating mode was selected to heat a 40-gallon tank of water which provided a dummy heating load. The water was pumped into the boiler from the bucket and then returned to the same bucket after being heated. Therefore, the water temperature inside of the bucket would gradually increase. The boiler could automatically modulate its heating rate to maintain the set point and match the system heating load. The default domestic hot water mode worked essentially the same as the default central heating mode, but these two modes could never be conducted at the same time. The supply water temperature reached the set point after 45 minutes and stabilized at the set point temperature after 20 more minutes. The burner shut off once the heating demand was satisfied, and the internal heat exchanger pump started anytime demand existed.

Table 3. Exhaust Gas Composition as Equivalence Ratio is Changed



Test	O_2(%)	CO_2(%)	CO(%)	HC(ppm)	NO(ppm)	NO_2(ppm)	NO_x(ppm)	Equivalence Ratio
1	0	6.1	7.97	22	60	0	60	1.47
2	0	6.6	7.23	5	60	0	60	1.41
3	0	7.7	5.61	3	58	0	58	1.33
4	0	8.8	4.16	0	59	0	59	1.23
5	0	9.6	3.02	13	67	0	67	1.19
6	0	10.6	1.68	6	90	0	90	1.13
7	0	11.6	0.21	3	120	0	120	1.07
8	0.9	11.1	0.01	0	93	0	93	1.03
9	2.5	10.1	0	15	52	2	54	0.95
10	4.2	9.2	0	0	21	0	21	0.86
11	5.8	8.2	0	0	7	0	7	0.79
12	7.5	7.3	0	0	2	0	2	0.70

After the boiler was confirmed to be operational and the ability to manually change operating parameters was established, experimentation began with the incoming fuel equivalence ratio and the resulting exhaust composition. SOFC operation is dependent on the presence of fuel which means the boiler combustion needs to be fuel rich. Table 3 shows the effects of equivalence ratio on exhaust composition. As can be seen at higher equivalence ratios (greater than 1.13) the presence of carbon monoxide (CO) increases. CO is an indicator of the production of syngas and therefore is also an indication of the increased presence of hydrogen which could not be detected by the gas chromatographer used to obtain these measurements. The measurements obtained here were then used in the model combustion tests that follow.

3.2 Model Combustion Tests

Though it was previously known that the fuel-rich combustion of natural gas produces syngas, an effective fuel for SOFC (Milcarek, Garrett, and Ahn 2016), the combustion exhaust gases seen in the boiler also included carbon dioxide as well as a large amount of nitrogen. The effects of this dilution and presence of other gases needed to be examined in order to confirm fuel cells would work effectively in the boiler. In order to do this, a mT-SOFC with SDC buffer layer as mentioned in the material selection section was fed with model combustion exhaust gases in a benchtop furnace. The fuel flow consisted of 174 mL/min N_2, 17 mL/min H_2, 17 mL/min CO, and 12 mL/min CO_2. Tests were performed at 800ºC and consisted of both performance tests as well as long term stability tests.

Performance tests done before the stability tests showed a drop in power production, as was expected due to the dilution of the exhaust gases, but the power produced was still substantial and would be effective in a stack design. Peak power reached was ~370 mW/cm^2 and the open circuit voltage (OCV) was just below 1 V as can be seen in Figure 8. The long-term stability test was also encouraging. As can be seen in figure 9, for the first ~18 hours, OCV was stable and dropped by less than 2%. As in the thermal cycling examination done previously (Milcarek et al. 2018), a small amount of carbon deposition on the anode is most likely the cause of this small drop but is not likely to be indicative of long-term issues. The OCV drops significantly at the ~18-hour mark and becomes unstable, this was due to hydrogen flow stopping due to the tank emptying.

Figure 8. Performance of Tubular SOFC with Buffer Layer at 800°C with 154 mL/min N_2, 17 mL/min H_2, 17 mL/min CO, 12 mL/min CO_2

