LUNAR ORGANIC WASTE REFORMER

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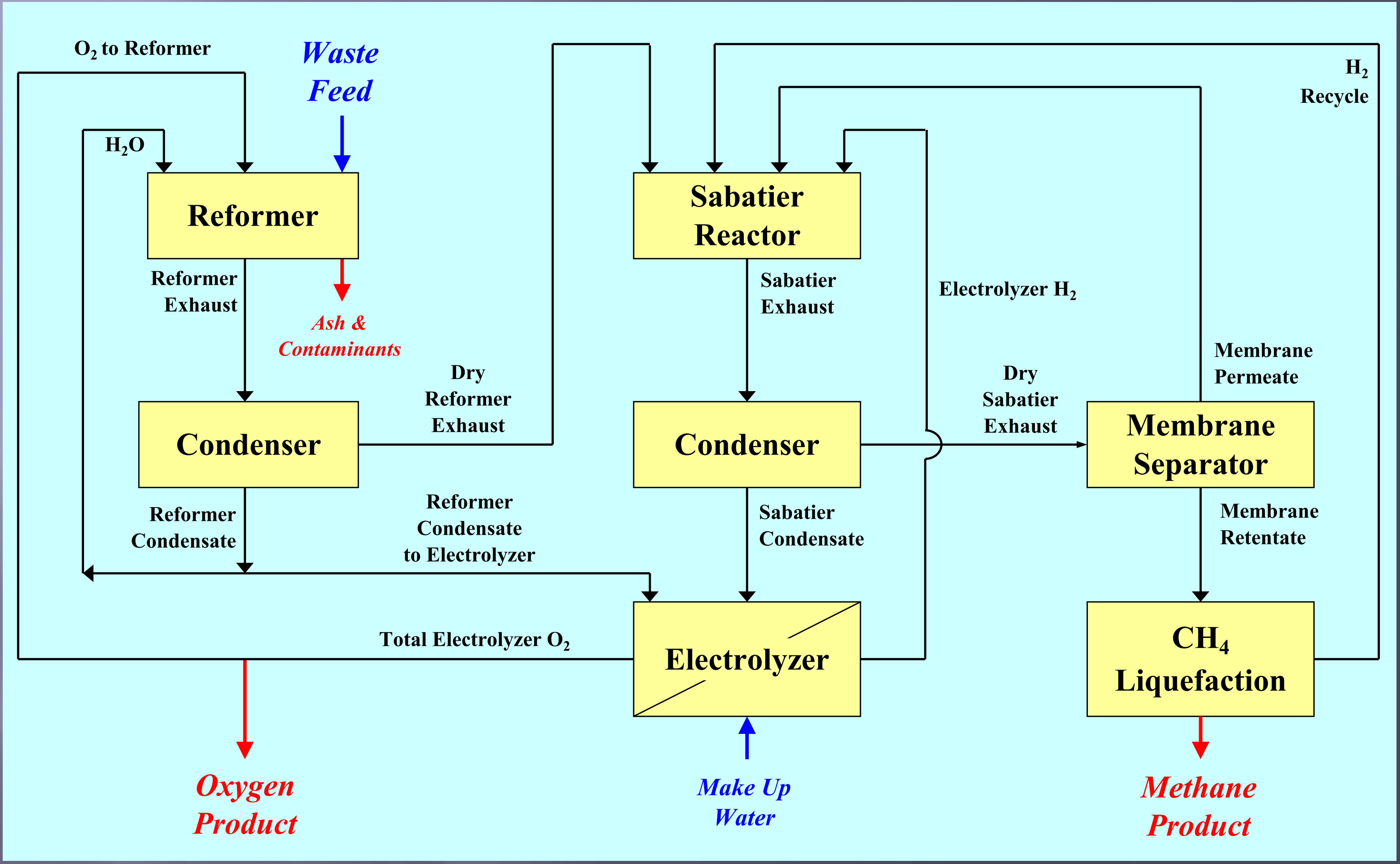
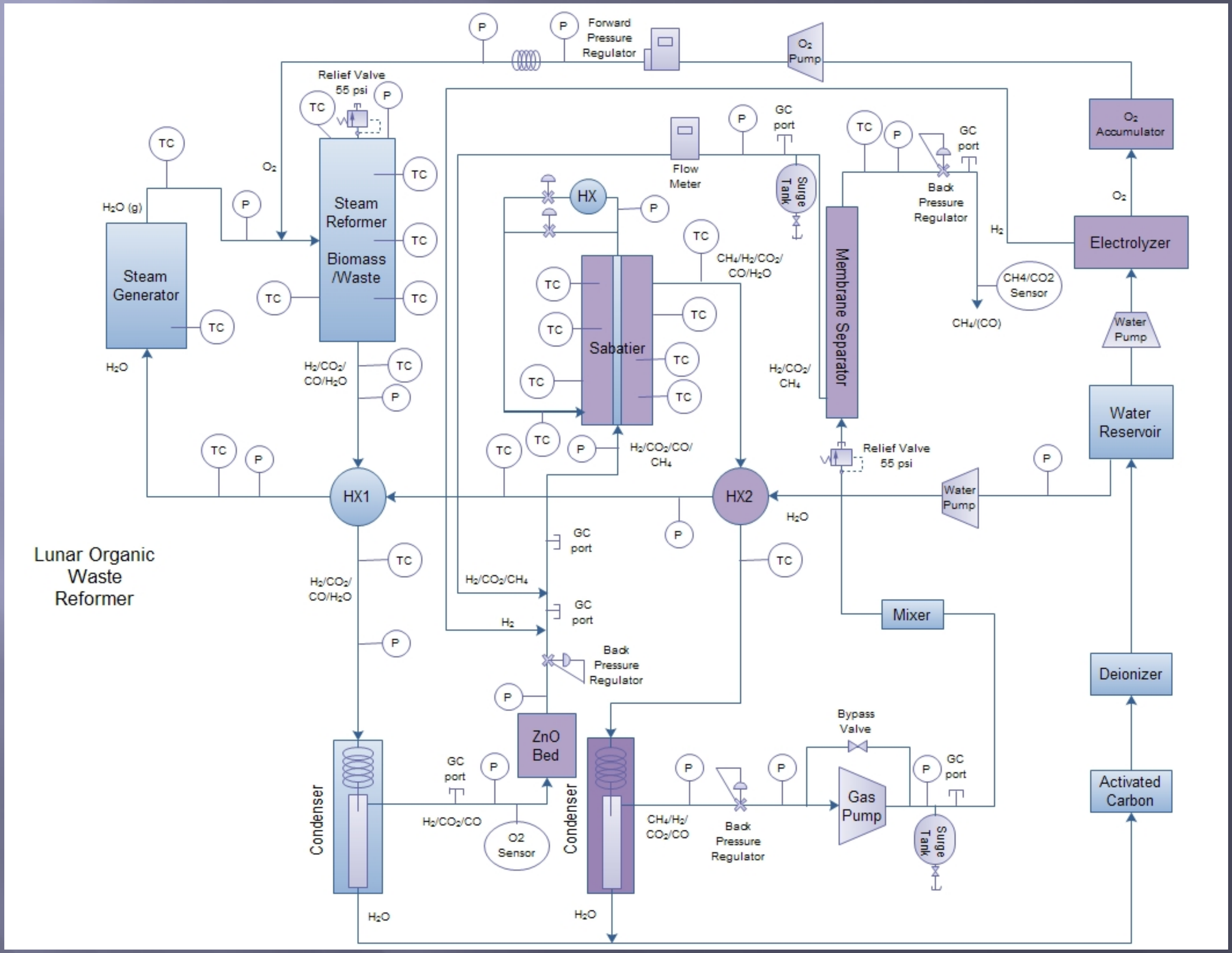
LOWR Project Summary

