Carbonaceous Asteroid Volatile Recovery System

Mark Berggren
Pioneer Astronautics
Lakewood, Colorado

Presented at:

Space Resources Roundtable
Planetary & Terrestrial Mining Sciences Symposium
Seventh Joint Meeting
Golden, Colorado
June 7-9, 2016

Carbonaceous Asteroid Volatile Recovery (CAVoR) System

NASA JPL SBIR

Phase I Contract NNX15CP30P
June 17 – December 17, 2015

Phase II Contract NNX16CP21C
April 26, 2016 – April 25, 2018

Pioneer Astronautics
Mark Berggren, Robert Zubrin, David DeMarco, Heather Rose,
Stacy Carrera, Boris Nizamov, and James Siebarth

NASA Jet Propulsion Laboratory
David Eisenman (Technical Monitor)

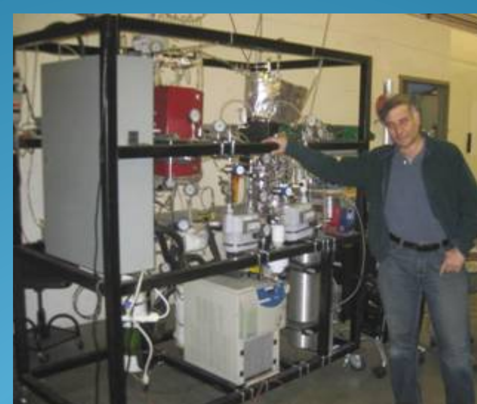
Carbonaceous Asteroid Volatile Recovery (CAVoR) System

- Thermally extracts water ice, bound water, and organic matter from carbonaceous chondrite asteroid regolith
- Uses partial oxidation to decompose and gasify organic compounds in the presence of steam
- Produces water, hydrogen, carbon monoxide, and carbon dioxide from non-catalytic reactions
- CAVoR reaction products are subjected to Sabatier-electrolysis to generate methane and oxygen for propellant

Pioneer Astronautics Reforming Heritage

- Lift Gas Cracker (Goddard)
  - Catalytic methanol reforming to produce lighter-than-air gas in support of stratospheric ballooning

- Lunar Organic Waste Reformer (Glenn)
  - Oxygenated steam reforming of human space outpost wastes to propellant components



- Green Oil (DOE/RPSEA)
  - Reforming of biomass/
  - organic matter to produce CO_2 for enhanced oil recovery and H_2 for carbon-free electric power

Carbonaceous Asteroid Volatile Recovery (CAVoR) System Challenges

- Asteroid regolith contains a majority of inorganic matter
  - Only a small reduction in volume after reaction
  - Requires heating of non-reactive components to >700°C
  - Thermal energy retained in residue
- Operation in microgravity
  - Feed preparation and handling issues
  - Controlled flow of regolith through reaction zone

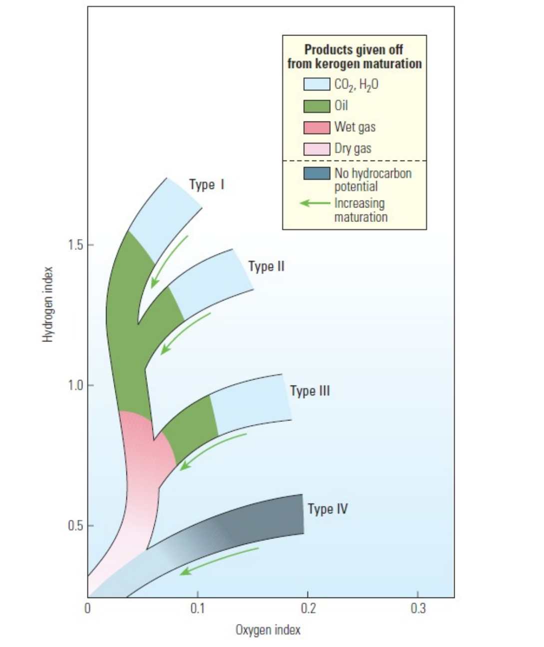
Carbonaceous Chondrite Asteroids

- Up to 20% water and 5% organic matter along with magnetite (Fe_3O_4) and troilite (FeS) in a matrix of phyllosilicate minerals
- Nitrogen (organic) and phosphorus (as phosphates) also present
- Consists of intimately mixed, accreted fine particles weathered by solar wind near the asteroid surface

- Much of composition data comes from meteorites and spectral analyses
- NASA OSIRIS-REx launches in 2016 to retrieve and return in 2023 up to 2 kg from Bennu, a carbon-rich near-Earth asteroid of about 500 m diameter
- Private industries are also developing asteroid prospecting and sample return technologies