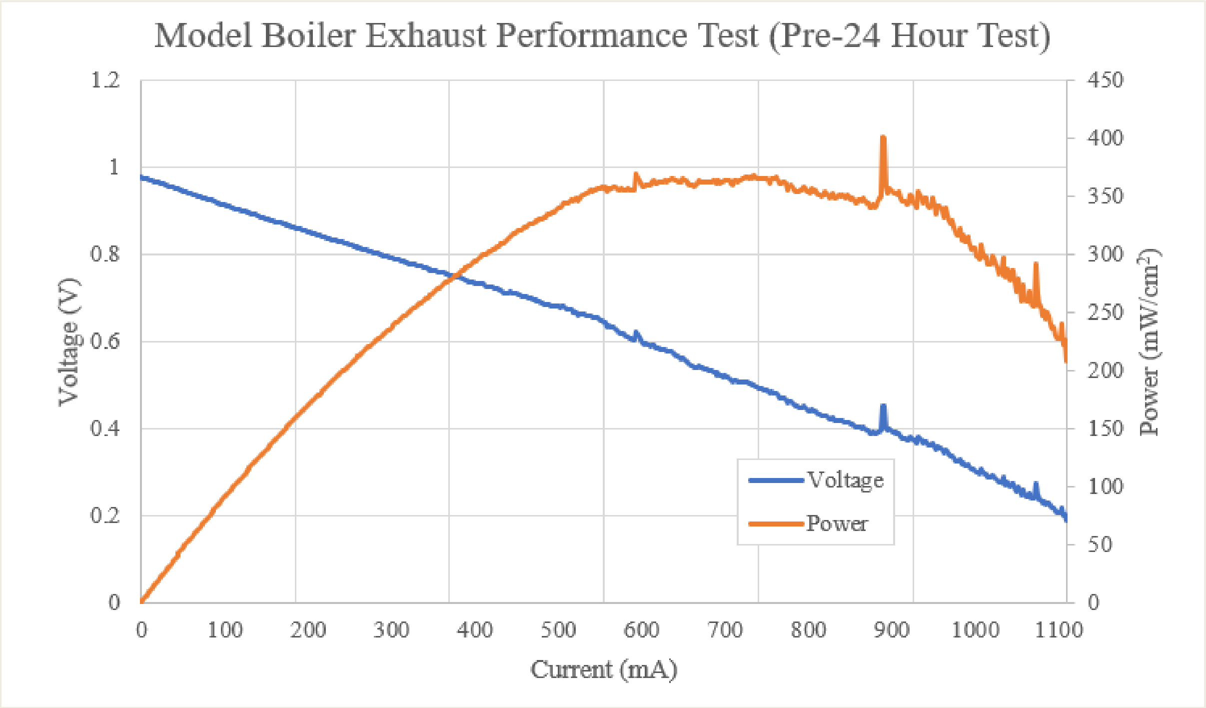
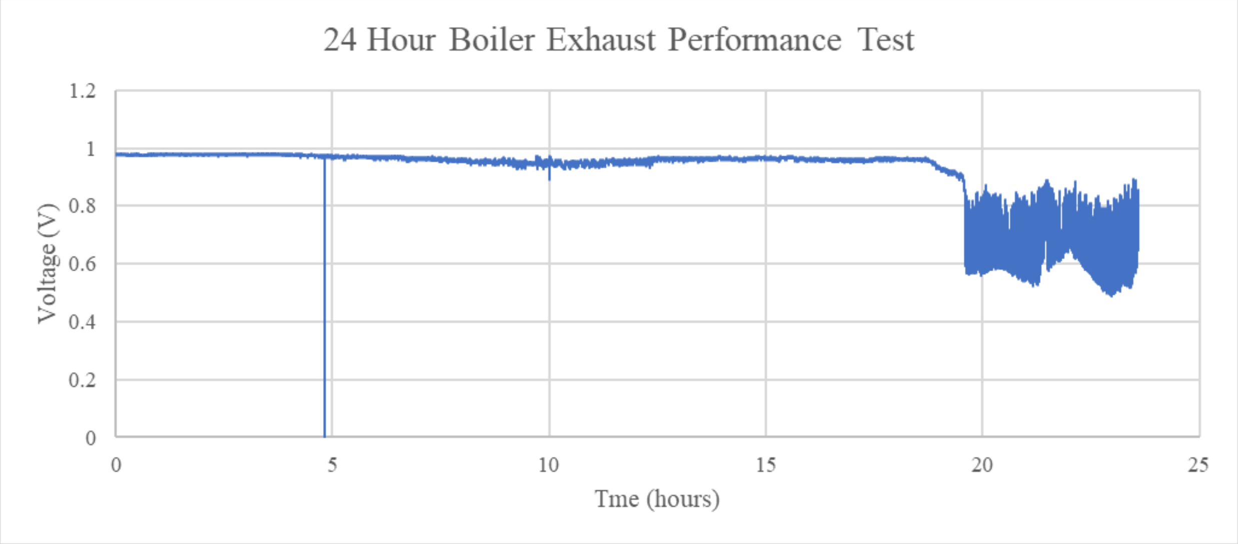


Figure 9. Performance Test Tracking (24 Hours) Open Circuit Voltage at 800°C with 154 mL/min N_2, 17 mL/min H_2, 17 mL/min CO, 12 mL/min CO_2



3.3 Stack Design and Development

In order to motivate commercialization of the technology developed in this project, the COMER intended to integrate an SOFC stack into the boiler that had been purchased. As seen in Figure 10, the mT-SOFCs would be mounted onto a hollow ring which would provide air to the center of the cells via a small external pump. The cells would surround the burner and come into contact with the hot combustion gases. This configuration allows for minimal alteration of the existing boiler system. Required alterations are additive and should have little effect on the boiler operation. With this configuration, however, standard tubular fuel cells cannot be used. Standard mT-SOFCs have their physical support provided by the anode which is then coated with electrolyte and cathode. With this geometry, oxidant must be delivered to the outside of the cell and fuel must be delivered to the inside of the cell. The boiler environment requires the opposite, fuel delivery to the outside of the cell and oxidant provided from an external source to the inside of the tubes. Ultimately, the development of an anode supported mT-SOFC with internal cathode (IC-tSOFC) is required. Cells with this geometry do not currently exist, but theoretically should provide the highest potential power output.

To examine fuel cell operation within the boiler, several planar cells were mounted inside of the combustion chamber as can be seen in Figure 11. Issues with air flow over the cathode causing large temperature gradients as well as difficulties positioning the cell in the chamber ultimately prevented these cells from producing any power. It was necessary to finish production of tubular cells with geometries that are appropriate for the boiler combustion chamber before in-boiler testing could begin.

The anode material remains highly porous even while going through the high-temperature sintering stage that the electrolyte requires to properly densify. This combined with the high-electrical conductivity of the material makes anode supported cells highly desirable. Cathode and electrolyte supported cells both face major limitations in performance (Singhal 2000). These problems can be addressed, but the majority of SOFC technology has focused on anode support. This geometry SOFC therefore requires the fuel to be routed through the inside of the tube. With some HVAC systems this can be easily achieved. For example, integration of SOFCs into a residential furnace requires no alterations to existing fuel cell manufacturing techniques. The burner and heat exchanger are in a linear arrangement. Air and fuel are combusted, can pass over the heat exchanger piping and then are exhausted. SOFCs can be inserted directly after the burner, have the exhaust gases routed through the center of the tubes, and then exit the SOFCs and pass over the heat exchanger. Alterations to the furnace are minimal and non-specific tubular SOFCs can be used (Milcarek, Wang, Falkenstein-Smith, et al. 2016a). The same is not true for boilers. In the combustion chamber of the residential boiler purchased by the COMER is a radial burner surrounded by concentric heat exchanger coils. The air and fuel enter this chamber premixed where they are ignited. Without major alterations to the boiler that would compromise its functionality, the required hot exhaust gases cannot be routed through the center of the fuel cells. This means standard tubular SOFCs cannot be used. They must be altered in a way to match this geometry, having anode exposed on the outside of the tube and cathode exposed on the inside of the tube, allowing for immersion within a fuel rich environment.

