46th INTERNATIONAL CONFERENCE ON ENVIRONMENTAL SYSTEMS
ICES 2016

Demonstration of Robustness and Integrated Operation of a Series-Bosch System

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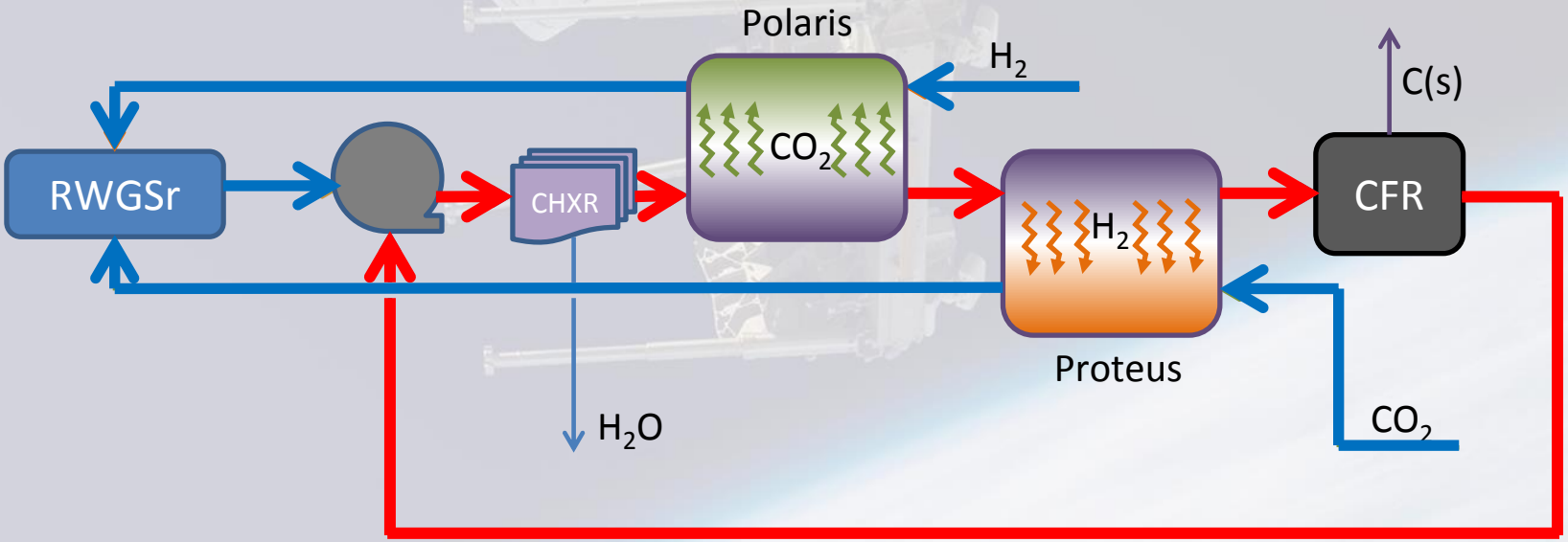
Agenda

- Background
- Purpose
- Hardware
- Test Configurations
- Results and Discussion
- Future Work

Background

- State-of-the-art O_2 recovery ~50% O_2 recovery from metabolic CO_2 (Sabatier Rxn)
- Bosch technology has potential to achieve >95% O_2 recovery

RWGS	$CO_2 + H_2 \leftrightarrow H_2O + CO$
CO Hydrogenation	$CO + H_2 \leftrightarrow H_2O + C(s)$
Boudouard	$2CO \leftrightarrow CO_2 + C(s)$
Bosch Process	$CO_2 + 2H_2 \leftrightarrow 2H_2O + C(s)$



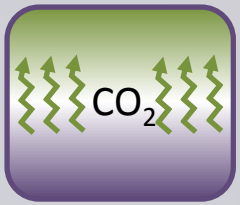
Background

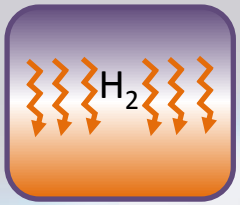
- RWGS Reactor Options

RWGSr

  - Microlith® reactor (Precision Combustion, Inc.)
  - Incofoam™ reactor (NASA-design)
- Previous testing
  - Membranes tore internal to housing
  - Due to development-scale housing design rather than membrane itself
  - Stand-alone performance for CFR characterized