Carbonaceous Chondrite Asteroid Organic Matter

- Oxidized polycyclic aromatic hydrocarbons with low H:C atomic ratio (~0.5:1) and O:C atomic ratio typically <0.15:1
- Type IV kerogen considered as Earth-analog material:



McCarthy et al. *Oilfield Review, v23, no. 2* (2011)

- Example N- and S-Free Composition of Organic Matter

  (by weight):

  - 81 % C
  - 3 % H
  - 16 % O

Murchison meteorite data, from Pizzarello and Shock
The Organic Composition of Carbonaceous Meteorites
(Cold Spring Harb Perspect Biol 2010;2:a002105)

Carbonaceous Asteroid Volatile Recovery (CAVoR) System

Reforming Reactions

To form Synthesis Gas

$C + H_2O_{(g)} \Rightarrow CO + H_2$ $\Delta H = +136$ kJ @ 750°C

Water Gas Shift

$CO + H_2O \Rightarrow CO_2 + H_2$ $\Delta H = -35$ kJ @ 750°C

Combined

$C + 2\ H_2O \Rightarrow CO_2 + 2\ H_2$ $\Delta H = +101$ kJ @ 750°C

Carbonaceous Asteroid Volatile Recovery (CAVoR) System

Partial Oxidation Reactions

- Generates heat to offset steam reforming reactions

With Carbon

$C + ½ O_2 = CO \quad \Delta H = -112$ kJ @ 750°C

With Carbon Monoxide

$CO + ½ O_2 = CO_2 \quad \Delta H = -283$ kJ @ 750°C

Carbonaceous Asteroid Volatile Recovery (CAVoR) System

Overall Autothermal Reforming Reaction

Using Naphthalene as a Model Compound (2:1 Steam:Carbon; 0.5:1 Oxygen:Carbon):

$$C_{10}H_{8\,(g)} + 5\ O_2 + 20\ H_2O_{(g)} \Rightarrow 10.3\ H_2 + 3.7\ CO + 6.3\ CO_2 + 13.7\ H_2O_{(g)}$$

