Testing and Modeling of the Mars Atmospheric Processing Module

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NASA – Kennedy Space Center

AIAA SPACE 2017

Orlando, FL

September 12-14, 2017

Outline

- Introduction
- CO_2 Freezer and Sabatier Subsystem Testing
- Sabatier Temperature and Catalyst Testing
- CO_2 Freezer Testing and Modeling
- Conclusions
- Acknowledgments

MARCO POLO Project

- **ISPP: In Situ Propellant Production**
  - Demonstrate production of Mars Sample Return propellant
  - Reduce risk for human Mars missions
- **MARCO POLO - M**ars **A**tmosphere and **R**egolith **CO**llector/**P**r**O**cessor for **L**ander **O**perations
  - Started in 2011
  - Continues as the **Mars ISRU Pathfinder** project
- The **A**tmospheric **P**rocessing **M**odule (**APM**)
  - Mars CO_2 Freezer Subsystem
  - Sabatier (Methanation) Subsystem
- Collect, purify, and pressurize CO_2 (≥88 g/h)
- Convert CO_2 into methane (CH_4) (32 g/h) and water (72 g/h) with H_2
- Other modules mine regolith, extract water from regolith, purify the water, electrolyze it to H_2 and O_2, send the H_2 to the Sabatier Subsystem, and liquefy/store the CH_4 and O_2

Interbartolo III, M.A., et al. "Prototype development of an integrated Mars atmosphere and soil-processing system." Journal of Aerospace Engineering 26.1 (2012): 57-66.

Lander Design Concept

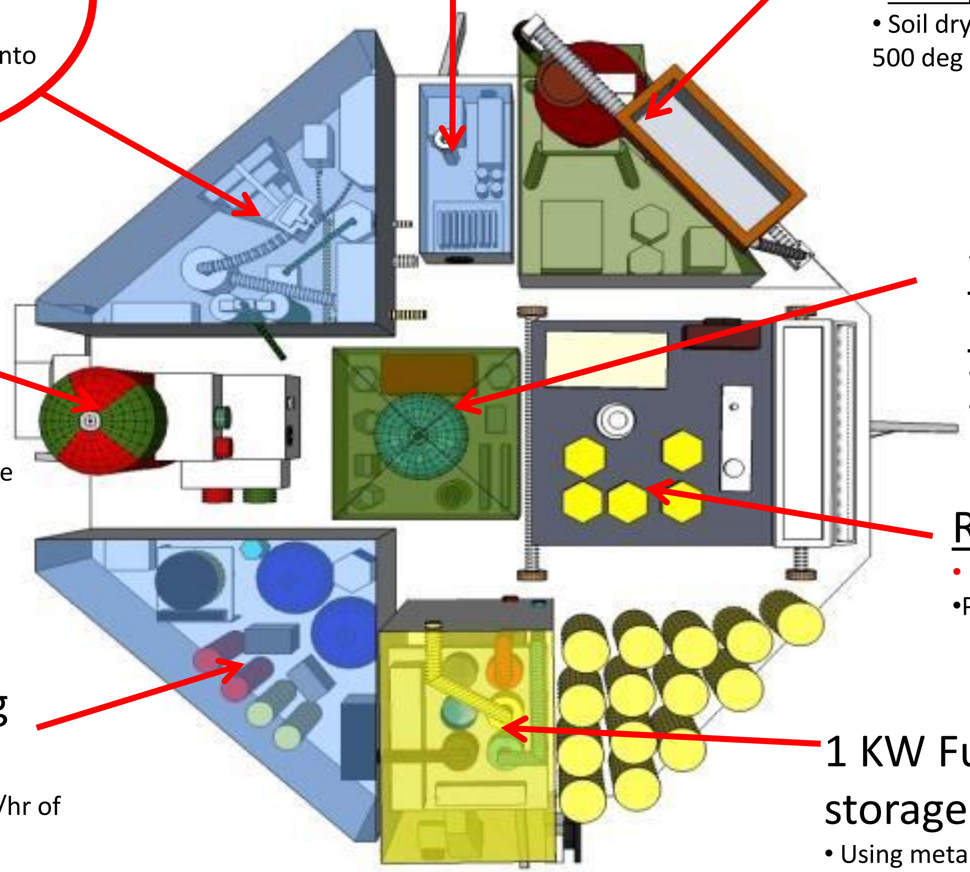
Atmo Processing Module:
- CO_2 capture from simulated Mars atmosphere (KSC)
- Sabatier converts H_2 and CO_2 into Methane and water (KSC)

C&DH/PDU Module: (JSC)
- Central executive S/W
- Power distribution

Soil Processing Module:
- Soil Hopper handles 30 kg (KSC)
- Soil dryer uses CO_2 sweep gas and 500 deg C to extract water (JSC)

Liquefaction Module: (TBD)
- Common bulkhead tank for Methane and Oxygen liquid storage

