Improving the Recovery of Oxygen from Carbon Dioxide

Summary Presentation

Daniel J. Barta, NASA Johnson Space Center, Houston, TX, USA

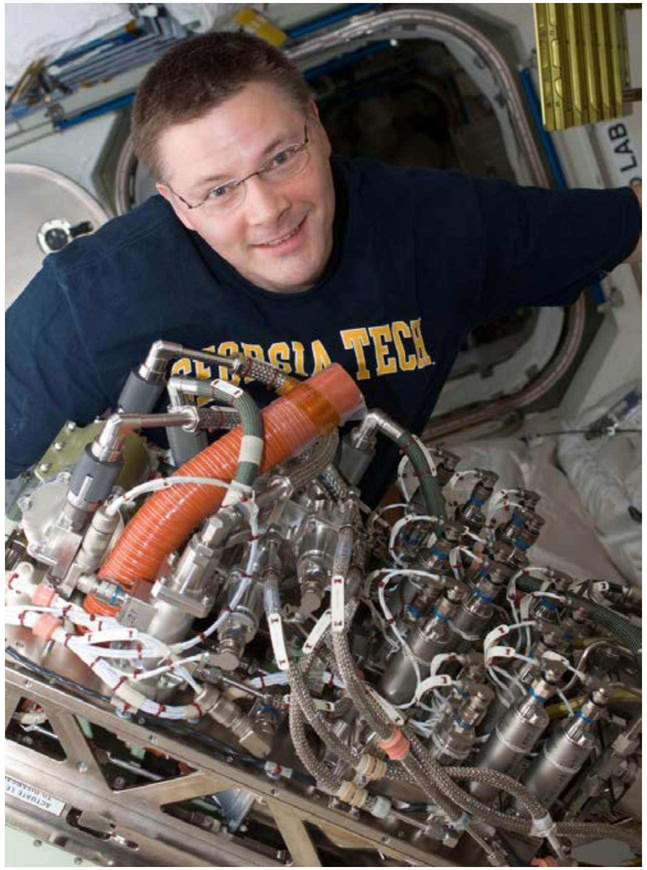
Christine Stanley, NASA Marshall Space Flight Center, Huntsville, AL USA

Kevin Lange, Jacobs Engineering, Houston, TX USA

43rd COSPAR Scientific Assembly, 28 January – 4 February 2021

Background and Overview

- **Oxygen is a critical life support systems consumable for human spaceflight**
- **On the International Space Station, oxygen is provided as a compressed gas or by electrolysis of stored water**
- **The mass of oxygen required for long duration human exploration missions can be prohibitive.**
- **Recovery of oxygen from metabolic carbon dioxide can reduce mission resupply requirements, providing benefit to long duration human exploration missions.**
- **This presentation**
  - Describes the state-of-the-art oxygen recovery technology used on the ISS
  - Provides an overview of several alternative oxygen recovery technology investments by NASA to improve the percentage of oxygen recovered
  - Reviews findings from trade studies comparing the equivalent systems mass estimates for life support system architectures using these alternative technologies



Astronaut Doug Wheelock installs the Sabatier CO_2 Reduction Assembly (CRA) on ISS. The CRA was returned to Earth in 2018. ESA's Advanced Closed Loop System (ACLS) launched in 2018, contains a Sabatier reactor.

