State of NASA Oxygen Recovery

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Historical O_2 Recovery Processes

CO_2 Electrolysis

- $2CO_2 \leftrightarrow CO + O_2$

Sabatier

- $CO_2 + 4H_2 \leftrightarrow CH_4 + 2H_2O$

Bosch Process

- $CO_2 + H_2 \leftrightarrow CO + H_2O$
- $2CO \leftrightarrow CO_2 + C(s)$
- $CO + H_2 \leftrightarrow H_2O + C(s)$

1980-90's Tech Development

Sabatier Development Unit developed by Hamilton Sundstrand

Competed for ISS

Sabatier won because:

- Lower power
- Smaller system
- No consumables
- Clean process
- Sufficient for low earth orbit

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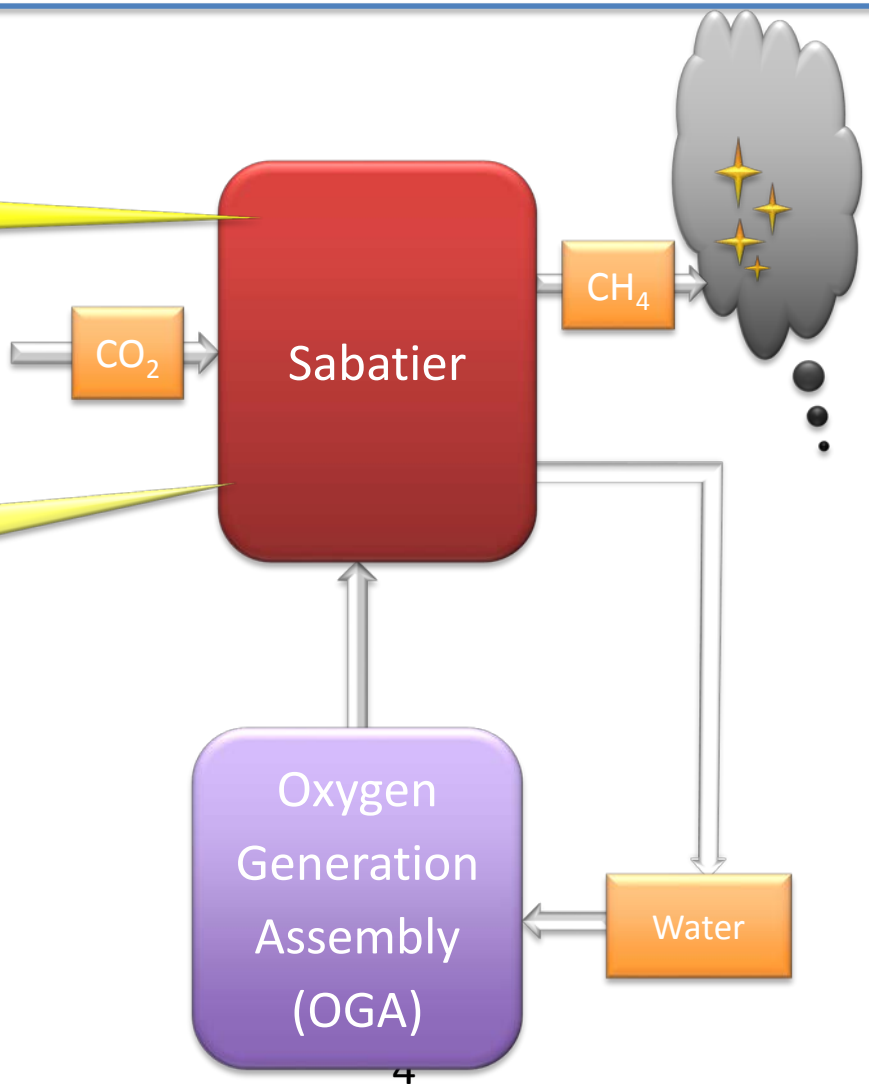
Oxygen Recovery