Figure 10. CAD Image of Boiler with Fuel Cell Stack Integrated

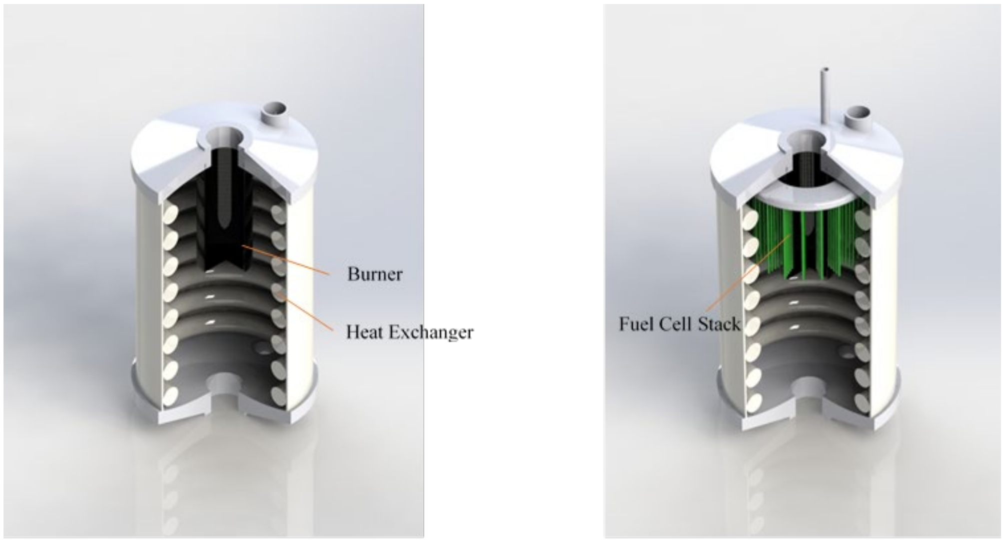


Figure 11. Residential Boiler Modified to Include Planar SOFC in Combustion Chamber

Boiler/combustion chamber specific SOFCs must be developed for continuation of CHP system design beyond furnaces to include boilers and other heating systems. There are two main options to do this, anode supported, and cathode supported. As previously stated, anode supported cells are desired; however, this requires the development of new manufacturing techniques. Standard mT-SOFCs have the electrolyte and cathode deposited on the cell by dip-coating, a process where the tube is closed at both ends and then dipped into a slurry of the required material. This process can be altered to allow for deposition of electrolyte and cathode on the inside of the cell. Method I investigated was to coat the outside of the cell with a sacrificial layer which would volatilize during sintering. Method II was to directly fill the inside of the tube with slurry. Method I proved ineffective. Performance was limited and power never exceeded 20 mW/cm^2 (Figure 12). Scanning electron microscopy (SEM) images reveal the most likely cause of this issue (Figure 13). Most importantly, the electrolyte layer (outlined in red) is highly nonuniform. A mT-SOFC with desirable electrolyte properties would have a highly dense electrolyte layer of uniform ~10 µm thickness. This allows all cell areas to experience equal resistance to ion transport within the electrolyte. When this is not the case, thin spots in the electrolyte where there is less resistance to ion transport experience increasing activity. These areas, called hotspots, contribute to accelerated cell degradation and performance limitations. In addition, the white areas toward the top center of the image indicate possible residue left by the sacrificial layer. This residue prevents fuel transport through the anode and thus low performance. These factors combined yield ineffective cells that cannot be used and motivated the development of Method II.

Figure 12. Performance of Novel Geometry Solid Oxide Fuel Cell Made with Sacrificial Layer Dip-Coating Method