Sabatier: The ISS State of the Art for Oxygen Recovery from CO_2

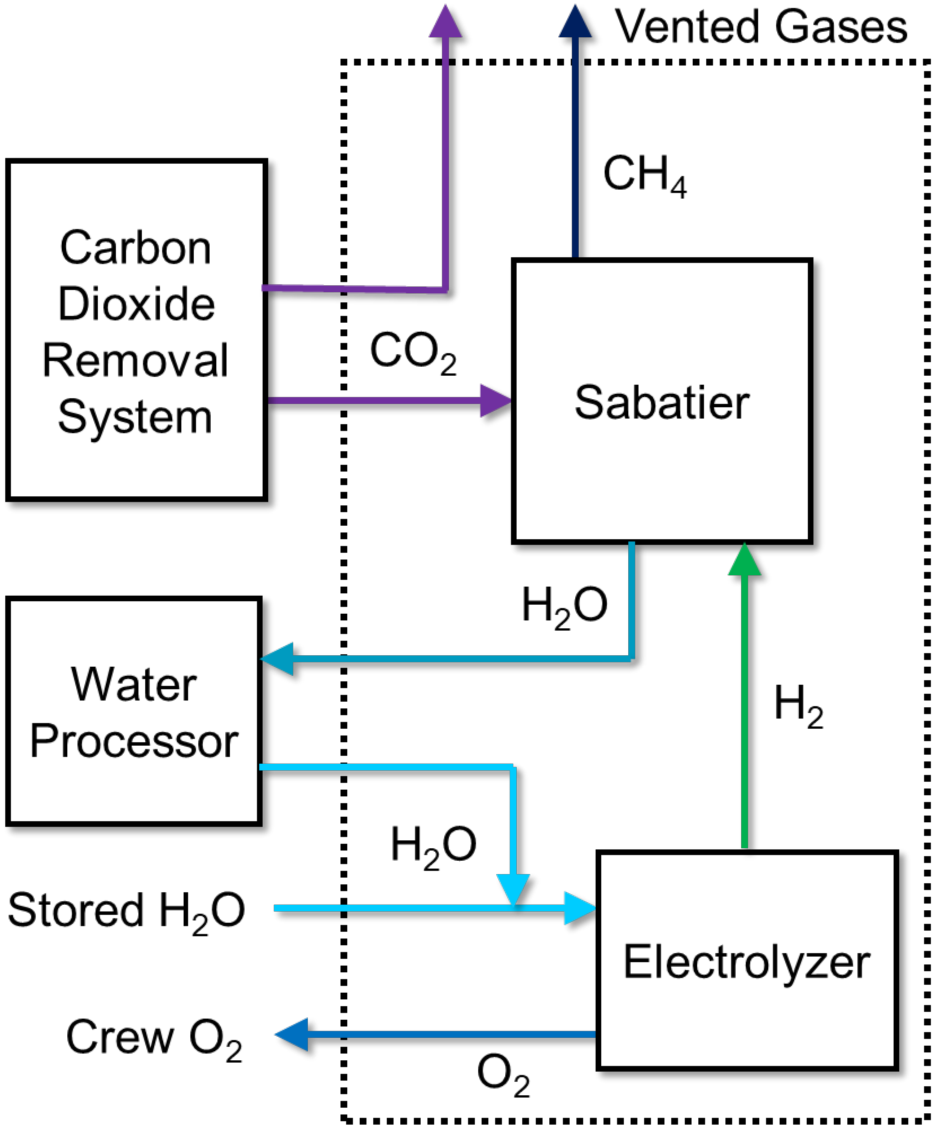
- **The state-of-the-art for oxygen recovery technology on the ISS is the Sabatier Reactor**
    - NASA's Carbon Dioxide Reduction Assembly (CRA).
    - ESA's Advanced Closed Loop System (ACLS)
- **Sabatier reactor operation**
    - Hydrogen (H_2) from an electrolyzer is combined with recovered Carbon Dioxide (CO_2) over catalysts at elevated temperature. Water (H_2O) and methane (CH_4) are produced as reaction products.

