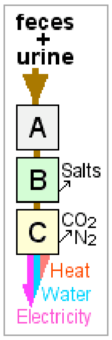
I. THE PROJECT.

The Institute for Residential Innovation, Inc. (www.iresi.org) is developing the Sewage Containment and Mineralization Device (SeCoM), a fully autonomous, low maintenance, high throughput, continuous flow, micro-sanitation and water re-purification system that will mineralize the organic matter from a single defecation and repurify the urine and flush water (regenerate potable water) by entirely physical (non-microbial) processes, in two minutes or less.

- No solid carbon residues or toxic liquids will be generated.
- No impure water will be reused or discharged.
- No harmful amounts of gas will be discharged.
- No supporting infrastructure will be needed.



II. GOAL.

To develop a compact SeCoM (~10x20x20cm) that will:

• facilitate on-site processing of pit latrine contents,

• enable the production of individual stand-alone toilets (no power-plugs; no plumbing) suitable for Improved Public Facilities (IPFs), watercraft, and residences of any type (inc. hi-rise) at any location (e.g. rock, or sand).

III. THE SeCoM.

Comprises three monolithic, micro-channel chemical reactors that sequentially: (A) sterilize and micronize, (B) deionize (remove salts such as sodium chloride), and (C) 'mineralize' (fully oxidize) raw sewage. The first two modules prepare the sewage slurry for injection into the third - the Solid Oxide Supercritical Water Electrochemical Cell (SOSWEC). This is the key innovation and the subject of the Phase I feasibility study.

IV. THE SOSWEC: **A NON-TECHNICAL SYNOPSIS.**

The SOSWEC is form of Solid Oxide Fuel Cell (SOFC), a miniature power station that burns fuel to generate electrical power. A conventional power station burns fuel to create heat which it then converts into electricity -- a two-stage process. The SOSWEC however harvests electrical energy directly[a] from the burning fuel -- a single-stage process. Most SOFCs burn hydrogen or methane; the SOSWEC is the only fuel cell that can burn wet biomass[b] (such as feces).

V. CONSTRUCTION AND TECHNICAL DESCRIPTION OF THE SOSWEC.

The SOSWEC simultaneously mineralizes organic matter, generates electrical and thermal energy, and regenerates potable water, by combining (i) oxidation (combustion) of biomass with oxygen in supercritical water (SCW*), and (ii) the passive flux of oxygen ions (O^{2-}) through a dense (non-porous) ion-conducting ceramic membrane.

The SOSWEC eliminates both the energy loss typically incurred by having to dry biomss before (or during) conventional combustion, and by simplifying the engineering, increases the overall efficiency of biomass oxidation in SCW.

The SOSWEC will also reduce the pollution, and enhance the recovery of useful energy from the oxidation of a variety of carbonaceous materials other than biomass.

The basic SOSWEC comprises a solid oxide fuel cell (SOFC) in which the usual fuel gas is replaced by sewage in SCW. Fecal organic matter is mineralized by electrochemical oxidation with O^{2-} ions† that are delivered into the SCW through the ceramic ion-conducting SOFC membrane.

Our lab. SOSWEC (Fig.1) comprises a tubular solid oxide fuel cell (tSOFC) membrane, sealed at one end and inserted into a closed cylindrical steel fuel chamber (see VI below). We have used pectin as an inexpensive, convenient surrogate for the carbohydrate polymers in biomass.

**water enters it's supercritical state once the temperature and presuure exceed 647K (374°C; 705°F) and 22.064 MPa (3200 PSIA;218 atm). SCW is very different from liquid water; viscosity is greatly decreased; salts precipitate; auto-ionization increases; and nonpolar molecules including gasses become highly soluble [1,2,3]. The properties vary with temperature and pressure, but are especially volatile around the critical point where extreme density fluctuations cause opalescent turbidity.*

† oxidation of biomass with oxygen gas in SCW is exothermic (generates heat). Once the biomass:water ratio exceeds ~4% w:w the reaction becomes autothermal (generates more heat than is needed to sustain the reaction) [4]; it is not yet known if this ratio remains valid for electrochemical oxidation with O^{2-} ions.