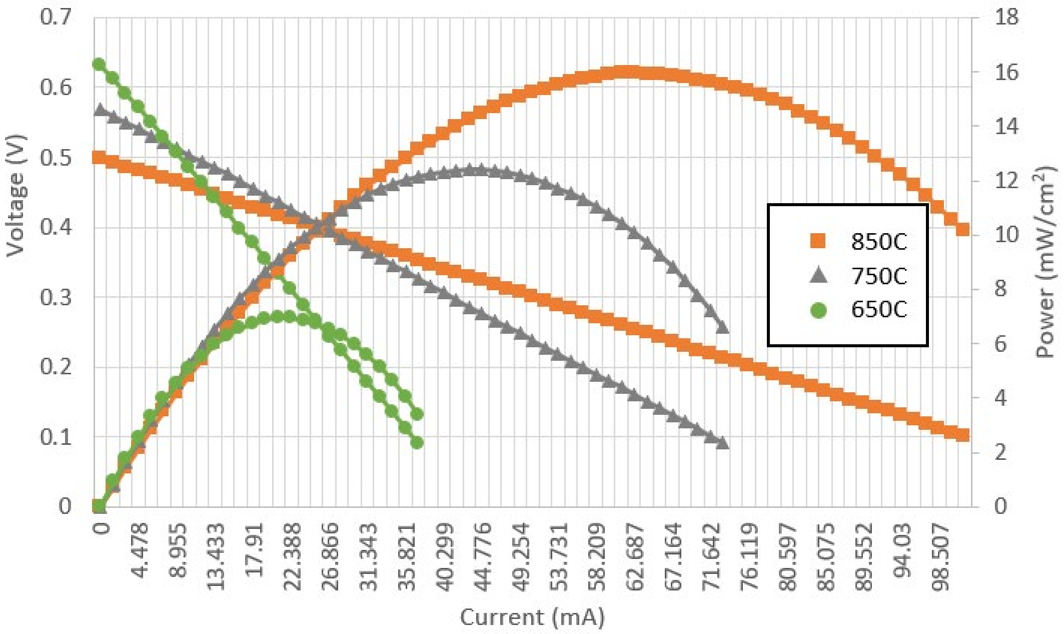
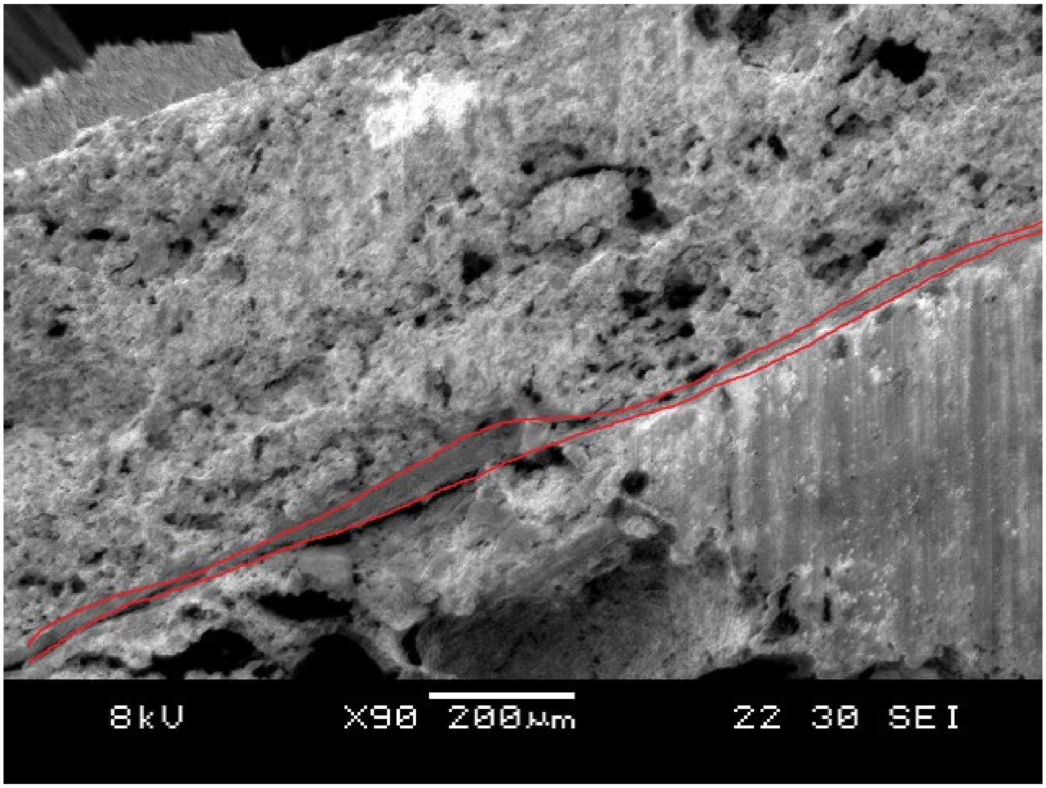


Figure 13. SEM Image of Novel Geometry SOFC Made with Sacrificial Layer Dip-Coating Method

Electrolyte layer outlined in red.



Method II was ultimately successful but has introduced unexpected issues most likely characteristic of this novel geometry. Deposited electrolyte layers have been highly uniform and should produce functional cells; however, all cells manufactured have faced issues with fracturing of the anode and subsequent shorting of the cell (Figure 14). During sintering, the ceramic materials of the SOFC densify and shrink. Each material behaves uniquely during this process and shrinks to different extents and at different temperatures. This results in stress concentrations that ultimately cause fractures originating at the cathode/electrolyte interface. Often these cracks were not visible at the tube surface prompting manufacturing of the cell to continue. When this was done, the cathode dip coat was able to penetrate the crack and make direct contact to the anode. As can be seen in Figure 15, the darker grey nonporous cathode toward the top of the tube cross section has surrounded the bright white electrolyte, and around the right side of the electrolyte had made contact to the slightly lighter grey, porous anode. When cathode and anode make contact, the cell becomes electrically shorted and cannot produce any power. Though the COMER has been able to identify this issue and confirm the cause of cell shorting, the solution is not yet clear. When identical material cells were made with a “normal” geometry, these cracks did not occur. This ultimately means that the only cause of this cracking is the geometry of the cell. The physical reasoning the geometry has such an impact is nontrivial and currently unknown. Work will continue to investigate both the phenomenon and a solution.

