LUNAR ORGANIC WASTE REFORMER.

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Introduction: The Lunar Organic Waste Reformer (LOWR) is a novel technology to convert organic wastes from human space exploration outposts into useful propellant constituents. The LOWR significantly reduces the mass and volume of wastes and reduces mission costs by producing a portion of important consumables on site.

The LOWR integrates steam reformation, methanation, and electrolysis to convert organic waste into methane and oxygen products. At reformer temperatures above 700°C, oxygenated steam reacts with organic matter to produce a gas mixture largely composed of hydrogen, carbon monoxide, and carbon dioxide. After condensing and removing excess water, the dry reformer exhaust gases are fed to a catalytic Sabatier reactor where they are combined with supplemental hydrogen at 350-500°C to produce methane and water. The methane product is liquefied for storage. Water obtained from the both the Sabatier and reformer reactors is electrolyzed to provide the supplemental hydrogen needed for methanation while simultaneously producing oxygen consumed during steam reforming. Excess oxygen is liquefied and stored as a product.

The LOWR addresses NASA's Trash to Supply Gas objective[1] under the Advanced Exploration Systems Logistics Reduction and Repurposing project[2]. Pioneer Astronautics designed, built, and demonstrated an integrated LOWR system during NASA SBIR Glenn Research Phase I and II projects. The LOWR successfully operated at a rate approximating that required to support a lunar outpost crew of four using a NASA high-fidelity waste simulant.

Background: Recycling of human metabolic waste, food wastes, plastic packaging material, maximum absorbency garments, and other organic matter to reduce the need to transport consumables in support of a space exploration crew has long been recognized as a high priority. The benefits of waste recycling increase as missions expand from low Earth orbit to the Moon, Near-Earth Objects, and Mars.

If energy is available, one promising way to transform organic waste into useful products is steam reformation, a technology that has been practiced on Earth for more than 150 years. Regardless of the details of its composition, if a material is organic, it can be reformed into a gas mixture predominantly composed of CO_2 and H_2 by reaction with high temperature steam. This makes steam reformation the ideal technology for recycling of organic wastes during human space exploration missions.

Waste Characterization: NASA has identified the primary wastes from human space missions as consisting of food packaging, food residues, human wastes, hygiene items, and clothing[1]. Included in the waste material are small amounts of inorganic matter such as aluminum and plastics fillers. Small amounts of other contaminants such as sulfur, nitrogen, and halides are mostly evolved as gases during processing. Table 1 shows a representative example of the waste composition.

Table 1: NASA High Fidelity Waste Simulant Composition

Waste Component	Mass, kg (average daily rate for a crew of 4)
Moisture	2.40
Total Organic Carbon	1.67
Total Organic Hydrogen	0.23
Total Organic Oxygen	0.59
Gaseous Contaminants	0.25
Solid Contaminants	0.25
Total	5.40

Except for the gaseous and solid contaminants, the Lunar Organic Waste Reformer converts all of the items listed in Table 1 into methane and oxygen products. The gaseous contaminants are removed from the reformer exhaust, and inorganic solid contaminants are recovered as ash exhibiting substantially reduced volume compared to the initial waste.

Wastes on the ISS are currently wrapped in plastic and sealed by tape to make "footballs" for disposal. Similar packaging is suitable for LOWR feeds because the reformer can accommodate large pieces.

Process Description: The Lunar Organic Waste Reformer system consists primarily of steam reforming, methanation, and electrolysis. The prototype LOWR reformer and Sabatier reactor systems are depicted in SolidWorks® drawings in Figure 1. For typical feeds, a small amount of additional water is required to balance the reactions discussed below for production of the desired methane and oxygen products.

Oxygenated Steam Reforming. Oxygenated steam reforming combines partial oxidation (highly exothermic) and steam reformation (highly endothermic). Example reactions are shown below.

$$C + \tfrac{1}{2} O_2 = CO \qquad \Delta H = -112 \text{ kJ at } 750°C \quad (1)$$

$$CO + \tfrac{1}{2} O_2 = CO_2 \qquad \Delta H = -283 \text{ kJ at } 750°C \quad (2)$$