VI. RESULTS OF PHASE 1 FEASIBILITY STUDY.

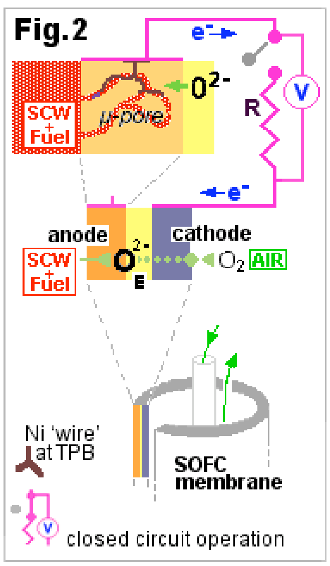
Conducted by N.M Sammes PhD FIMMM CEng, Prof. of Chemical Engineering, and H. Kim, at POSTECH, S.Korea.

Proof-of-principle for the SOSWEC has been demonstrated.

• The tSOFC membrane was undamaged by prolonged exposure to SCW at temperatures and presures of between 374-480°C and 50-100MPa.

• The SOSWEC generated 58±6 $mW.cm^{-2}$ at 0.5V, at ≈430⁰C and 50MPa (2 separate expts) using Pectin (a complex carbohydrate) at a concentration of 5gms/100ml of water as the fuel. This is approximately 60-75% of the power that would be generated by a similar tSOFC fuelled with hydrogen gas at 450°C in a conventional furnace; N.M. Sammes, personal communication).

VII. COMPOSITION AND OPERATION OF THE tSOFC (Fig.2)



The tSOFC is composed of three strongly bonded but structurally and functionally distinct concentric cylindrical ceramic layers.

• The outermost layer is the anode. This is is exposed to the SCW and is riddled with interconnected micropores within which the Fuel (see text next to Fig.4) is oxidized.

• The middle layer is the electrolyte (E). This is a dense (non-porous) ceramic that is impermeable to molecular oxygen (O_2 gas) and a very poor conductor of free electrons (electrical insulator). At temperatures greater than about 450°C however negatively charged oxygen ions (O^{2-}) can pass directly through the lattices and grain boundaries of the fused nanocrystals that form the ceramic, flowing passively down the transmembrane gradient in oxygen concentration [5] that exists berweeen air and SCW. The O^{2-} ions also 'ferry' the electrons needed to close the electrical circuit of the fuel cell, thus circumventing the poor free electron conductivity of the electrolyte.

• The cathode lines the central lumen of the tube. It is highly porous, and catalyzes the reduction of O_2 from air, to O^{2-} ions.

Electrochemical oxidation of Fuel takes place at the 'three phase boundaries' where the Fuel, the nascent O^{2-} ions, and the electron collector (uninsulated nickel 'tendrils' ⅄) co-locate. The TPBs extend through the lumen of many, but not all, of the anode micropores (Fig. 3, modified from [6], in which only the nickel deposits are displayed and the ceramic support material is not visible; and Fig. 4, modified from [7]).

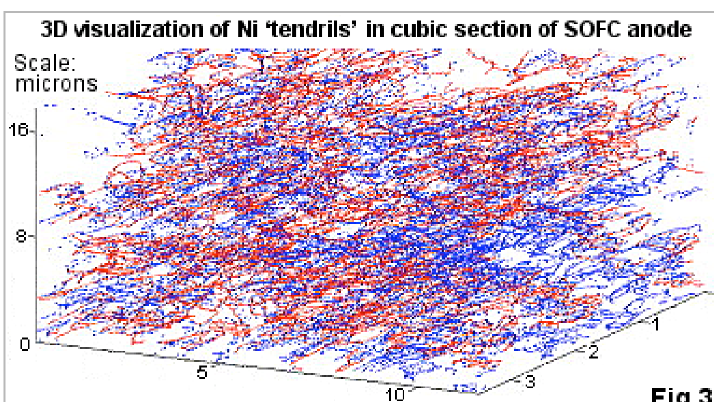
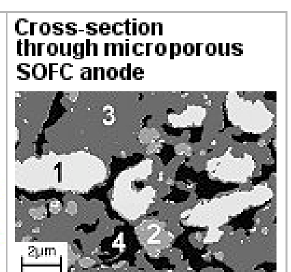


Fig.3

Blue: interconnected Ni tendrils that form the 'wires' of the anode current collector
Red: isolated Ni tendrils likely to have electrocatalytic activity *[14]*