Polaris





Proteus

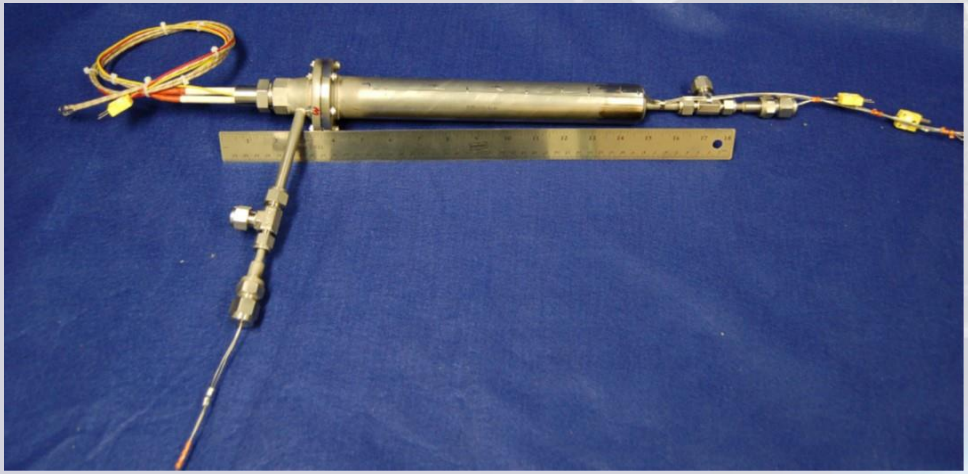
CFR

Purpose

1. Conduct head-to-head testing of RWGS reactor options
   A. Base performance
   B. Robustness testing
2. Evaluate membrane performance (following repair)
3. Evaluate integrated performance of the Series-Bosch system
4. Evaluate the effect of membrane failure on system performance (risk mitigation)

Hardware

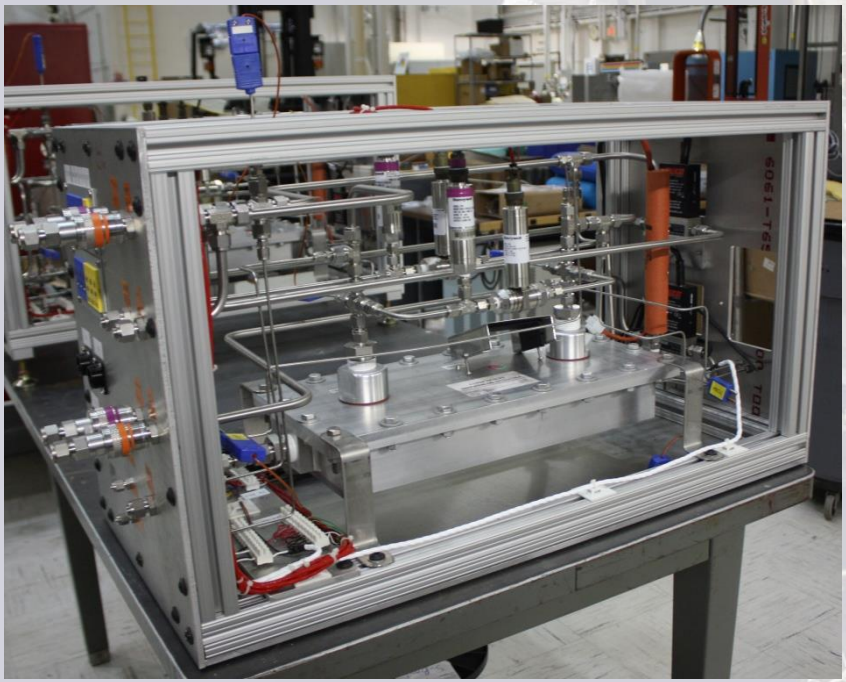
Characteristic	Microlith®	Incofoam™
Reactor Volume (cm^3)	89.4	2438
Reactor Diameter (cm)	3.81	12.7
Reactor Length (cm)	38.1	27.6
Design Temperature (°C)	800	500-750
Catalyst	Co on Microlith®	Incofoam Ni foam
Gas Hourly Space Velocity (h^{-1})	1893-3785	69-139



Microlith® Reactor

Incofoam™ Reactor

Hardware



Proteus Membrane shown in assembly without heaters or insulation (Polaris is identical)

Batch Carbon Formation Reactor – closed (left) and during steel bead packing (right)

Test Configurations

- Stand-Alone RWGS testing

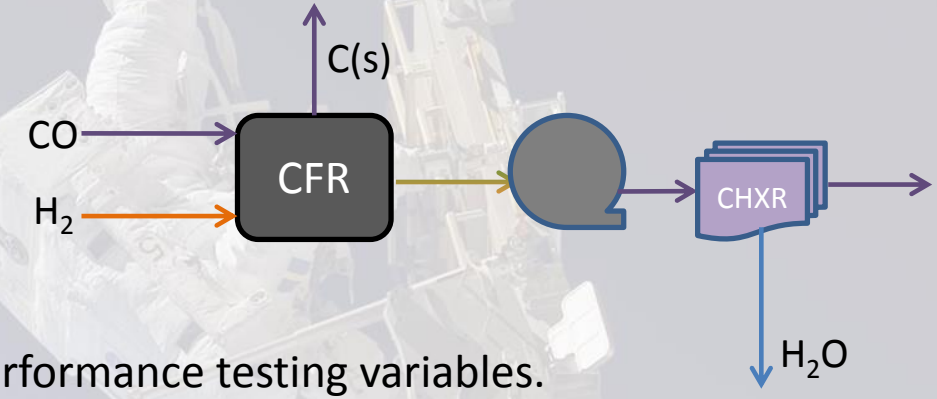


Table 1. Standard performance testing variables.