$$C + H_2O = CO + H_2 \qquad \Delta H = 136 \text{ kJ at } 750°C \quad (3)$$

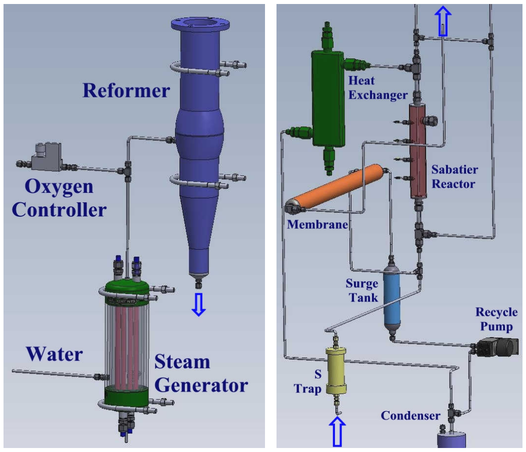

Figure 1: Steam reformer system (left) showing oxygen and steam injection to the reaction zone and the Sabatier reactor system (right) showing heat exchanger, product gas separation membrane, and recycle pump.

The exothermic partial oxidation reactions (1 and 2 above) supply thermal energy to support non-catalytic steam reforming (3 above). The oxygen feed rate controls the overall reforming rate. The steam feed rate is set to provide a stoichiometric excess to push the reforming reactions to completion and to control reactor temperatures. Some non-catalytic water gas shift also takes place during reformation according to the following reaction:

$$CO + H_2O = CO_2 + H_2 \qquad \Delta H = -35 \text{ kJ at } 750°C \quad (4)$$

After condensing excess steam, the dry reformer gas consists of H_2, CO_2, CO, and small amounts of CH_4. This gas is passed through traps to remove small amounts of gaseous contaminants and is fed to the Sabatier system described below.

Sabatier Methanation. The dry reformer gas is fed to a Sabatier reactor containing ruthenium catalyst. Hydrogen generated during reformation is supplemented with hydrogen from electrolysis to satisfy the following methanation reactions.

$$CO + 3H_2 = CH_4 + H_2O \quad \Delta H = -219 \text{ kJ at } 400°C \quad (5)$$

$$CO_2 + 4H_2 = CH_4 + 2H_2O \quad \Delta H = -181 \text{ kJ at } 400°C \quad (6)$$

High per-pass conversions are obtained as a result of high equilibrium constants for the methanation reactions. After condensing water, the product gases are fed to a membrane separator and gas recycle system that maintains an excess of hydrogen in the Sabatier reactor to ensure virtually complete conversion of CO and CO_2 to methane while providing diluent to help control reactor temperatures.

Electrolysis. Electrolysis serves to provide supplemental hydrogen required for methanation while co-producing oxygen that is in part consumed in the reformer and also recovered as a final product. The electrolysis rate is set to provide an overall system hydrogen balance – hydrogen is not stored or made as a final product. Electrolysis proceeds according to the following reaction.

$$H_2O = H_2 + \tfrac{1}{2} O_2 \qquad \Delta H = 286 \text{ kJ at } 25°C \quad (7)$$

LOWR Demonstration: Integrated reformer and methanation systems were operated to demonstrate the LOWR at a scale representative of that needed to process 4-person outpost wastes during a target 16 hour period in a 24 hour day (67 percent on-stream). The electrolyzer was simulated by supplying the oxygen for reforming and hydrogen for methanation via compressed gas cylinders.

Nearly complete conversion of all of organic matter from a wide range of individual and mixed feeds was achieved, and efficient heat recovery was demonstrated. The simple semi-batch feed and ash recovery systems were proven effective. The LOWR was found to require only small amounts of consumables (occasional seal replacement and sorbents). A straightforward control system allowed for automated operation after startup. A methane product of 98 to 99 percent purity was recovered with balance hydrogen. After methane liquefaction and recycle of hydrogen to the process, the methane purity is nearly 100 percent. The operating hardware was found to be robust through multiple operational cycles.

An important advantage of the LOWR is that a significant amount of hydrogen is produced during reforming, thereby reducing electrolysis input power by as much as 40 percent compared to that needed for combustion-based processes to generate methane and oxygen products. LOWR electrical power is projected to be about 2 kW (mostly for electrolysis). The projected system mass of about 113 kg results in about a one month breakeven time for a lunar application. The LOWR can be readily adapted to reduced and micro-gravity operations.

References: [1] Hintze, Paul E., Michael J. Kulis, John K. Lytle, John W. Fisher, Helen Vaccaro, Michael K Ewert, and James L. Broyan, “Trash to Supply Gas (TsSG) Project Overview”, AIAA Space 2012 Conference, September 11-13, 2012, Pasadena, CA. [2] Broyan, James Lee and Michael K. Ewert, “Logistic Reduction and Repurposing Beyond Low Earth Orbit”, AIAA 42nd International Conference on Environmental Systems (ICES), July 15-19, 2012, San Diego, CA.

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