

# State of NASA Oxygen Recovery

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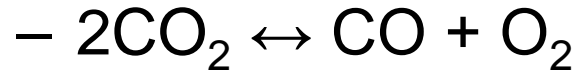
*NASA, George C. Marshall Space Flight Center*



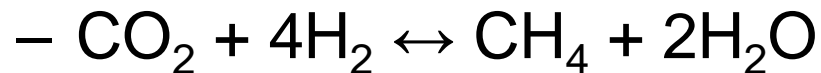
# Historical O<sub>2</sub> Recovery Processes

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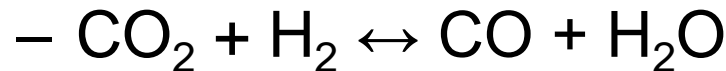
## CO<sub>2</sub> Electrolysis



## Sabatier



## Bosch Process



# 1980-90's Tech Development

Sabatier Development Unit  
developed by Hamilton  
Sundstrand



Sabatier won because:

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

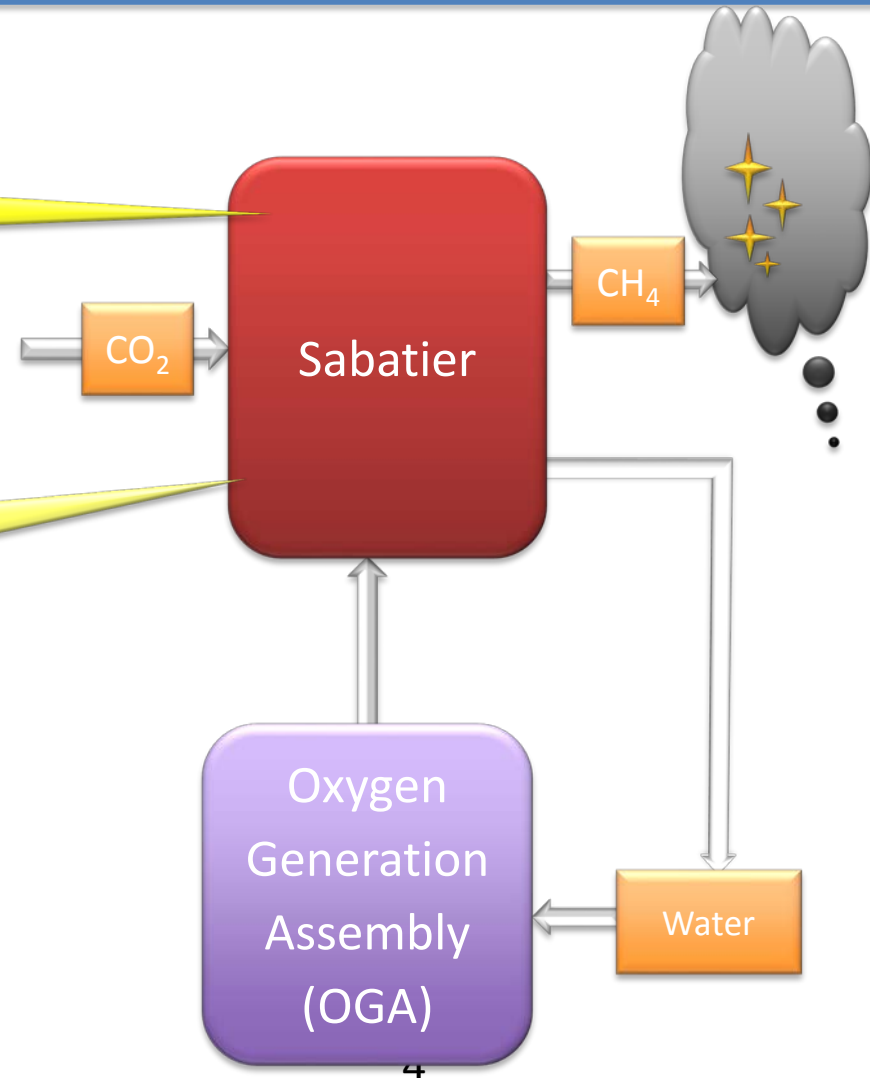


# Oxygen Recovery

Net loss of hydrogen  
must be resupplied as  
water from Earth

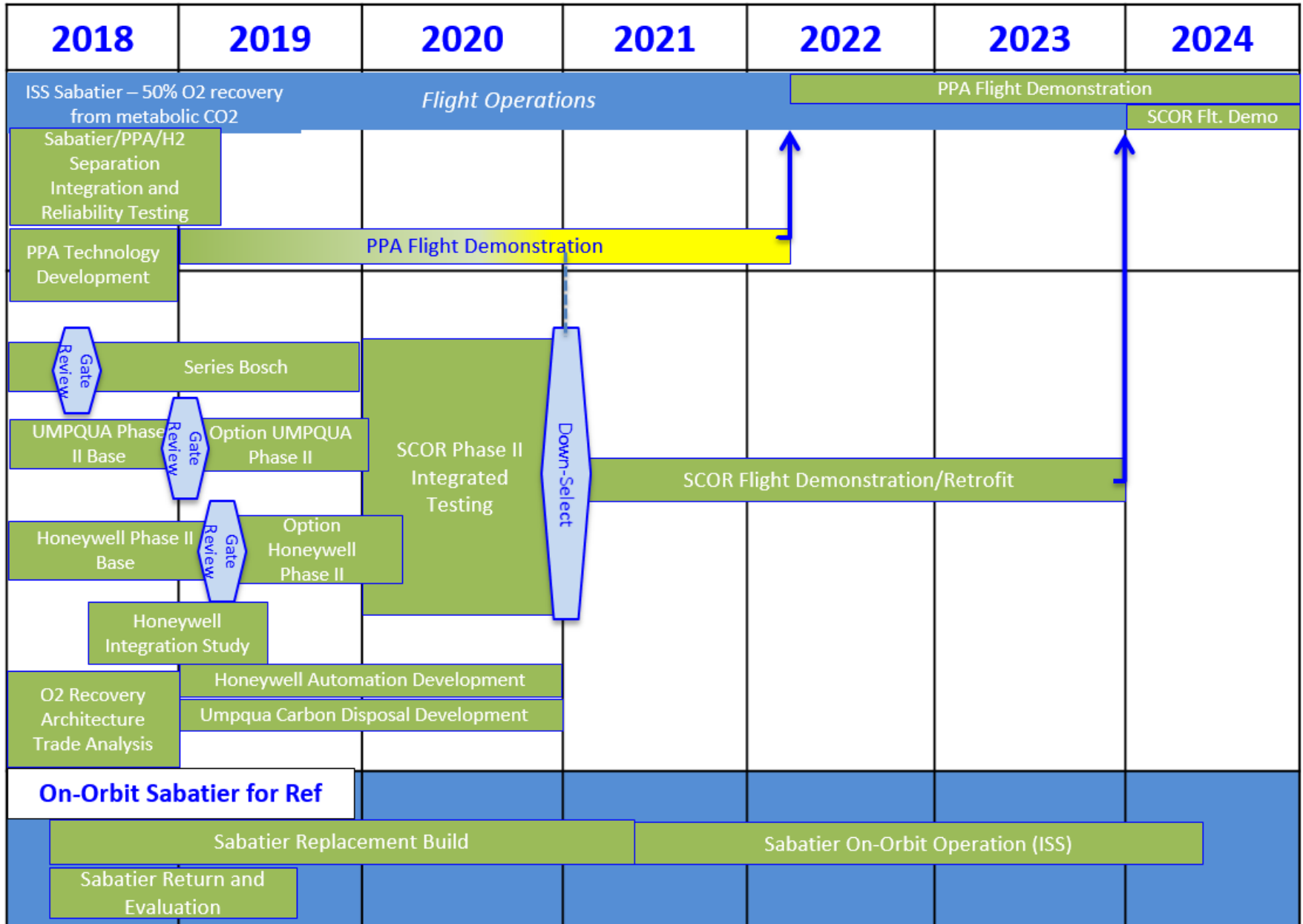
Launch Costs  
1kg ~ \$68,000  
Water for one year for  
four crew ~\$45M