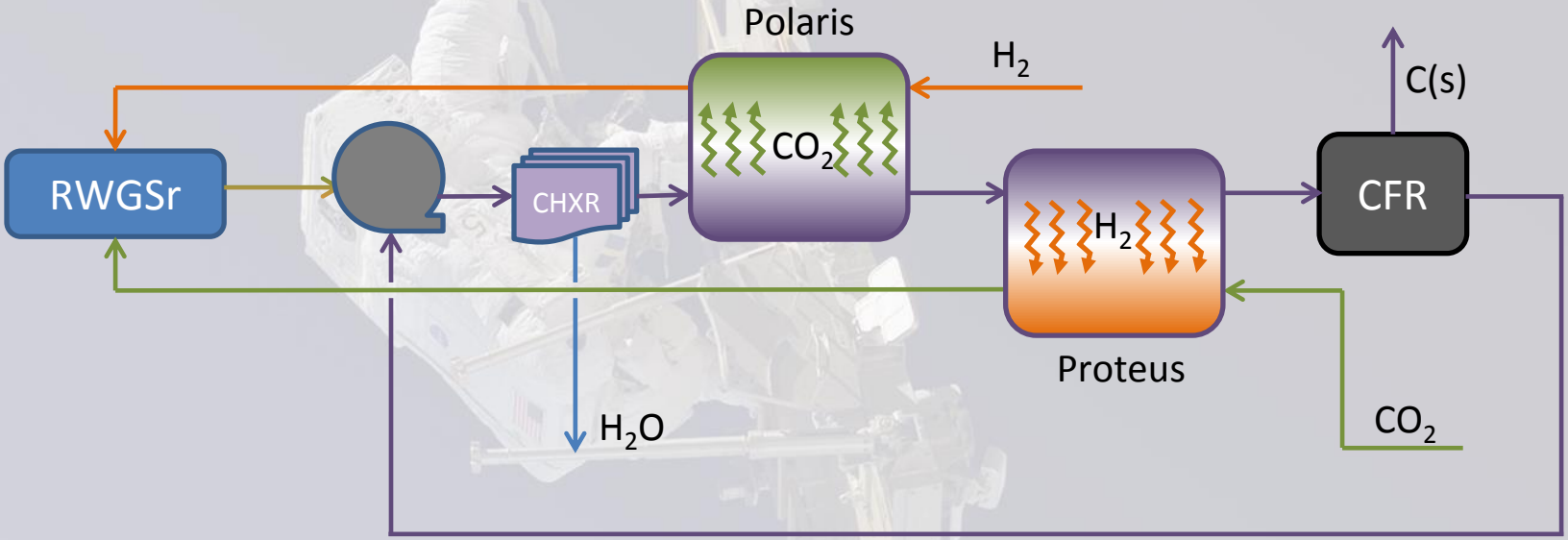
Parameter	Values
Heater Set Points	600°C, 650°C, 700°C
CO_2 Feed Rates	1.41 SLPM, 2.82 SLPM
H_2:CO_2 Ratios	1:1, 2:1, 3:1
Inlet Pressures	20.7 kPa (3 psia), 34.5 kPa (5 psia), 55.1 kPa (8 psia)

Table 2. Fouling testing variables

Parameter	Test Values
Heater Set Points	600°C, 650°C, 700°C
CO Feed Rates	0.04 SLPM – 0.57 SLPM
H_2:CO Ratios	100:1, 70:1, 50:1
Inlet Pressures	34.5 kPa (5 psia), 55.1 kPa (8 psia)

