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# A SWISS ROLL STYLE COMBUSTION REACTOR FOR NON-CATALYTIC REFORMING OF JP-8

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## ABSTRACT

*ACT's non-catalytic, sulfur-tolerant "Swiss-roll" reforming technology is an effective way to provide the required reformate composition for the Army's SOFC system. This technology will enable DoD to implement efficient and low acoustic signature Solid Oxide Fuel Cell (SOFC) system in the field and satisfy the Single Fuel Policy. While the high sulfur content of JP-8 and coke formation pose significant challenges for catalytic-based reforming systems, the thermal partial oxidation based reformer is comparatively less complex, highly compact, lightweight and requires minimal power consumption. These advantages allow for a fuel cell fed with JP-8 be implemented in a transportable system, such as ground vehicle, with low acoustic signature for the US Army.*

## INTRODUCTION

Various technologies for the reforming of higher hydrocarbons into syngas have been studied in recent years. The most studied methods include catalytic partial oxidation reforming (CPOX), and more recently, researchers have also introduced plasma aided methods of hydrocarbon reforming [1-5].

Catalytic processes have various advantages and disadvantages for hydrocarbon fuel reforming. Advantages include high conversion of the feedstock and a manageable operating temperature ranging from 500-1000°C. On the other hand, catalysts often contain precious metals that drive the economic efficiency of any process very low [1,2]. Catalysts also face challenges when the fuel contains a high concentration of sulfur species. Sulfur is often found in heavy hydrocarbon liquid fuels such as JP-8, which contains sulfur concentrations up to 3,000 ppm by mass [6]. Sulfur will poison many catalysts, causing a need for replacement of the catalyst or pretreatment of the fuel before introduction to the reforming system. In addition, additional care for startup and shut down processes is typically required for catalyst, which increases overall system complexity.

Plasma aided methods have shown reasonable conversion efficiencies, however the energy input required to produce the plasma contributes to a lower overall energy efficiency. The additional electrical power input also contributes to size, weight, and system complexity [3,4].

Under contract with The Department of Defense, Advanced Cooling Technologies, Inc. has worked to develop a non-catalytic reforming device for military grade jet fuel, JP-8. The technology relies on the process of thermal partial oxidation (TPOX) to produce syngas. Using a high heat recuperation combustion device, known as the "Swiss-roll", combustion at high fuel-to-air ratios can be self-sustained and partial oxidation products are produced without the aid of a catalyst. The Swiss-roll design recycles thermal energy from the reformate stream to preheat the inlet reactants. With this heat recovery, the reactants are actually heated several hundred degrees Celsius above room temperature before entering the combustion chamber, where they are reformed into syngas. Because it does not rely on a catalyst, the entire system is sulfur tolerant.

Figure 1A shows a schematic of the Swiss-roll concept. The cold reactants (Air and JP-8 in fuel-rich conditions) flow through the inlet channel and into the center reaction zone. The traditional design of the Swiss-roll introduces both the fuel and the air in the inlet channel [7-12]. However, it was observed that the auto-ignition in the inlet channel significantly reduces the reforming efficiency. In this work, a novel design where only cold air is introduced at the inlet channel and the fuel is directly injected into the center. The air flows through the Swiss-roll and meets the fuel, just before the center reaction zone. This design prevents auto-ignition of reactants before the center combustion chamber. After partial oxidation, the hot products (reformate) flow out from the center through the adjacent outlet channel. The heat exchange through the spiral heat exchanger design significantly increases the reactants' temperatures and thus the reaction zone temperature. Figure 1B further illustrates the temperature increase resulting from heat recirculation. Without heat recirculation, the reaction temperature increase is due to the exothermic reaction only, yet with heat recirculation, the reaction zone temperature is increased by both chemical reaction and heat recirculation. As such, the resulting reaction temperature can be higher than the adiabatic flame temperature; this is called the "super-adiabatic" flame temperature. For example, for a propane and air mixture with equivalence ratio ($\Phi$) equal to 3, the adiabatic flame temperature is around $800^{o}$C, while the experimental measurement shows more than $1100^{o}$C can be easily achieved in the center of the reaction zone.

