CO_2 Cryofreezer Coldhead and Cycle Design Insights for Mars ISRU

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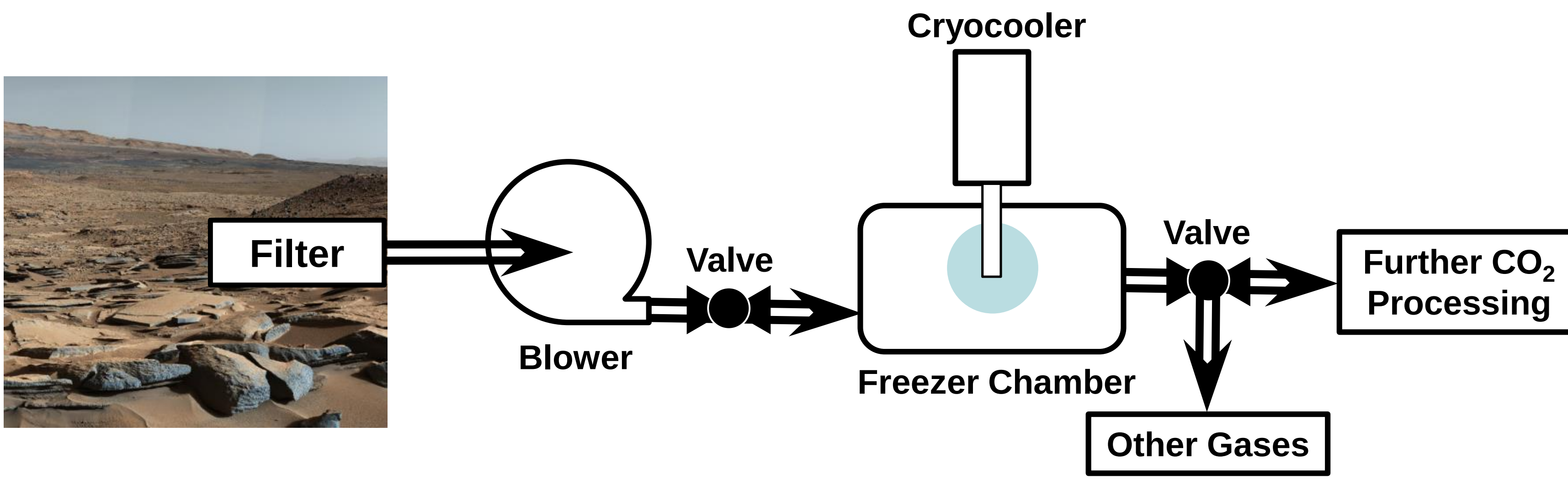
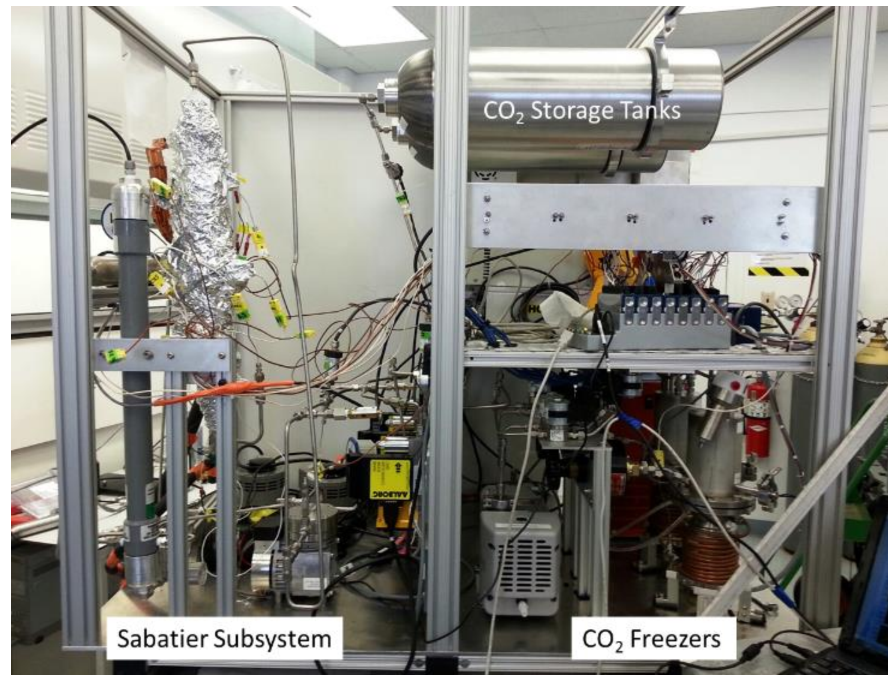
Background

