46th International Conference on Environmental Systems
10-14 July 2016, Vienna, Austria

ICES-2016- 272

# Solid Oxide Electrolysis and Nafion System Architecture for Oxygen Recovery and Fuel Production

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**Solid Oxide Electrolysis is a technology that can generate oxygen from water vapor and carbon dioxide. Embedding Sabatier reactors allows for reclaiming oxygen from carbon monoxide produced by electrolysis as well as producing methane for fuel. Nafion is a technology that can passively pull water from a cabin atmosphere to be combined with carbon dioxide and feed the electrolysis reactor. As little as 30% of water vapor contained in the cabin air may be required to supply 100% of oxygen supplies to crew. This paper describes an air revitalization system that uses solid oxide electrolysis, Sabatier reactors and Nafion to regenerate oxygen and produce fuel. Analyses will be presented to explore oxygen recovery, water recovery, system size and system power.**

## Nomenclature

*ARS* = air revitalization system
*CCDev* = Commercial Crew Development
*CDRA* = Carbon Dioxide Removal Assembly
*CFR* = carbon formation reactor
$CH_4$ = methane
$C_6H_{10}O_5$ = amylase and amylopectin
$C_{57}H_{98}O_6$ = trilinolein
$CO_2$ = carbon dioxide
*CO* = carbon monoxide
$e^-$ = electron charge
*ESR* = embedded Sabatier reactor
$H_2$ = hydrogen
$H_2O$ = water
*ISS* = International Space Station
$Kp_{wgs}$ = water gas shift equilibrium constant
*Ni* = nickel
$O_2$ = oxygen
$O^{2-}$ = doubly charged oxygen ion
$NH_3$ = ammonia
*SBIR* = Small Business Innovation Research
*SOA* = state of the art
*SOE* = solid oxide electrolysis
*TCCS* = trace contaminant control system
*YSZ* = yttria-stabilized zirconia

## I. Introduction

CURRENT oxygen ($O_2$) recovery processes used in space electrolyze liquid water ($H_2O$) to produce gaseous $O_2$. Available resources of liquid $H_2O$ within a habitat or spacecraft include metabolically-produced $H_2O$ by the

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crew (via condensation from the cabin atmosphere or post-processed waste) as well as that obtained as a fuel cell by-product (if fuel cells are present). If only enough water is delivered to the crew to keep them alive (drinking, food) then these sources do not provide enough $H_2O$ to recover all the necessary $O_2$.

To increase the amounts of recovered $O_2$, $O_2$ must also be obtained from carbon dioxide ($CO_2$) produced by the crew. Current methods are to react hydrogen ($H_2$) left over from the electrolysis process (rather than vent it) with some of the $CO_2$ via a Sabatier reaction to produce methane ($CH_4$) and more $H_2O$ in the form of a vapor. The $H_2O$ vapor is then condensed and electrolyzed. The $CH_4$ could be stored as a fuel or vented. Mass balance calculations have shown that, given a crew's diet, there is not sufficient $H_2$ available to convert enough $CO_2$ to completely recover all the $O_2$ required. The only way to provide enough $H_2$ is to supply the system with additional resources outside of those used for crew consumption. This is usually in the form of liquid $H_2O$.

To completely close the loop, the remaining $CO_2$ will have to be utilized. Solid oxide electrolysis (SOE) is a technology that can do this – it can recover $O_2$ from $CO_2$. Further, it can also electrolyze $H_2O$. Thus, SOE with a Sabatier reactor can provide 100% $O_2$ regeneration from crew metabolic products alone.[1] No consumables beyond those already required by the crew would be necessary.

Technology exists and has been used in space to collect and store $CO_2$ as well as supply $CO_2$ to air revitalization systems (ARS). Supplying $H_2O$ vapor in conjunction with the $CO_2$ has not been demonstrated in space. Recent advancements in Nafion® technology make this achievable and straightforward. This paper will discuss SOE/ESR technology coupled with Nafion humidity control technology to provide 100% oxygen recovery from crew metabolic waste products. The technologies and their integration into an ARS will be briefly discussed. A comparison of a SOE/ESR/Nafion system will be made to the states of the art (SOA). A resulting oxygen recovery and water recycling analysis will also be presented. Resulting figures of merit and performance parameters will also be discussed.

## A. Background

### 1. *Solid Oxide Electrolysis*

SOE technology uses an electrolyte made of a *nonporous* ceramic oxide, such as yttria-stabilized zirconia (YSZ), which conducts oxygen ions at elevated temperatures (750°C to 850°C). Electrically-conducting porous cathodes and anodes attached on opposite sides of the electrolyte facilitate gas/electron transport and act as catalysts.