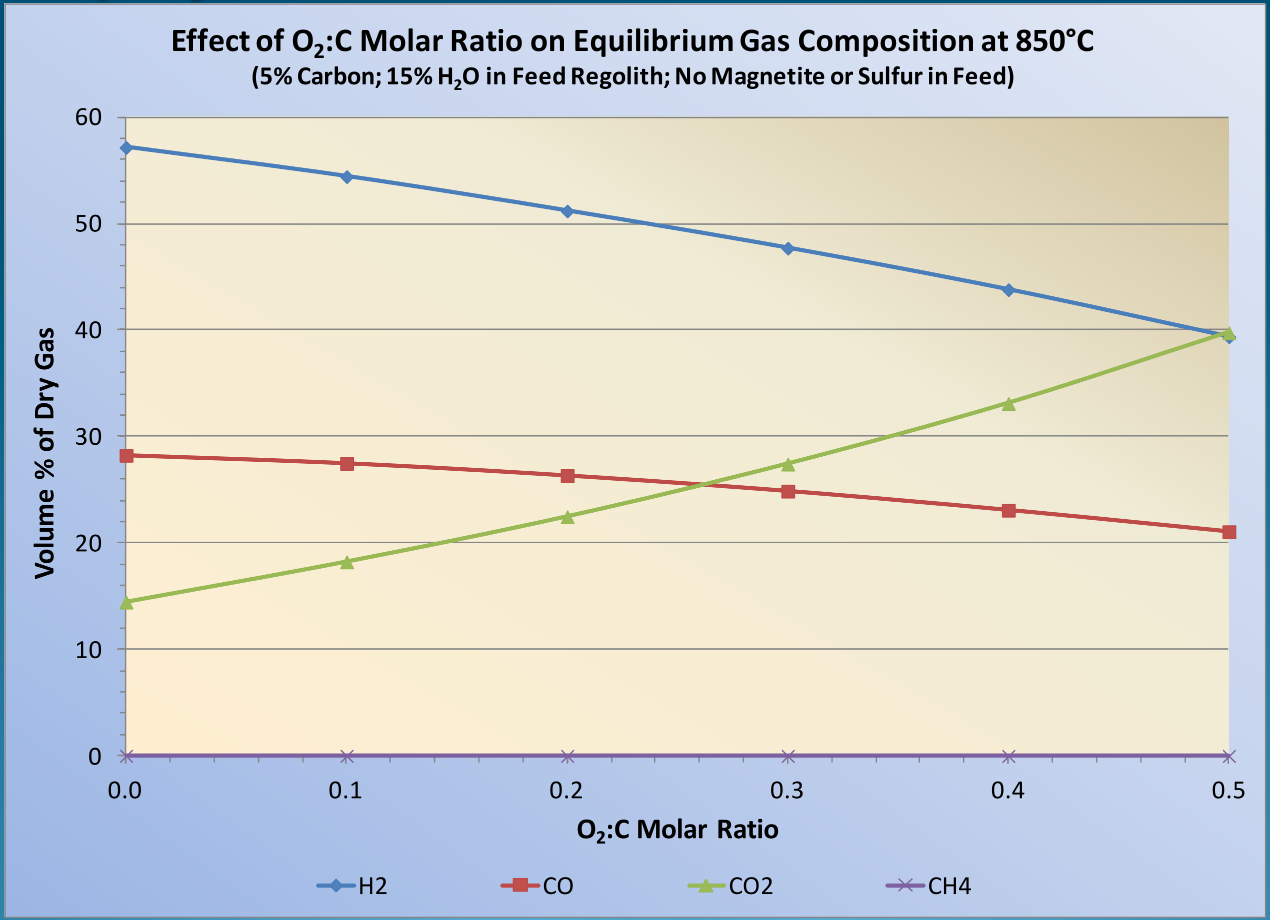
$\Delta H = -1467$ kJ (thermal) @ 750°C

Electrolysis:

$$10\ H_2O \Rightarrow 10\ H_2 + 5\ O_2$$

$\Delta H = +2858$ kJ (electric) @ STP

Carbonaceous Asteroid Volatile Recovery (CAVoR) System

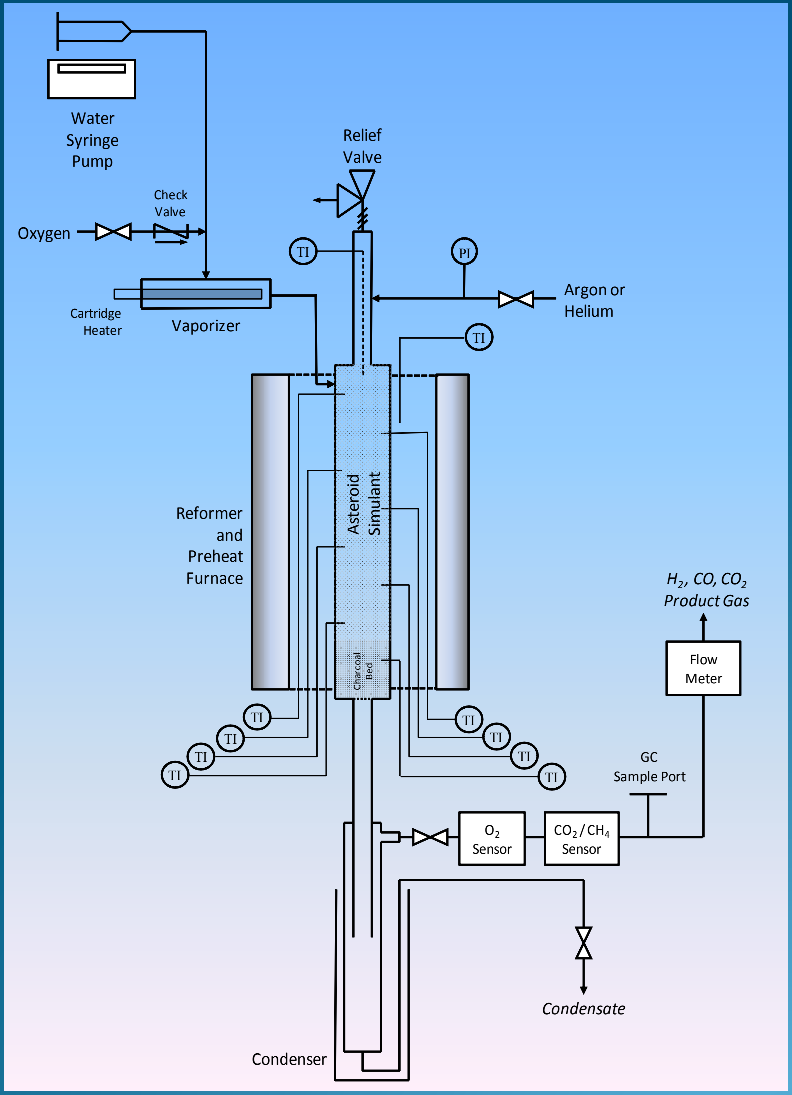


Carbonaceous Asteroid Volatile Recovery (CAVoR) System

Phase I Summary

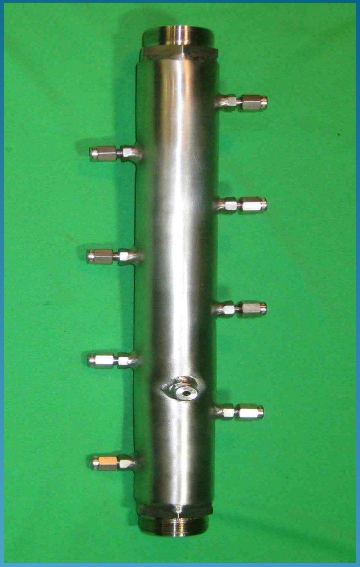
- Established proof-of-concept design for testing
- Determined feasibility of oxygenated steam reforming via experiments using simulants prepared from several organic constituents (oil sands, petroleum coke, Gilsonite, oil shale) and water in phyllosilicate clay substrate
- Prepared system material balances
- Generated model to predict performance under a wide range of operating scenarios
- Formulated initial estimates of mass and power