Test Configurations

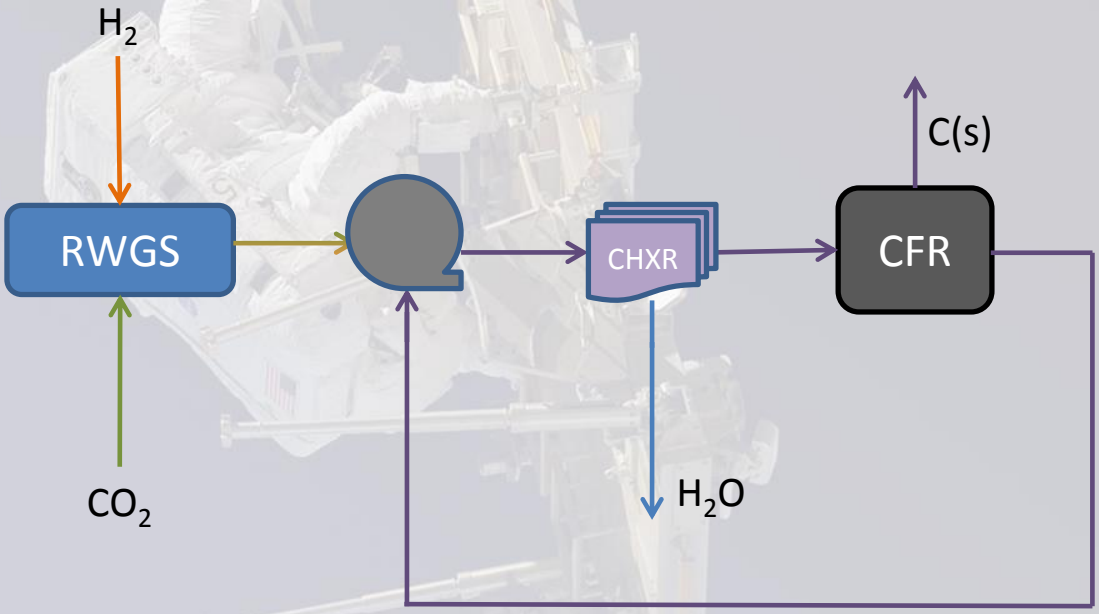
- Fully Integrated S-Bosch Testing



Parameter	Test Values
Incofoam ™ RWGS Temp	650°C
Incofoam ™ Pre-heater Temp	400°C
CFR Temp	350-550°C
CO_2 Feed Rate	0.35-1.41 SLPM
H_2:CO_2 Ratios	1:1 at start-up, 2:1 at stead-state
System dP	34.5 kPa (5 psid)

Test Configurations

- Risk Mitigation Testing



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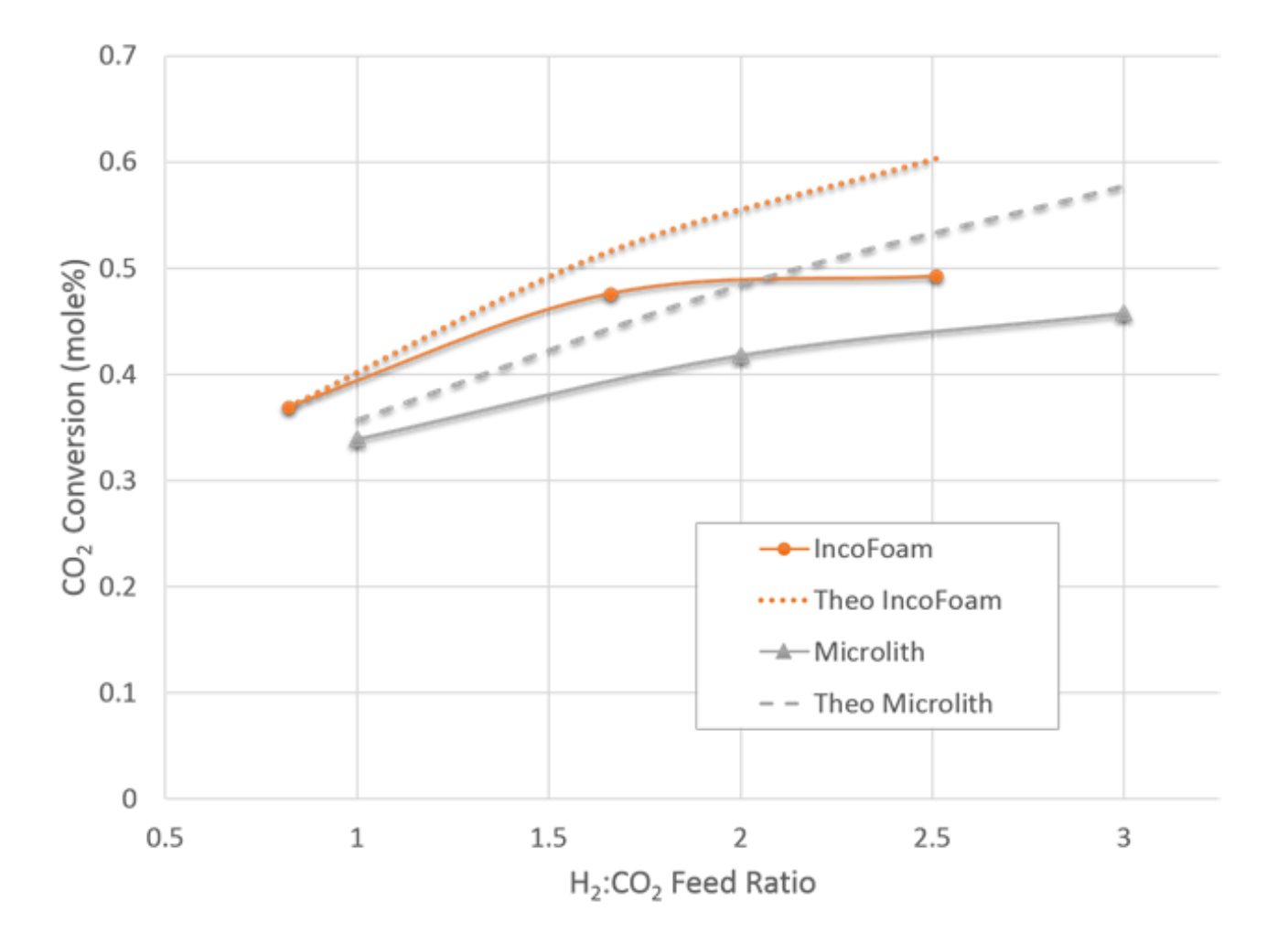
CFR Temp	350-550°C
CO_2 Feed Rate	0.35-1.41 SLPM
H_2:CO_2 Ratios	1:1 at start-up, 2:1 at stead-state
System dP	0 - 34.5 kPa (0 - 5 psid)