<u>**Primary Reactions**</u>

Sabatier: $CO_2 + 4\ H_2 \leftrightarrow CH_4 + 2\ H_2O$

OGA: $2\ H_2O \rightarrow 2\ H_2 + O_2$

- **The availability of H_2 is limited by the electrolyzer, based on the crew's oxygen requirement**
- **There is insufficient hydrogen to react all the CO_2**
- **Only about ~50% of the O_2 from metabolic CO_2 can be recovered based on this H_2 limitation.**

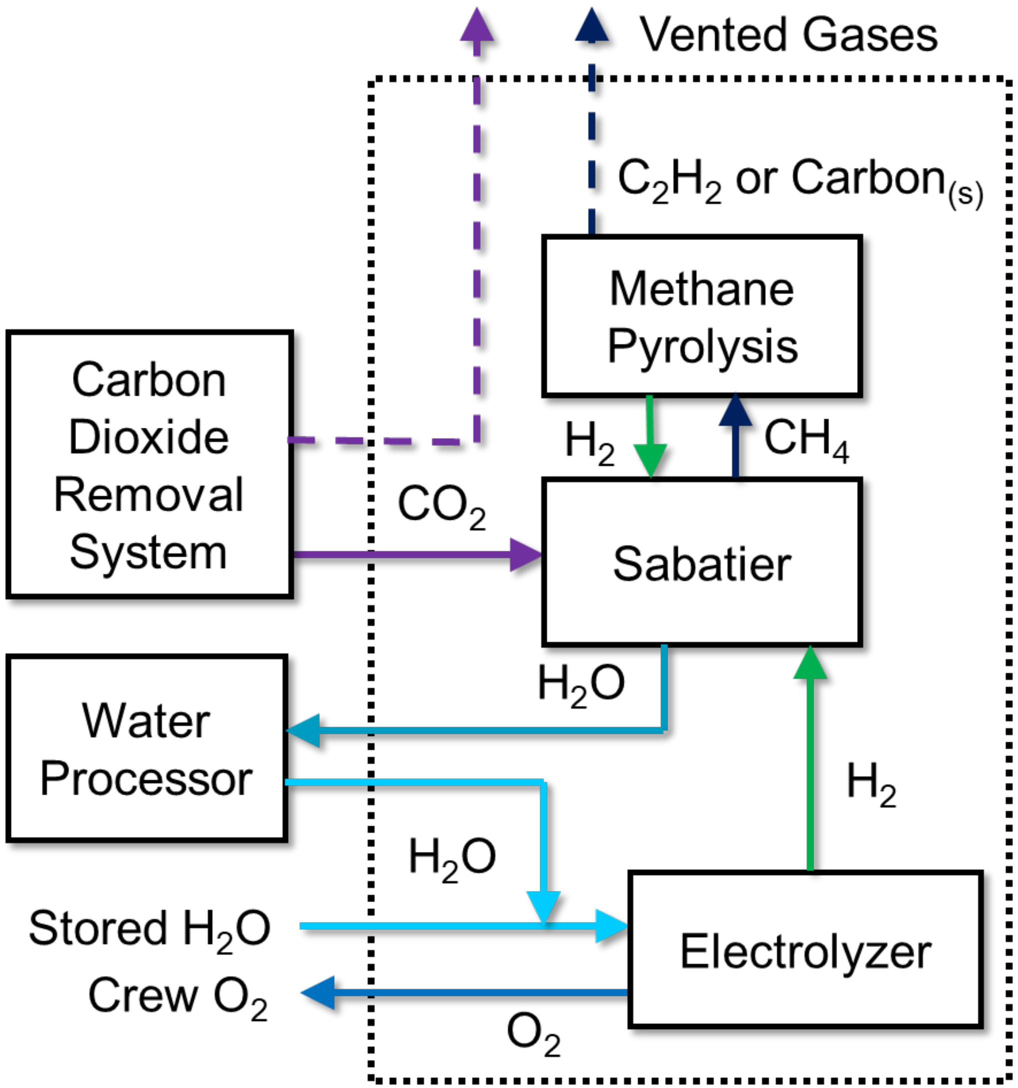


Methane Pyrolysis: Recovery of Hydrogen Lost as Methane

- **The limitation of available H_2 for Sabatier can be overcome by recovery of H_2 by methane pyrolysis.**
- **Two methane pyrolysis technologies are under investigation by NASA:**
  1) The Plasma Pyrolysis Assembly - PPA (Umpqua Research) degrades methane (CH_4) into H_2 and acetylene.
     - Can approach 75% hydrogen recovery efficiency