Phase I CAVoR Reactor

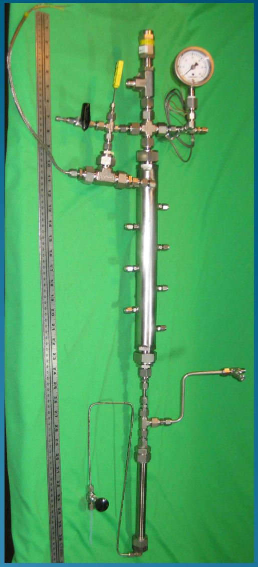


1.5" OD Reactor

x 12" long

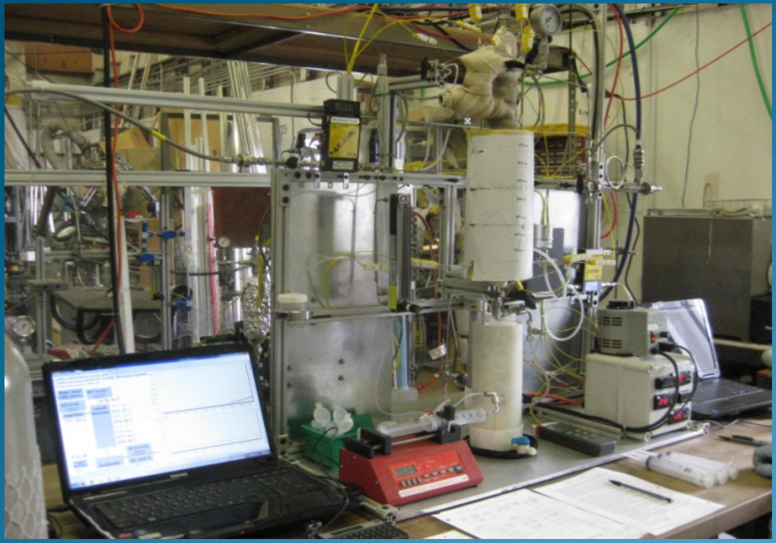


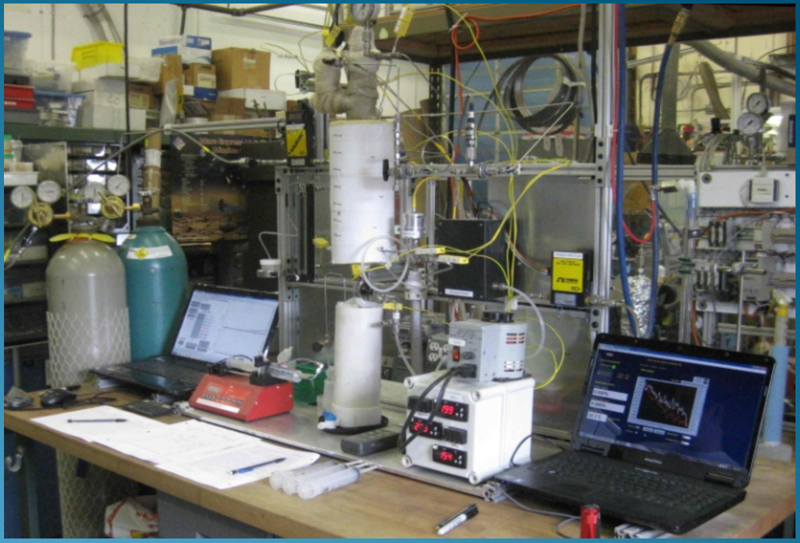
Reactor with Gas Inlet, Vaporizer, and Condenser Systems



Phase I CAVoR Reactor System

Assembled apparatus with feed/exhaust systems, temperature controllers, and data acquisition systems