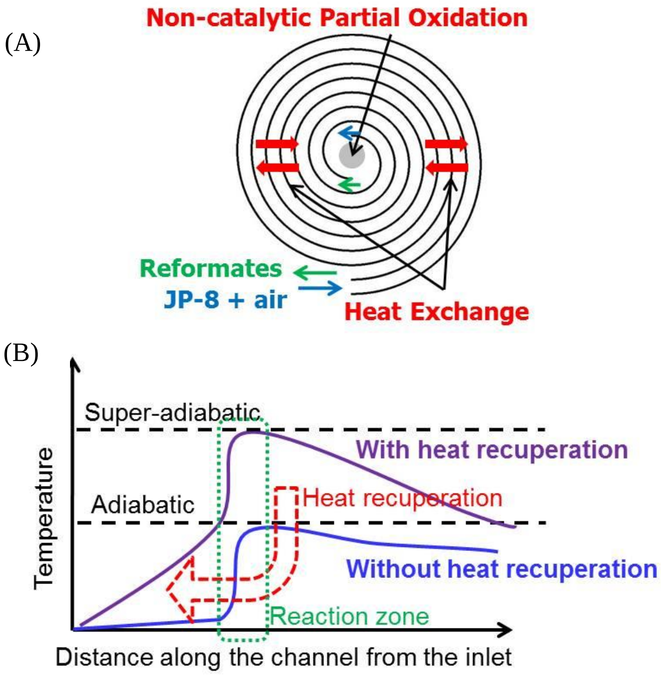

**Figure 1:** (A) Schematic diagram of the Swiss-roll reformer. (B) Temperature profile for reaction with and without heat-recirculation.

The Swiss-roll combustor was first proposed by Professor Weinberg in 1974 [7, 8]. Many studies have demonstrated its superior performance in heat recirculation and the effect on promoting internal reaction [9-12]. Specifically, it has been shown effective at extending the flammability of a variety of fuels and enabling achievement of equilibrium state concentrations. Several features make the Swiss-roll combustor extremely thermally efficient. First, the large heat transfer to heat loss area ratio enables highly efficient heat exchange in a very confined volume. Second, the curvature of the channel creates a centrifugal instability (Dean vortices) that further enhances heat transfer. Third, the reaction zone, which has the largest propensity for heat loss, is surrounded by the spiral heat exchanger so most of the heat loss is actually recovered. Fourth, long inlet channels with elevated temperature provide a long residence time that may significantly reduce the formation of non-equilibrium state products such as soot.

One application of the Swiss-roll reformer is for transportable system such as ground vehicles. A ground vehicle's auxiliary power unit (APU), powered by a solid oxide fuel cell (SOFC), can be fueled by higher hydrocarbon liquid fuels if the Swiss-roll reformer is used to reform the fuel. Its non-catalytic nature makes whole system much simple, compact, and have a long lifetime without maintenance.

There are however some additional considerations for reforming JP-8. JP-8 is notoriously high in sulfur compounds. When reformed to syngas, the sulfur exits the reformer in the form of hydrogen sulfide ($H_2S$). Although the sulfur does not affect the Swiss-roll, hydrogen sulfide will poison most SOFC systems. Another consideration is non-equilibrium products. Initial testing has shown up to 1% concentration of acetylene in the reformate stream. Acetylene will coke any downstream fuel cell system. Each of these compounds must be removed before the syngas can be introduced to power the fuel cell.

## MATERIALS AND METHODS

Advanced Cooling Technologies, Inc. leveraged previous experimental data, computational simulations, and its experience with Swiss-roll design to create a Swiss-roll fuel reformer capable of converting military logistic fuel (JP-8) to syngas for use in a Solid Oxide Fuel Cell (SOFC). The fuel reformer was built by additive manufacturing, using Direct Metal Laser Sintering (DMLS), which allows for complex features that would otherwise be too expensive to manufacture, to be built layer-by-layer. The stainless-steel prototype, Figure 2, stands roughly 9” tall with an overall diameter of 6.5”. The prototype has no moving parts, is lightweight and compact, and does not require a catalyst to reform JP-8.