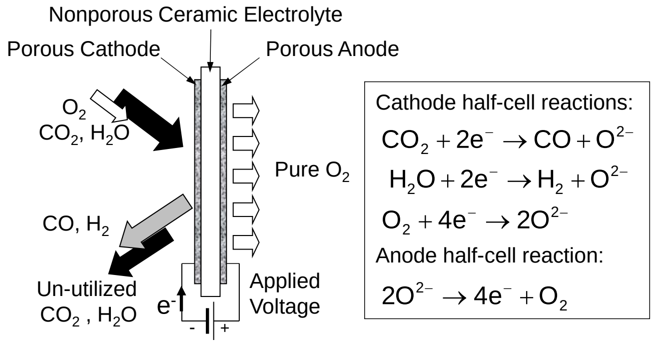


**Figure 1: Solid Oxide Electrolysis Illustration (cell cross section)**

At the cathode, an oxygen atom is liberated from $CO_2$, via an endothermic reaction. The oxygen atom receives two electrons from the cathode to become a doubly charged oxygen ion, $O^{2-}$. A voltage applied to the electrodes drives the oxygen ion through vacancies in the crystal lattice of the nonporous electrolyte. When the ion reaches the other side of the cell it releases the electrons to the anode and combines with another oxygen atom to form an $O_2$ molecule. The voltage applied across the cell in conjunction with the $CO_2$ supply rate drive the $O_2$ recovery rate. Several SOE cells can be combined in a stack to increase $O_2$ recovery. A SOE stack can also recover $O_2$ from $H_2O$ vapor via the exact same process but instead of producing carbon monoxide (CO) in the cathode exhaust, it produces $H_2$. The overall process and half-cell reactions are shown in Figure 1.

### 2. *Embedded Sabatier Reactors*

To safely handle the CO and $H_2$ by-products of electrolysis, and to further recover $O_2$ from the CO, a reactor can be employed downstream of the SOE stack to catalyze Sabatier reactions, creating $CH_4$ and $H_2O$. Sabatier reactions initiate at temperatures above 200°C and as high as 967°C, depending upon the catalyst. Once initiated, cooler temperatures, from 450°C down to 35ºC, favor forward equilibrium. Since nickel (Ni) is a catalyst for the Sabatier reaction *and electrolysis*, the Sabatier reactor can be "embedded" by using a Ni cathode in a SOE cell and operated at a lower temperature.[1,2,3] If desired, the embedded Sabatier reactor (ESR) can also perform electrolysis with an applied potential at higher temperature. Thus, the same hardware used for $O_2$ production doubles as a Sabatier reactor.

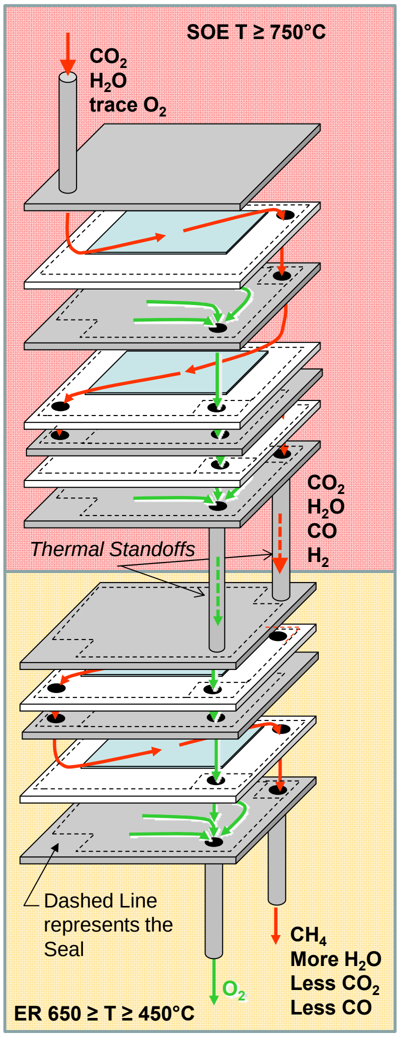
The concept of Sabatier reactors embedded into a SOE system is further illustrated in Figure 2. The first substack is supplied $CO_2$ and $H_2O$ and operated as an electrolyzer at high temperature and under an applied potential. The output of the first substack will be CO, $H_2$, and unutilized $CO_2$ and $H_2O$. This output is sent to a second substack operated at lower temperature and no applied voltage as an ESR to consume CO, $CO_2$ and $H_2$ and produce more $H_2O$. The process can be repeated, sending the process stream to a third substack that is operated as an electrolyzer to increase the utilization of remaining $CO_2$ and newly-produced $H_2O$. At this point, $O_2$ recovery is complete with an over 90% utilization of the initial $CO_2$ and $H_2O$ supply.[3] However, the exhaust of this third substack still contains valuable $H_2$ and trapped oxygen in CO. A fourth substack is operated as an ESR to convert these products into water, which can be condensed or recycled back to the SOE/ESR supply. Stack operation is optimized to control the final system output by varying applied voltage and each substack temperature. Performance is then rather consistent over a broad range of $CO_2$ to $H_2O$ mixture ratios given that materials used throughout the system promote the water gas shift reaction ($CO_2 + H_2 \rightarrow CO + H_2O$).[4]