Results and Discussion

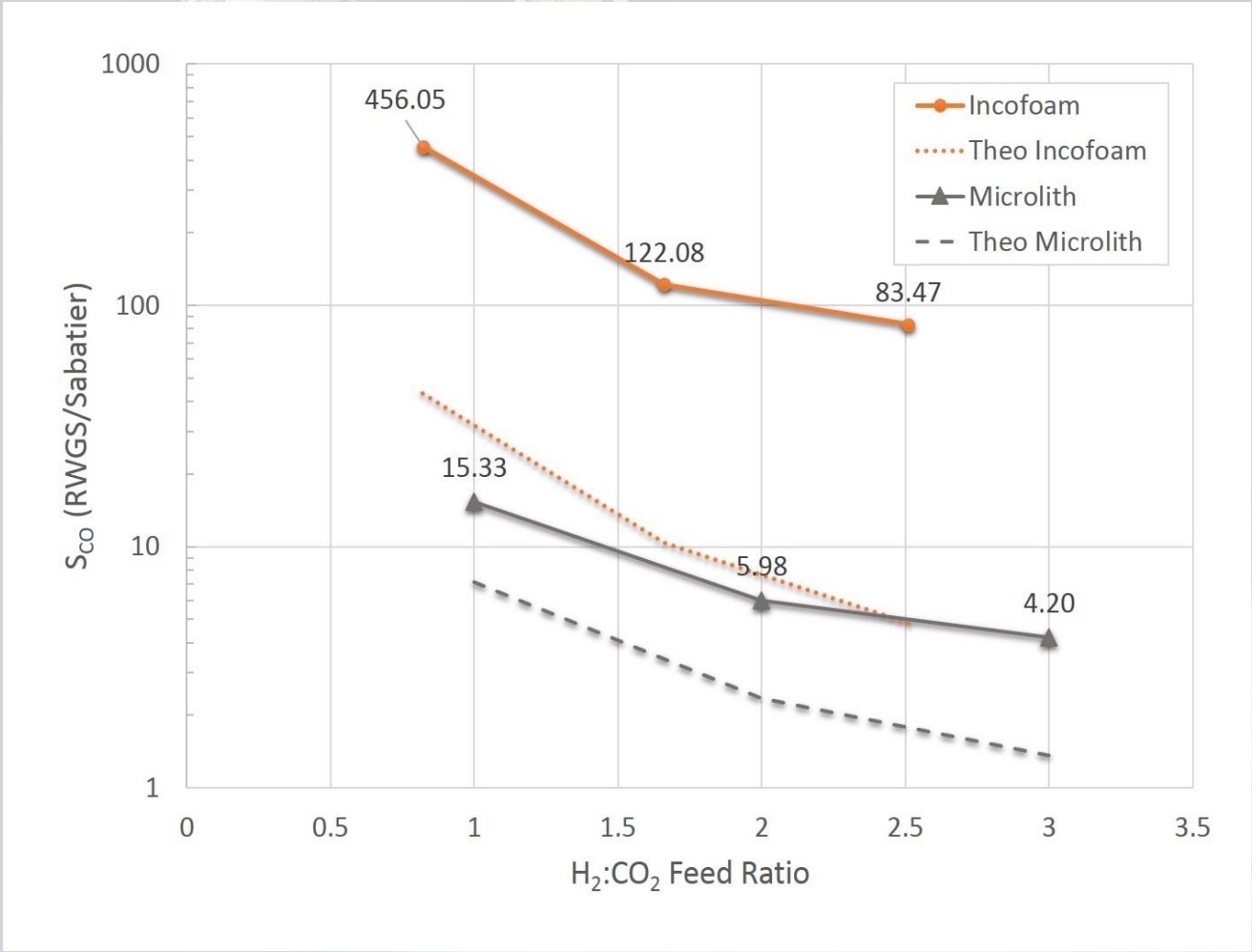
- RWGS Stand-alone performance comparison