- In Situ Resource Utilization (ISRU) on Mars
  - Create propellant from Mars atmosphere
    - Must separate and compress CO_2 to utilize
      - Mars ~7 Torr (~0.1 psi), 95% CO_2, 3% N_2, 2% Ar
      - Approaches include direct compression, sorption pumps, freezer
  - Cryofreezer concept for ISRU discussed in 90s literature
    - Clark, Payne, and Trevathan experiment in 2001 (LM+JSC)
      - Describes basic configuration and tested simple coldheads



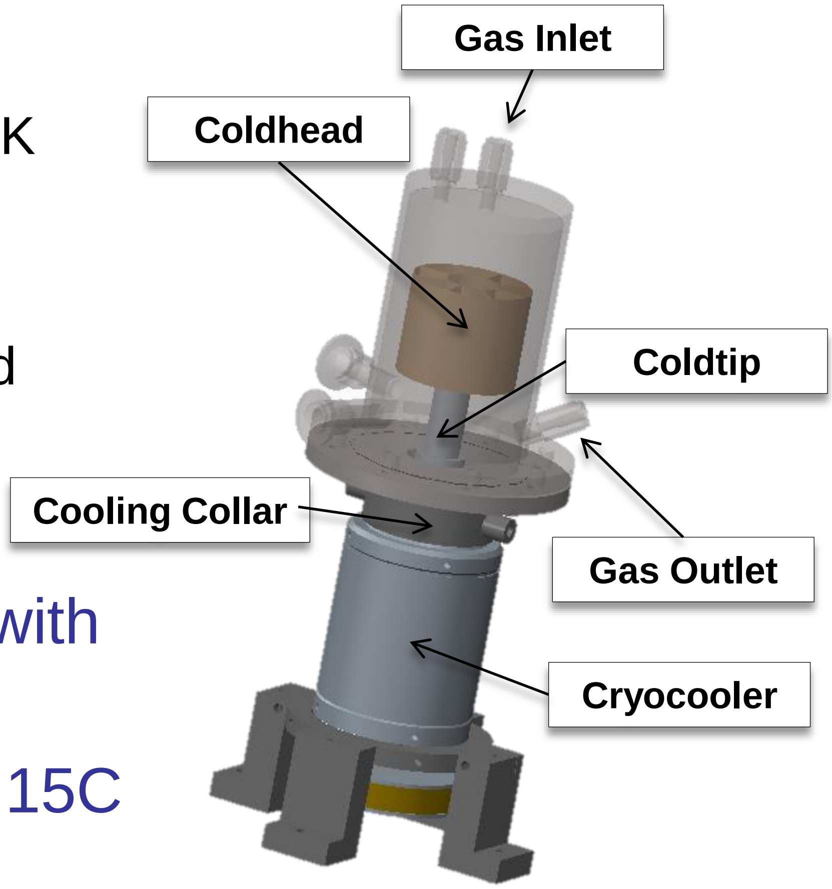
Atmospheric Processing Module

- Mars ISRU Pathfinder project APM (KSC)
  - CO_2 Freezer – Twin units
  - Sabatier reactor – Combine with H_2 to make CH_4