Thermodynamic calculations have been performed and verified with experiment to show that due to the presence of $CH_4$, the process stream in an SOE/ESR system should not encourage carbon deposition at operating temperature[2,3] – a benefit of incorporating the reactor inside the SOE stack. However, carbon deposition could occur in the outlet tube as the exhaust cools if the CO to $CO_2$ ratio remains high. Operation of the last substack as an ESR lowers this CO to $CO_2$ ratio and carbon deposition is avoided altogether.

## 3. *Nafion Bundle Technology*

Paragon is developing Nafion-based humidity control systems (Patent No. US 8,985,474) for spaceflight.[5,6] Nafion® is a fluorinated ionomer copolymer of tetrafluoroethylene (Teflon®) and perfluro-3,6-dioxa-4-methyl-7-octene-sulfonic acid. It is not porous but contains exposed and permanently embedded sulfonic acid groups that participate in chemical reactions. The sulfonic acid groups form ionic channels that allow water to be transported through the bulk hydrophobic polymer. In this sense, Nafion functions like a very selective, semi-permeable membrane to water vapor.

The function of a typical Nafion-based water extractor is shown in Figure 3. The actual driving force for moving water is the water partial pressure differential across the Nafion membrane. This differential can be created by exposing the other side of the membrane to vacuum, or by flowing dry gas. Under steady state conditions there is no evaporative cooling since the water does not undergo a phase change across the membrane.



Sabatier Reactions:
$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$
$CO + 3H_2 \rightarrow CH_4 + H_2O$

**Figure 2: Illustration of a SOE and ESR Substacks in Series**

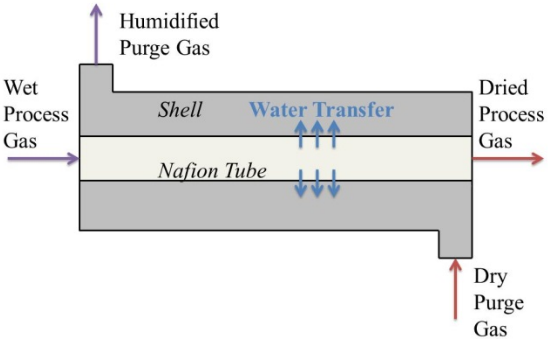


**Figure 3. Illustration of example flow in a Nafion-based water extractor.** *A dry gas is used external to the humid air to create a water vapor partial pressure across the Nafion membrane.*

To implement Nafion, Paragon developed and manufactures spaceflight Nafion bundles as shown in Figure 4. A given bundle can package hundreds to thousands of small diameter Nafion tubes. A single bundle or sets of bundles can be configured in parallel or series to achieve a specified water removal performance requirement.

**Figure 4. Example Paragon Nafion bundle.** *The size is ~2.5" diameter x 4.5" long.*

## II. System Integration

As exemplified in Figure 5 (left), SOE/ESR technology may integrate with pre-existing technologies as that used on the International Space Station (ISS).[7] A direct swap of a SOE/ESR unit with the existing Sabatier reactor allows for demonstration of the $CO_2$ electrolysis and embedded Sabatier functions in a flight-qualified unit.

Figure 5 (right) illustrates a "clean sheet" example architecture that incorporates Nafion bundles as a means for providing $H_2O$ management directly with $CO_2$ removal and reduction. As ammonia ($NH_3$) in aqueous solution can degrade Nafion performance over time[5] and the SOE/ESR unit only requires a fraction of the total humidity content found in the cabin air (see section IV), the cabin air would first pass through the trace contaminant control system (TCCS) and then a condensing heat exchanger. This allows for maximum removal of $NH_3$ (primarily via the TCCS and secondarily via residual $NH_3$ solubilized in the condensed water). A TCCS upstream of the condensing heat exchanger also reduces the contaminant load on the condensate and lower water treatment costs.[8] The remaining humidified air then passes through the "wet" side of the Nafion humidity control module. Dry $CO_2$ from the $CO_2$ removal and accumulator function is fed to the "dry" side of the Nafion humidity control module and humidified. This humidified $CO_2/H_2O$ is fed to the SOE/ESR unit. A bypass valve is used to control the delivered $H_2O/CO_2$ ratio. The outlet of the "wet" side of the Nafion humidity control module has a dew point less than 0 °C and as low as -20 °C pending module design.[5] As on the ISS, the air stream is sent through the Carbon Dioxide Removal Assembly (CDRA). As the humidity is lower, there is less contamination risk to the $CO_2$ removal sorbent. The $CO_2$ is compressed and stored in an accumulator. The $CO_2$-free low humidity air is sent into the "dry" side of another Nafion humidity control module to recuperate water from the outlet of the SOE/ESR unit. This now humidified air is returned to the cabin atmosphere.