Water Cleanup Module: (KSC)
- Cleans water prior to electrolysis
- Provides clean water storage



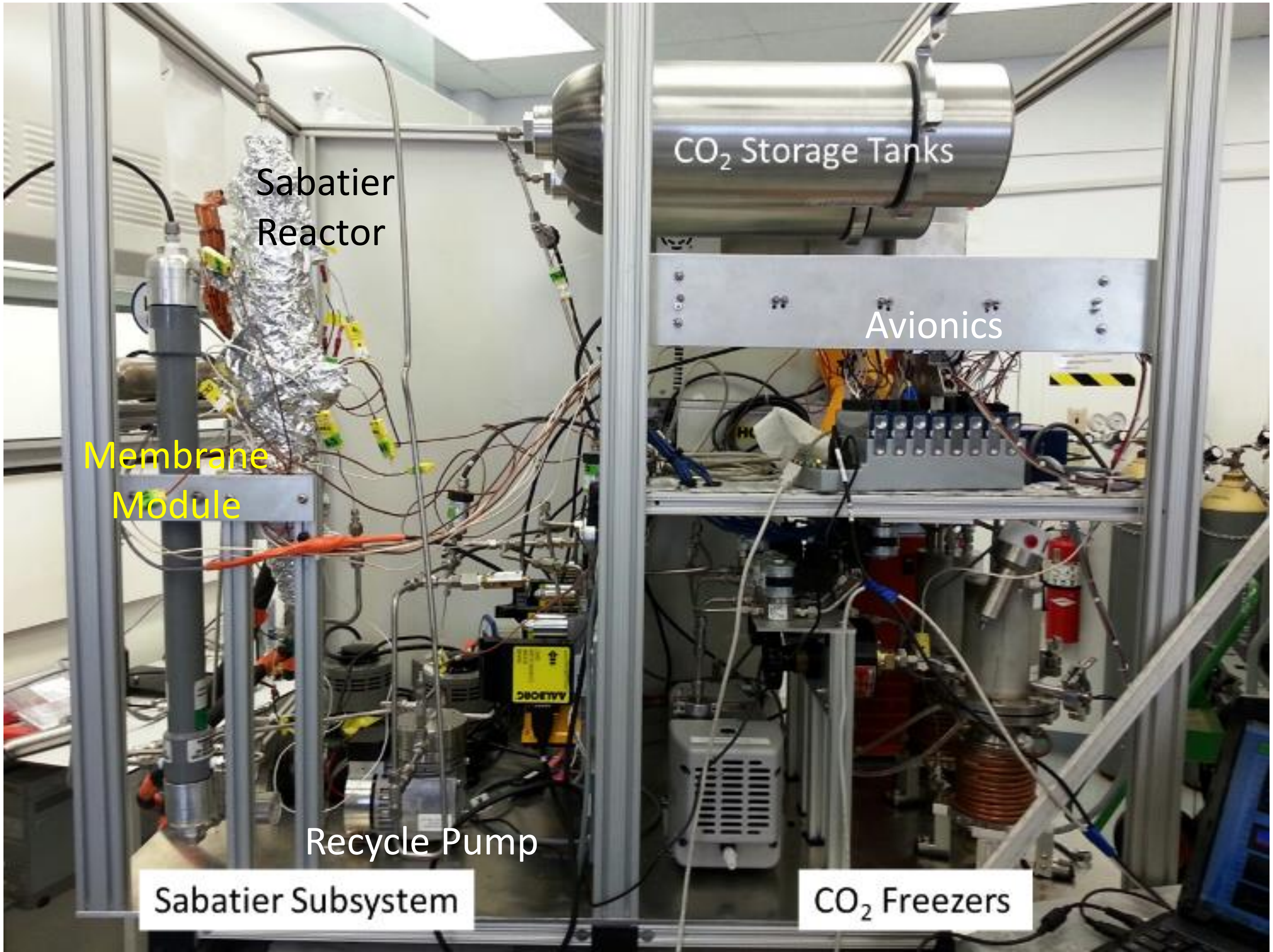
RASSOR 2.0: (KSC)
- Excavator
- Provides feed to Soil Dryer

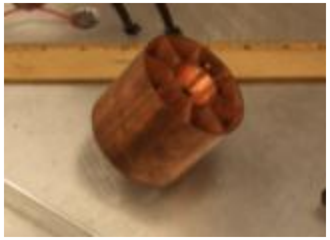
Water Processing Module: (JSC)
- Currently can process 520g/hr of water (max 694 g/hr)

1 KW Fuel Cell and consumable storage (JSC & GRC)
- Using metal hydride for H storage due to available
- 1 KW No Flow Through FC (GRC)
- 10 KW main power FC not shown (JSC)