**Need to recover and  
recycle more for long-  
duration missions**



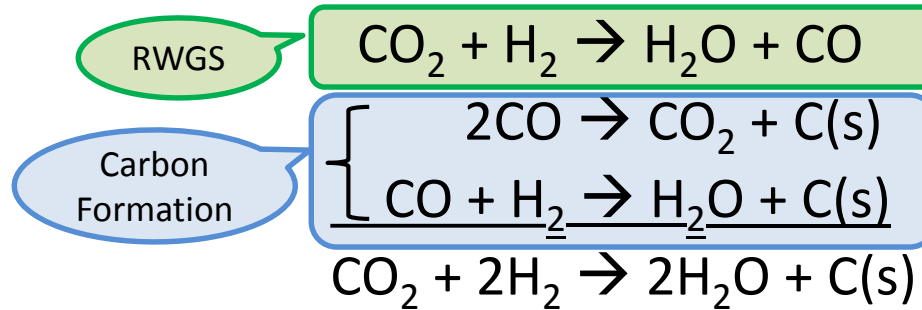
# CO2 Reduction/Resource Recovery: Current Plan

*Fiscal Year*



# Bosch Technology

Chemistry:



## Challenges for Space Application

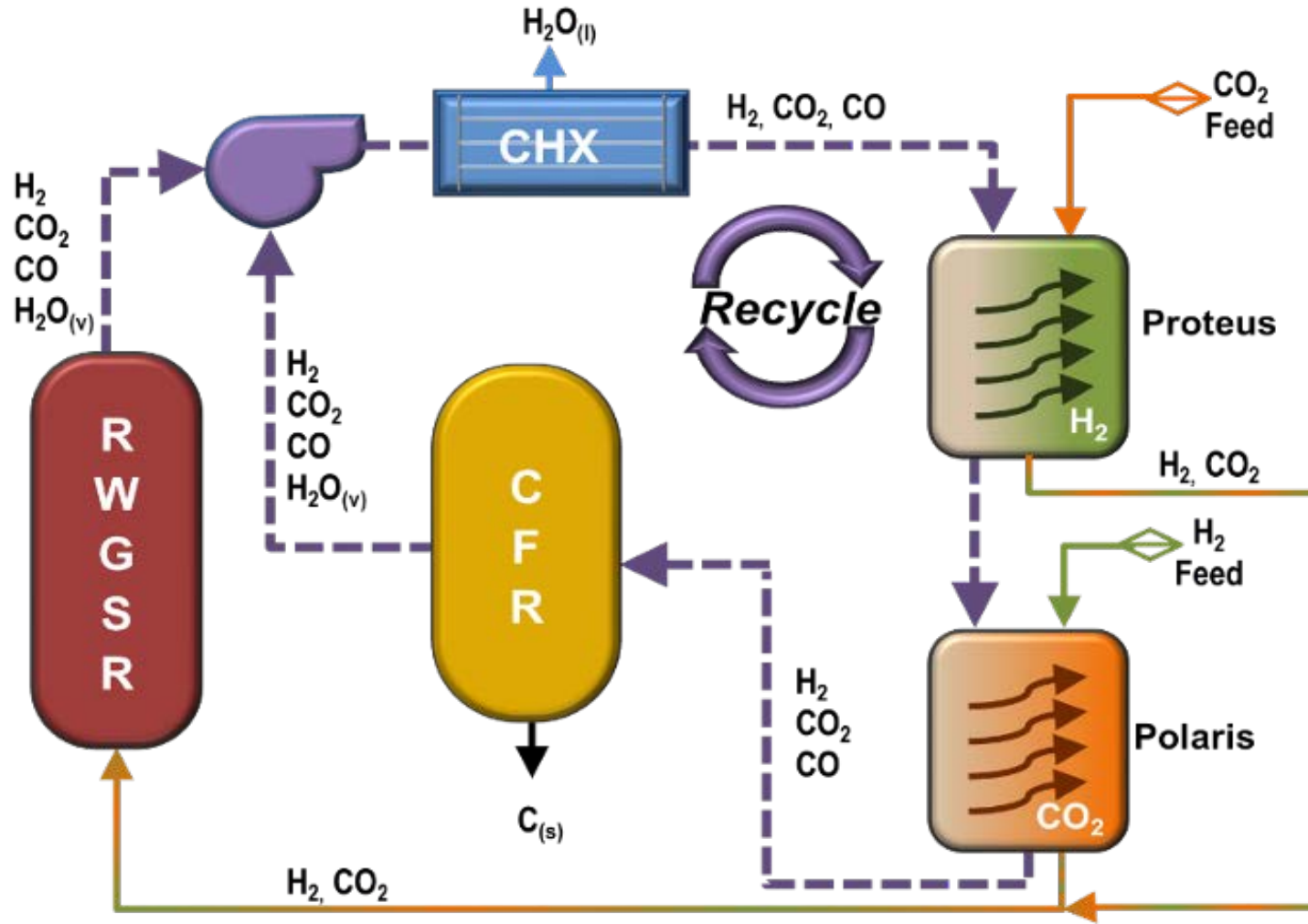
- Power Consumption
  - High Temperature Endothermic Reactions
- Catalyst Resupply
- Volume/Mass