- The Lunar Organic Waste Reformer (LOWR) converts organic wastes generated at lunar bases or other space outposts into useful gases. Waste volume is substantially reduced while producing methane and oxygen.
- Oxygenated steam reacts with organic matter at elevated temperatures to produce mostly hydrogen, carbon monoxide, and carbon dioxide.
- The reformer exhaust is then combined with supplemental hydrogen in a catalytic Sabatier reactor to make methane.
- The LOWR was shown to be highly reliable and suitable for automated, continuous operation. During the NASA Phase II project, Pioneer Astronautics built and demonstrated a system capable of converting multi-kilogram quantities of organic waste per day into propellant components.

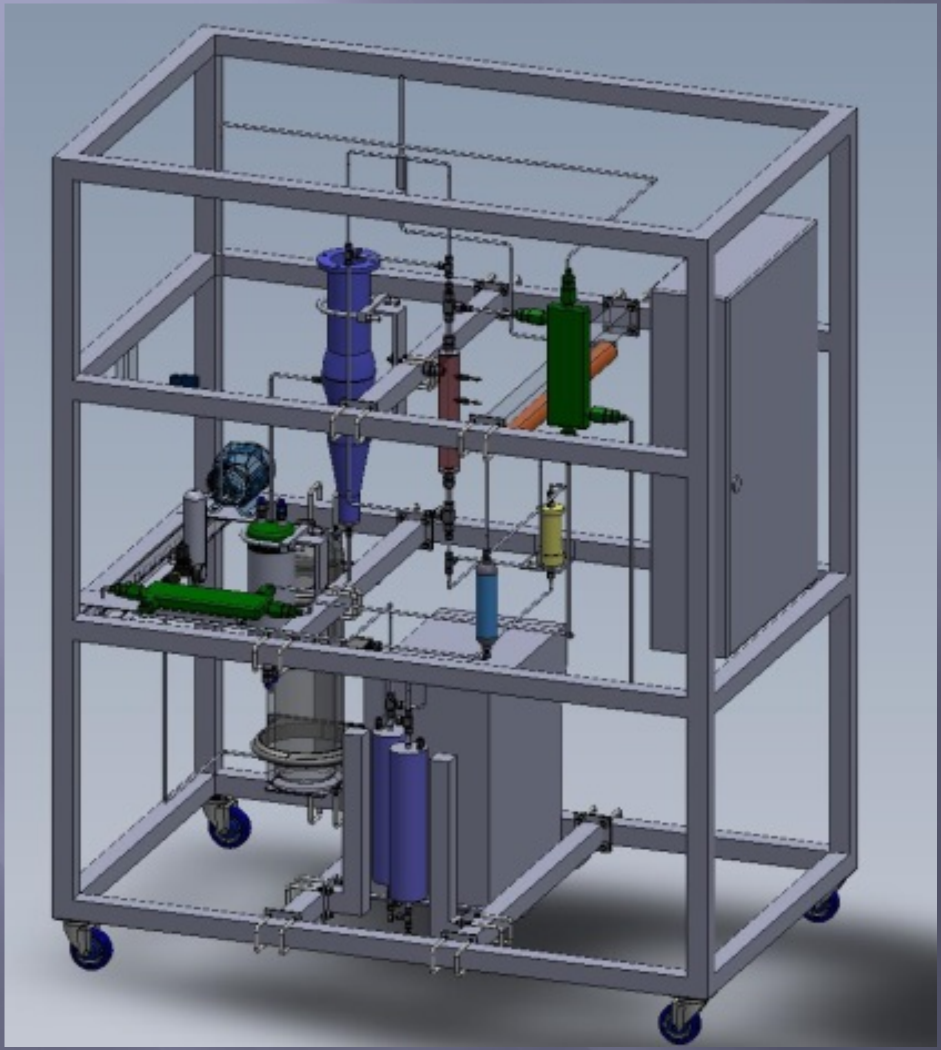
LOWR Block Flow Diagram

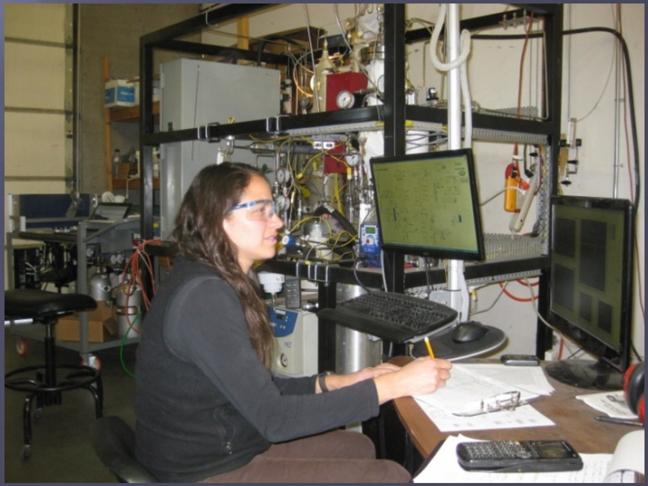


LOWR Process Flow Diagram



SolidWorks and As-Built LOWR





LOWR Mass and Power

- The LOWR optimized for a 4-person crew is projected to weigh 113 kg
- At the design operating rate, break even is achieved in less than 30 days
- Electrical power is projected to be about 2 kilowatts (exclusive of product liquefaction) based on a 67 percent on-stream factor
- Electrolysis is the major electrical power consumer

LOWR Reactions

Example Partial Oxidation Reactions

$$C + \frac{1}{2} O_2 = CO \qquad \Delta H = -112.1 \text{ kJ @ } 750°C$$

$$CO + \frac{1}{2} O_2 = CO_2 \qquad \Delta H = -282.5 \text{ kJ @ } 750°C$$

Example Steam Reforming Reaction

$$C + H_2O_{(g)} = CO + H_2 \qquad \Delta H = 135.8 \text{ kJ @ } 750°C$$

The exothermic partial oxidation reactions supply thermal energy to support non-catalytic endothermic steam reforming. The oxygen flow rate controls the overall waste processing rate. The steam rate is set to provide a stoichiometric excess to push the reforming reaction to completion and to provide reactor temperature control.

LOWR Reactions

Water Gas Shift Reaction (uncatalyzed)

$CO + H_2O_{(g)} = CO_2 + H_2$ $\quad\quad \Delta H = -34.6$ kJ @ 750°C

The water gas shift reaction partially takes place depending on reactor temperature and steam content.