For future life support systems, other advantages of an SOE/ESR subsystem can be exploited to simplify system design and increase $O_2$ recovery further. Waste heat from SOE/ESR can be used by other processes such as a TCCS or a $CO_2$ removal system. The SOE/ESR exhaust could eventually be fed to a carbon formation reactor (CFR) to recover additional $O_2$ otherwise trapped in CO. Recent progress has been made in Bosch reactors ($CO_2 + 2H_2$ $2H_2O + C(s)$).[9,10] The CFR converts CO into $H_2O$, where the $H_2O$ is recycled back to the SOE/ESR unit in order to increase the net $O_2$ recovery. Although consumables are required in replacing catalysts over time, including a CFR may be desirable to conserve water.

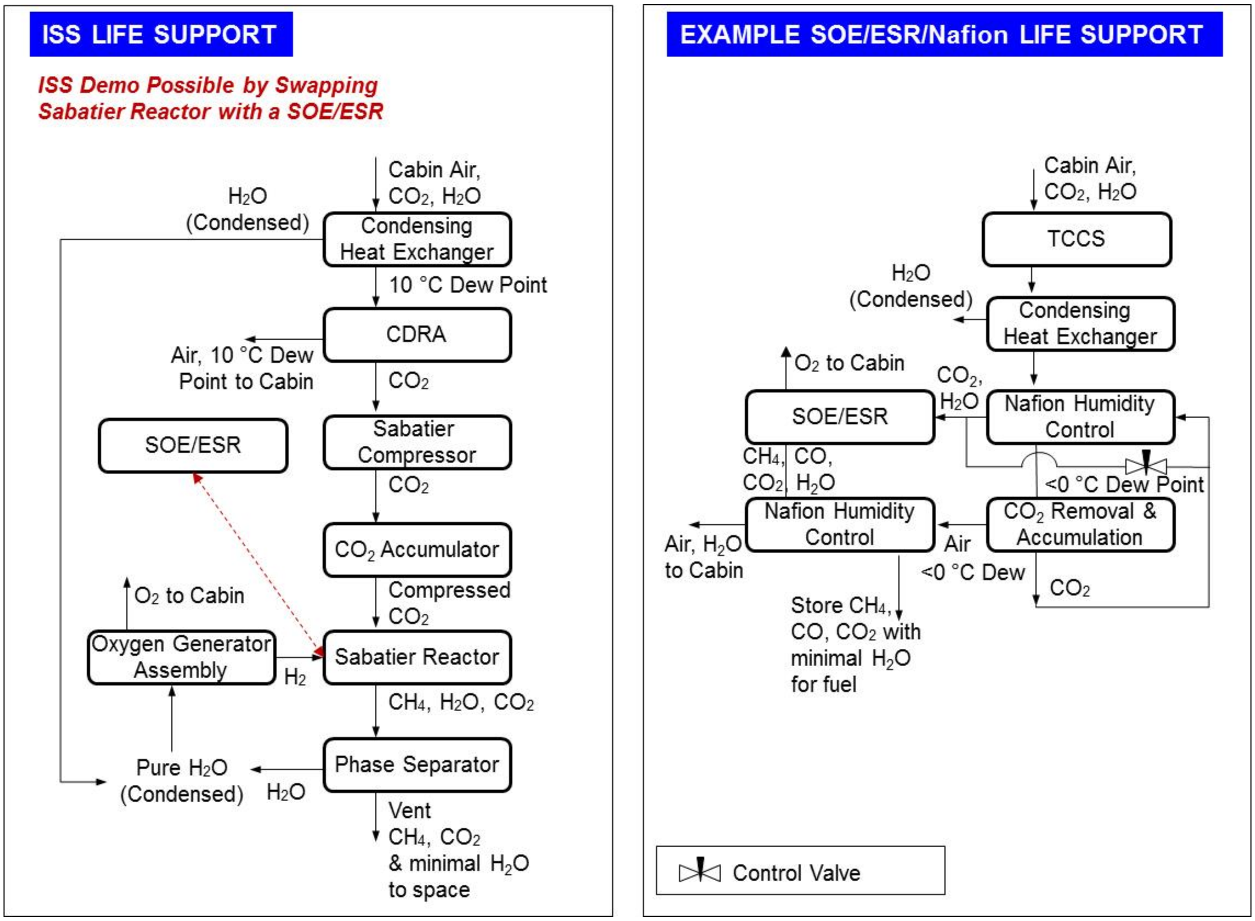


**Figure 5. Architectures employing SOE/ESR and Nafion Humidity Control.** *(Left) Possible demonstration using hardware currently installed on the International Space Station. (Right) Possible clean-sheet architecture that incorporates Nafion bundle water management (spacecraft and surface habitats).*

## III. SOE/ESR Enables Improved Performance over the SOA

The benefits of SOE/ESR over competing technologies are numerous: instantaneous, clean, dry oxygen production; single gas phase operation; one unit – flexible operation; carbon deposition-resistance; high single pass utilization; and elimination of $H_2$ handling.

### *1. Improved Oxygen Recovery*

Ultimately, the primary waste products of human food metabolism, $H_2O$ and $CO_2$, are the only source materials that a regenerative air revitalization system can use to recover breathing $O_2$ without the need to bring additional consumables. It is therefore important to carefully examine the mass balance which is best illustrated by analyzing the stoichiometry of a common carbohydrate and a fat and then showing how the technology would perform when processing the $H_2O$ and $CO_2$ from a normal diet.