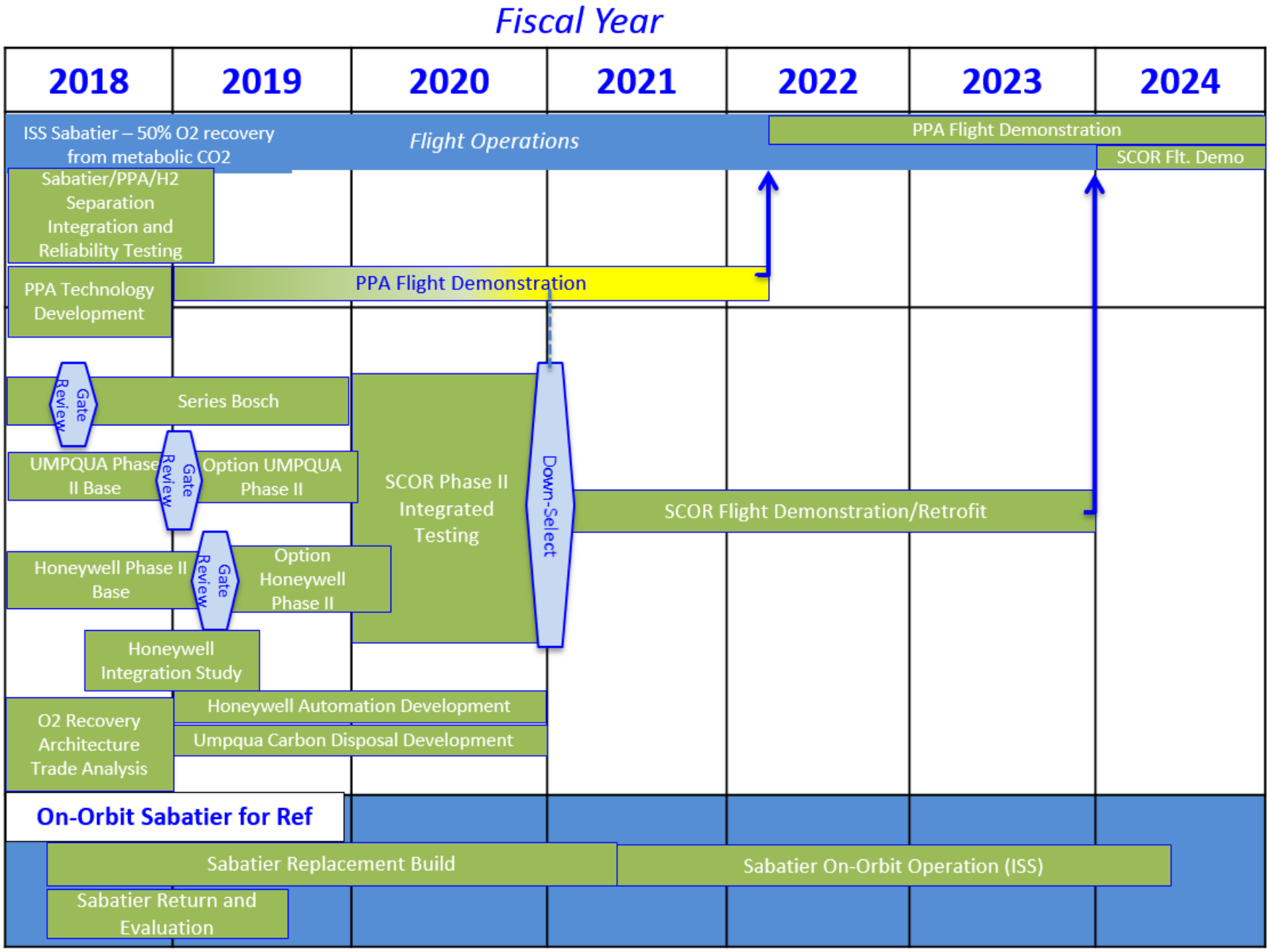
Net loss of hydrogen must be resupplied as water from Earth