3m x 3m octagon lander deck

Atmospheric Processing Module





Copper Heat Exchanger

CO_2 Freezers and Chiller

CO_2 Freezer and Sabatier Subsystem Testing

- **Previously demonstrated nominal operations of both the CO_2 Freezers and the Sabatier Subsystem (Earth & Space 2014 and 2016 Conferences)**
- **Measured power to freeze CO_2 at 0.22 W/kg (108% of theoretical) → 680 W for 3.1 kg CO_2/h (full scale ISRU module)**
  - **Froze ≥70% of incoming CO_2 @ ~100 g/h**
- **Sabatier subsystem produced 32 g CH_4/h at >99.9% pure**
- **Water production rate = 64-70 g/h**
  - **Not due to vapor in CH_4 or in membrane module**
  - **Still looking for missing water**

CO_2 Freezer and Sabatier Subsystem Testing (Cont.)

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- Tested CO2 Freezers @ 1.0-1.6 SLPM (nominal 1.2 SLPM)
  - Froze 87-71% of incoming CO_2
- Tested Sabatier subsystem at 0.3-1.2 SLPM (nominal 0.75 SLPM)
  - 550°C maximum temperature observed
  - <u>CO observed in product @ higher feed rates</u>
- Performed "virtual" integrated test ("Dust to Thrust") w/other KSC hardware in Sept. 2016
  - Very successful
  - Met goals
  - CO_2 flow rate was 11% high due to Mass Flow Controller issues
  - https://www.youtube.com/watch?v=cRLnAeL3wdU (142,000 views so far!)
- Plan partial integrated KSC hardware test in October 2017
  - WCM on lander, transferring water through DTAU to a rover w/3 tanks: water, simulated liquid methane, and simulated liquid oxygen
  - APM transmitting and receiving data

Results of the APM Virtual Integrated Test

Test Duration, 6 h, 50 min	Total	Average Flow Rate	Average Mass Rate	Target	Delta, %
Methane Production	243 liters	0.831 SLPM	35.6 g/h	32 g/h	+11.1%
Water Production	516.1 g	-	75.5 g/h	72 g/h	+4.9% (-5.8%)
Calculated CO_2		0.831 SLPM		0.750 SLPM	+11.1%

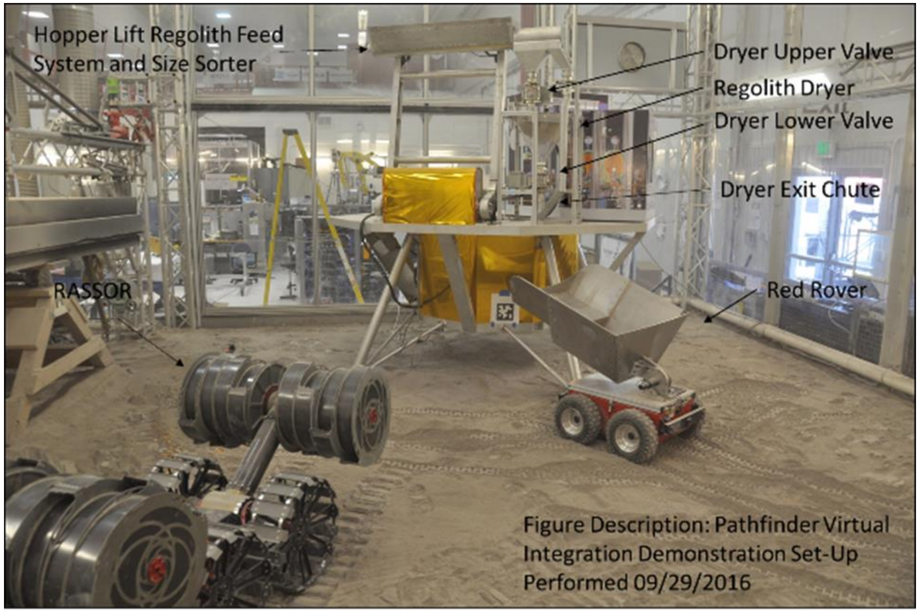

Figure Description: Pathfinder Virtual Integration Demonstration Set-Up Performed 09/29/2016

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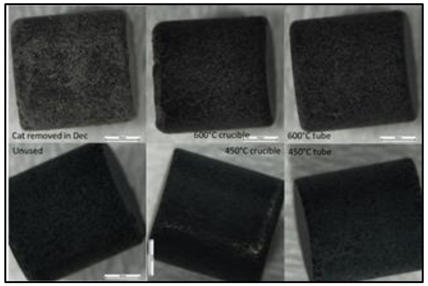
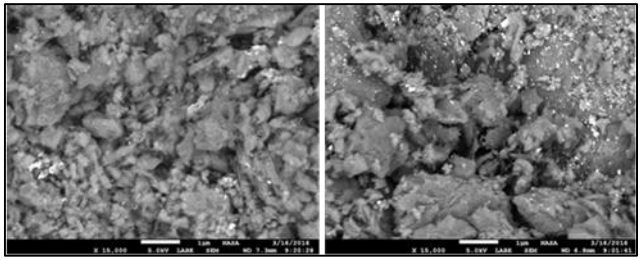
Sabatier Temperature and Catalyst Testing