Results and Discussion

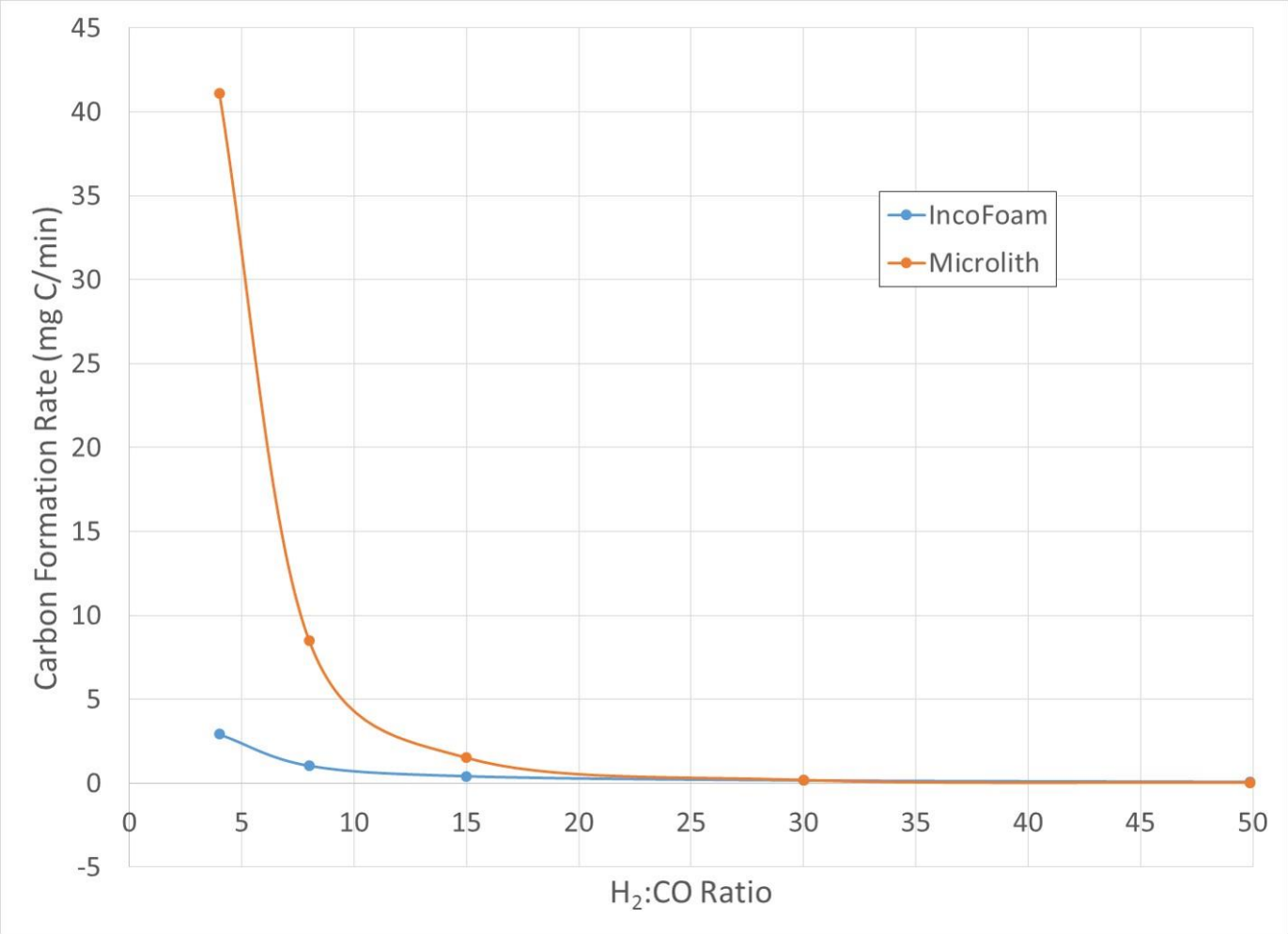
- RWGS Stand-alone performance comparison

$$S_o = \frac{\text{moles CO produced/min}}{\text{moles } CH_4 \text{ produced/min}}$$