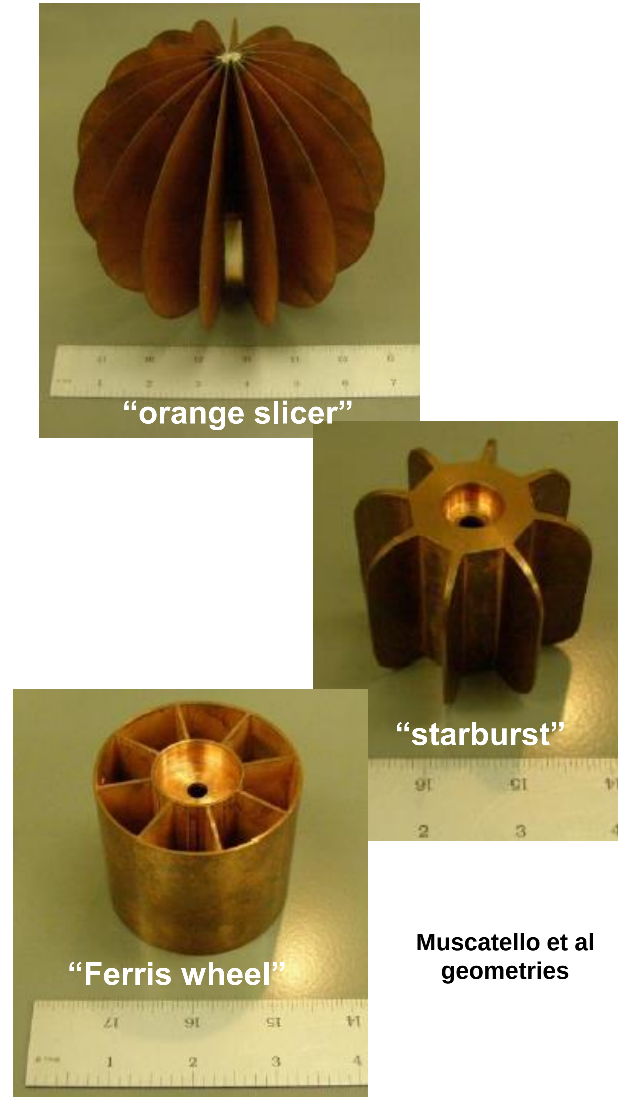
Cryofreezer Detail

- Sunpower CryoTel GT cryocooler
  - ~37 W lift @ 150 K
  - ~20% of Carnot efficiency @ 150K
  - 240 W input
  - External water cooling loop
  - Stirling cycle, helium working fluid
- Coldtip protrudes into freezing chamber
- Coldhead mounted on coldtip with thermal grease, securing nut
- External chiller loop maintains 15C rejection temperature



Why a coldhead?

- Initial sizing of cryocooler based on target production rate
  - How many Watts to cool gas and change phase?
  - Coldhead adds additional mass (launch and thermal) to increase collection performance
- Accretion insulates coldtip
  - Solid CO_2 ~0.1 W/m/K (Cook et al)
- Previous work explored some shapes
  - Muscatello and Zubrin SBIR used metal foams
  - Clark et al. tested bare coldtip and simple coldhead geometry
  - Muscatello et al. tried three other shapes with mixed results