- **Normal operating temps = 453-467°C**
- **At 1.25 SLPM CO_2, T = 586°C**
- **CO observed during test and subsequent tests**
- **Ru/Al_2O_3 catalyst much lighter w/broken pellets**
- **Sintering possible @>500°C**
- **Thermal shock investigated @450 and 600°C**
- **High temperatures experienced by the pellets or the rapid increase in temperature was the driving factor in the change in performance and not other factors such as poisoning**



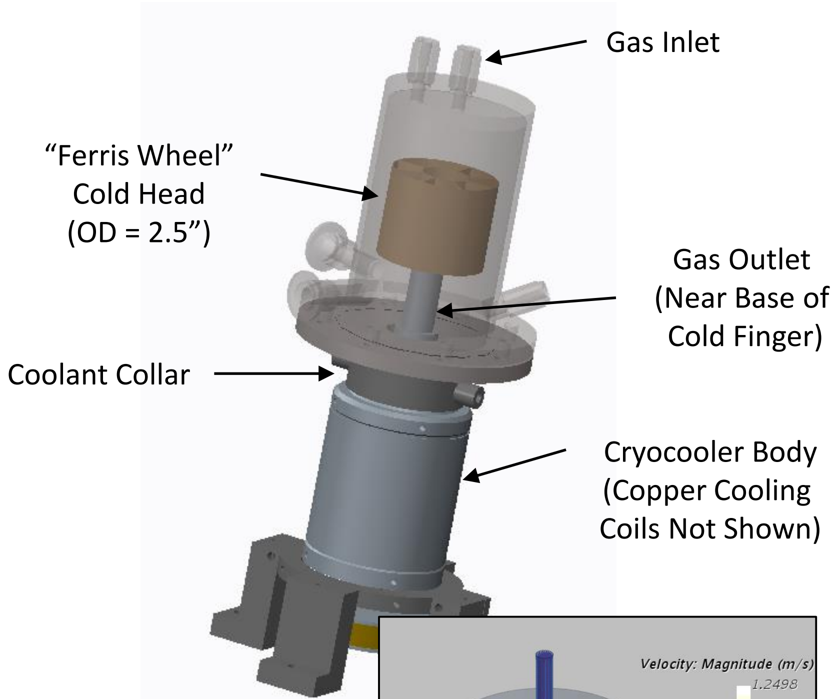
Catalyst pellets after five thermal cycles (magnification of 55x)

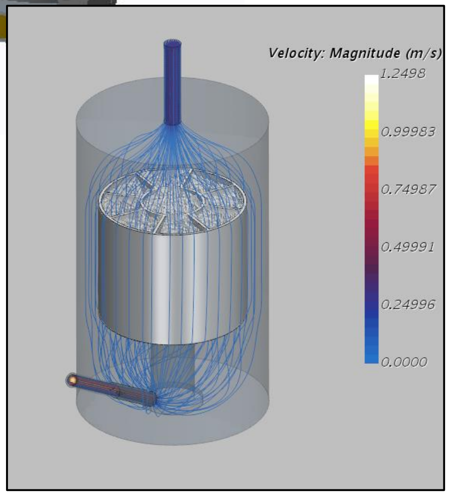


Unused catalyst (left) shows fewer bright specks than the spent catalyst (right) when imaged at 15,000x magnification on an FESEM

CO_2 Freezer Testing and Modeling

- **New NASA ISRU Project formed to develop full-scale Mars ISRU system**
- **Organized existing resources to develop physics-based models for scale-up**
- **Initiated modeling and testing of CO_2 Freezer and the Sabatier reactor**
- **Developed CFD/FEA/VOF (Volume of Fluid) model of existing CO_2 freezer and "Ferris Wheel" cold head**
- **Sabatier reactor modeling reported at ICES-2017 and TFAWS**
  - **Good agreement between model and experimental results**

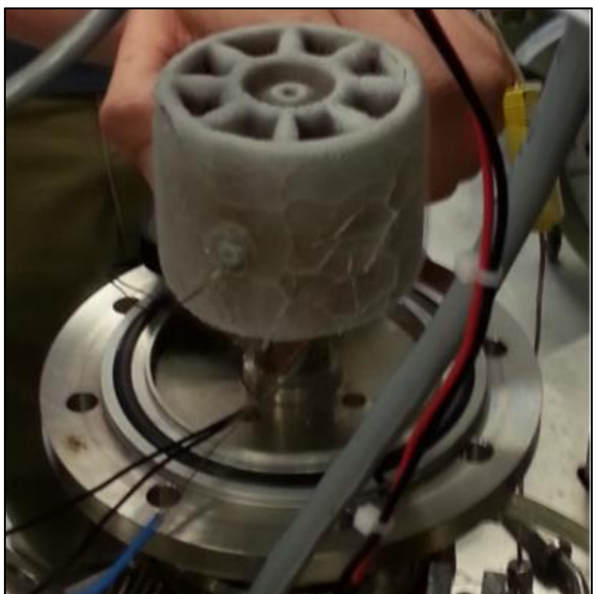




Creo 3D model of current CO_2 Freezer & gas flow streamlines around cold head w/VOF model