     Reaction: $2\ CH_4 \leftrightarrow 3\ H_2 + C_2H_2$
  1) Hydrogen Recovery by Carbon Vapor Deposition (Honeywell) degrades CH_4 into solid carbon and H_2
     - Can approach 100% hydrogen recovery efficiency

     Reaction: $CH_4 \leftrightarrow 2\ H_2 + C_{(s)}$
- **Challenges**
  - o Gas purity and separation
  - o Consumables (particle filters and substrates)
  - o Particulates and carbon waste
  - o High temperature reactors



Bosch: A Replacement for the Sabatier

- **Replaces the Sabatier reactor in an ECLSS architecture**
  - All H_2 in the reaction results in water production.
  - Approaches 100% efficiency in recovery of O_2 from CO_2
  - Requires expendable catalyst as a consumable

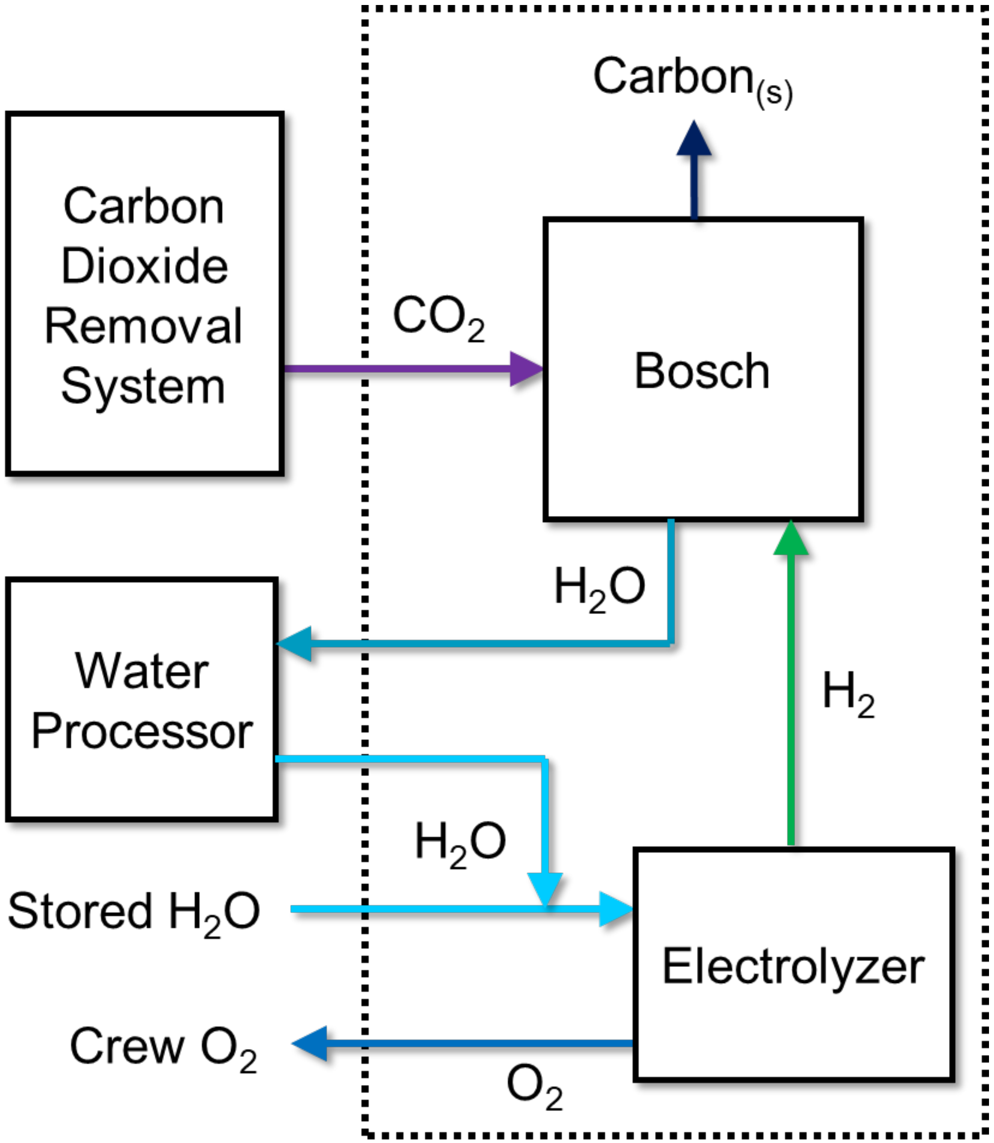
<u>Bosch Reactions</u>

RWGS:	$CO_2 + H_2 \leftrightarrow CO + H_2O$
CO Hydrogenation:	$CO + H_2 \leftrightarrow H_2O + C_{(s)}$
Boudouard:	$2CO \leftrightarrow CO_2 + C_{(s)}$