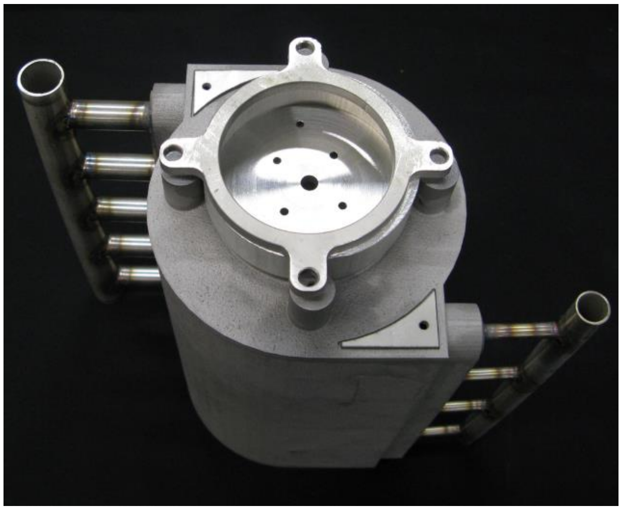

**Figure 2:** The Swiss-roll fuel reformer prototype, manufactured by an additive manufacturing technique known as Direct Metal Laser Sintering (DMLS), integrated with accessory components.

This Swiss-roll prototype design focused on optimizing geometric parameters, such as number of turns, channel cross-sectional area, and center volume, to stabilize a partial oxidation reaction in the central combustion zone. Previous experimental results found that the fuel-air mixture in the inlet channel of a Swiss-roll was prone to autoignition under the highly preheated conditions [13]. However, the inlet channel is solely designed to exchange thermal energy between the reactants and reformate. If the reaction occurs in the inlet channel, there will not be sufficient preheating to allow for the high temperature TPOX process to occur. The thin channels will also hinder the residence time of the reaction if it occurs within the walls. The center combustion zone of the Swiss-roll is designed to have the longest residence time and will allow for sufficient preheat of the inlet air. Therefore a reaction at the center would yield the highest conversion efficiency.

One way to suppress inlet channel auto-ignition is to reduce the residence time of the reactants in the inlet channel by decreasing the channel width and reducing the number of turns. This action effectively increases the reactant flow speed and reduces the degree of heat recuperation. With this mechanism in mind, this Swiss-roll was designed with a small channel width and only 5 turns. It was found, however, in previous work that this alone was not enough to prevent autoignition in the inlet channels [13].

Another way to eliminate the inlet channel auto-ignition issue is by directly injecting the fuel into the center combustion zone. The Swiss-roll prototype was designed with complete fuel injection flexibility such that any thermocouple port could be used to directly inject fuel to the Swiss-roll.

The center combustion zone was also enhanced in the fuel reformer with an end-to-end flow path design. Previous Swiss-roll designs [7-12] used a stream wise center reaction zone which allowed gas to flow in and out of the center along the entire length of the channels. While the stream wise design is simple, it also allows a recirculation zone to form which reduces the effective reactor volume and reduces residence time. Alternatively, an end-to-end flow path forces the flow to enter the combustion zone at one end, and exit at the other (Figure 3). When incorporated with a ceramic flow straightener, this design can eliminate the recirculation zone in the center of the Swiss-roll, thus improving total process flow rate, reactor residence time, and syngas yield.

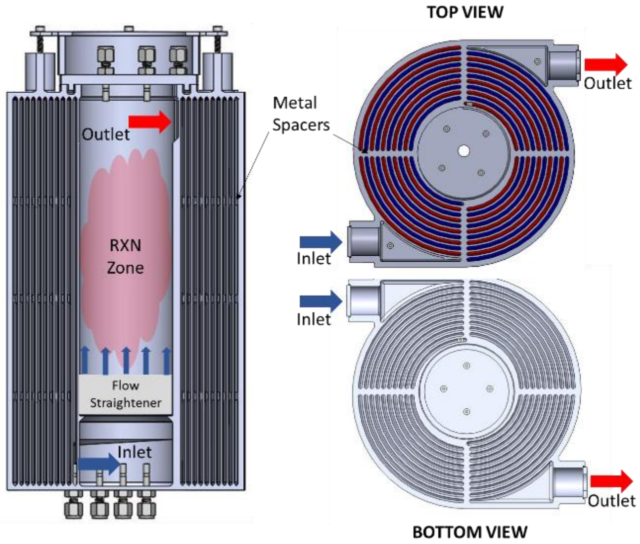

**Figure 3:** Multiple views of the Swiss-roll fuel reformer prototype depicting the end-to-end flow pattern in the center combustion zone.