Such an analysis was performed[1] by applying metabolic and process chemistry to common carbohydrates amylase ($C_6H_{10}O_5$) and amylopectin ($C_6H_{10}O_5$), and the common fat trilinolein ($C_{57}H_{98}O_6$). The SOA was compared to SOE/ESR technology. The SOA produces less moles of $O_2$ than was used to metabolize the carbohydrates in the first place; whereas, SOE/ESR could fully recover the $O_2$. In addition, SOE/ESR could recover water or even extra $O_2$. When analyzing fats, neither could fully recover the $O_2$ used in metabolizing fats. Fortunately, the excess $O_2$ produced by the SOE/ESR when treating the products of carbohydrate metabolism can make up for the losses associated with fat metabolism, because diets contain from 3.5 to 4.5 more carbohydrate by weight than fat.

Therefore, balancing crew $O_2$ consumption and SOE $O_2$ recovery requires a careful analysis of the carbohydrate, fat, and protein in the diet in order to determine the metabolic $CO_2$ and $H_2O$ production relative to $O_2$ consumption. Because hydrogen is used to reduce $CO_2$, this analysis is sensitive to the relative proportions of carbohydrates, protein, and fat in the diet. Thus, analysis of the ability of a technology to recover $O_2$ cannot be performed on the basis of respiratory quotient (RQ) alone. The higher the proportion of carbohydrates in the diet, the more $O_2$ can be recovered.

Analyzing different diets, it was shown[1] that the SOA (ISS) was only able to produce 80% of the crew requirement. SOE/ESR produced 102% of the crew requirement; SOE/ESR w/CFR produced 114% of the crew requirement. While the addition of consumable hydrogen could bring the SOA rate up, this requires long term handling and storage of hydrogen which does not store efficiently. It should be noted that if all the carbon was ultimately deposited (infinite number of passes through the CRF), then the combination of SOE/ESR and CFR would eventually recover all the available $O_2$.

2. *Reduced Mass*

Mass of an SOE/ESR unit for a 4-crew life support system is projected to be approximately 56 kg when adjusting for a fourth substack.[3] Assuming an implementation like that shown on the right in Figure 5, two Paragon Nafion humidity control modules would total approximately 10 kg. This leaves over 500 kg of hardware mass for the $CO_2$ collection/delivery system and water condenser (for drinking) before the total system mass would exceed six months of $O_2$ recovered by the system.