Net Bosch Reaction:	$CO_2 + 2H_2 \leftrightarrow C_{(s)} + 2H_2O$

- **Two technologies under investigation by NASA:**

1) <u>Continuous Bosch Reactor</u> (Umpqua Research, Inc.)
   - Single reactor, continuously operated.
   - Fresh catalyst is introduced and particulate carbon is removed while the reactor is operating

1) <u>Series Bosch Reactor: a 2 reactor system</u> (NASA MSFC)
   - Two reactors optimize each reaction step
     - ➢ Reverse Water Gas Shift (RWGS) as first reactor
     - ➢ Carbon Formation Reactor as second
   - Requires hydrogen and carbon dioxide separation membranes



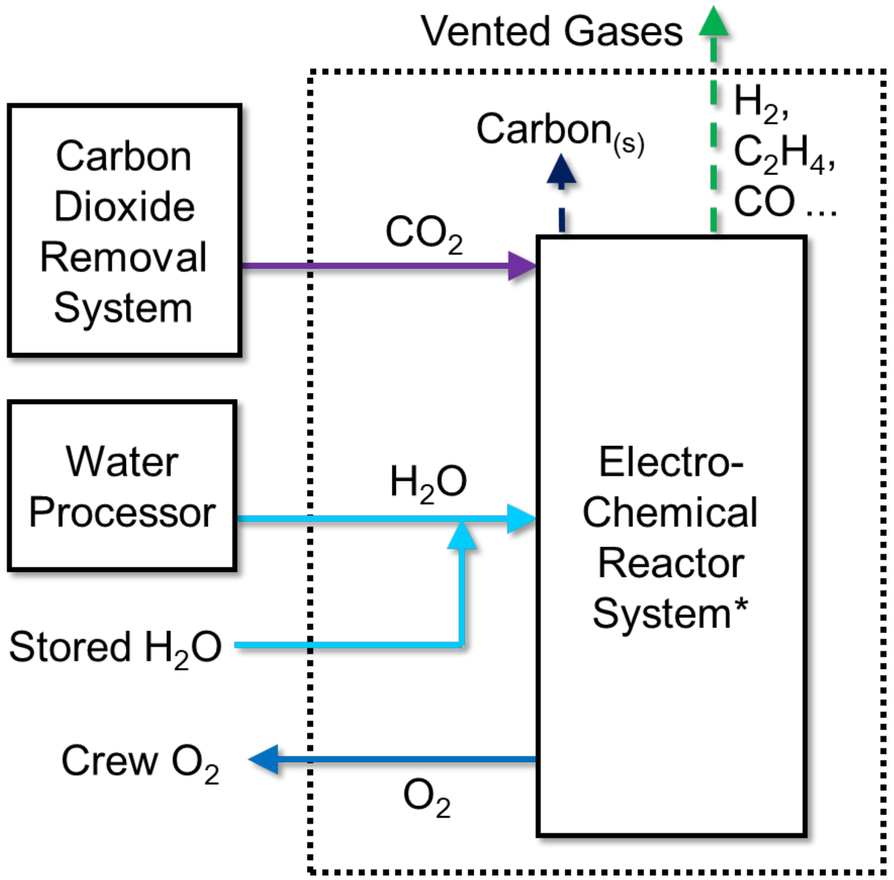
Electrochemical Reactors

- **Direct generation of oxygen from CO_2**
- **May eliminate need for a separate water electrolyzer (OGA)**
- **May be coupled with carbon formation reactors (CFR)***
- **Several technologies have been investigated**