Some naturally produced methane is also formed in the reactor as a result of pyrolysis of hydrocarbons in the waste feed.

After condensing water, the reformer exhaust gas consists of hydrogen, carbon monoxide, carbon dioxide, and methane.

LOWR Reactions

Sabatier Reactions *(over Ruthenium catalyst)*

$$CO + 3\ H_2 = CH_4 + H_2O_{(g)} \qquad \Delta H = -219.2\ kJ\ @\ 400°C$$

$$CO_2 + 4\ H_2 = CH_4 + 2\ H_2O_{(g)} \qquad \Delta H = -180.9\ kJ\ @\ 400°C$$

Hydrogen present in the reformer exhaust is supplemented by hydrogen from electrolysis to satisfy the exothermic reactions shown above. Equilibrium constants are high, leading to high per-pass conversions. In addition, a membrane and gas recycle system provides excess hydrogen in the reactor to ensure complete conversion of CO and CO_2 to CH_4 while providing diluent to control reactor temperatures. Methane is collected as a LOWR product, and water is fed to electrolysis.

LOWR Reactions

Electrolysis

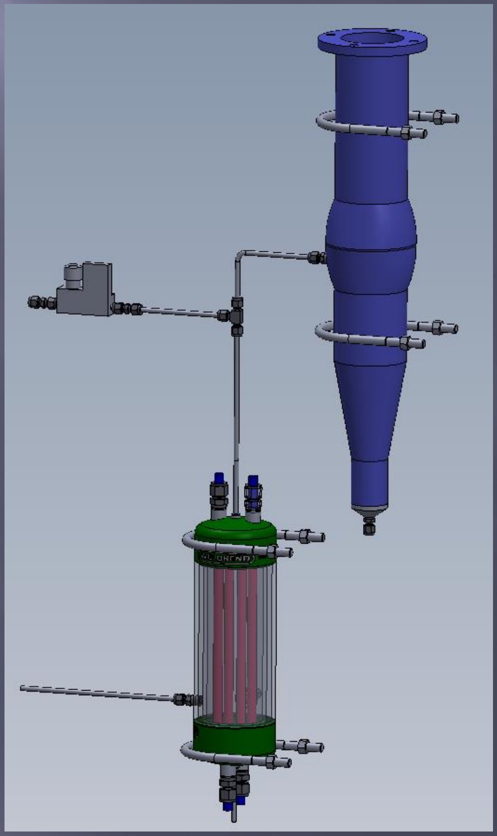
$H_2O_{(l)} = H_2 + ½\ O_2$ $\Delta H = 285.8$ kJ @ 25°C

The electrolysis rate is set to provide the supplemental hydrogen needed for methanation of CO and CO_2 while simultaneously producing oxygen. A portion of the oxygen is used for partial oxidation in the reformer while the remainder is collected as product.

LOWR System Components

Steam Reformer, Steam Generator, O_2 Delivery System, Sulfur Trap

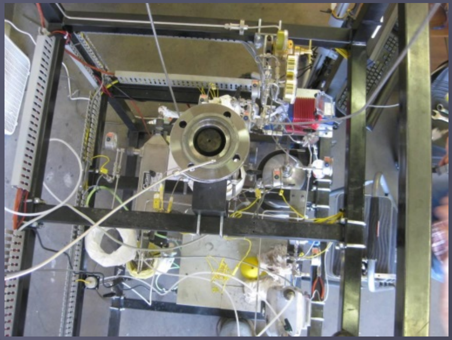
- Reformer is stainless steel and consists of a vertical vessel of 3 inches inside diameter.
- Coarse charcoal is loaded into the reformer to a level just above the oxygenated steam injection ports.
  - The charcoal produces minimal tars during preheating and start up.
- Waste is loaded into upper feed magazine.
  - NASA High Fidelity Waste Simulant represents food waste and packaging, urine brine, fecal matter, paper, wipes and towels, gloves, and maximum absorbency garments.
- Oxygen is mixed with steam just upstream of the injection plenum.