3. *Similar Power*

Power of a SOE/ESR system should be similar to the SOA on ISS, if not slightly less. Though SOE is a high-temperature process, it has been shown that the total energy (power and heat) is the same as that required by any electrolyzer technology since a fixed finite amount of energy is required to break down a $CO_2$ or $H_2O$ molecule.[11] Power reductions may be realized as the waste heat from SOE can be leveraged to reduce electrical heating of the embedded Sabatier reactors. Further, a mechanical water phase separator is not required at the SOE/ESR exhaust (while one is required for operation of the SOA ISS Sabatier Reactor). Rather, the Paragon Nafion humidity control technology is passive with a pressure drop less than 0.18 kPa at a nominal flow rate of 2 SCFM per bundle, assuming two bundles in series for redundancy.[5]

4. *Similar Volume*

Volume of a SOE/ESR system may be larger than the SOA; however, when taking into account the consumables required by the SOA to meet a crew's $O_2$ needs, SOE/ESR may be similar and less as mission duration increases. The SOE/ESR (which essentially replaces the Oxygen Generation Assembly, Sabatier reactor and their integration hardware) is approximately 88 L and includes insulation to keep touch temperature safe. However, final thermal modeling and support structure (heat leak) may require additional insulation, increasing the SOE/ESR volume estimate. The Nafion humidity control unit at the system exhaust is approximately 1.5 L and appears to be on the same order of magnitude as the SOA Sabatier Reactor phase separator.[12] The additional Nafion humidity control unit used to provide the SOE/ESR $H_2O$ and $CO_2$ simultaneously is an *additional* 12 L over that required by the SOA for humidity control. However, if the SOA can only recover 80% of the $O_2$ using the existing metabolic products from the crew, approximately 135 L of additional water will be required to make up the remaining 20% of $O_2$ for a six month mission.

5. *Reduced Complexity & Potentially Increased Reliability*

An SOE/ESR-based system is less complex than the SOA as it eliminates the need for a rotary phase separator, a separate liquid water electrolysis system, and their associated integration hardware. Water delivery control is via a by-pass valve and passive flight-qualified Nafion membrane technology. This translates to less moving parts and less issues with condensing water – all favorable for increased reliability.

## IV. Oxygen Recovery and Water Recycling Analysis

Assessment of $O_2$ recovery can be analytically demonstrated via conservation of mass and chemical thermodynamic analyses, corroborated by experimental testing.[2,3] $O_2$ is first recovered in the first substack via combined electrolysis of $CO_2$ and $H_2O$ vapor. Because of catalysts present in the unit, data show the mixture equilibrium is also highly driven by the water gas shift reaction ($H_2O + CO \leftrightarrow CO_2 + H_2$).[4] Selecting an $O_2$ recovery rate and assuming the water gas shift equilibrium constant ($Kp_{wgs}$) at the operating temperature, the exit exhaust composition can be determined.

The amount of $O_2$ recovered from solid oxide electrolysis alone can be described as the utilization of the supplied $O_2$-bearing molecules (i.e. $CO_2$ and $H_2O$). For a given supply mixture, utilization is inversely proportional to flow rate (the lower the flow, the higher the utilization), and directly proportional to applied potential (the higher applied voltage, the higher the utilization). If utilization is too high (greater than 90%), cells may degrade over time as the cells are not sufficiently supplied with $O_2$-bearing gas to electrolyze. To protect the stack, no greater than 80% utilization is assumed.

If only supplying $CO_2$, SOE alone recovers only half the oxygen ($CO_2 \rightarrow CO + ½ O_2$). Operating at only 80% utilization limits recovery to 40%. Adding water can increase the total % recovery since SOE recovers all oxygen from an electrolyzed water molecule ($H_2O \rightarrow H_2 + ½ O_2$).

To demonstrate the flexibility of an SOE/ESR unit to achieve higher oxygen recovery, three cases are presented in Table 1. Case A assumes only two substacks, the first operated in SOE mode followed by the second operated as an ESR. Case B assumes two additional substacks where the third is operated in SOE mode and the fourth is operated as an ESR. Case C assumes four substacks like Case B but the last ESR substack is operated at lower temperature. The columns of Table 1 summarize the input and output of each substack for a given case. For example, "Input" is the $CO_2$ and $H_2O$ input to the 1st substack (operated in SOE mode). The next section lists the 1st substack's output which is also the input to the 2nd substack. The next section assumes the previous as input and lists the resulting output (operated as an ESR). And so on.

1. *Case A – One SOE Substack & One ESR Substack*

As shown in Table 1, to recover enough $O_2$ with only one SOE substack to satisfy a crew of four, approximately 3 kg/day of water would be required. As described in Section III, SOE/ESR technology's ability to provide all a crew's $O_2$ with only crew metabolic byproducts outperforms the SOA. However, this is only 60% $O_2$ recovery.

To conserve water and mitigate carbon deposition, the exhaust is routed through an ESR. The Sabatier reactions convert the newly produced $H_2$ and CO from electrolysis into $CH_4$ and $H_2O$, reclaiming some of the $O_2$ trapped in the CO. The Nafion dryer returns 0.7 kg/day water to the atmosphere and the overall water required is now only 2.2 kg/day. This is 79% $O_2$ recovery.