1) Solid Oxide Co-Electrolysis - SOCE (NASA GRC and JPL)
   - o High temperature; up to 100% recovery

1) Microfluidic Electrochemical Reactor - MFECR (U. Texas Arlington)
   - o Ambient temperature; aliphatic byproducts; up to 73% recovery

3) Ion Exchange Membrane Electrolysis – IEME (Univ. of Delaware)
   - o Ambient temperature; CO_2 must be dissolved in electrolyte; up to 100% recovery



Primary Reactions

SOCE:
$$2\,H_2O \rightarrow 2\,H_2 + O_2$$
$$2\,CO_2 \rightarrow 2\,CO + O_2$$
$$CO_2 + H_2 \leftrightarrow CO + H_2O$$

CFR:
$$CO + H_2 \leftrightarrow C(s) + H_2O$$
$$2\,CO \leftrightarrow C(s) + CO_2$$

Net: $CO_2 \rightarrow C(s) + O_2$

IEME:
$$2\,H_2O \rightarrow 2\,H_2 + O_2$$
$$2\,CO_2 \rightarrow 2\,CO + O_2$$

CFR:
$$CO + H_2 \leftrightarrow C(s) + H_2O$$
$$2\,CO \leftrightarrow C(s) + CO_2$$

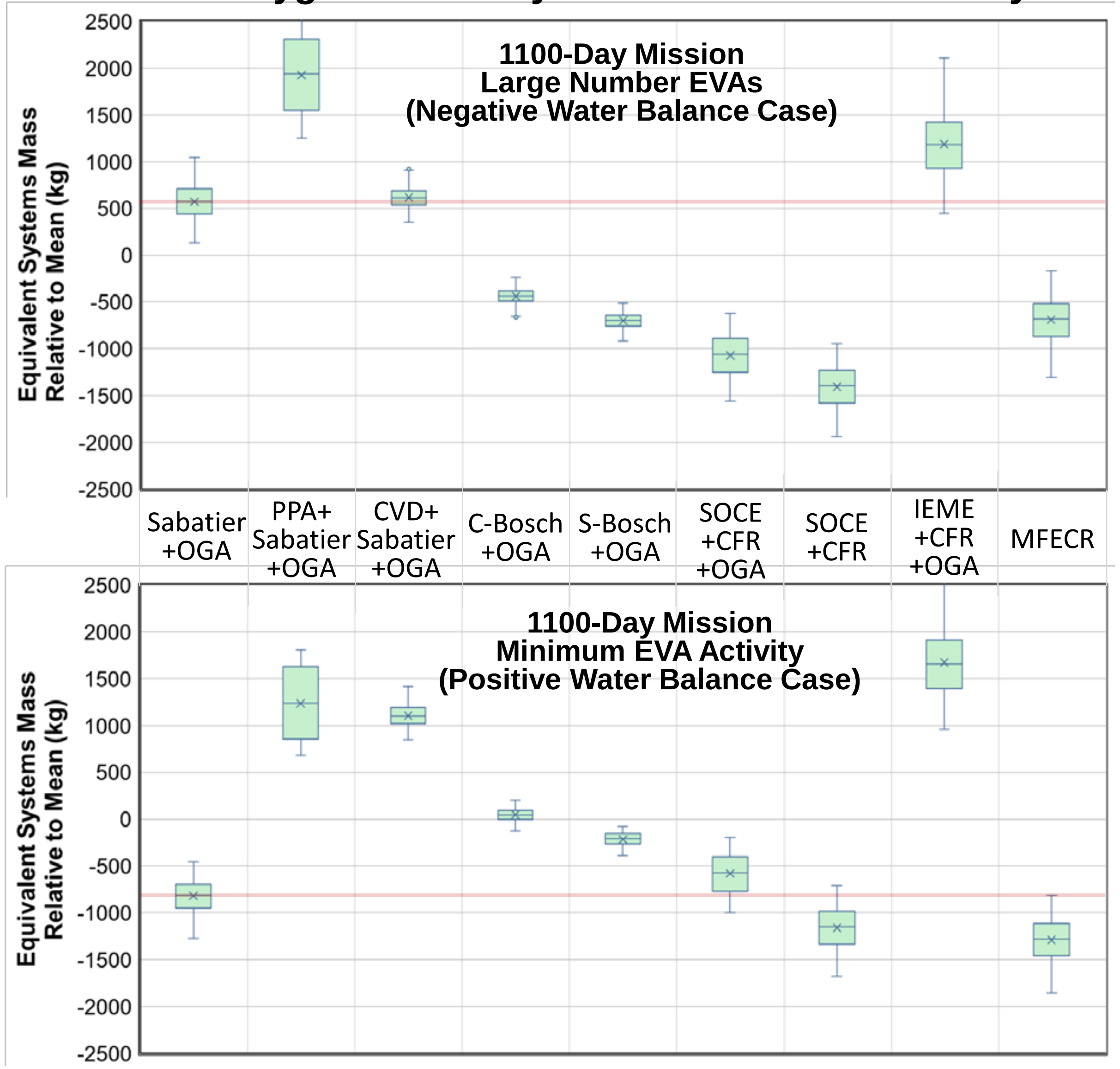
Net: $CO_2 \rightarrow C(s) + O_2$

MFECR:
$$2\,H_2O \rightarrow 2\,H_2 + O_2$$
$$2\,CO_2 + 2\,H_2O \rightarrow C_2H_4 + 3\,O_2$$

Trade Studies: General Findings and Conclusions

- **Key drivers for trades are mission duration and overall life support system water balance.**
  - Advanced technologies generally don't trade well for mission duration < 400-500 days or for ECLSS closure with a positive water balance
  - Negative water balances are more likely to occur on surface missions due to EVA losses.
  - Does not consider possible ISRU resources.