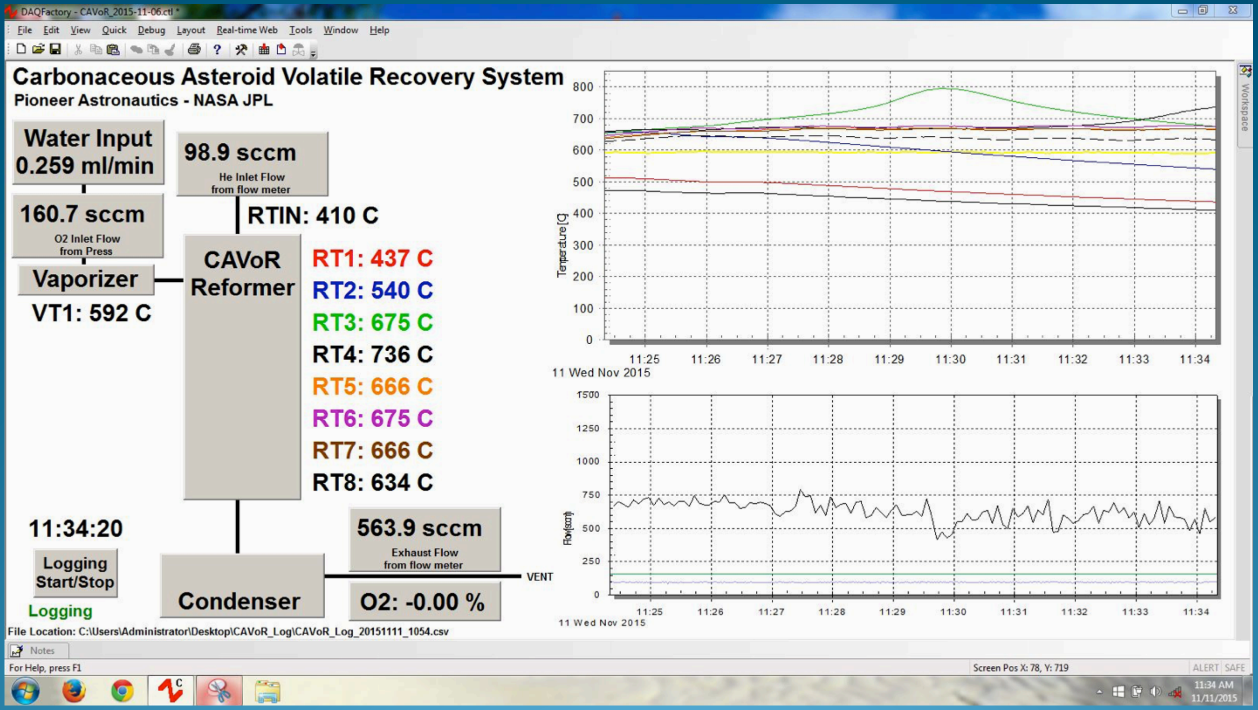
Phase I CAVoR Experiments

General Test Procedures

- Prepare and load simulant into the reactor
- Seal, perform leak checks, start low flow of helium
- Preheat reactor shell to ~450°C
- Start oxygen and steam flow
- Collect periodic condensate samples and exhaust gas samples
- Continue running until the peak temperature approaches the bottom of the reactor
- Stop oxygen and steam; cool reactor; discharge and weigh residue