Figure 14. SEM Image of Crack Going through IC-tSOFC

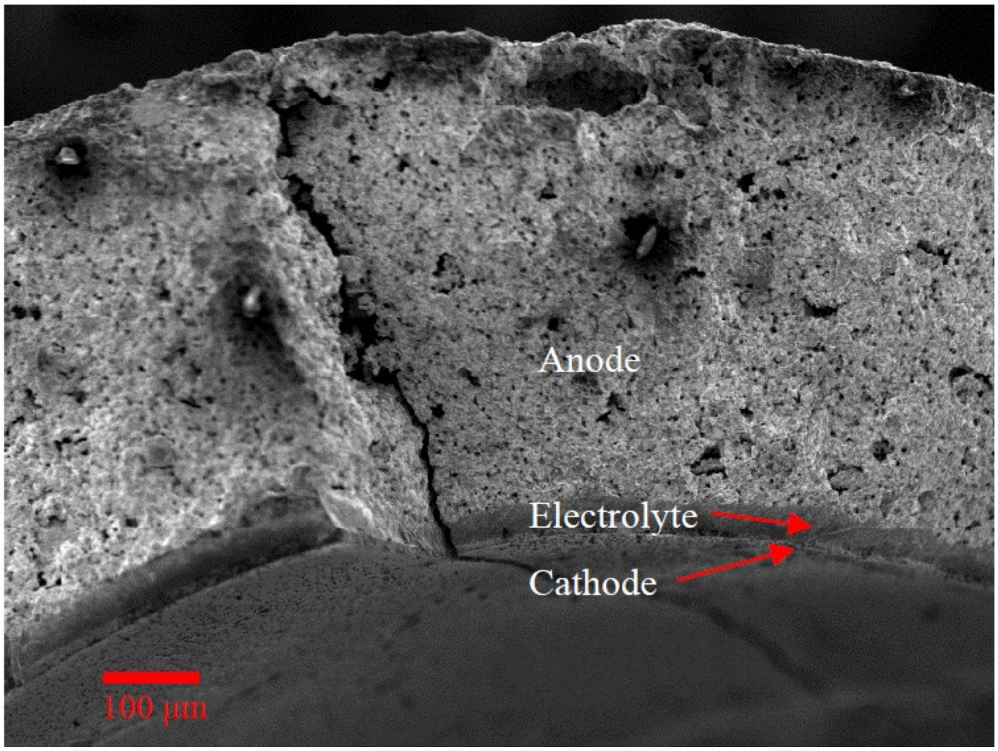
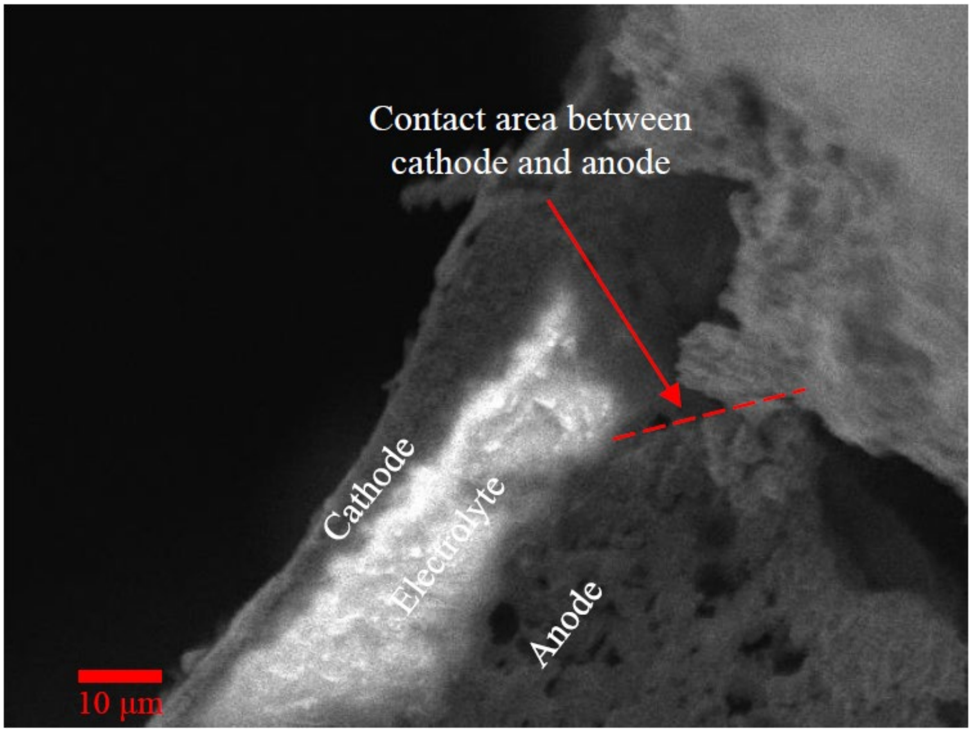


Figure 15. SEM of Cathode (Black) Surrounding Electrolyte (White) and Making Contact with the Anode (porous grey)