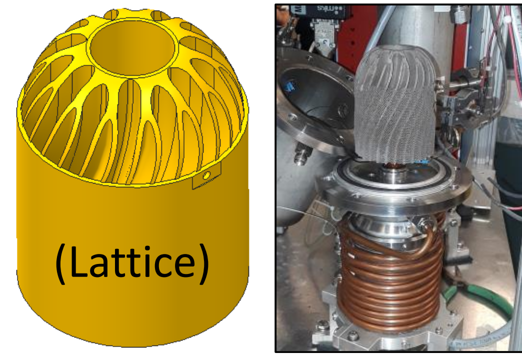
CO_2 Freezer Testing and Modeling (Cont.)

- Opened freezing chamber to observe actual dry ice distribution on Ferris Wheel cold head
- Designed, built, and tested alternate cold heads at long durations

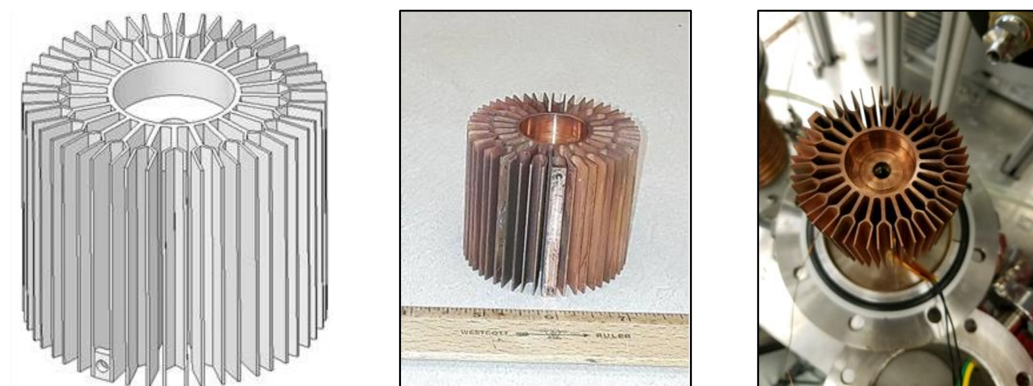


Dry ice and water ice frost accumulation on the Ferris Wheel cold head (T = 1.4 h)

“Starburst” cold head, a precursor to the Ferris Wheel cold head



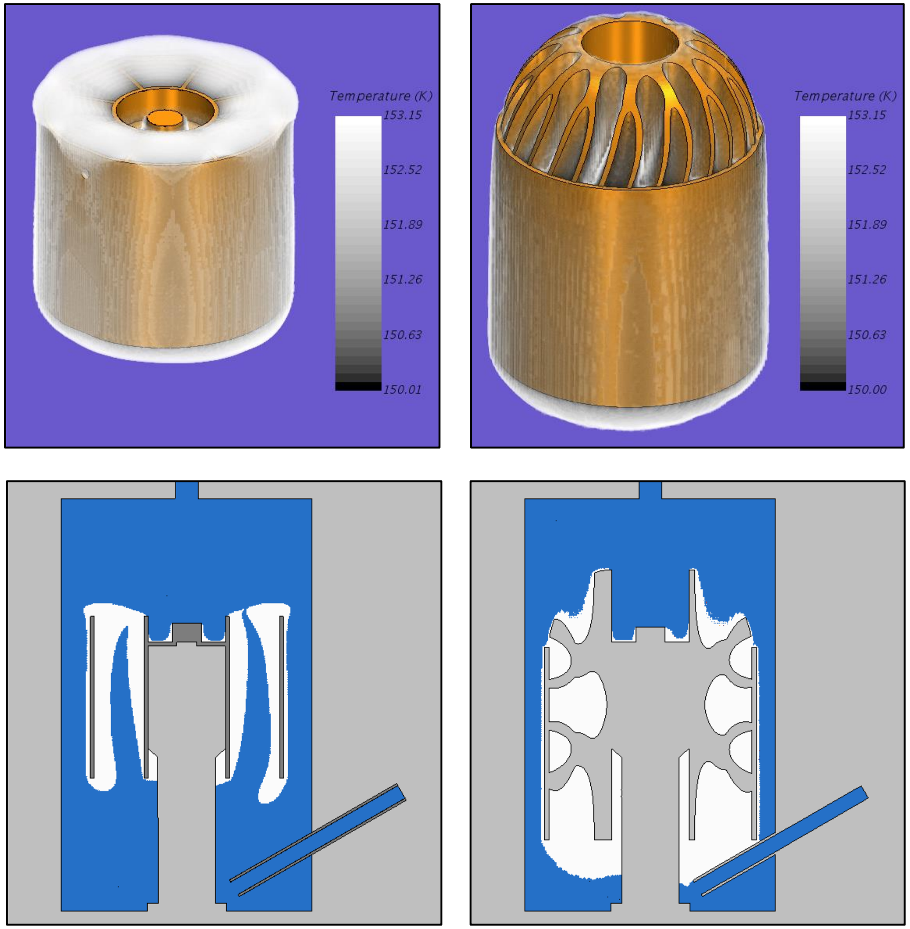
“Branching” cold head CAD drawing & 3D printed version (GRCop-84) from MSFC mounted on cryocooler