Phase I CAVoR Experiments

Data Acquisition Screen Shot During Operation



Phase I CAVoR Experiments

Asteroid Simulant Before and After Reforming

Gilsonite Feed Simulant

Reformer Residue

Reformer Residue Below Reaction Zone

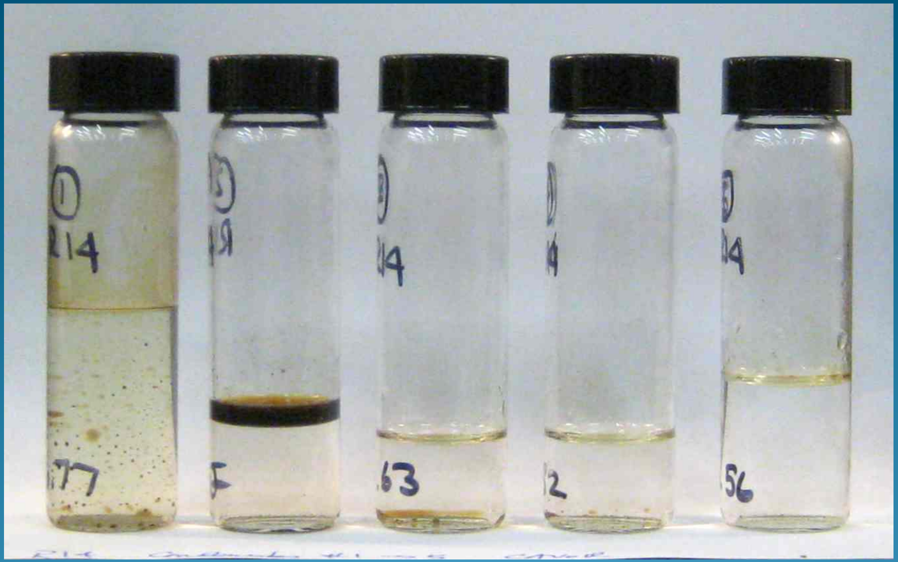
Carbon Guard Bed Pellets

NASA

PIONEER ASTRONAUTICS

Phase I CAVoR Experiment

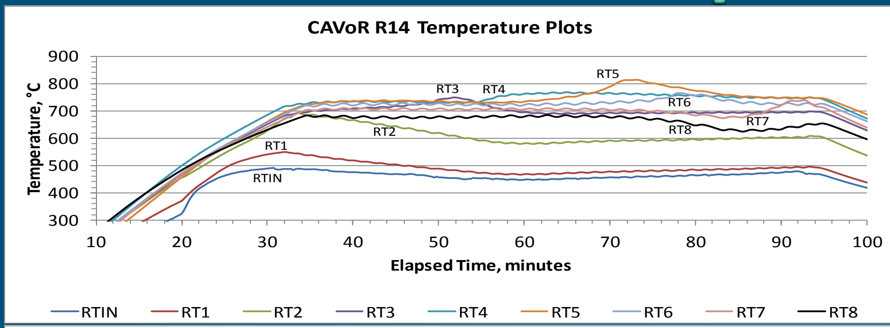
Reformer Condensate

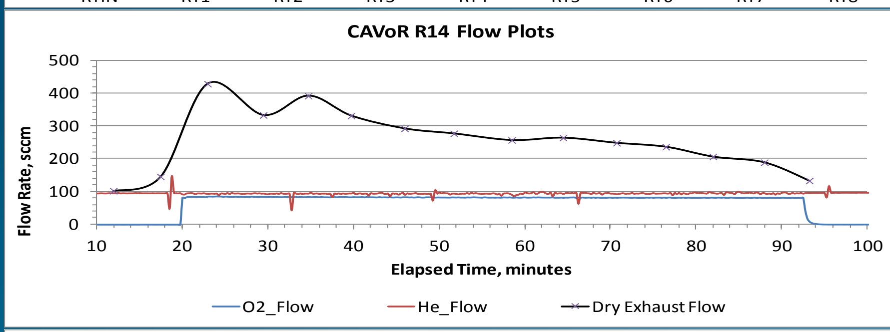


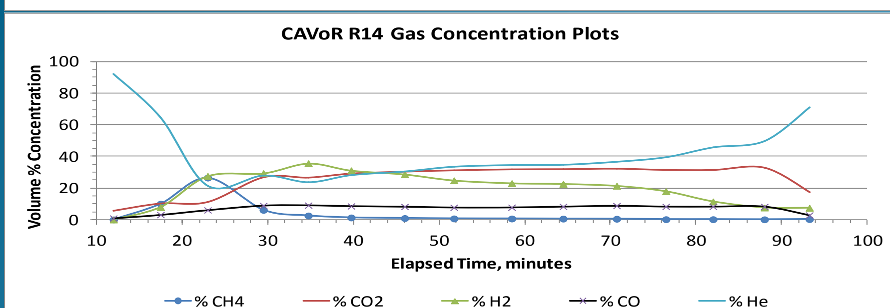
Pre-Heat Condensates

Reformer Condensates

Phase I CAVoR Experiment







R14:

174 g Simulant (5% Gilsonite; 15% H_2O)

2:1 Steam:Carbon (0.55 g/min H_2O)

0.25:1 Oxygen:Carbon (85 sccm O_2)

Product Gas (He-free)