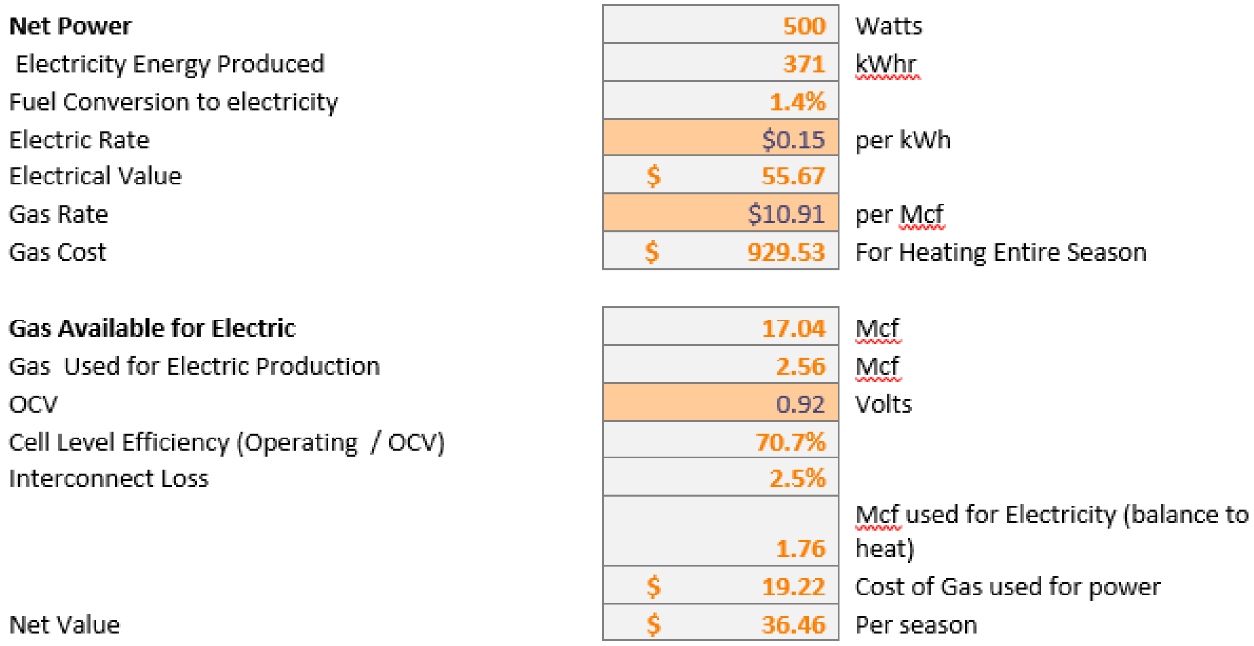
The current issues with the anode supported IC-tSOFC have prompted the development of a cathode supported IC-tSOFC cell. As previously discussed, the cathode support will ultimately limit performance to below that of anode support due to the issues with cathode densification, but these cells can serve as an intermediary until the cracking of the anode supported cells can be resolved. Cathode supported IC-tSOFCs have been developed previously (Singhal 2000), but were complicated by a cathode current collector that penetrated the anode and electrolyte. This complicates manufacturing and impacts cell performance due to the limited electrical conductivity of the cathode and the relatively long path electrons need to take to reach the cathode current collector. Our design made use of an internal current collector to avoid these issues, yielding easy to manufacture cells with a higher potential performance. These cells, however, also proved unsuccessful. The anode dip coat layer had substantial issues adhering to the electrolyte, causing manufacturing issues, and testing of the cells manufactured resulted in voltage behavior which is currently without an explanation. As with the anode supported cells, the geometry being developed has complicated cell manufacturing much more than expected, causing significant investigation to remedy all issues. Once these issues are fixed the resulting cells will represent a significant technological innovation and will open the door to a wide variety of new SOFC applications.

4 Commercial Analysis

4.1 Techno Economic Assessment

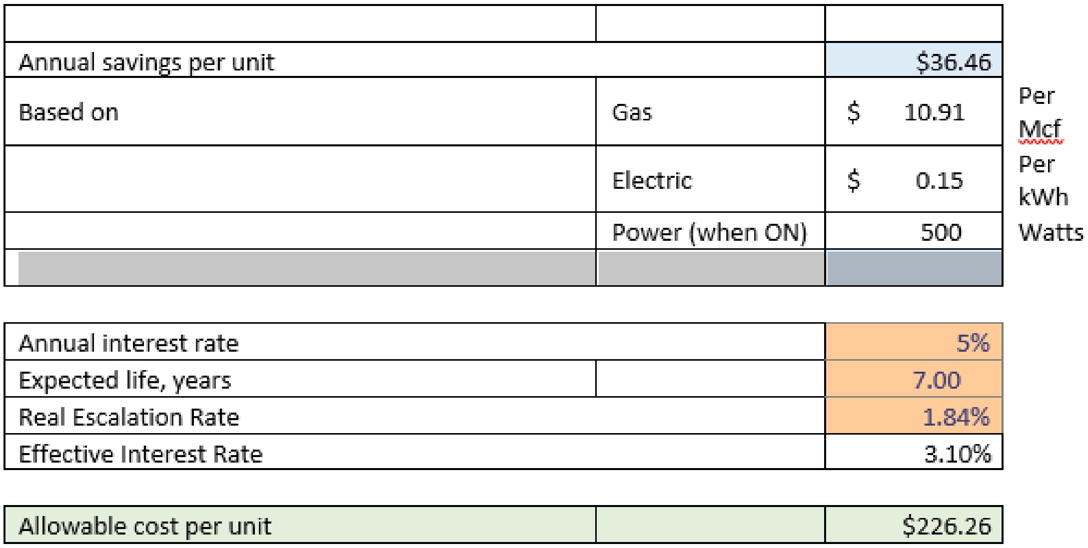
It is necessary to investigate the economic feasibility of the technology developed in this project. The system components including DC converter, batteries, and blowers are readily available, invariable, and only account for a very small portion of the SOFC system cost. The majority of the cost comes from the SOFC stack itself. Prices for SOFC stacks are highly variable due to limited commercialization of the technology as well as large variations in the technology itself. As such, the techno economic assessment focused on the SOFC stack itself. A demonstration calculation for a 500-Watt system is shown in Tables 4 to 6. The preseason allowable cost for this season based on fuel usage is $36.46 (Table 4). Ultimately, for a 500-Watt system with a seven-year lifetime, stack cost would need to be less than $226 (Table 5) for the system to compete economically with grid provided electricity. The current estimated stack cost, however, is $2,077 (Table 6). Highly conservative performance estimates as well as current technological limitations contribute to this mismatch in costs. As will be discussed in the future work section, there are paths to eliminate this high cost.