Several other design features were also added to improve the reactor performance, lifetime, and experimental flexibility. Twelve (12) strategically placed holes for experimental instrumentation, such as thermocouples or fuel injection tubes, were integrated into the design. A larger hole was placed on the outlet face of the center combustion zone to accommodate a spark ignition system for fast and simple reaction startup. Spacers were 3D printed between the channel walls at regular intervals along the axial dimension of the Swiss-roll for added structural integrity. Also, a removable top plate was designed to allow access to the center combustion zone for visual observation after experimentation or future modifications.

The material used for fabrication was stainless steel PH1, which is the powder form of stainless steel used in 3-D printing to produce a material with the same chemistry as stainless steel 15-5. [13]

For preliminary testing, the Swiss-roll was piped to a compressed air source. A propane line was fed a few centimeters upstream of the reaction zone where it mixed with the preheated air. The reactant flow was controlled using mass flow controllers wired to a National Instruments DAQ and monitored through the LabVIEW interface. The temperatures at several key points in the Swiss-roll were closely monitored using an array of thermocouples inserted through pre-drilled holes. Figure 4 depicts the thermocouple setup.

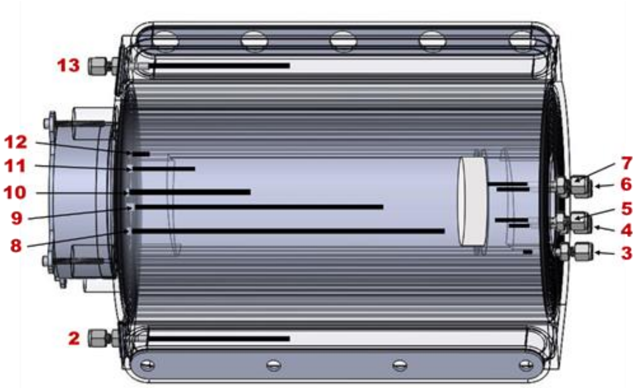

**Figure 4:** Swiss-roll test setup thermocouple placement.

It is important to note that the thermocouple labeled “3” was removed and replaced with the propane fuel injection line.

The outlet manifold of the Swiss-roll contained a port for reformate sampling to analyze the composition using a gas chromatograph. The remaining reformate was flared off for safety purposes.

## RESULTS AND DISCUSSION

For proof of concept, propane was tested in place of JP-8 due to simplicity in its chemistry. Preliminary testing has shown the capability of the Swiss-roll reformer to produce meaningful amounts of hydrogen from a propane-air mixture.

The Swiss-roll reformer ignites instantaneously using a spark plug located at the entrance to the center reaction zone. The premixed reactants, fuel and air, showed the tendency to auto-ignite before entering the center reaction zone. The resulting out of center reaction seemed to severely hinder the production of synthesis gas products. To combat this problem, fuel was injected at the inlet to the center reaction zone instead of premixed with air. The resulting preheat is less effective, but the Swiss-roll was still able to sustain the rich reaction conditions.

Table 1 outlines test results in several different conditions. It is important to note the difference in hydrogen yield between a traditional premixed approach and the direct fuel injection approach. With a stabilized reaction zone and direct injection of propane, the hydrogen yield begins to approach the equilibrium value, which at equivalence ratio 2 is around 18%.

Along with an increase in hydrogen production, there is also a significant decrease in acetylene concentration when direct injection is introduced. This is an important result because it greatly improves the lifetime of any downstream acetylene removal operation.

It was also observed that the observed carbon monoxide levels in the reformate stream were approaching the expected equilibrium value. The reformer is successfully performing thermal partial oxidation based on these observations.

High flow rates showed the tendency to leave a higher concentration of unburned methane and acetylene in the reformate. The most plausible explanation for this is the reduction of residence time in the center reaction zone. Unburned methane will not serve as a detriment to the SOFC system, but unburned acetylene will rapidly coke up the SOFC.