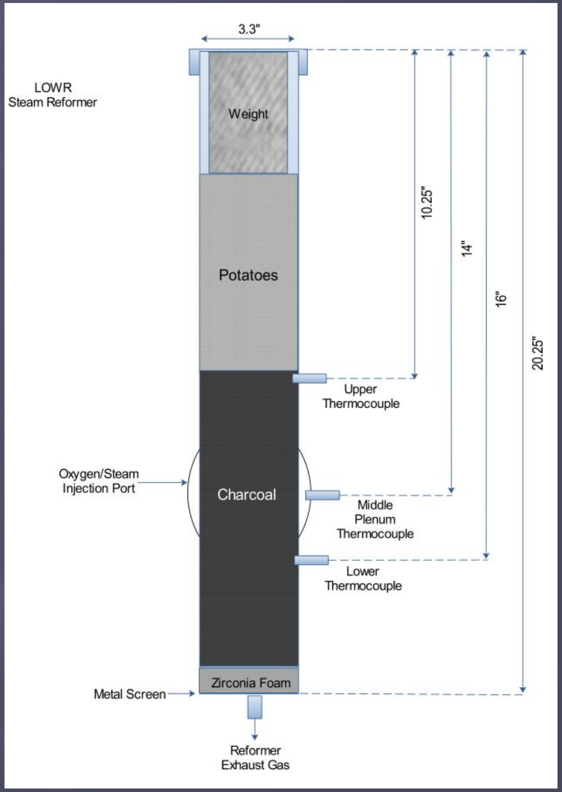


Steam Reformer Feed

Robust system processes variety of feeds …
potatoes, plastics, dog residue, charcoal, NASA simulant

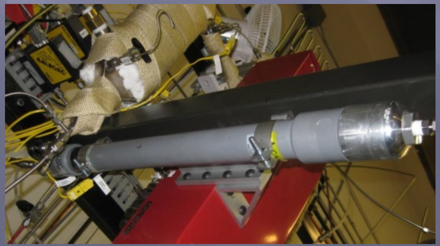
- A weight forces feed into the reaction zone as the waste is consumed near the oxygenated steam inlet. Alternatively, a spring could be used in microgravity applications.
- The feed magazine volume can be increased to boost the operating time.



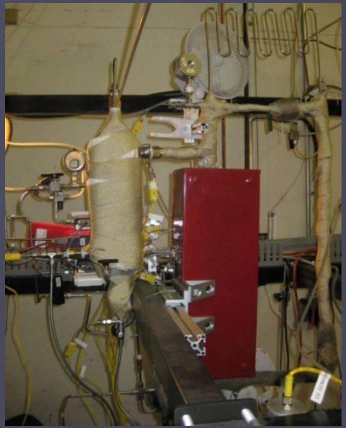


LOWR System Components

Sabatier Reactor, Membrane Separator, Recycle Pump



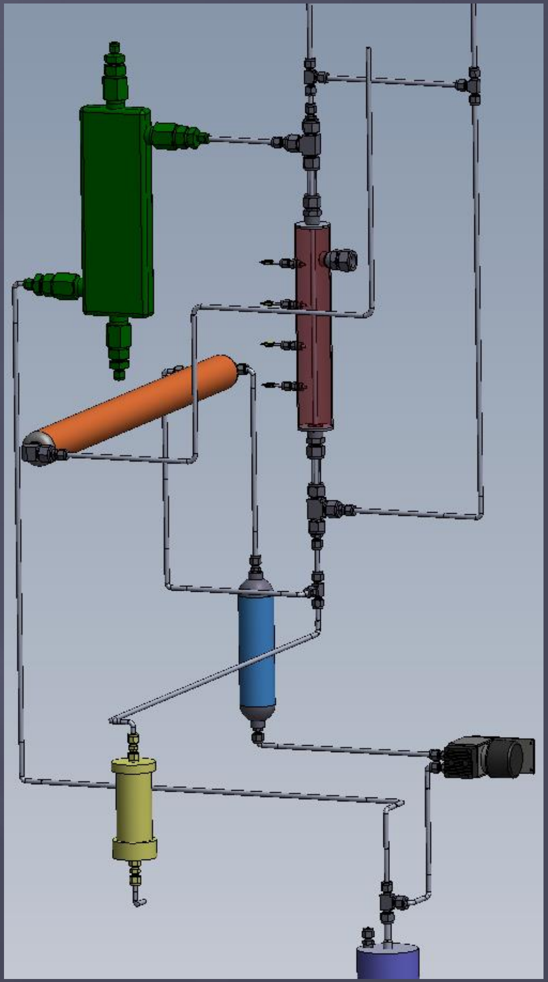
- Sabatier inlet gases consist of the dry reformer exhaust, supplemental hydrogen, and hydrogen-rich recycled membrane permeate.
- The Sabatier reactor is configured as an up-flow, fixed-bed vessel of 2 inches inside diameter
- The Sabatier catalyst is ruthenium on alumina.
- Inlet gas is conveyed through a co-current, indirect heat exchanger inside the reactor to help remove the heat of reaction.
- The indirectly heated inlet gas is then partially cooled and re-directed to the catalyst bed.