CAD drawing of the “Tuning Fork” cold head w/25 fins, EDM machined version, & unit installed on cryocooler

Flow-Considered Steady-State Model Predictions

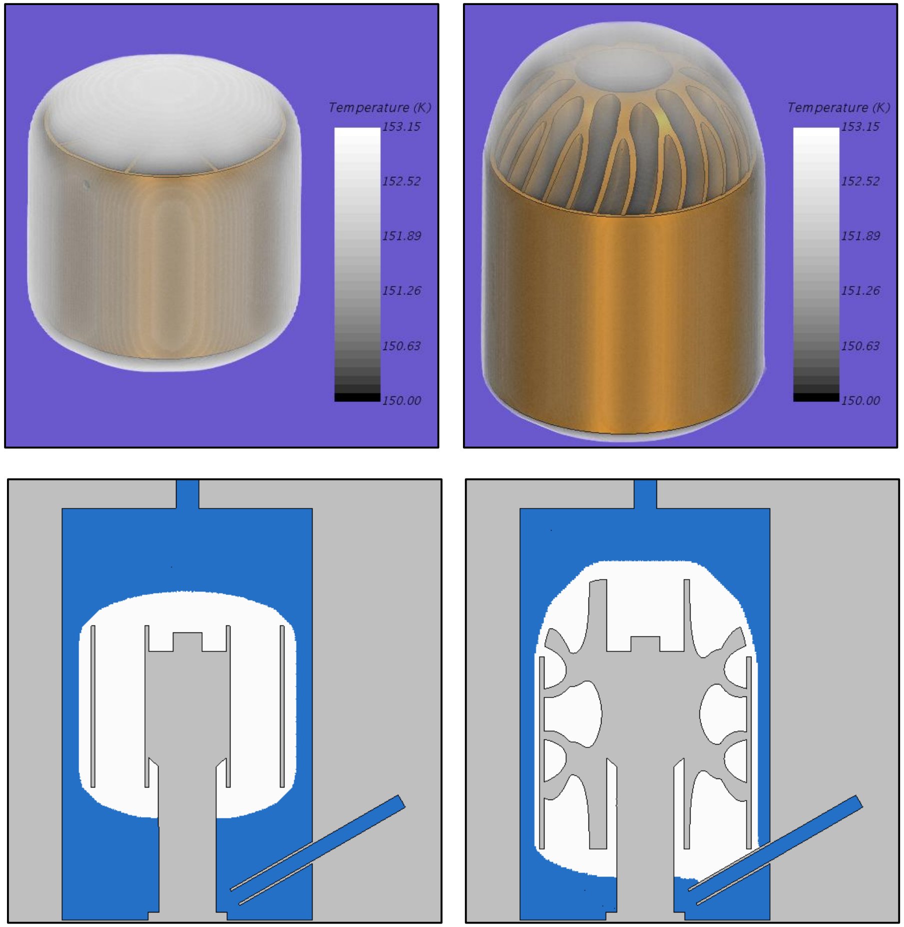
- **Ferris Wheel model**
  - Did not completely fill in channels
  - Little dry ice at attachment screw
  - Very thin layer on outer walls
- **Branching model**
  - Did fill in channels
  - Little dry ice on top
  - Thin layer on outer walls



Drawings of the Ferris Wheel cold head (left) and the Branching design (right) with predicted dry ice accumulations at steady-state

No-Flow-Considered Steady-State Model Predictions

- **Ferris Wheel model**
  - Did completely fill in channels
  - Heavy dry ice at attachment screw
  - Thicker layer on outer walls
- **Branching model**
  - Did fill in channels
  - Thick dry ice on top
  - Thin layer on outer walls