When considering the water that is recycled back into the atmosphere, only 31% of the crew-generated water[7] is required. 2.2 kg/day is approximately 0.085 mol/min which is a fraction of the water available to typical spacecraft humidity control systems. Thus, this water is assumed present in the atmosphere and is easily collected in vapor form with the Nafion humidity control technology – no phase change and separation is required.

**Table 1: SOE/ESR % $O_2$ Recovery for Various Supply Gas and Operations**

| Cases | A<br>(2 Sub-stacks) | B<br>(4 Sub-stacks) | C<br>(Case B w/Last Sub-stack Operated at Lower Temp) |
|---|---|---|---|
| **Input** | | | |
| $CO_2$, kg/day | 4 | 4 | 4 |
| $H_2O$ Vapor, kg/day | 2.96 | 2.13 | 2.13 |
| **1st Substack - Combined Electrolysis (750°C)** | | | |
| $O_2$ Recovered kg/day | 3.34 | 2.69 | 2.69 |
| % $O_2$ Recovery | 60% | 56% | 56% |
| $H_2O$ Output, kg/day | 0.5 | 0.38 | 0.38 |
| $CO_2$ Output, kg/day | 0.83 | 0.88 | 0.88 |
| $H_2$ Output, kg/day | 0.27 | 0.19 | 0.19 |
| CO Output, kg/day | 2.02 | 1.98 | 1.98 |
| **2nd Substack - Embedded Sabatier Reactor** | | | |
| Reactor Temp, °C | 650 | 650 | 650 |
| $H_2O$ Output, kg/day | 0.73 | 0.54 | 0.54 |
| $CO_2$ Output, kg/day | 0.83 | 0.88 | 0.88 |
| $H_2$ Output, kg/day | 0.2 | 0.14 | 0.14 |
| CO Output, kg/day | 1.67 | 1.75 | 1.75 |
| $CH_4$ Output, kg/day | 0.2 | 0.13 | 0.13 |
| **3rd Substack - Combined Electrolysis (750°C)** | | | |
| $O_2$, additional, kg/day | | 0.64 | 0.64 |
| $H_2O$ Output, kg/day | | 0.10 | 0.10 |
| $CO_2$ Output, kg/day | | 0.19 | 0.19 |
| $H_2$ Output, kg/day | | 0.19 | 0.19 |
| CO Output, kg/day | | 2.19 | 2.19 |
| $CH_4$ Output, kg/day | | 0.13 | 0.13 |
| **4th Substack - Embedded Sabatier Reactor** | | | |
| Reactor Temp, °C | | 650 | 450 |
| $H_2O$ Output, kg/day | | 0.22 | 0.56 |
| $CO_2$ Output, kg/day | | 0.37 | 1.51 |
| $H_2$ Output, kg/day | | 0.14 | 0.04 |
| CO Output, kg/day | | 1.78 | 1.51 |
| $CH_4$ Output, kg/day | | 0.30 | 0.53 |
| **SUMMARY** | | | |
| $O_2$ Recovered, kg/day | 3.34 | 3.33 | 3.33 |
| % $O_2$ Recovery | 79% | 75% | 87% |
| Net $H_2O$ Vapor Supply Required, kg/day | 2.23 | 1.91 | 1.57 |
| % of Crew-generated Water in Atmosphere Required | 31% | 26% | 22% |

These calculations assume an ESR operation at 650°C to be conservative and in line with that demonstrated in an SOE/ESR system. Lowering the temperature along the ESR will increase the $H_2O$ recovery even more. Regardless, as $H_2$ content is low, there will still be oxygen in CO and $CO_2$ being exhausted with $CH_4$. Thus, $O_2$ recovery can be increased with an additional set of substacks – one for SOE followed by another ESR. This in turn, will also lower the overall water required.

2. *Case B – One SOE Substack & One ESR Substack Followed by Another set of SOE & ESR Substacks*

Repeating the analysis with four substacks, 75% $O_2$ recovery can be achieved while meeting a 4-person crew $O_2$ requirements with approximately 1.9 kg-$H_2O$/day (26% of available water in the atmosphere).

3. *Case C – Case B with the Last ESR Operated at Lower Temperature*

Lowering the last ESR from 650°C to 450°C alone decreases the water required to approximately 1.6 kg/day (22% of available water in the atmosphere) and increases the $O_2$ recovery to 87%.

This analysis demonstrates the flexibility of an SOE/ESR unit with multiple independently-controlled substacks. It should be noted that system-level performance predictions need to be confirmed through testing and operation will undoubtedly require optimization. Specifically, this analysis assumes average water production from each ESR as ESR water output falls within a range of calculated values for a given temperature. Depending upon performance, ESR temperature can be adjusted to achieve the end goal.