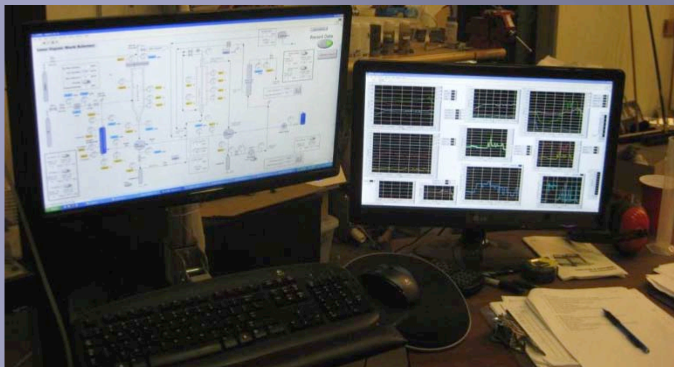
LOWR System Components

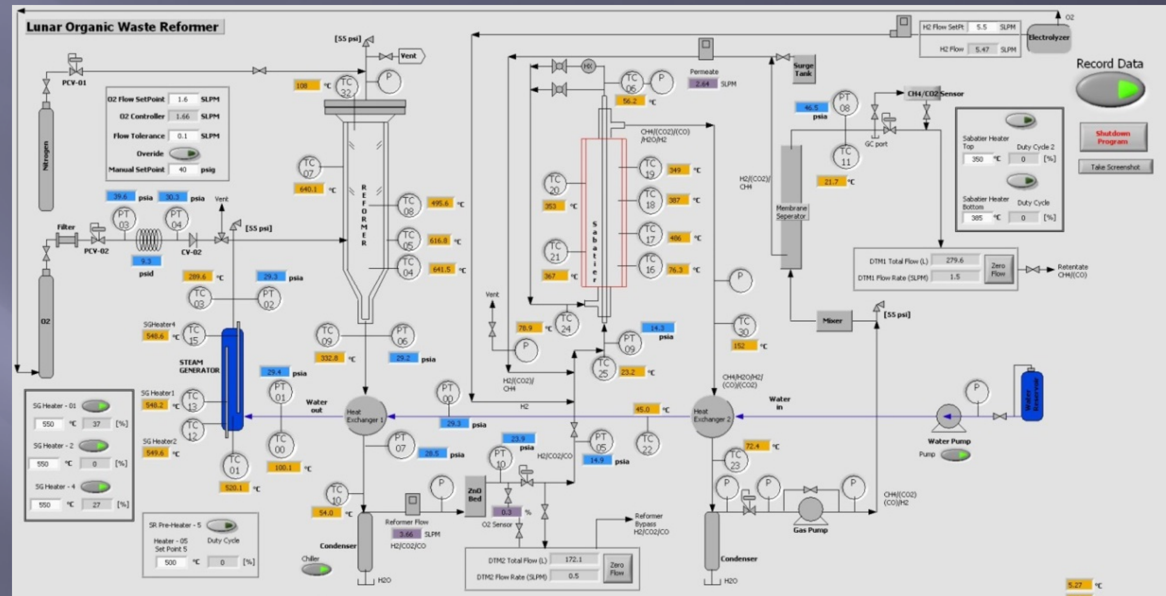
Sabatier Reactor, Membrane Separator, Recycle Pump

- The Sabatier inlet gas has about 10 percent stoichiometric excess hydrogen which serves to drive the conversion of carbon oxides to methane while further diluting the heat of reaction.
- The Phase II reactor results in a temperature profile in which high temperatures are obtained to provide fast kinetics in the middle portion of the reactor and lower temperatures (in the 350C range) to provide favorable thermodynamics near the reactor outlet.
- Sabatier exhaust is cooled and water is condensed for use in electrolysis.
- The dry Sabatier exhaust gas is introduced to a compressor that boosts the pressure from about 1 bar absolute to about 3 bar absolute.
- The compressed gas is fed to a membrane to recover hydrogen-rich permeate for recycle to the reactor while generating a methane-rich retentate (at 90 to 98 percent methane) product.
- In a fully integrated system, the methane rich product is liquefied to produce a nearly pure product.