Launch Costs
1kg ~ $68,000
Water for one year for four crew ~$45M



Need to recover and recycle more for long-duration missions

CO2 Reduction/Resource Recovery: Current Plan



Bosch Technology

Chemistry:

RWGS: $CO_2 + H_2 \rightarrow H_2O + CO$

Carbon Formation:

$$2CO \rightarrow CO_2 + C(s)$$
$$CO + H_2 \rightarrow H_2O + C(s)$$

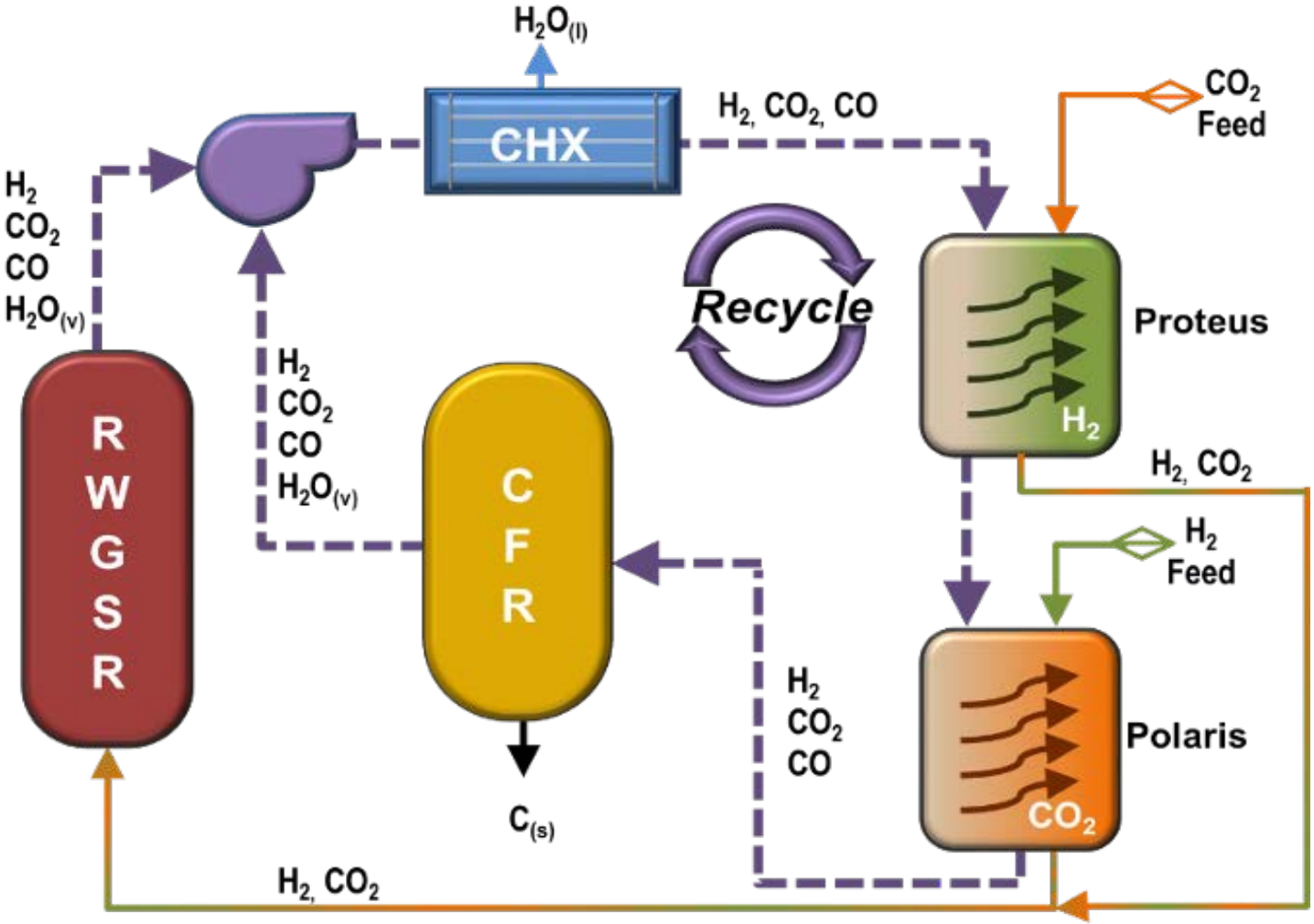
$$CO_2 + 2H_2 \rightarrow 2H_2O + C(s)$$