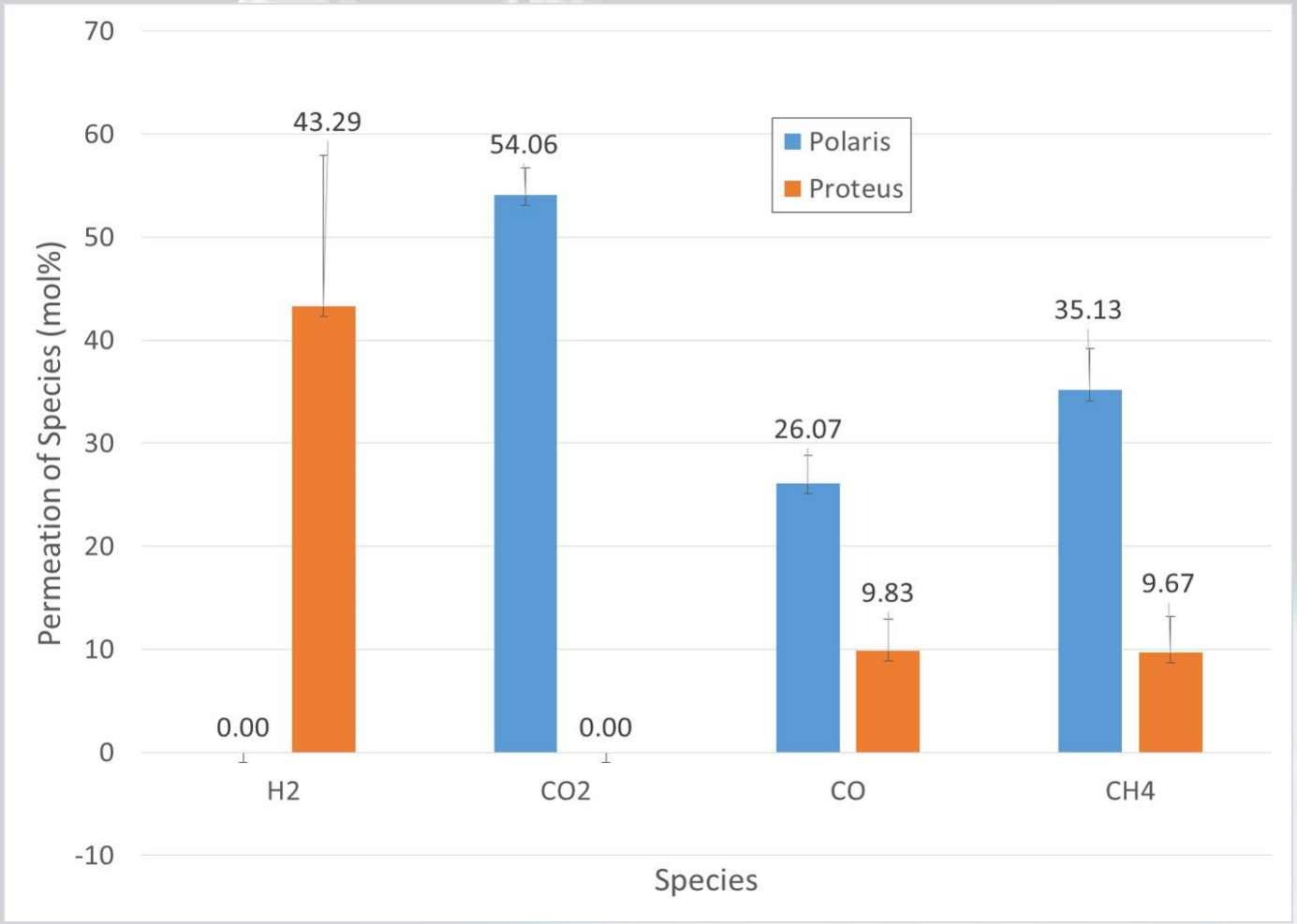
Results and Discussion

- RWGS fouling performance



Results and Discussion

- Membrane performance



Results and Discussion

- Risk Mitigation Testing (no membranes)

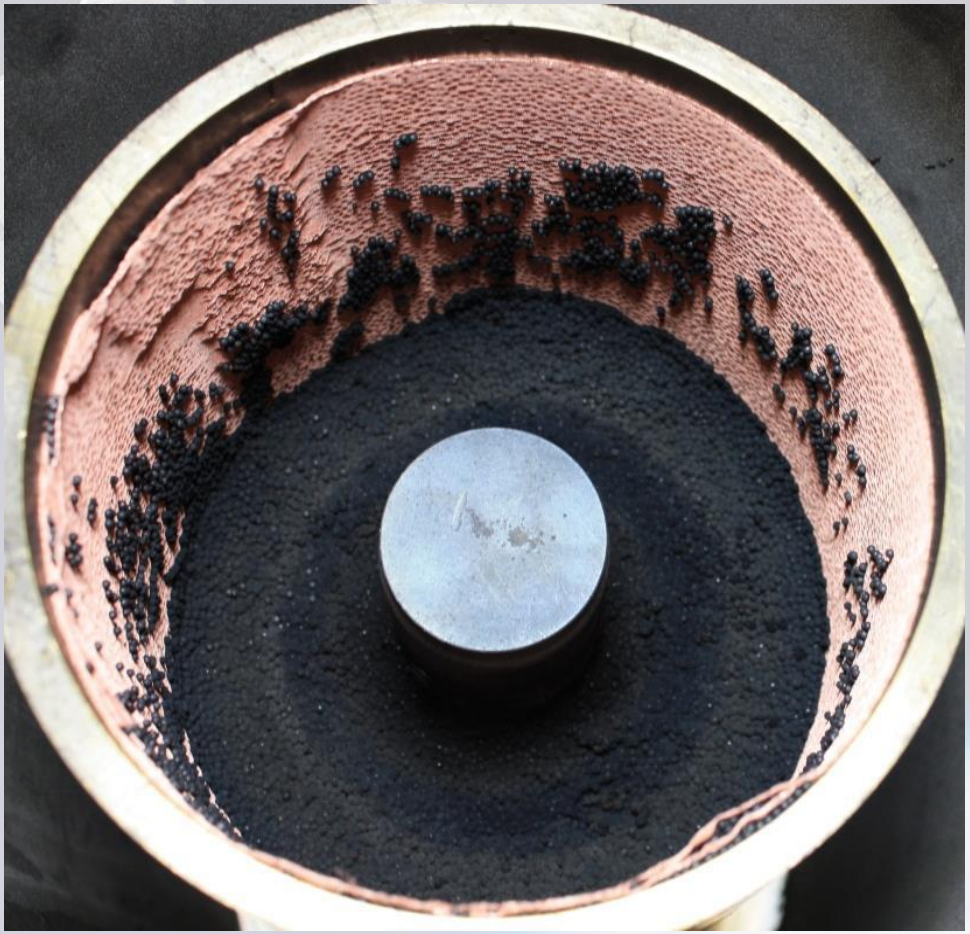
Recycle Ratio = Recycle Flow Rate (SLPM): Fresh Feed Rate (SLPM)