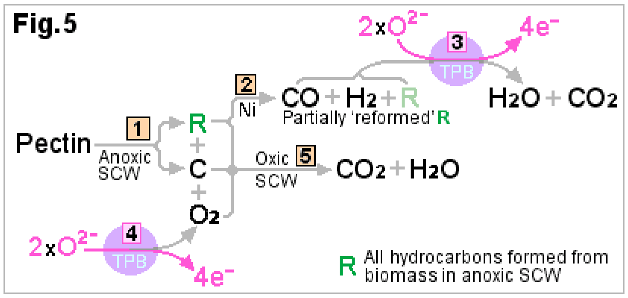
1. X-sectn of thro' nickel tendrils that form part of the current collector
2. Isolated nickel tendrils
3. Ceramic support material of anode
4. Empty space inside micropore

Fig.4

The Fuel that is oxidized at the TPB however is no longer pectin. In oxygen-free SCW pectin is rapidly and spontaneously converted into a mix of hydrocarbons [8,9], which are themselves further converted into the Fuel (ideally a mix of hydrogen and carbon monoxide) by a Ni-catalyzed process called 'reforming' [10,11,12].

Mineralization of pectin ultimately results in the production of CO_2, H_2O, and excess energy. The latter manifests as heat, and as the energy imparted to the electrons generated during the oxidation. These electrons are collected and conducted through an external circuit back to the cathode, where they are consumed for the reduction of more O_2, to O^{2-} ions.

VIII. REACTION SEQUENCES POSTULATED FOR MINERALIZATION OF BIOMASS (a qualitative schematic)



Sequence 1 [1] [2] [3] Electrochemical oxidation of products of 'reformed' pectin: H_2, CO, gaseous and liquid hydrocarbons, and some free Carbon.

Sequence 2 [1] [4] [5] Oxidation of free Carbon¶ and poorly permeable large hydrocarbons with molecular oxygen dissolved in SCW.

¶ *production depends on type of biomass, and on physical conditions during incubation in anoxic SCW.*

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FOOTNOTES

[a] A gas cooker mixes air (oxygen) and natural gas so that they burn as a single flame. A SOFC on the other hand keeps the oxygen and its fuel gas apart from each other on either side of a thin ceramic barrier (looks like porcelein) which is constructed in such a way as to control where and how quickly they mix. This barrier contains millions of interconnected, thread-like 'channels' that are highly selective for a particular form of oxygen (oxygen ions) and through which it can traverse the barrier to mix with the fuel. In this way a SOFC breaks down the single flame of the cooker into millions of tiny sparks, each at a point on the surface of the barrier where the oxygen ions and the fuel finally meet. Under these conditions each spark releases a small amount of electrical energy that is harvested by the SOFC. The electrical power generated by the SOFC is the total collected from all the sparks.

[b] Possible because the biomass is dissolved in Supercritical Water (SCW) -- a special state of water that exists only when it's very hot (≥705°F; 374°C) and under very high pressure (≥3200 psi; 218 atm). SCW is unlike any of the familiar forms of water such as ice (solid water), regular water (liquid water), or steam (gaseous water). Oils and greases for example dissolve in SCW, as do normally insoluble bio-polymers such as lignin, and gasses such as oxygen and methane; mineral salts such as sodium chloride (table salt) however are no longr soluble, and so crystallize and precipitate. The water molecule itself (H_2O) breaks apart into highly reactive fragments that rapidly convert dissolved biomass into a variety of hydrocarbon oils and gasses, turning the SCW dark brown. If oxygen is added at this stage however the hydrocarbons are almost instantaneously oxidized ('burnt') and the SCW becomes completely clean and clear. This reaction creates so much extra heat that it's able keep itself going with just a very small amount of fuel (approx. 4% biomass).

HWAN KIM, PhD STUDENT, PREPARES THE SOSWEC FOR ANOTHER EXPERIMENT

a. Tubular SOFC wired and ready for use.
b. Removable top plate of the SCW reactor.
c. Top plate with tSOFC clamped in place.
d. Top plate + tSOFC is inserted into the SCW reactor.
e. Fully assembled SOSWEC placed in insulated casing, inside containment chamber.
f. Containment chamber closed; SOSWEC controls and gauges remain accesible.
g. Hwan Kim at work.