LabView and CO_2/CH_4 Sensor Control Station



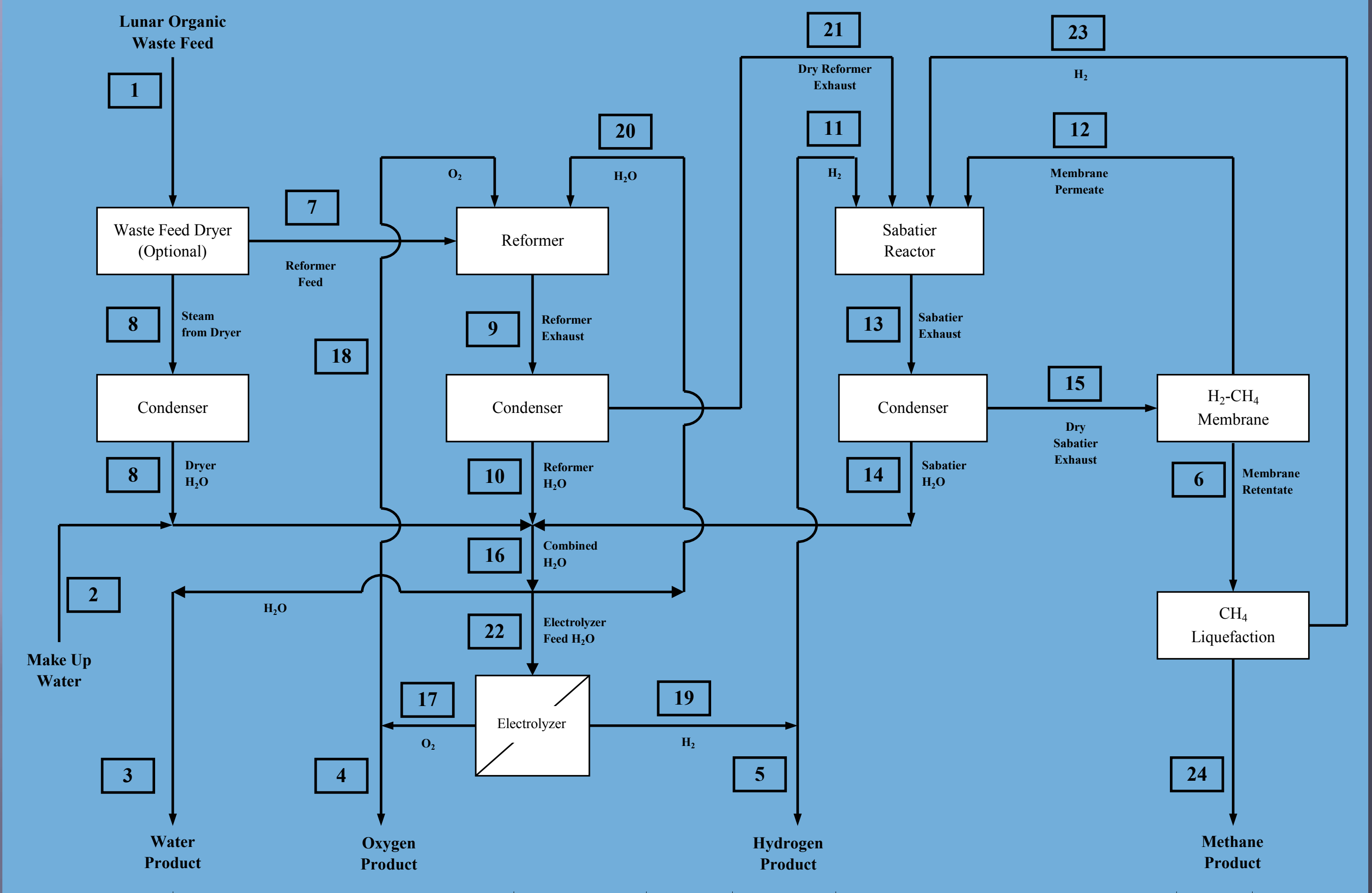


- National Instruments C-Rio® links signals between the system and the computer.
- Analog and digital inputs and outputs accommodate thermocouples, pressure transducers, mass flow meters, electronic regulators, an oxygen sensor and heaters that are controlled and monitored by LabView®.

LOWR Model

- An Excel® model was written to aid the development of the LOWR process
- The model calculates effects of feed composition and throughput on process flow rates, process gas compositions, water balance, and power requirements
- Available waste heat can be matched to LOWR thermal needs
- Key inputs include waste feed rate, feed moisture content, H-C-O concentrations, O_2:C ratio, and H_2O:C ratio
- The CO_2:CO ratio in the reformer exhaust is specified based on operating experience
- The targeted excess of H_2 in the Sabatier reactor is specified
- The Sabatier membrane performance is specified based on previously observed separation results.
- An on-stream factor is specified to calculate instantaneous operating rates and power inputs to account for process down time.