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



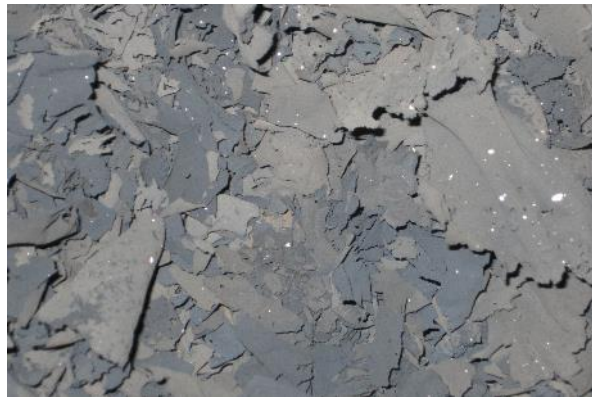
SCOR UMPQUA Carbon Formation Reactor





# 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

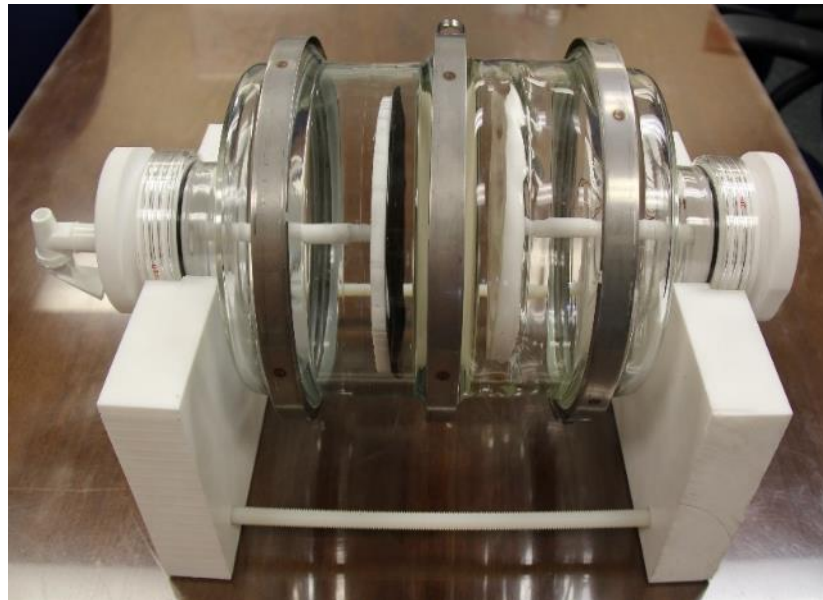
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- Feb. 2017, SCOR Phase II projects selected:
  - Honeywell Aerospace - Methane Pyrolysis System for High-Yield Soot-Free Recovery of Oxygen from Carbon Dioxide
    - Sabatier methane-post processing technology
  - UMPQUA Research Company – Continuous Bosch Reactor
- 75% O<sub>2</sub> recovery from metabolic CO<sub>2</sub> for four crew
- Technology Readiness Level 5