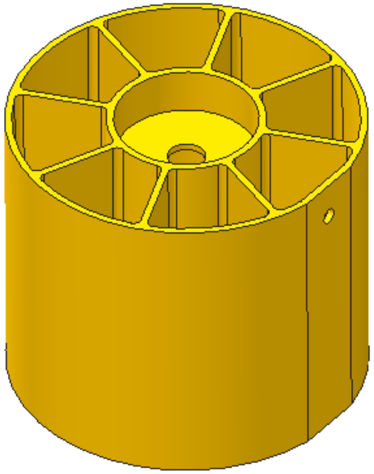
Muscatello et al geometries

Similar Problems in Literature

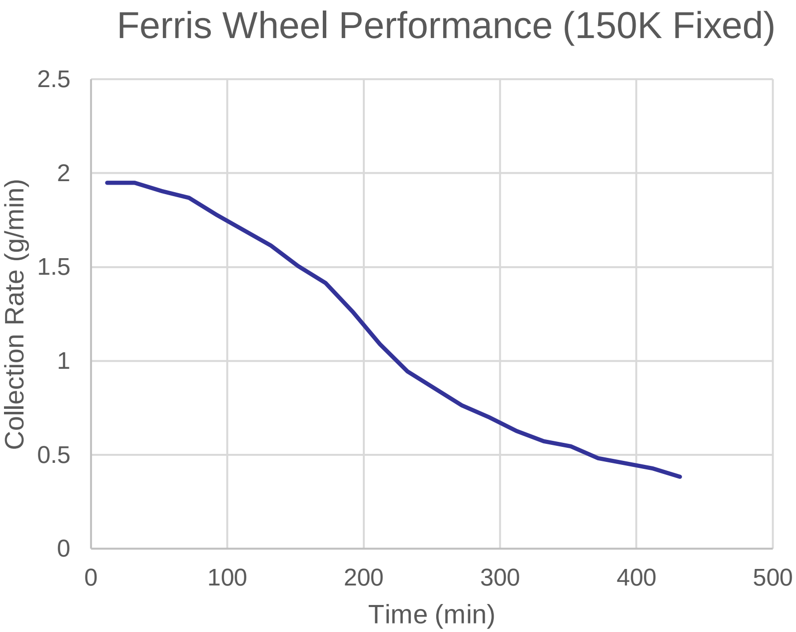
- Heat sinks – well explored area, but phase change and accretion typically absent, mass-production design constraints
  - Dede et al study of 3D printed, flat plate, air-cooled heat sink, gradient-based optimizer
  - Iga et al study of 2D heat sink topology, continuous material distribution interpolated with finite element method
  - These and other approaches (genetic algorithms) yield “spikey,” “natural-looking” designs
- Phase change energy storage – liquid-solid transition, different density and convection regimes, cycling between states
  - Sparrow et al study with paraffin freezing on finned tubes
    - Fin area / temperature boundary condition / time correlation with collected mass
  - Pizzolato et al study of topology for phase change storage, acknowledges high physics complexity and design limitations of previous work
    - Density-based optimization, conduction dominated
    - Defined time minimization and steadiness maximization metrics

Initial Testing

- Based on previous experimental paradigm
  - Ferris wheel coldhead
  - Long freezing cycles (~8 hrs) going to "steady state" accretion levels
  - Temperature based cryocooler control (150K setpoint)
  - 1.2 SLPM CO_2 flow rate
- Steady state goal was attempt to correlate with CFD models
- Question assumptions
  - Why run so long?
  - Why use temperature control of cryocooler?
  - Why care about final collected mass?

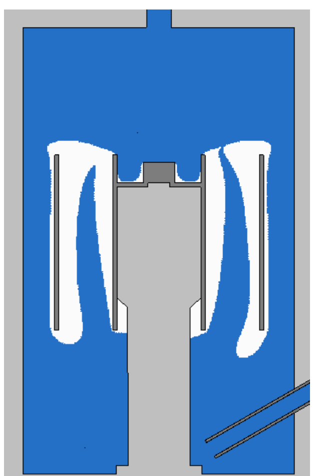


"Ferris Wheel"

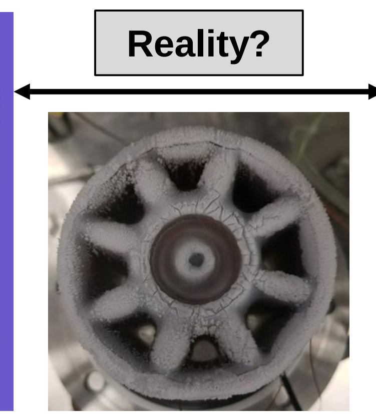


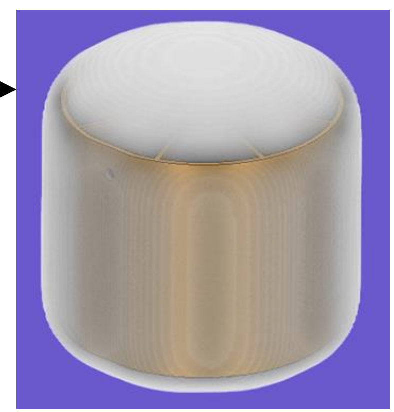
Computational Methods?