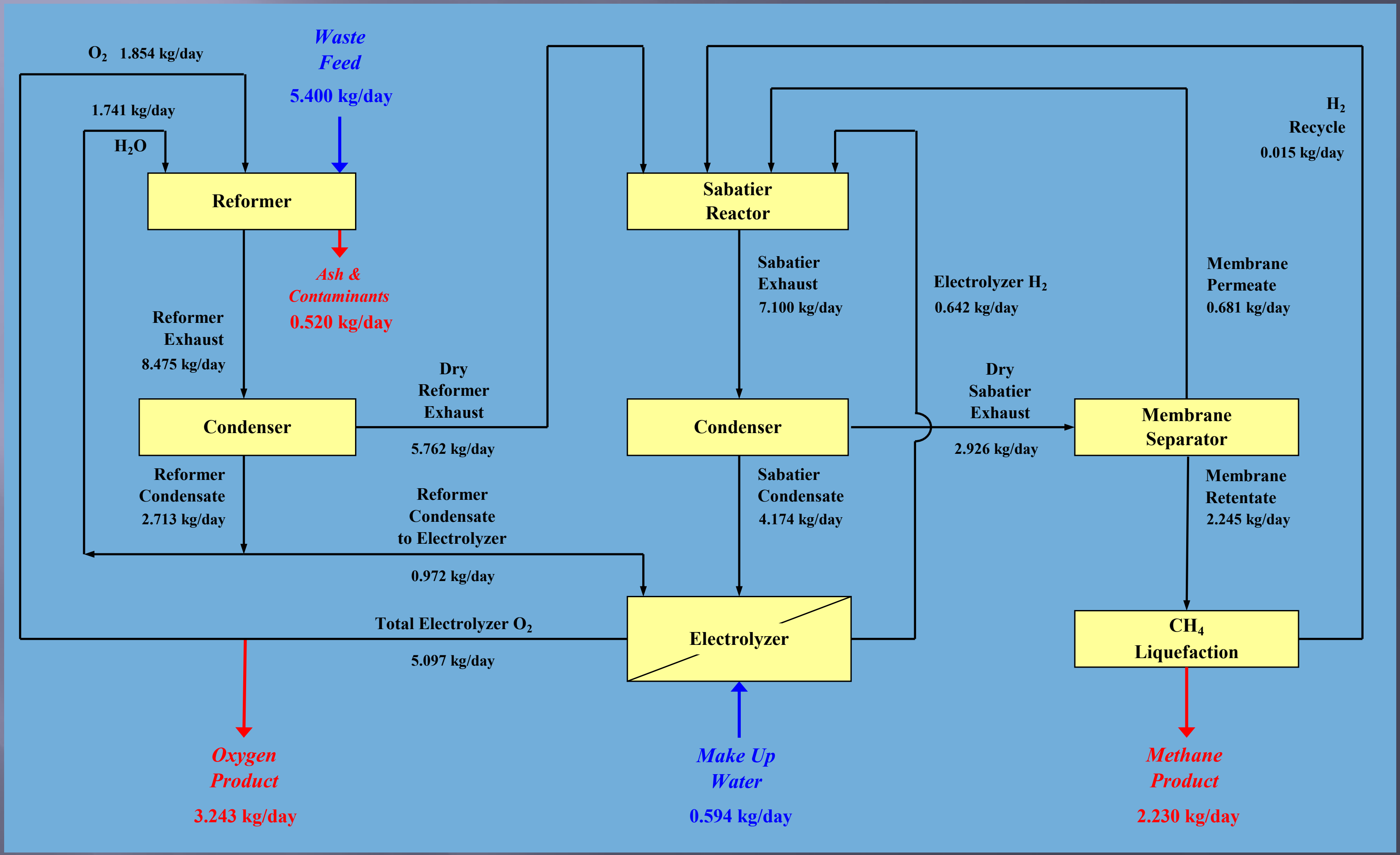
LOWR Model



Lunar Organic Waste Reformer Flow Sheet and Material Balance

LOWR Model

NASA High Fidelity Waste Simulant



PIONEER ASTRONAUTICS

LOWR Phase II Accomplishments

- Reformer
  - Operated with a wide range of individual feed constituents and mixtures
  - Successfully fed NASA High Fidelity Waste Simulant with minimal preparation
  - Operated reformer at rates approximating NASA full scale needs
  - Achieved virtually complete conversion of organics to H_2, CO, CO_2, and CH_4
  - Successfully cleaned condensate to levels suitable for electrolysis feed water
- Sabatier
  - Scaled up to accommodate full flow from reformer
  - Developed novel reactor system with enhanced thermal controls
  - Utilized Sabatier product gas membrane separation and recycle system to achieve virtually complete conversion of carbon oxides to methane
  - Established control method to meter supplemental Sabatier reactor hydrogen feed using on-line methane and carbon dioxide product analyses

NASA

PIONEER ASTRONAUTICS

LOWR Phase II Accomplishments

- Integrated System
  - Incorporated heat exchangers to recover exhaust gas heat from reformer and Sabatier for reformer steam preheating
  - Established benefits of reforming to generate valuable products while minimizing electrolysis power input compared to alternate waste treatment systems
  - Demonstrated successful operation with a wide range of feeds (and variable reformer exhaust gas compositions) while achieving virtually complete conversion
  - Showed that estimated LOWR system mass results in rapid break even time
  - Demonstrated low consumables requirements
  - Verified robust nature of hardware and controls through multiple start up/ shut down cycles
  - Showed potential for LOWR to be adapted to non-Lunar applications in reduced- or micro-gravity environments

Acknowledgements

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- Pioneer Astronautics Staff, Engineers, Scientists and Machinists
- SRR - PTMSS