# Ionic Liquids

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

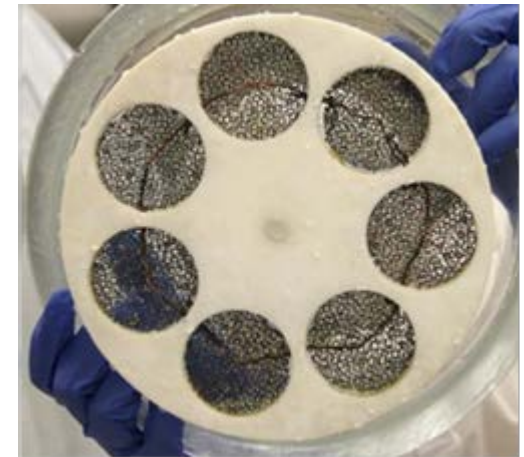


**Multi-substrate Regeneration Chamber.**



# 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



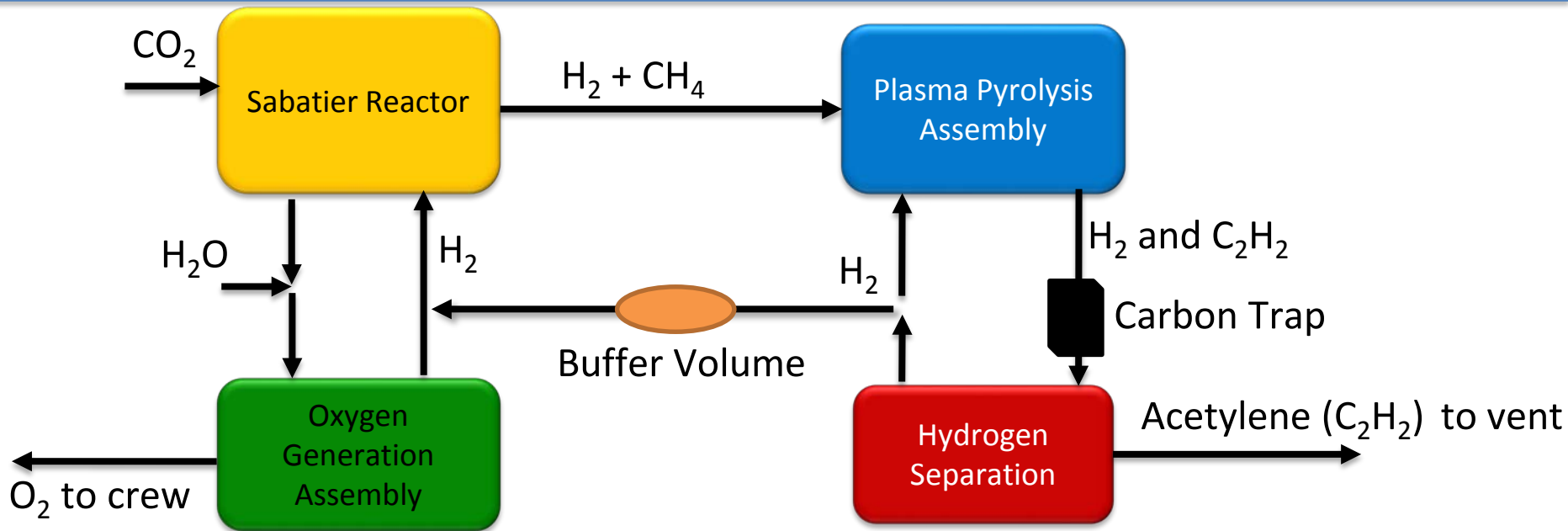
# University of Colorado IL Work

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- University of Colorado - Boulder, O<sub>2</sub> recovery technology that uses IL's to convert CO<sub>2</sub> into CO and O<sub>2</sub>
- Funded by NASA Space Technology Research Grant
- Benefits include:
  - Room temperature operation
  - Direct O<sub>2</sub> 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

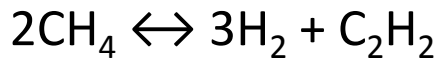


- O<sub>2</sub> recovery architecture incorporating Plasma Pyrolysis technology for methane post-processing
  - H<sub>2</sub> recovered from CH<sub>4</sub> and sent to Sabatier to recover additional O<sub>2</sub> from CO<sub>2</sub>
    - ~50% O<sub>2</sub> recovery with Sabatier
    - Potentially >85% total O<sub>2</sub> recovery with PPA