- CFD
  - STAR-CCM+ Melting and Solidification toolbox, volume of fluid method
  - Flow / no flow configurations
  - Single compound, solid / gas density change
    - Questionable accretion patterns, pseudotime
- Thermal Desktop
  - ACCRETE routine (basically reverse of ablation)
    - Stacked-layer technique not great for complex geometry
      - New feature, tricky to implement
    - Assumes energy is only limit on accretion rate

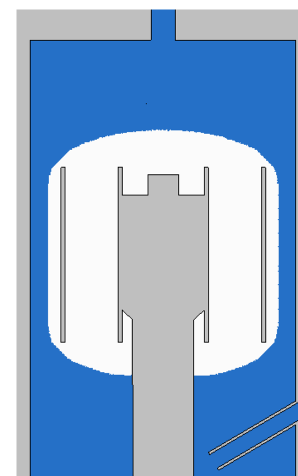


STAR-CCM+, flow included



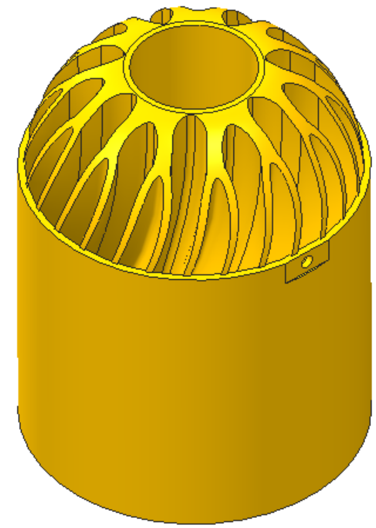


STAR-CCM+, no flow

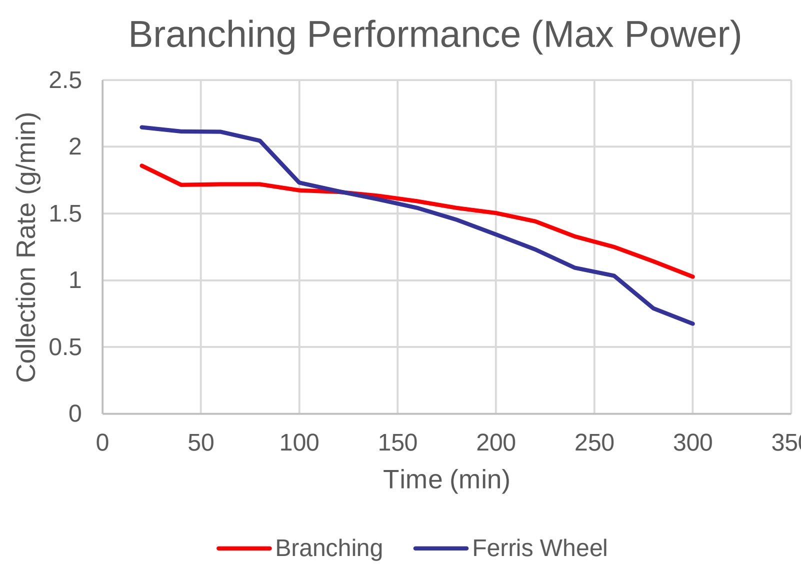


Alternate Design

- Goals
  - Distribute metal more efficiently
    - “Biomimetic” branching shape
    - Curved top edge
  - Increase surface area
    - Increased diameter and length
    - Lattice-like surrounding belt
  - Flatten and extend collection performance curve
  - Demonstrate 3D printing with GRCop-84
- Results
  - Lower initial performance
    - Heat leaks
  - Superior late-cycle performance
  - 45 min to cool to 150K vs. 13 min for Ferris Wheel
- Success, but failure…