Configuration	Recycle Ratio
Fully Integrated	3:1 to 7:1
Risk Mitigation	20:1

- Operation will continue if membranes are fouled/lost
- Efficiency of the system decreases

Results and Discussion

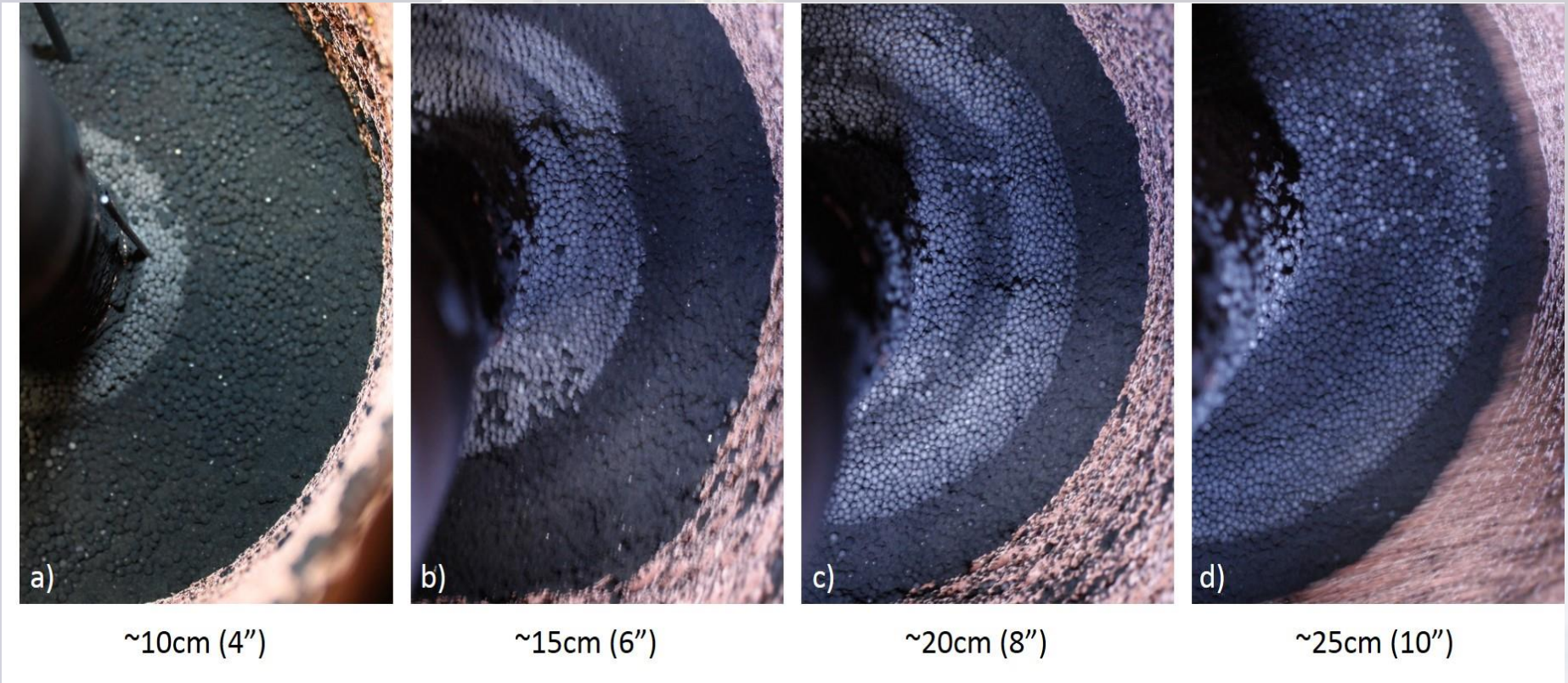
- Carbon Formation Reactor performance



Carbon formation across entire radius of reactor, though concentrated near annulus outlet

Results and Discussion

- Carbon Formation Reactor performance



Carbon formation distribution as a function of distance from the gas feed annulus.

Variation due to overly large ratio of outer annulus to inner annulus within the reactor.

Future Work

- Microlith® RWGS refurbishment and testing with carbon resistant catalyst
- Modification of batch CFR to target outer/inner annulus ratio of 0.21-1.00
  - Should improve flow distribution in reactor
- Continuous CFR assembly and testing

Questions?