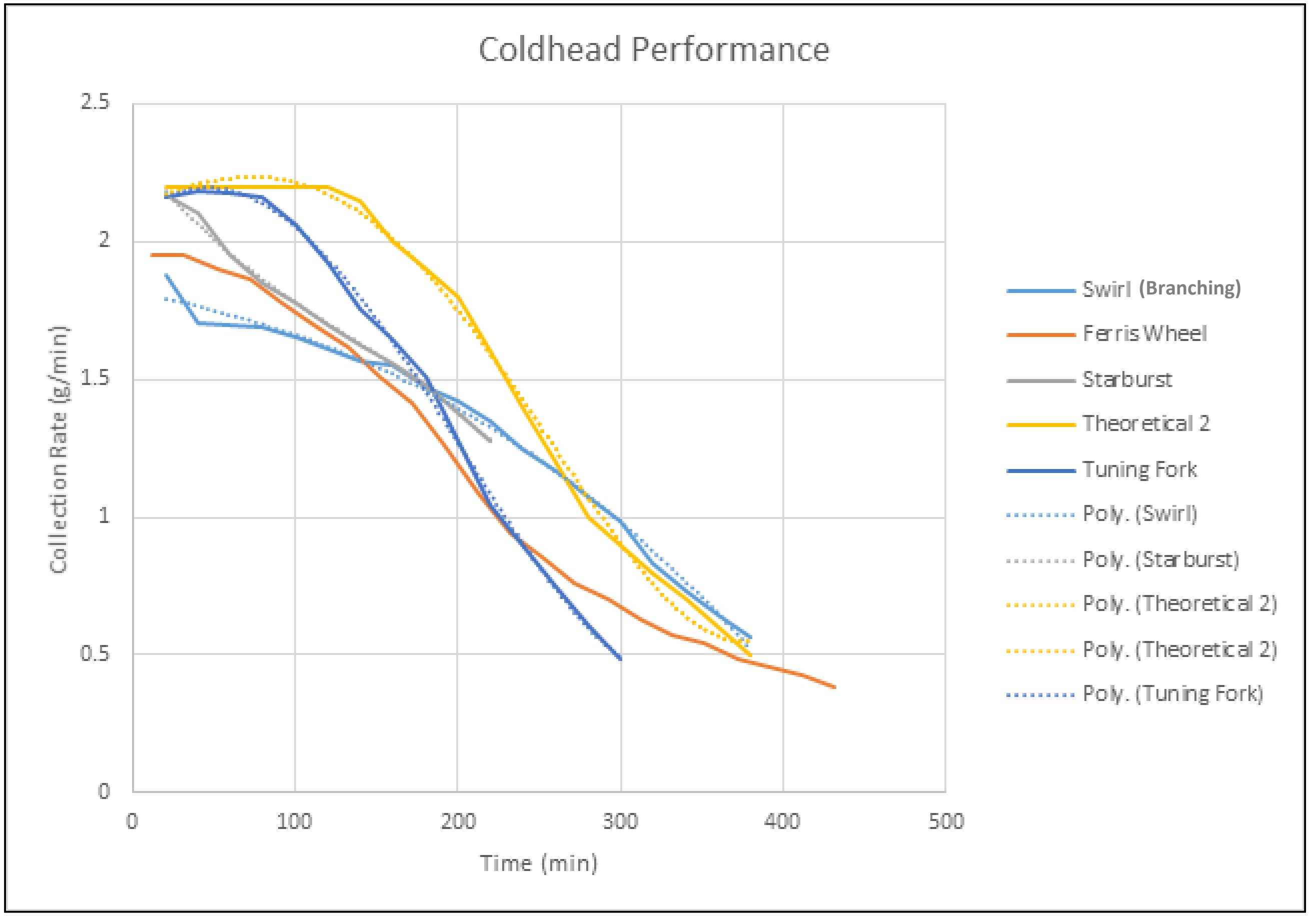
Drawings of the Ferris Wheel cold head (left) and the Branching design (right) with predicted dry ice accumulations at steady-state

Comparison of Predicted and Actual Dry Ice Mass at Steady State for Cold Head Designs

Property or Simulation Type	Ferris Wheel, g	Branching, g	Branching (Lattice), g
Mass	265 g	NA	843 g
Cooling Time to 150 K	8.5 min	NA	45 min
Flow-Considered	207 g	296 g	312 g
No-Flow- Considered	339 g	388 g	404 g
Experimental Results	406 g (7.0 h)	NA	502 g (6.33 h)