38 % H_2

12 % CO

43 % CO_2

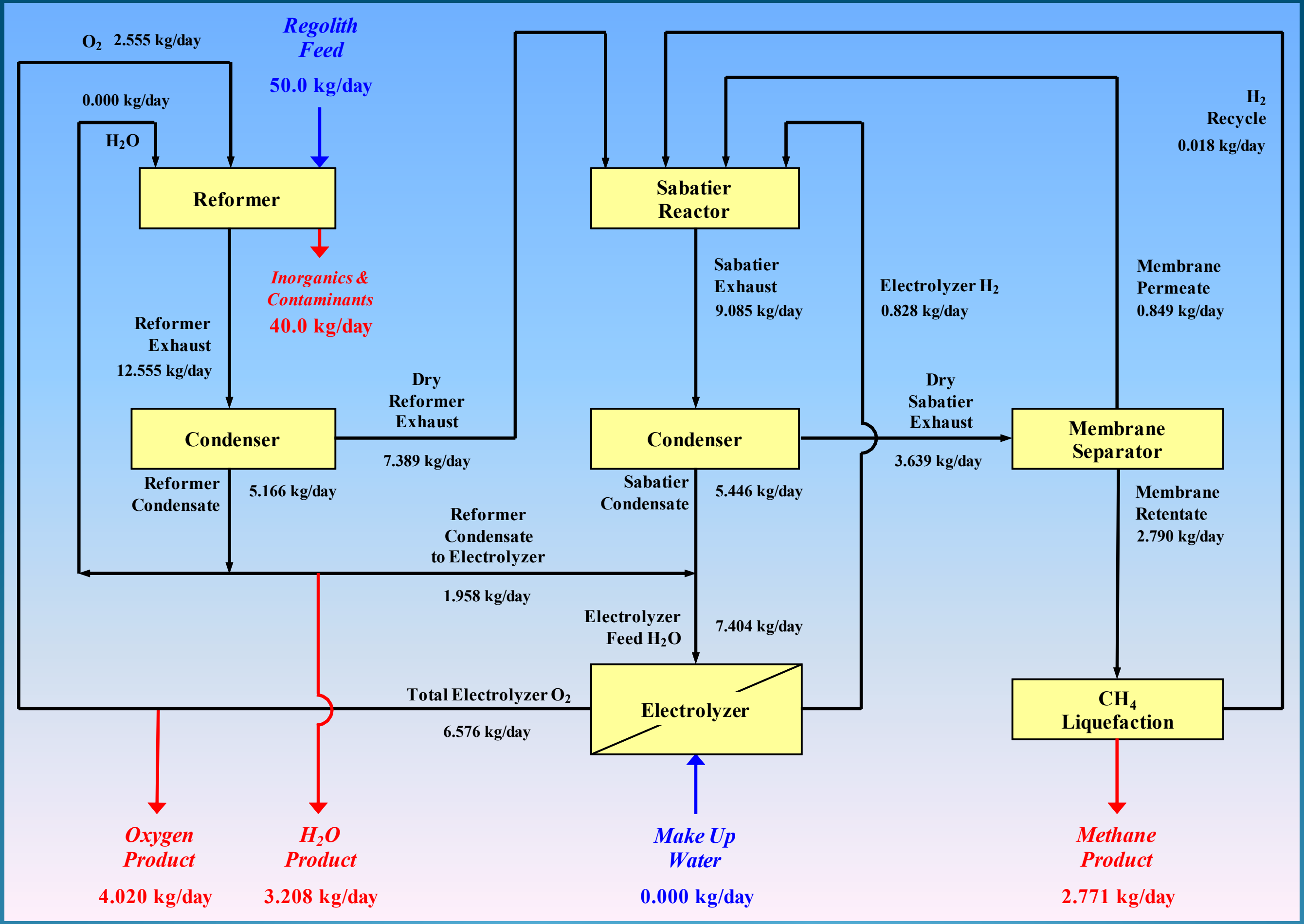
7 % CH_4

Phase I CAVoR Model

Example Inputs:

- Total Water (15 wt %) and Total Organic (5 wt%) in simulant
- Organic Composition of 83.0% C, 8.7% H, 8.3% O (by wt)
- O_2:C Molar Ratio = 0.5; H_2O:C Molar Ratio = 2
- Regolith Feed Rate of 50 kg/day
- Sabatier parameters (CO_2/CO feed ratio; membrane performance) based on historical experience

Phase I CAVoR Model (Kerogen feed)



CAVoR Power – Reforming (50kg/day)

Regolith, Organics, H_2O, and O_2 Feed Heating	1)	Heat Ice in Regolith from -73 to 0C	13.4
	2)	Melt Contained Ice at 0C	29 W
	3)	Heat Contained Water from 0 to 100C	36 W
	4)	Boil Contained Water at 100C	197 W
	5)	Heat Contained Steam from 100 to 700C	112 W
	6)	Heat Solid Organic Matter in Regolith from -73 to 78C	6 W
	7)	Melt Contained Organics at 78C	4 W
	8)	Heat Contained Liquid Organic Matter from 78 to 218C	6 W
	9)	Vaporize Contained Organic Matter at 218C	16 W
	10)	Heat Vaporized Organic Matter from 218 to 700C	34 W
	11)	Heat Inorganic Matter from -73 to 700C	494 W
	12)	Heat Oxygen from 20 to 700C	21 W
		Total Reformer Regolith & O_2 Heating Power	**969 W**

CAVoR Power – Methanation

Operation		Description	Thermal Power, Watts
Sabatier Reactor Cooling	1)	Indirect Heat Exchange by Reactor Feed Gas	**-99**
Sabatier Exhaust Gas Cooling	1)	Cool Exhaust Gas from 450 to 100C	-66
	2)	Condense Sabatier Exhaust Water at 100C	-143
	3)	Cool Dry Sabatier Exhaust Gas from 100 to 20C	-5
	4)	Cool Sabatier Condensate from 100 to 20C	-21
		Total Sabatier Exhaust Cooling Power	**-235**
		Total Operating Power	**-334**