Challenges for Space Application

- Power Consumption
  - High Temperature Endothermic Reactions
- Catalyst Resupply
- Volume/Mass

1980's Bosch System

Series-Bosch Systems



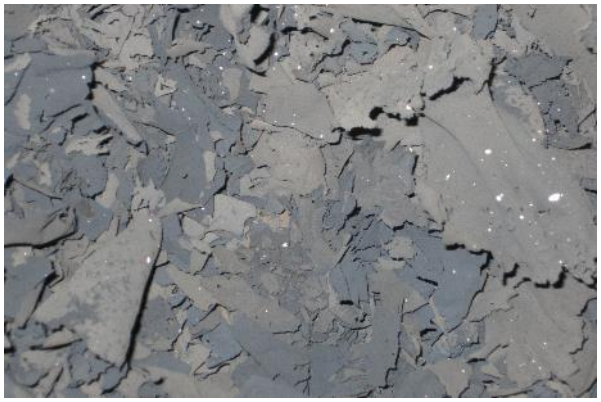
Series-Bosch Development

- pH Matter and UMPQUA reactors delivered to MSFC under Game Changing Development Program, Spacecraft Oxygen Recovery (SCOR)
  - Evaluated stand-alone prior to delivery
  - Integrated testing with MSFC Carbon Dioxide Reduction Test Stand

SCOR UMPQUA Carbon Formation Reactor

Series-Bosch Development

- Integrated test showed higher carbon formation rate than stand-alone testing
  - "Alternative Carbon Formation Reactors for the Series-Bosch System"