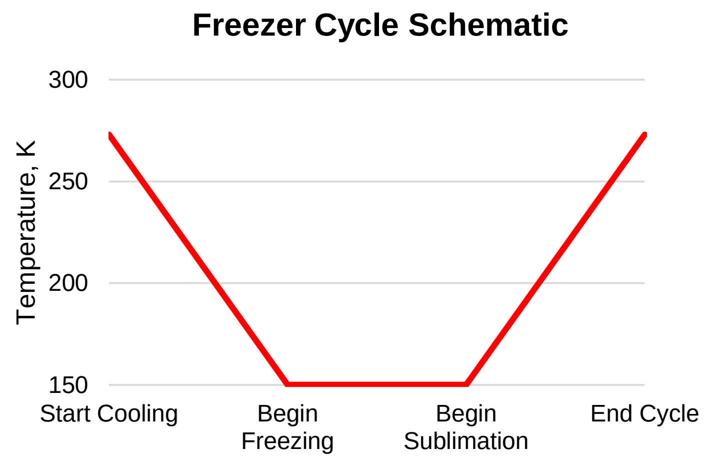


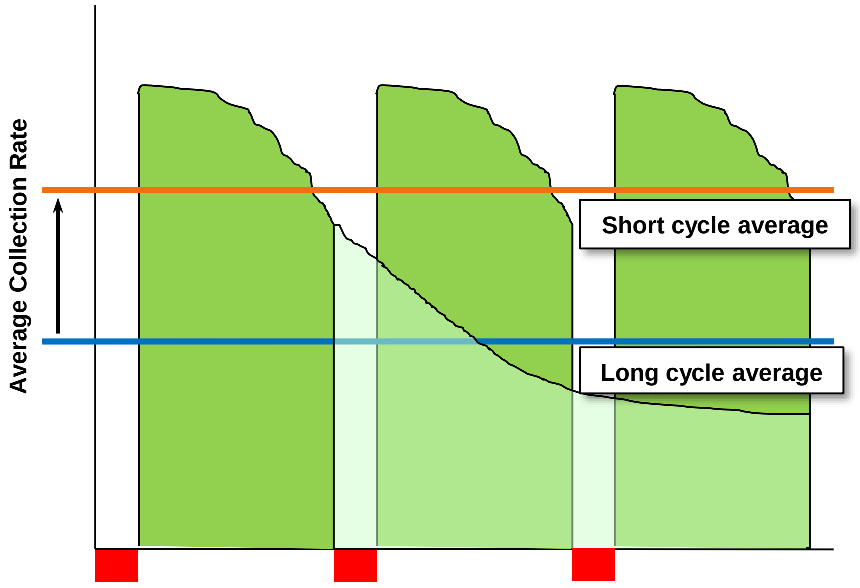
“Branching”



Cycle Insights

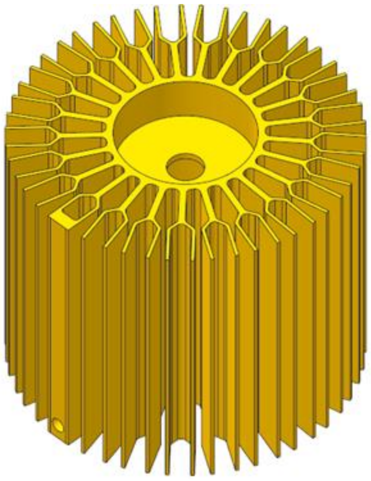
- Collection performance is a complicated function of surface area, conductive material distribution, etc.
- Because of temperature swing, any design must have sufficient performance to "pay off" time spent cooling 270K -> 150K
  - Minimize total mass of coldhead
  - Specific heat / conductivity
  - Scale up limit?
- Parasitic heat leaks from chamber
  - Radiation, convection to hot wall, bypass flow heating
- Early cycle performance is most critical
  - When has performance degraded sufficiently to stop and restart cycle?
    - Much shorter than we thought
  - How do the cycle and coldhead geometry interact?
- Simple optimization needed to determine ideal length of cycle and compare designs