**Table 1:** Comparison of reformate composition with premixed reactants and direct injection of fuel.

| | Traditional Premixed | | | Direct Injection | |
|---|---|---|---|---|---|
| **Flow Rate (SLPM)** | 20 | 30 | 42 | 11 | 14 |
| **Fuel %** | 8.1 | 10.4 | 12 | 8.73 | 8.73 |
| **Inlet Re** | 110.30 | 165.45 | 231.63 | 60.67 | 77.21 |
| **Equivalence Ratio** | 1.94 | 2.49 | 2.87 | 2.09 | 2.09 |
| **H2%** | 0.96 | 5.15 | 6.61 | 13.69 | 14.11 |
| **O2%** | 4.44 | 0.00 | 0.00 | 0.00 | 0.00 |
| **N2%** | 82.60 | 78.21 | 74.15 | 70.24 | 68.68 |
| **CH4%** | 1.93 | 4.67 | 5.11 | 1.52 | 1.89 |
| **CO%** | 1.73 | 5.05 | 4.96 | 15.67 | 15.96 |
| **CO2%** | 8.99 | 9.61 | 9.09 | 4.88 | 4.50 |
| **C2H2%** | 2.08 | 4.16 | 5.62 | 1.38 | 1.82 |
| **C2H6%** | 0.20 | 0.16 | 0.22 | 0.00 | 0.00 |
| **C3H8%** | 3.32 | 0.12 | 0.17 | 0.00 | 0.00 |

A secondary test for propane direct injection allowed us to compare different flow rates and different equivalence ratios, the data is shown in table 2.

**Table 2:** Direct injection of propane at several flow conditions.

| | **1** | **2** | **3** |
|---|---|---|---|
| **Flow Rate (SLPM)** | **20** | **30** | **20** |
| **Fuel %** | **12.54** | **12.54** | **12.54** |
| **Inlet Re** | **110.30** | **165.45** | **110.30** |
| **Equivalence Ratio** | **3.00** | **3.00** | **3.00** |
| H2% | 9.567203 | 19.09403 | 19.73954 |
| O2% | 0 | 0 | 0 |
| N2% | 70.79002 | 60.603 | 59.96276 |
| CH4% | 5.525696 | 2.801699 | 3.440554 |
| CO% | 13.70637 | 22.3487 | 22.5742 |
| CO2% | 5.456292 | 3.268824 | 3.100245 |
| C2H2% | 3.80522 | 0.60026 | 0.549535 |
| C2H6% | 0.18227 | 0 | 0 |
| C3H8% | 0.625246 | 0 | 0 |

Test number 1 was taken early in the Swiss-roll run, when the thermal mass was not properly preheated. Tests 2 and 3 were taken at steady state. This test gives a good insight to the potency of high preheat. At low preheat, the fuel remains partially unburnt, and meaningful levels of methane are observed as well. After a proper preheat, each run demonstrated high hydrogen yield. The test at the higher Re, 165, yielded very similar results to the test at a Re of 110. Compared to the first direct injection test, we can see that hydrogen yield is lower at a lower equivalence ratio, which is expected.

The results of these direct injection tests helped prove that direct injection provides a stable reaction zone in the center of the Swiss-roll. Figure 5 shows a propane test where a clean blue flame is visible.

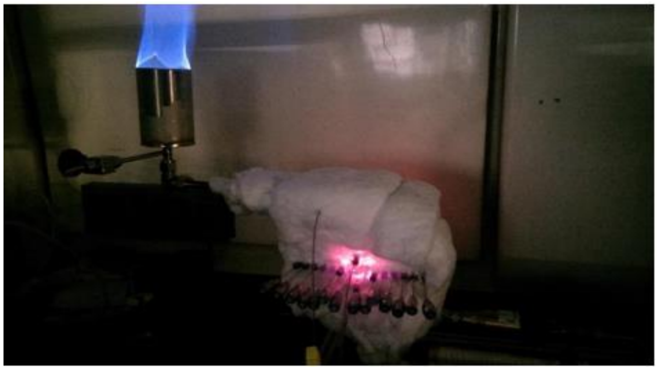

**Figure 5:** A Swiss-roll reforming propane with a blue flame and a bright center reaction zone.

The concentration of reactants in the center allows for an even distribution of preheating as well. The Swiss-roll must also fully heat up before any meaningful amount of hydrogen can be produced. In the next step, a lean propane flame is used to heat up the Swiss-roll before JP-8 is introduced. This will help reduce the formation of unwanted byproducts of low temperature JP-8 combustion.

## ***JP-8 Testing***

After proving the capability of the reformer to convert propane into synthesis gas, the next step was to use actual JP-8 as the fuel. A system for introducing vaporized JP-8 was developed. Figure 6 outlines the vaporization system.