Carbon produced in pH Matter Carbon Formation Reactor

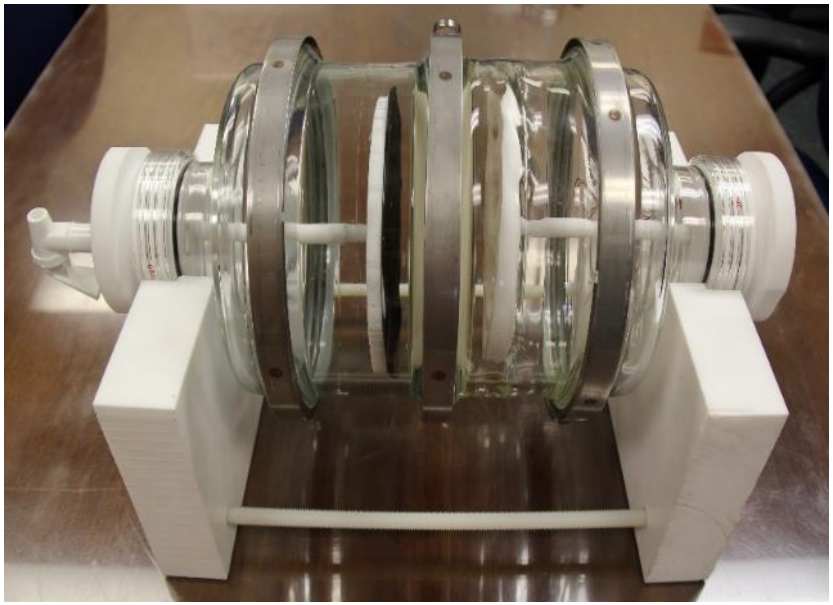
SCOR pH Matter Carbon Formation Reactor

SCOR Phase II

- Feb. 2017, SCOR Phase II projects selected:
  - Honeywell Aerospace - Methane Pyrolysis System for High-Yield Soot-Free Recovery of Oxygen from Carbon Dioxide
    - Sabatier methane-post processing technology
  - UMPQUA Research Company – Continuous Bosch Reactor
- 75% O_2 recovery from metabolic CO_2 for four crew
- Technology Readiness Level 5

Ionic Liquids

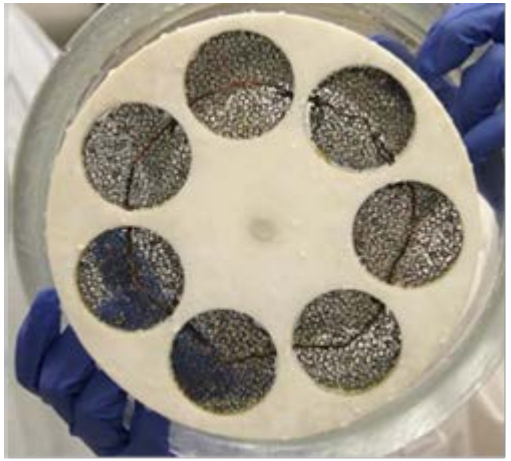
- Liquid organic salts
  - Low flammability
  - No vapor pressure
  - Tailored to a specific task



Multi-substrate Regeneration Chamber.

MSFC Ionic Liquid Work

- Bosch catalyst extraction and reuse
  1) Use IL to extract catalyst (Fe or Ni) from regolith
  2) Electroplate catalyst onto copper substrate
  3) Extract catalyst from carbon and re-plate
- IL electroplated copper has been shown to be catalytic
- Iron extraction with IL from high carbon mixture demonstrated
- Currently working system scale-up
  - "Utilizing Ionic Liquids to Enable the Future of Closed-Loop Life Support Technology"