Table 4. Estimate of Net Value of SOFC System per Season



Net Power	500	Watts
Electricity Energy Produced	371	kWhr
Fuel Conversion to electricity	1.4%	
Electric Rate	$0.15	per kWh
Electrical Value	$ 55.67	
Gas Rate	$10.91	per Mcf
Gas Cost	$ 929.53	For Heating Entire Season
Gas Available for Electric	17.04	Mcf
Gas Used for Electric Production	2.56	Mcf
OCV	0.92	Volts
Cell Level Efficiency (Operating / OCV)	70.7%	
Interconnect Loss	2.5%	
	1.76	Mcf used for Electricity (balance to heat)
	$ 19.22	Cost of Gas used for power
Net Value	$ 36.46	Per season

Table 5. Estimate of Potential Savings over Seven-Year Lifespan

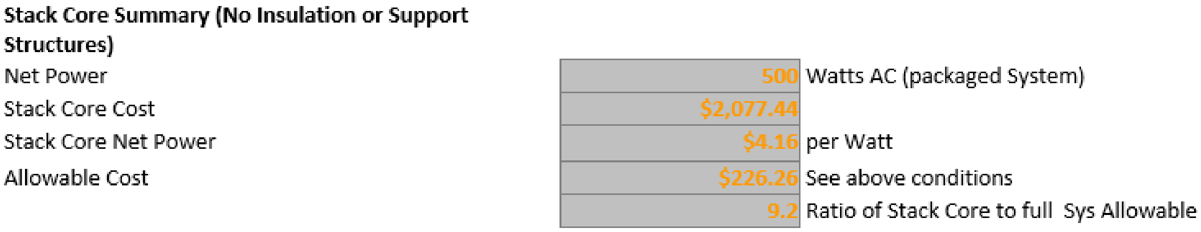


Annual savings per unit		$36.46	
Based on	Gas	$ 10.91	Per Mcf
	Electric	$ 0.15	Per kWh
	Power (when ON)	500	Watts

Annual interest rate		5%
Expected life, years		7.00
Real Escalation Rate		1.84%
Effective Interest Rate		3.10%

Allowable cost per unit		$226.26

Table 6. Estimate of Stack Cost and Comparison to Energy Savings

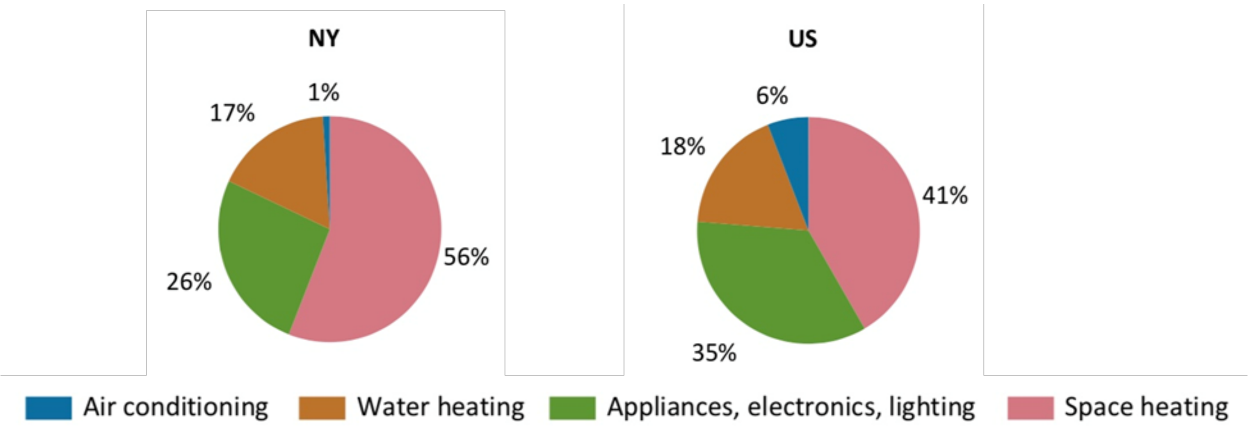


Stack Core Summary (No Insulation or Support Structures)		
Net Power	500	Watts AC (packaged System)
Stack Core Cost	$2,077.44	
Stack Core Net Power	$4.16	per Watt
Allowable Cost	$226.26	See above conditions
	9.2	Ratio of Stack Core to full Sys Allowable

4.2 Market Analysis

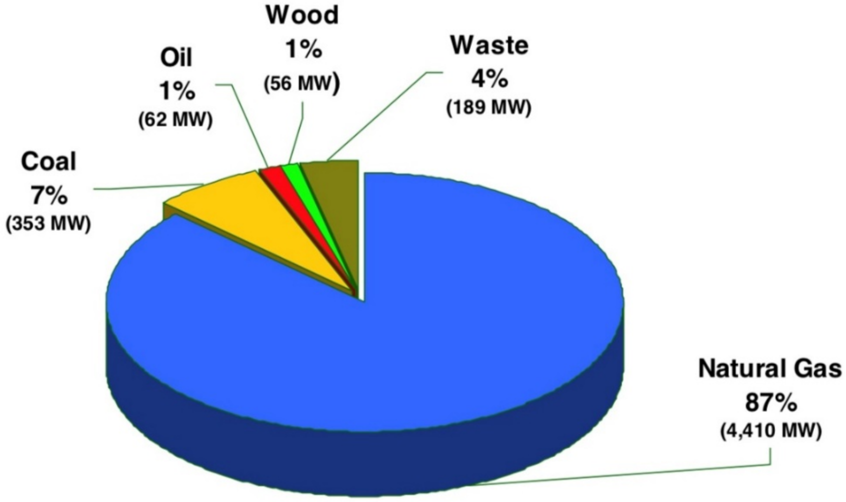
We have also conducted a market analysis to assess the potential for the commercialization of the fuel cell boiler in New York State. We first made an investigation for household energy consumption. The total annual energy consumption of these households in the State reaches an average of 103 million Btu, which is 15% more than the national average, and a large portion of the energy is consumed by space heating (56%) and domestic hot water heating (17%) due to relatively cold weather in the region Figure 16 (U.S. Energy Information Administration 2009).

Figure 16. Comparison of Energy Usage by Category between New York State and National Average



Boilers are widely used for space heating in the United States because they can generate heat from natural gas instead of relatively more expensive electricity. According to the U.S. Energy Information Administration (EIA) survey in 2015 (U.S. Energy Information Administration 2015), natural gas accounts for the largest portion (57%) of primary heating source for the residential sector. The portion is significant when compared to its competitor's fuel oil (29%) and electricity (7%) (Perez, Baldea, and Edgar 2016). At the same time, there is a trend of increased demand for natural gas consumption. The number of New York State natural gas customers rose from 3.7 to 4.2 million between 2005 and 2014, whereas reliance on other fuel sources for heating only increased slightly for the same period (Waldman and Mahoney 2015).