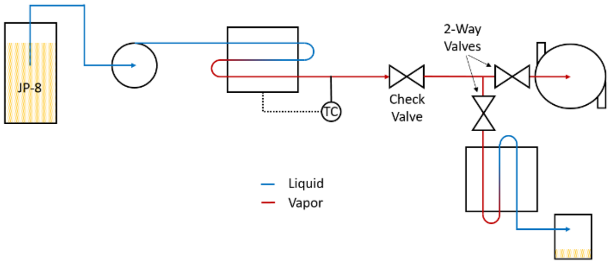

**Figure 6:** Schematic of JP-8 vaporization system.

The JP-8 is pumped from a reservoir and enters a heat exchanger where the fuel is heated up to approximately 320°C. The resulting mixture is then condensed into a cooled reservoir when the Swiss-roll is not active, or fed directly to the center reaction zone of the Swiss-roll when it is active.

The JP-8 vaporization device was tested separately under controlled conditions. The device was capable of fully vaporizing the JP-8 feed at a controlled temperature of approximately 320°C. This temperature would be the set point for future JP-8 testing.

The first Swiss-roll test with JP-8 as the fuel demonstrated the ability to generate synthesis gas from JP-8 in a non-catalytic system. The Swiss-roll was preheated using the more stable fuel, propane, in fuel lean conditions. After reaching stable conditions at high temperatures, the JP-8 preheating device was activated and JP-8 was directly injected to the center. An unsteady reaction was observed with small oscillations in temperature of the reaction zone. The flare that can be seen in figure 7 oscillated between a bright yellow flame, and a transparent blue flame.

**Figure 7:** Side view of Swiss-roll reformer with flare visible.

The yellow colored flame likely due to soot formation from poor premixing of the reactions before the reaction occurs. This can be attributed to the oscillatory nature of the JP-8 vaporizor. The vaporizor exhibits a pulsing behavior where high velocity jets of JP-8 oscillate with low velocity jets. The high end of the oscillations causes very low mixing time before a reaction is occuring. This issue can be solved by introducing a steady mechanism of JP-8 vaporization. Adding an additional chamber where a steady pressure of JP-8 vapor can build up before being injected would solve this issue.

Although an unsteady reaction was observed, the hydrogen yield was at a similar level to that of the propane testing. The observed reformate compositions are listed in table 3. At each test with equivalence ratio 3.0, there was around 21% hydrogen yield. This hydrogen yield corresponds to about 75% of the equilibrium yield for TPOX of hydrocarbons.

**Table 3:** Reformate composition with JP-8 direct injection at several flow conditions.

| | 1.00 | 2.00 | 3.00 | 4.00 |
|---|---|---|---|---|
| **Flow Rate** | **20.00** | **20.00** | **23.00** | **30.00** |
| **Fuel %** | **3.33** | **2.44** | **2.00** | **3.33** |
| **Inlet Re** | **110.30** | **110.30** | **126.85** | **165.45** |
| **Equivalence Ratio** | **3.00** | **2.20** | **1.80** | **3.00** |
| H2 | 21.21 | 14.44 | 9.43 | 20.56 |
| O2 | 0.00 | 0.00 | 0.00 | 0.00 |
| N2 | 58.29 | 73.00 | 79.77 | 62.69 |
| CH4 | 3.51 | 0.91 | 0.04 | 0.72 |
| CO | 18.54 | 13.71 | 14.92 | 20.57 |
| CO2 | 5.06 | 8.00 | 9.19 | 4.35 |
| C2H2 | 1.43 | 0.06 | 0.00 | 0.05 |
| C2H6 | 0.03 | 0.00 | 0.00 | 0.00 |
| H2O | 3.06 | 3.59 | 3.16 | 2.36 |
| C3H8 | 0.00 | 0.00 | 0.00 | 0.00 |

The highest center temperature during a JP-8 test is measured higher than propane test. The thermocouple shows the temperature reached up to 1300°C during the JP-8 test at similar equivalence ratios to the propane tests, where temperatures above 1100°C were rare. This is probably due to the fact that the JP-8 is preheated to at least 320°C during the testing, where the propane is directly injected at room temperature.

During the JP-8 tests, the equivalence ratio was varied from 1.8 to 3.0, demonstrating the turndown ratio of the device. Although hydrogen yields are much lower at a low equivalence ratio, a reaction was still able to be sustained.