## V. Figures of Merit and Performance Parameters

**Table 2: Figures of Merit of a SOE/ESR Unit that Supports a 4-person Crew**

| Figure of Merit | Prediction |
|---|---|
| System mass per $O_2$ recovery rate | 298 kg-hr/kg-$O_2$ |
| Power consumption per $O_2$ recovery rate | 6.5 kW-hr/kg-$O_2$ |
| Volume per $O_2$ recovery rate | 27 L-hr/kg-$O_2$ |
| Consumable mass per $O_2$ recovery rate | 0 |

**Table 3: Key Performance Parameters of a SOE/ESR**

| Key Performance Parameter | Threshold | Goal * |
|---|---|---|
| Current Density (A/cm$^2$) | 0.1 | 0.4 |
| Number of Thermal Cycles | 20 | 100 |
| $O_2$ Recovery Rate | 75% | 87% |
| Supply H:C Molar Ratio | 2.7 | 1.9 |
| * Proposed cost-effectively achieved performance levels that offer significant improvement but remain well below theoretical limits. | | |

Key figures of merit are identified and quantified in Table 2. Key performance parameters are identified and quantified in Table 3.

Current density is a measure of oxygen transport across the electrolyte per electrode area. 0.1 A/cm$^2$ has been demonstrated at 750°C for Paragon's SOE/ESR series configuration, a configuration that is limited by the cell with the least $O_2$-bearing supply gas. A substack operated in parallel will provide higher current. Operational temperature of 850°C historically increases performance for a single cell to 0.4 – 0.6 A/cm$^2$.[4]

Even if the SOE/ESR unit is operated continuously, thermal cycles will be required to pass qualification and acceptance testing, integrated system checkout, and life support system maintenance cycles. The SOE/ESR seal design has been improved since prior efforts,[13] demonstrating 20 thermally cycles without failure and the ability to hold over 13 psig.[14] The ultimate requirements will depend upon mission design and system application.

The supply H:C molar ratio is a measure of the water loss via unused $H_2$ and generated $CH_4$ when achieving a given $O_2$ recovery. The threshold assumes 79% $O_2$ recovery with poor ESR performance (e.g. case A in Table 1). Research should be performed to explore the last ESR substack at lower temperature to encourage higher conversion of unused $H_2$. Design modifications to thermal integration, ESR catalyst and flow distributions within the ESR could influence higher $H_2$ conversion also. Another route may be to integrate a dedicated Sabatier reactor already optimized. It should be noted that including a CFR would lower water required as well.

## VI. Conclusion

The fundamentals of SOE/ESR electrochemistry have been established, quantified, and demonstrated at the laboratory-scale through a series of development cycles. A subsystem architecture that takes maximum advantage of the SOE/ESR's single phase operating characteristic has been developed, and incorporation of Paragon's patented Nafion humidity control technology allows for management of water into and out of the subsystem without complex electromechanical phase change and separation hardware. The architecture also integrates with other life support subsystems such as trace contaminant control and $CO_2$ removal in a manner that benefits the individual subsystems (e.g. the TCCS removes ammonia and the Nafion reduces water load to the $CO_2$ removal subsystem).

Minimum threshold and realistically achievable levels for key performance parameters have been established. SOE/ESR subsystem performance, with a conservatively high ESR operating temperature and incorporation of only four substacks, is predicted to offer significant advantages over the state of the art. Significant progress maturing the SOE/ESR subsystem design and retiring development risks has been made with the demonstration of 20 thermal cycles and operating pressures up to 13 psig. The next step in the development of SOE/ESR is to manufacture and test a full-scale engineering development unit. Demonstrating long-term performance while exceeding threshold performance parameters will establish SOE as a viable candidate for inclusion in NASA's long-duration deep space exploration plans over the coming decades.

## Acknowledgments

Paragon gratefully acknowledges past funding from NASA through the Small Business Innovation Research (SBIR) program to develop solid oxide technology for space applications. Specifically, Phase 1, 2 and 3 contracts for SOE/ESR life support applications (NNJ06JD56C, NNJ07JA12C, and NNJ10HC33P, respectively), Phase 1 and 2 contracts for SOE/ESR oxygen and fuel production (NNX13CJ10P and NNX14CJ05C, respectively), and Phase 1 for thermal cycle and pressurization improvements (NNX14CJ11P). Paragon also gratefully acknowledges past funding from NASA through the Commercial Crew Development (CCDev) program to develop Nafion humidity control systems (Space Act Agreement Number NNJ10TA03S).

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