Figure 17. Chart of Fuel Type Proportions for CHP Systems in New York State



CHP systems can take advantage of facilities that require both electricity and thermal energy. The current New York CHP market consists almost entirely of the industrial sector and commercial sector, and the existing market is highly natural gas dependent. However, with the growing demand of on-site household power generation, the concept of micro-CHP has been proposed and it has been considered an important technology for future energy production in the residential sector. In 2017, 59.4% of State households heated with natural gas, which was relatively higher compared to the national average (48%) (U.S. Energy Information Administration 2019). Also, the State residential electricity consumption in 2017 was 49,081 million kilowatt-hours (kWh) with an average site consumption of about 7000 kWh per household. The potential of using residential CHP devices in New York State households is obviously higher than in some other states. In addition, as can be seen in Figure 17, the vast majority (87%) of existing CHP systems in the State use natural gas as the fuel source, indicating the market for natural gas CHP systems is currently the most widely developed—confirming this is a good initial CHP technology to commercialize.

If FFC integrated boilers can be commercialized, then a micro-CHP system can be created in every household, so that on-site heat and electricity generation can be achieved. As a result, dependence on the grid would be reduced and fully self-sustaining houses would be possible. Strategically, this kind of boiler should be installed where the cost of electricity is relatively high, and the cost of natural gas is relatively low (Milcarek, Garrett, and Ahn 2016).

4.3 Intellectual Property Landscape

The Syracuse University College of Law Technology Commercialization Program completed a comprehensive review of the IP (intellectual property) landscape for the technology developed in this project. A focus was placed on the unique anode supported FFCs as well as their integration into HVAC systems. It was found that many technologies exist that are similar to those developed here; however, there are sufficient novel elements in this work to avoid issues when seeking patent protection. The key difference was the use of the natural reforming effect of the natural gas burner. Other systems tended to still require a fuel reformer system in order to operate. The advantages this system offers also act as the unique features which will allow its protection. It was advised that any additional unique features of the system be identified. One such element could include the IC-tSOFCs, which were investigated specifically to match the geometry of the boiler combustion chamber.

4.4 Competitive Analysis

The Syracuse University College of Law Technology Commercialization Program also analyzed the potential competition this technology would come up against. In general, the HVAC market is controlled by large companies with which the COMER lab cannot directly compete. Instead forming a partnership with these companies and forming a licensing agreement would be a more effective way to commercialize the technology. It was also discovered that the CHP system discussed in the report is unique and no other companies were found to have developed a similar technology. Some small companies have partnered with larger manufacturers as was recommended, but these systems are substantially different. They tend to require either ICEs, solar panels, or SOFCs with a myriad of subsystems which are not required in our novel CHP system. Ultimately, it was determined that this technology would most likely be able to successfully compete with alternate systems assuming an effective major company partnership is formed.

5 Conclusion and Future Work

The potential for a novel CHP system in which SOFCs are directly integrated into a residential boiler has been demonstrated. The temperatures and exhaust species presented in a boiler's combustion chamber can be altered successfully by adjusting the equivalence ratio without impacting boiler performance. SOFC materials and geometry have also been investigated to optimize performance in this specific application. Though there remains an issue with constructing cells of the correct geometry, the work completed here can be used in a variety of combustion systems, and ultimately, as work continues and all defects are eliminated, the intended boiler-based CHP system can be produced.

It has also been demonstrated that there is a growing market for CHP systems such as one studied in the report. Particularly in communities where electricity prices are expected to remain higher than natural gas prices. The ability to power high-power consumption devices with the natural gas already in use represents a large incentive to technology adoption. There is also no evidence of competing patents or technologies that would prevent commercialization of the technology. The unique combination of FFC stack with boiler, without thermal management and fuel reformer subsystems has not yet been produced.

Finally, the greenhouse gas reducing capabilities of the CHP system developed here combined with the increased efficiency this system offers over other CHP technologies is well suited to succeed in an increasingly environmentally conscious HVAC market. When operating on biogas, the system is ultimately carbon neutral and can transform undesired methane into carbon dioxide, reducing the impact on climate change that agriculture, waste management, and food manufacturing can have. This is all achieved with the resiliency and small system footprint that has traditionally been most associated with fossil fuels such as natural gas or oil.

5.1 Recommended Future Work

At this time, the main technology limitation preventing commercialization is the previously described cracking issue with the anode supported IC-tSOFCs. The successful development of this novel geometry fuel cell is key to the finalization of this CHP system. The COMER plans to continue seeking a solution to this issue. Consultation with a group focusing in solid mechanics/fracture mechanics may be helpful given the complex influence that geometry has on the stress concentrations within the fuel cell. It is also possible that further alterations in material selection as well as sintering procedures could have a positive effect on the development of these cells.

As seen in the economic assessment in this project, it is also desirable to lower the stack cost. The annual energy savings produce an allowable cost of $226 for a 500-Watt system, however, current cost estimates put the full stack cost at $2,000. It is immediately possible that this cost could be reduced dramatically by using a less conservative power density (for example, 300 mW/cm^2 as opposed to the 120 mW/cm^2 used in this analysis) as is supported by experimental tests done in this project. The majority of the stack cost is from the individual cells, so a finished design using properly optimized, high-performance cells could show a stack cost closer to $800. Of course, further improvements need to be made to produce an economically feasible stack. Improvements in manufacturing as well as discovery of low-cost high-performance materials could assist in this as well.

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