## *Post Reformer Operations*

In testing where JP-8 was used as the fuel, the reformate composition contained acetylene concentrations varying from 0 to 14,300 ppm. Because of the uncertainty of acetylene destruction in the reaction zone, a post reformer operation has been implemented.

A Rh/$CeO_2$ catalyst has been tested for its potency in reducing the concentration of acetylene in the reformate stream to levels that a SOFC can handle. Figure 8 shows the destruction efficiency of acetylene in a simulated reformate stream.

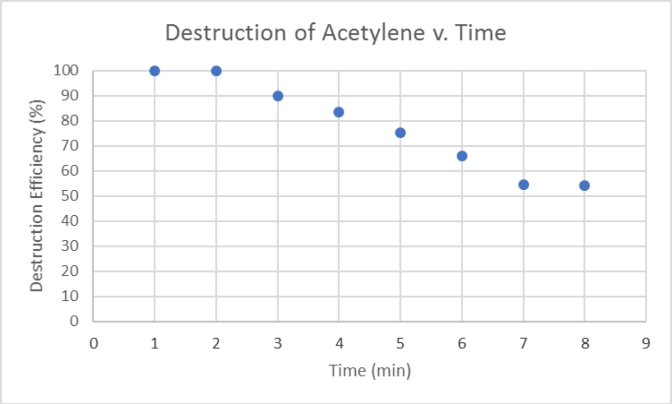

**Figure 8:** Plot showing the destruction efficiency of Rh/$CeO_2$ on acetylene.

A second post reformer consideration is the removal of sulfur compounds from the reformate. The sulfur containing compounds in JP-8 are converted to hydrogen sulfide during the thermal partial oxidation process. We introduced a ZnO sorbent downstream of the reformer that has shown a strong ability to remove virtually all $H_2S$ at temperatures around 250-300°C. Figure 9 shows the startup and shutdown flexibility of the ZnO sorbent.

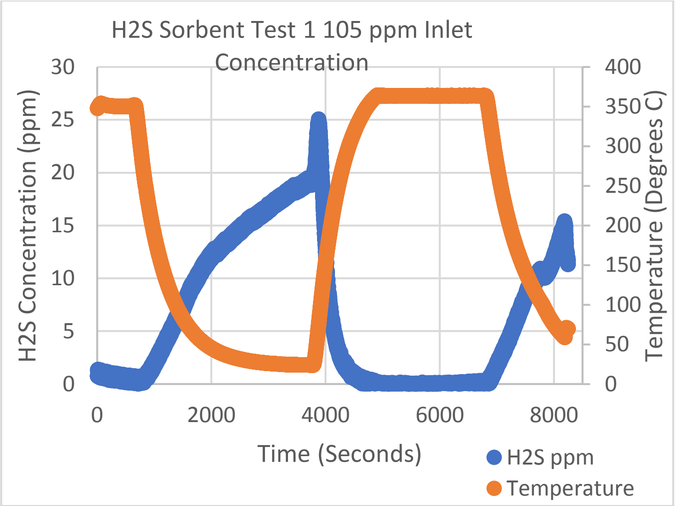

**Figure 9:** Plot showing transient behavior of ZnO sorbent.

The ZnO sorbent successfully destroyed all $H_2S$ even after cycling temperature from 350°C to 25°C and back.

## CONCLUSION

The Swiss-roll reformer demonstrates the ability to perform non-catalytic partial oxidation of JP-8 in a compact, lightweight system. The Swiss-roll reformer produced ~70% of the expected equilibrium level of hydrogen, and ~99% of the expected equilibrium level of carbon monoxide.

Due to its non-catalytic nature, and robust 3-D printing manufacturing technique, the Swiss-roll reformer will be able to operate for a very long time with no maintenance required. The post reformer operations can be refined to extend their lifetime as well without the need to regenerate or replace catalyst or sorbent. It should be noted however that if these do need replacement it is a very simple maintenance.

The Swiss-roll reformer also boasts the ability to be compatible with almost any fuel, be it a liquid, solid, or a gas. The overall flexibility and compactness of the Swiss-roll allows it to be a powerful technology, capable of silently converting a heavy liquid fuel into gas that can feed into a fuel cell with low acoustic signature for mobile application.

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