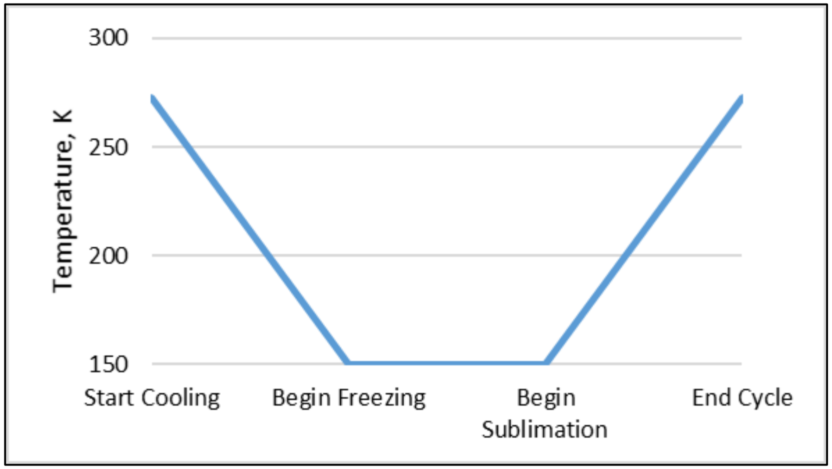
- Model is better for cold head *comparisons* vs. explicit predictions for an individual design
- Improvements between the Branching and the Ferris Wheel designs are on the order of 15 – 50%
  - Actual improvement lies between these two extremes
- *Rate* of accumulation may be estimated by normalizing the results when compared to completed steady-state experimental runs

Cold Head Performance Optimization



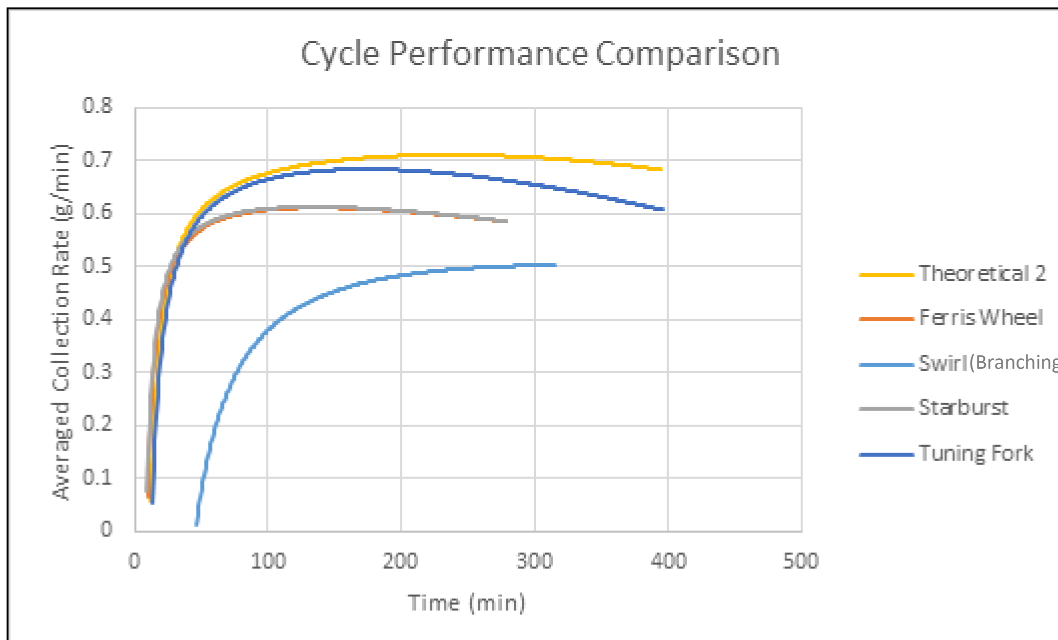
- CO_2 Performance Comparison – Test Results vs. "Theoretical Cold Head"
  - Initial Tuning Fork freezing rate closest to hypothetical "Theoretical 2" rate
  - Exceeded 110 g/h for 120 min; averaged 90 g/h for 5 h

Cold Head Performance Optimization (Cont.)



- <u>Cycle Performance Comparison</u>
- **Ideal cycle time for the Tuning Fork is 173 min**
  - **80.5 min actual freezing time**
  - **Average collection rate = 41.0 g/h**
  - **Pair of cryocoolers = 82 g/h**

- <u>CO_2 collection cycle overview</u>
- **Optimization:**
  - **Minimize cool down time (reduce mass, maximize thermal conductivity)**
  - **Maximize freezing rate (increase area, maximize thermal conductivity)**
  - **Sublimation rate (supply sufficient heat to close cycle time)**



Conclusions

- CAD models provided info for modeling
- Modeling of the CO_2 freezing process has provided great insight into ways to optimize the process
- Sabatier reactor modeling gives good agreement of predictions with test results
- Sabatier catalysts require protection from thermal shock
- Excellent progress has been made in preparing for designing full-scale CO_2 freezers and Sabatier reactors in FY18

Acknowledgments

- Multiple NASA interns in addition to the coauthors
- Space Technology Mission Directorate (STMD) Game Changing Development (GCD), Next Generation Life Support (NGLS) funding
- KSC Continuing Technical Competence (CTC) and Independent Research and Technology Development (IR&TD) projects.
- We also especially thank Omar Mireles and Zachary Jones of MSFC for providing Additive Manufacturing cold heads

Questions?

MARCO POLO/Mars ISRU Pathfinder Modules