- Heat recovered from Sabatier system can be used to partially preheat asteroid regolith (334W against 969W reformer feed requirement)
- Additional heat can be recovered from processed regolith

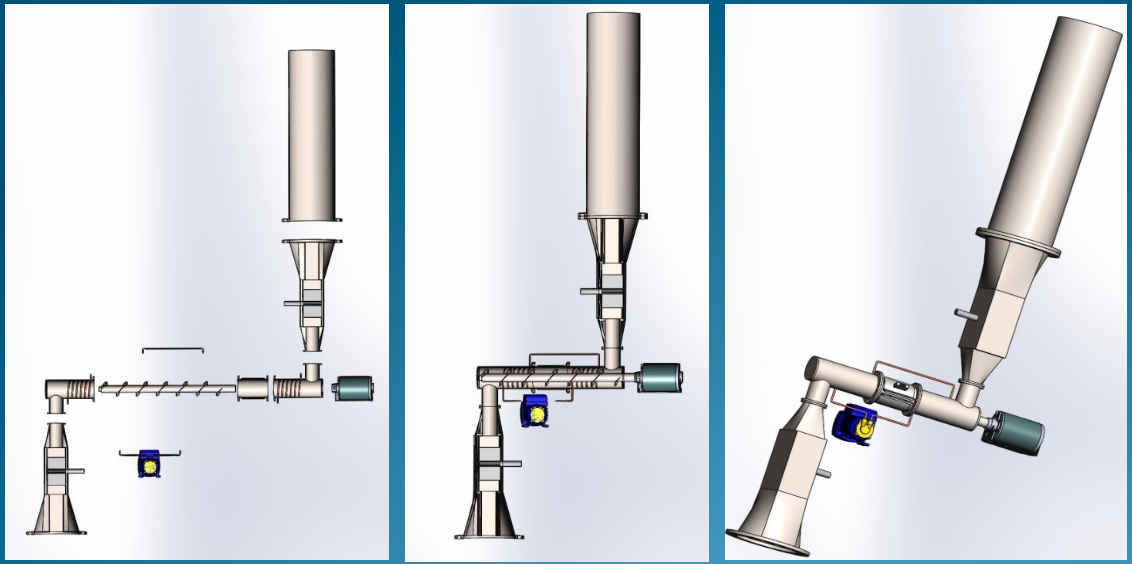
CAVoR Power – Electrolysis

- Electrolysis is the primary electrical power requirement
- 50 kg/day regolith case:
  - 1.4 kWe (@100 % efficiency)
  - 1.75 kWe (@80 % efficiency)

CAVoR Interim Conclusions

- Phase I system demonstrated overall feasibility:
  - Heat recovery plus thermochemical production of hydrogen result in low thermal and electrical power inputs
  - CAVoR is a viable method to produce methane and oxygen
- Shortcomings of Phase I design were identified:
  - Oxygen passes through spent regolith and is partially consumed by oxidation of magnetite
  - Batch mode limits heat recovery options from spent regolith
  - Preheating in batch mode allows some organic matter to pyrolyze in the absence of oxygenated steam (tar formation)
  - Frequent start up/shut down makes downstream system operations more difficult
- Continuous auger reactor system addresses system shortcomings

CAVoR Continuous Flow Auger Reactor



- Static Reaction Zone
- Allows Independent Auger Speed and Oxygen Rate
- Option for Co-Current or Counter-Current Flow
- Large Feed Magazine (minimizes start up transients)
- Uses In-situ H_2O Efficiently/ Avoids Pyrolysis Tar (all volatiles pass through reaction zone)
- Minimizes Valve and Seal Requirements
- Facilitates Heat Transfer from Residue to Feed
- Enables additional O_2 yield from magnetite

CAVoR Preliminary Mass Estimate

50 kg/day Regolith Feed Basis:

Reformer: 70 kg

Methanation/Electrolysis: 85 kg

Total System Mass: 200 kg

Produces 10 kg/day water + oxygen + methane

Breakeven = 20 days

Limited Consumables Requirements (high leverage)

CAVoR Phase II

- Refine auger reactor system design including feed/discharge mechanisms and controls
- Establish protocols and controls for materials handling in microgravity
- Improve fidelity of simulants
- Optimize heat recovery and heat transfer to feed regolith
- Implement contaminant recovery technologies
- Demonstrate operation in vacuum chamber
- Develop system in the context of an example mission
- Re-assess mass, volume, and power requirements

Acknowledgements

- SRR/PTMSS
- NASA Jet Propulsion Laboratory/SBIR Program
- Pioneer Astronautics Staff, Engineers, Scientists, and Machinists