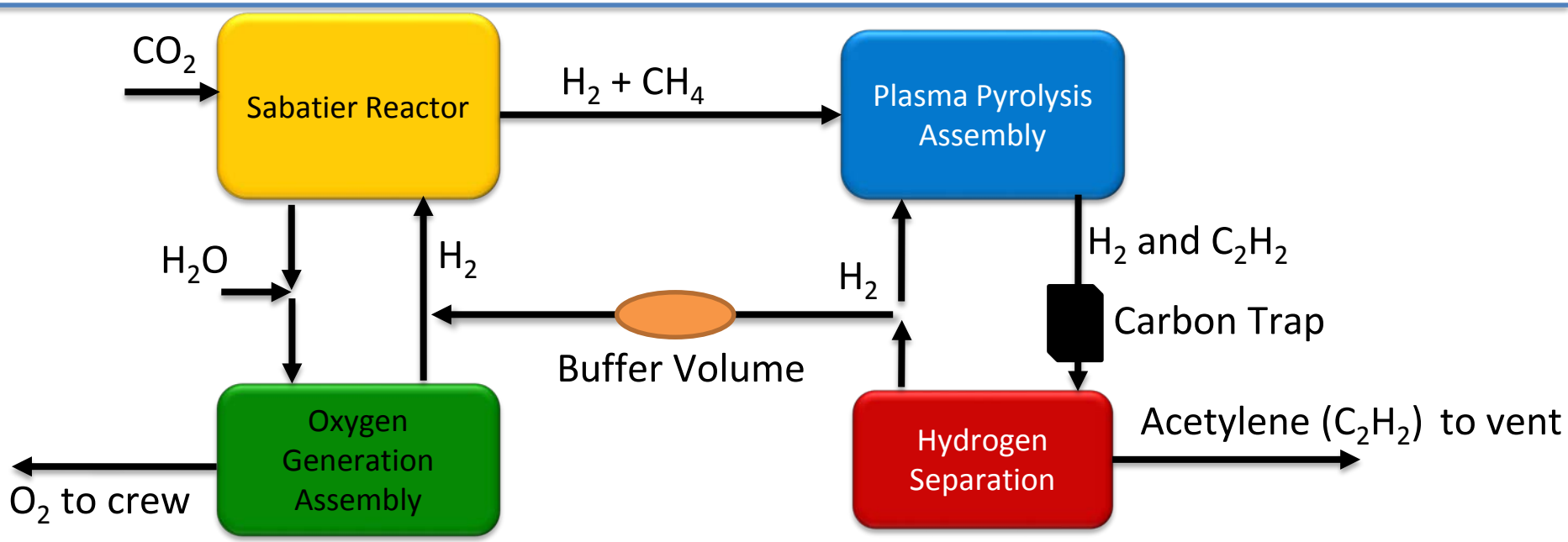


Copper substrates before (above) and after plating with Fe

University of Colorado IL Work

- University of Colorado - Boulder, O_2 recovery technology that uses IL's to convert CO_2 into CO and O_2
- Funded by NASA Space Technology Research Grant
- Benefits include:
  - Room temperature operation
  - Direct O_2 production
  - Product that can be combined with a variety of other architectures to meet mission needs
- See Holquist *et al* for additional information

Sabatier Methane Post-Processing



- O_2 recovery architecture incorporating Plasma Pyrolysis technology for methane post-processing
  - H_2 recovered from CH_4 and sent to Sabatier to recover additional O_2 from CO_2
    - ~50% O_2 recovery with Sabatier
    - Potentially >85% total O_2 recovery with PPA

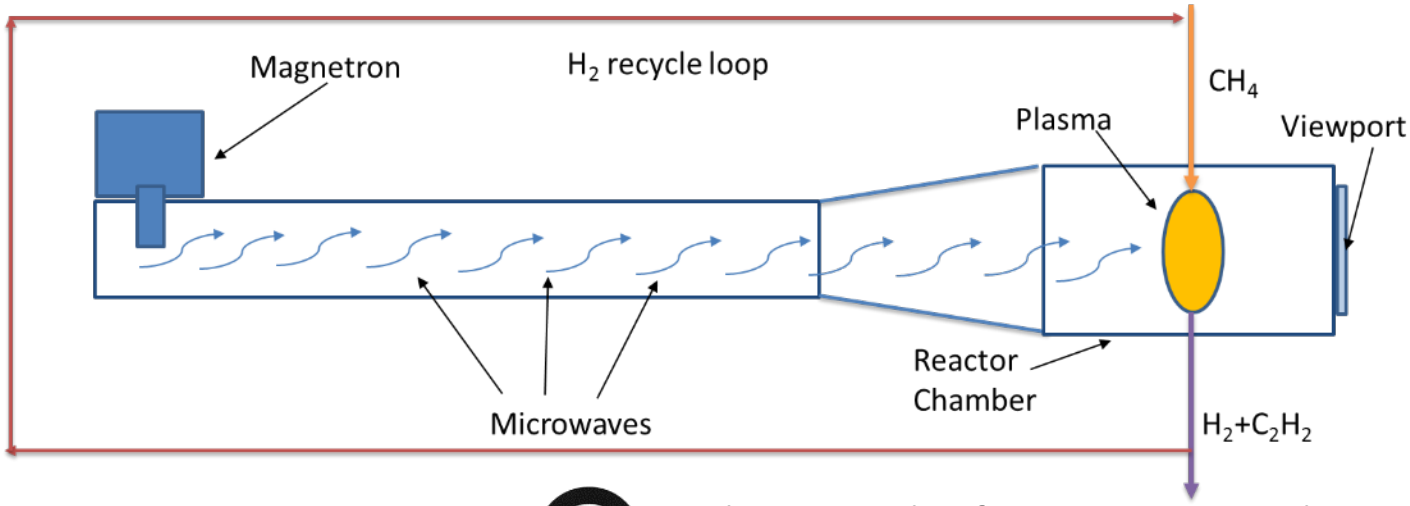
PPA Background

- PPA reactor developed by UMPQUA Research Co.
- Methane converted to hydrogen and acetylene by partial pyrolysis in microwave generated plasma
- Targeted PPA Reaction:

$$2CH_4 \leftrightarrow 3H_2 + C_2H_2$$

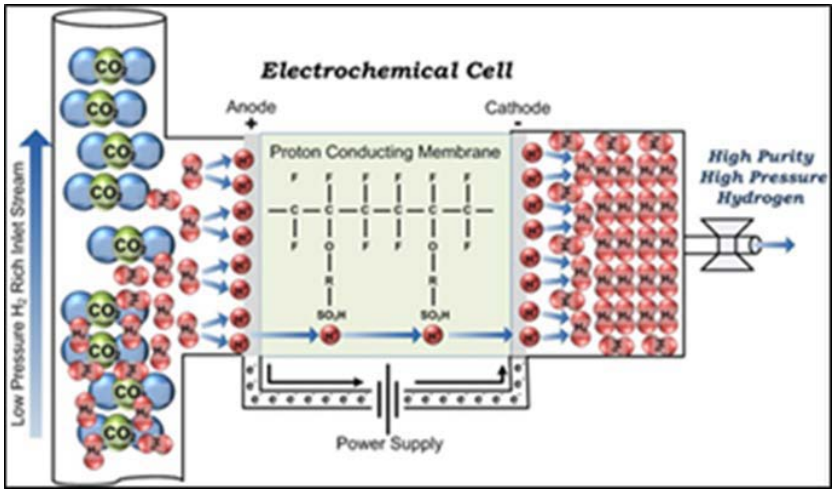
H_2/CH_4 Plasma

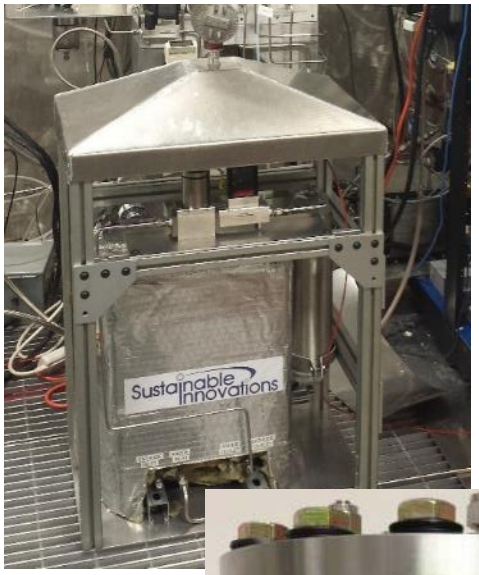
Plasma Pyrolysis Assembly



Hydrogen Separator Background

- Acetylene must be removed from PPA outlet stream before hydrogen can be sent to Sabatier
- Hydrogen separation carried out with electrochemical cell stack
- Developed by Skyre, Inc.