  - Lower-moisture packaged food would improve trades for SCOR technologies beyond Sabatier.
- **Advanced technologies are generally expected to trade better for partial-gravity surface missions. Factors affecting trades:**
  - Lower food water content
  - Availability of ISRU surface resources
  - Mass benefits of surplus water recovery (such as radiation shielding)
  - Dormancy considerations involving repeated shorter-duration operational segments.

Oxygen Recovery Architecture Trade Study



Thank You!

Selected References:

Greenwood, Z., Abney, M., Brown, B., Fox, E., and Stanley, C., “State of NASA Oxygen Recovery”, ICES-2018-48

Abney, M., Schneider, W., Brown, B., Stanley, C., Lange, K., Wetzel, J., Morrow, R. and Gatens, R., “Comparison of Exploration Oxygen Recovery Technology Options Using ESM and LSMAC”. ICES-2020-108

Yates, S., Childers, A., Brom, N., Skomurski, S., Lo, C., Abney, M.; “Hydrogen Recovery by Methane Pyrolysis to Elemental Carbon,” 49th International Conference on Environmental Systems, ICES-2019-103

Tacconi, N., Chanmanee, W., Rege, A., Dennis, B., Rajeshwar, K., “Microfluidic Electrochemical Reactor for Oxygen Recovery via Carbon Dioxide Electrolysis," NASA/CR-2016, July 2016.

Levri, J., Drysdale, A., Ewert, M., Fisher, J., Hanford, A., Hogan J., Jones, H., Joshi, J., Vaccari, D., “Advanced Life Support Equivalent System Mass Guidelines Document,” NASA TM-2003-212278, NASA Ames Research Center, 2003.