# PPA Background

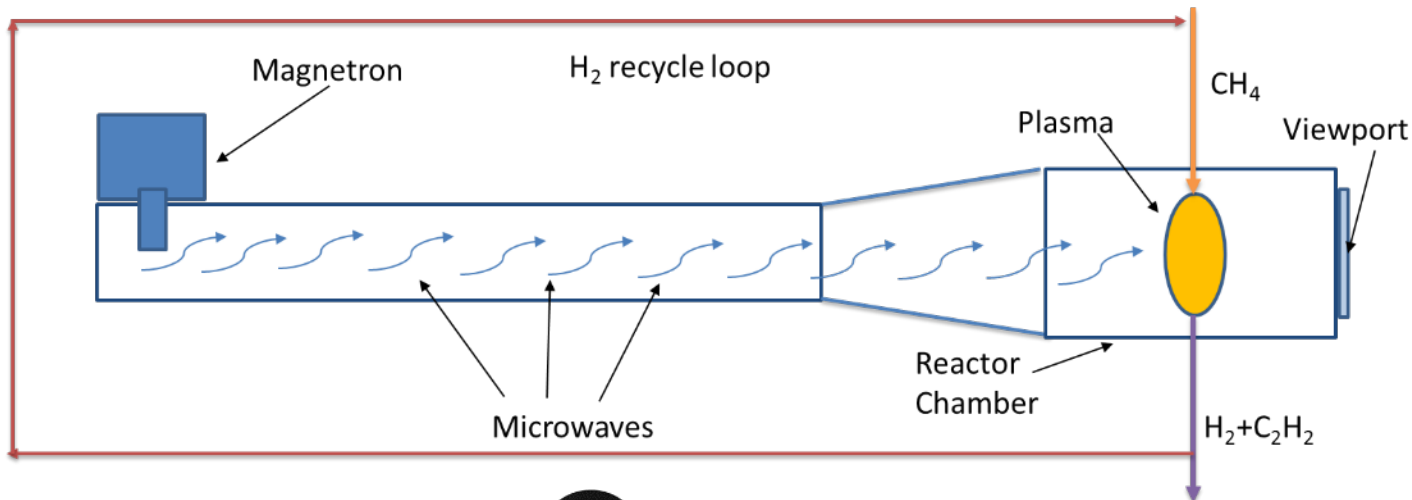
- PPA reactor developed by UMPQUA Research Co.
- Methane converted to hydrogen and acetylene by partial pyrolysis in microwave generated plasma
- Targeted PPA Reaction:



H<sub>2</sub>/CH<sub>4</sub> Plasma



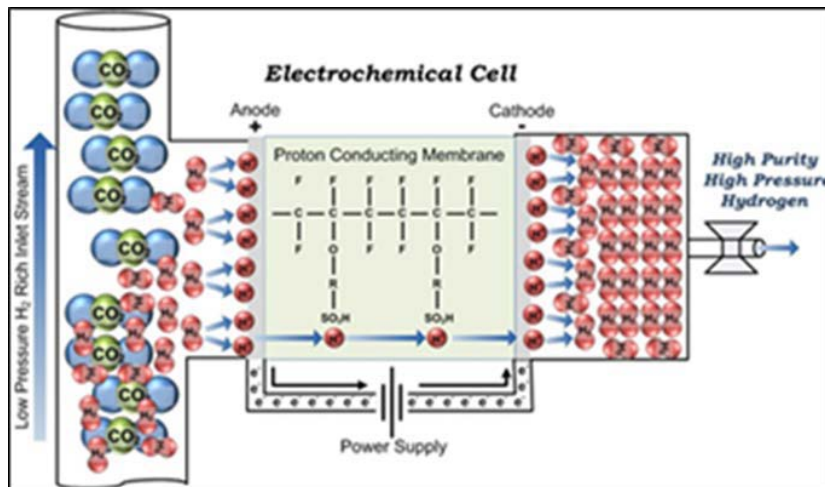
Plasma Pyrolysis Assembly





# 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.





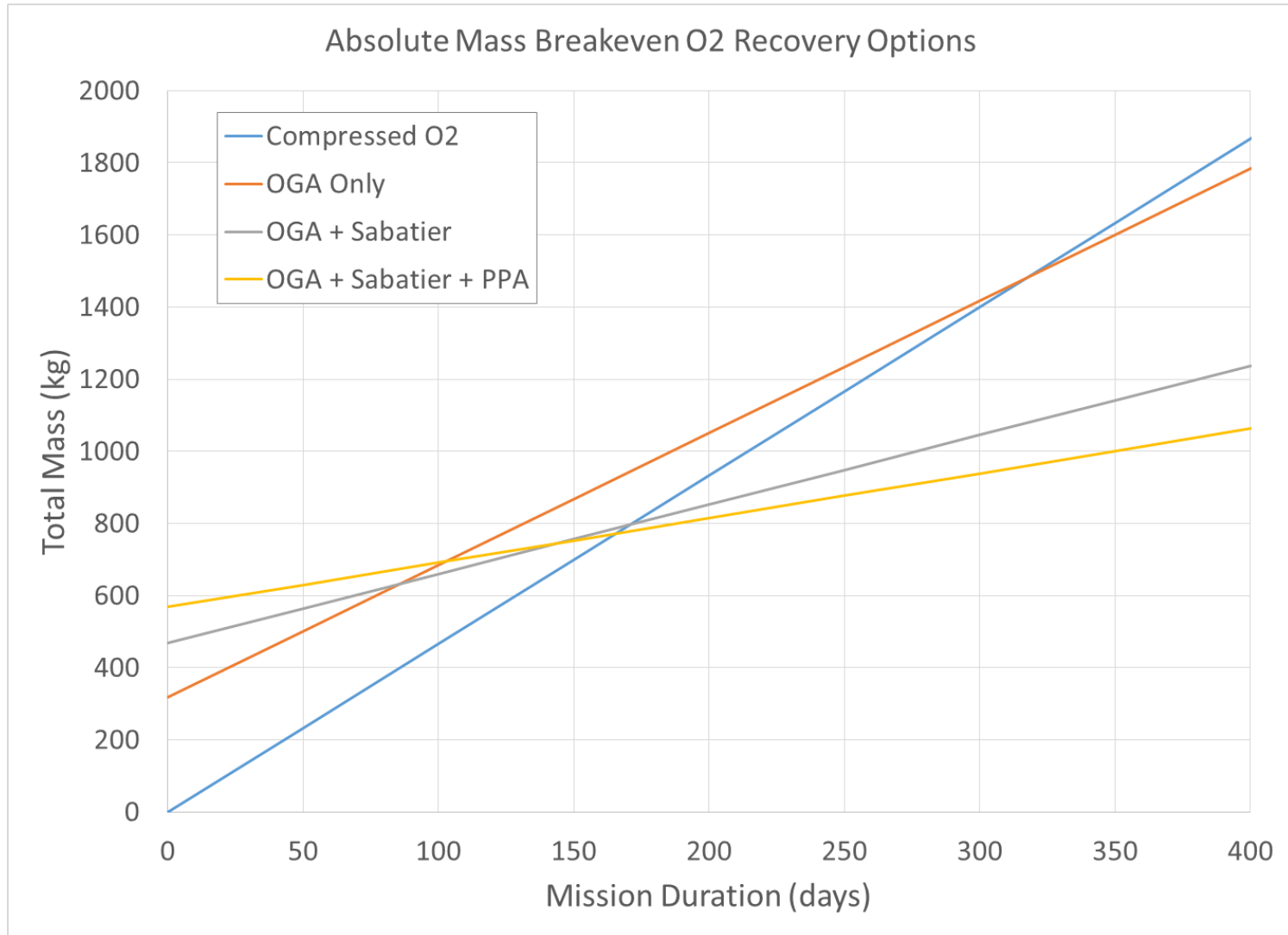
# Current PPA Work

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- 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<sub>2</sub> Recovery Breakeven



# Conclusion

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- 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

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- Advanced Exploration Systems Program Life Support Systems Project
- Game Changing Development Program Spacecraft Oxygen Recovery Project
- Heath Mullins, Kenny Bodkin, Tom Williams, and Ken Frederick



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# Questions?