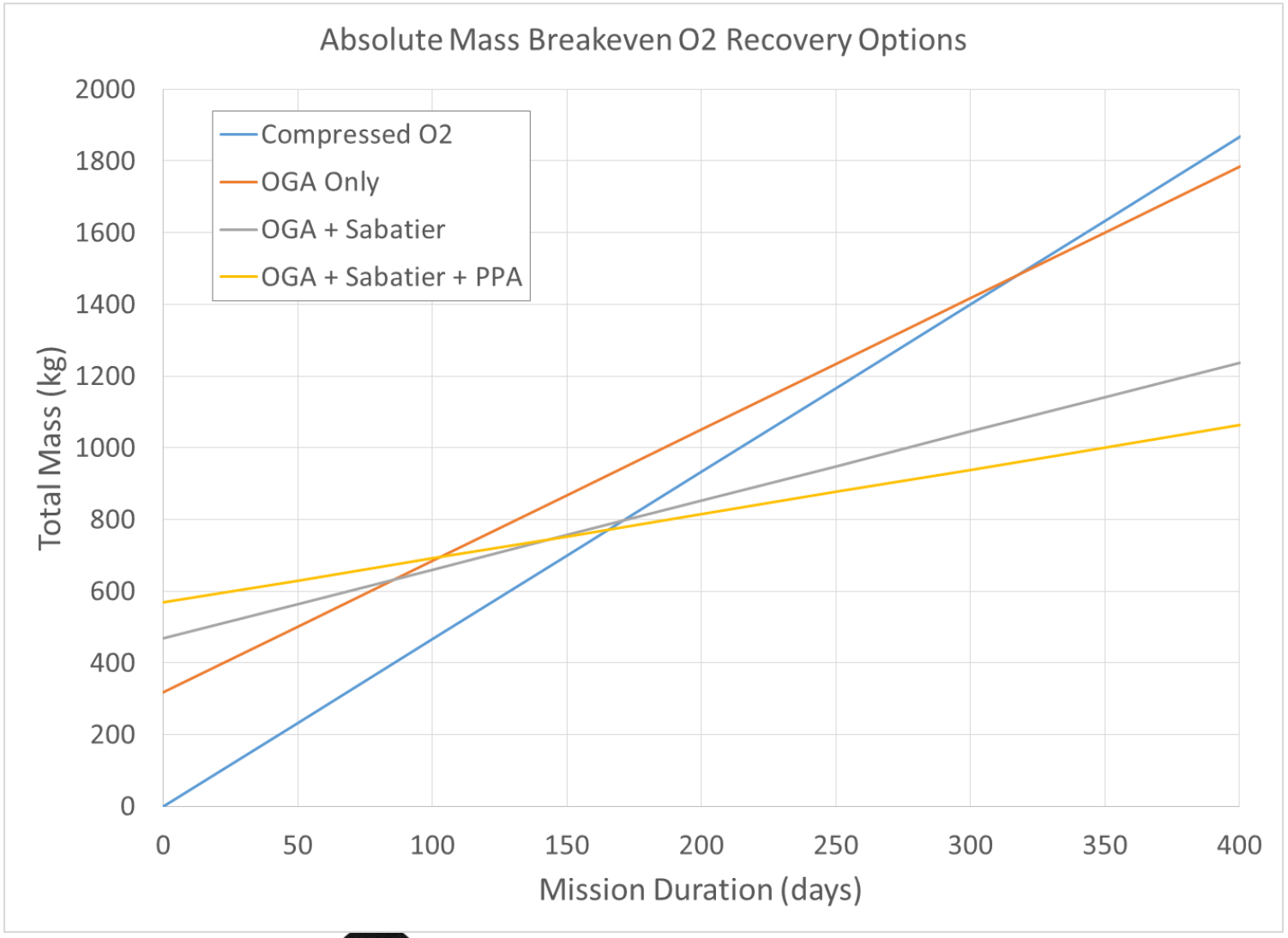




Current PPA Work

- Improve hydrogen separator, Skyre
- Investigate microgravity plasma dynamics, UMPQUA
- Characterize integrated operations
- Investigate solid-state microwave generator
- Develop ISS flight project plan
- ISS Sabatier refurbishment

O_2 Recovery Breakeven



Conclusion

- Numerous technologies under investigation and development
    - Evolutionary:
        - Methane post-processing
    - Revolutionary
        - Bosch
- Definition of mission architectures will help to evaluate and select optimal technology solutions

Acknowledgements

- Advanced Exploration Systems Program Life Support Systems Project
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Questions?