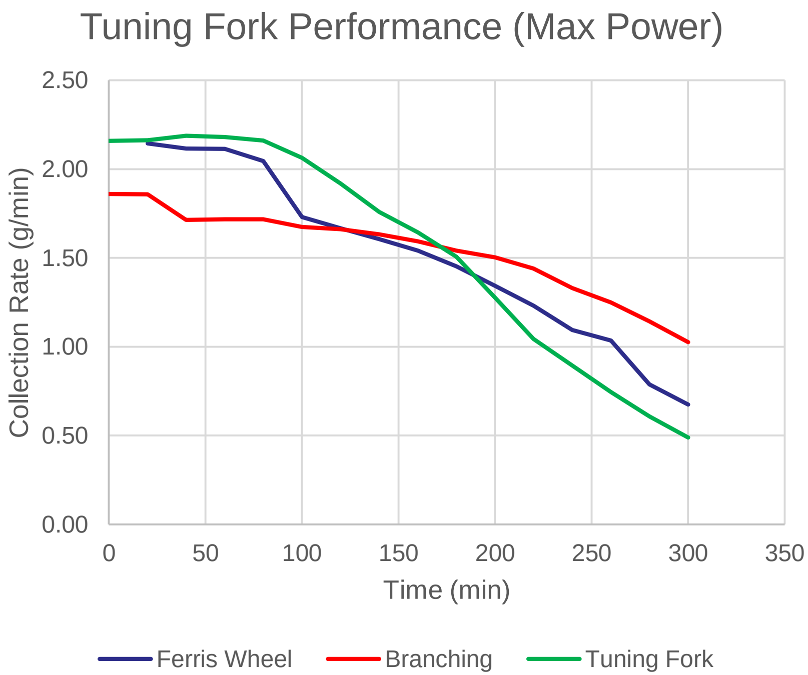


Redesign

- Goals
  - Minimize mass to shorten cooling cycle
  - Increase surface area, but limit size to reduce heat leaks
  - Target early-cycle performance only
- Results
  - Max performance at beginning of cycle
  - Slow performance drop after peak
  - Poor late-cycle performance

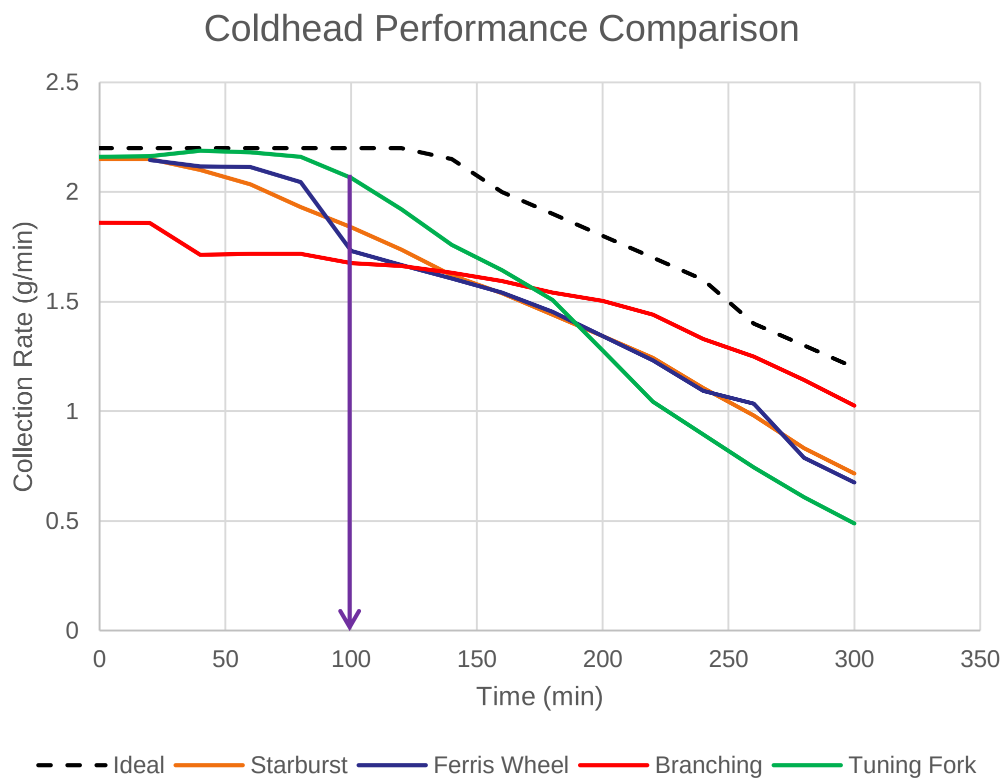


"Tuning Fork"



More Testing

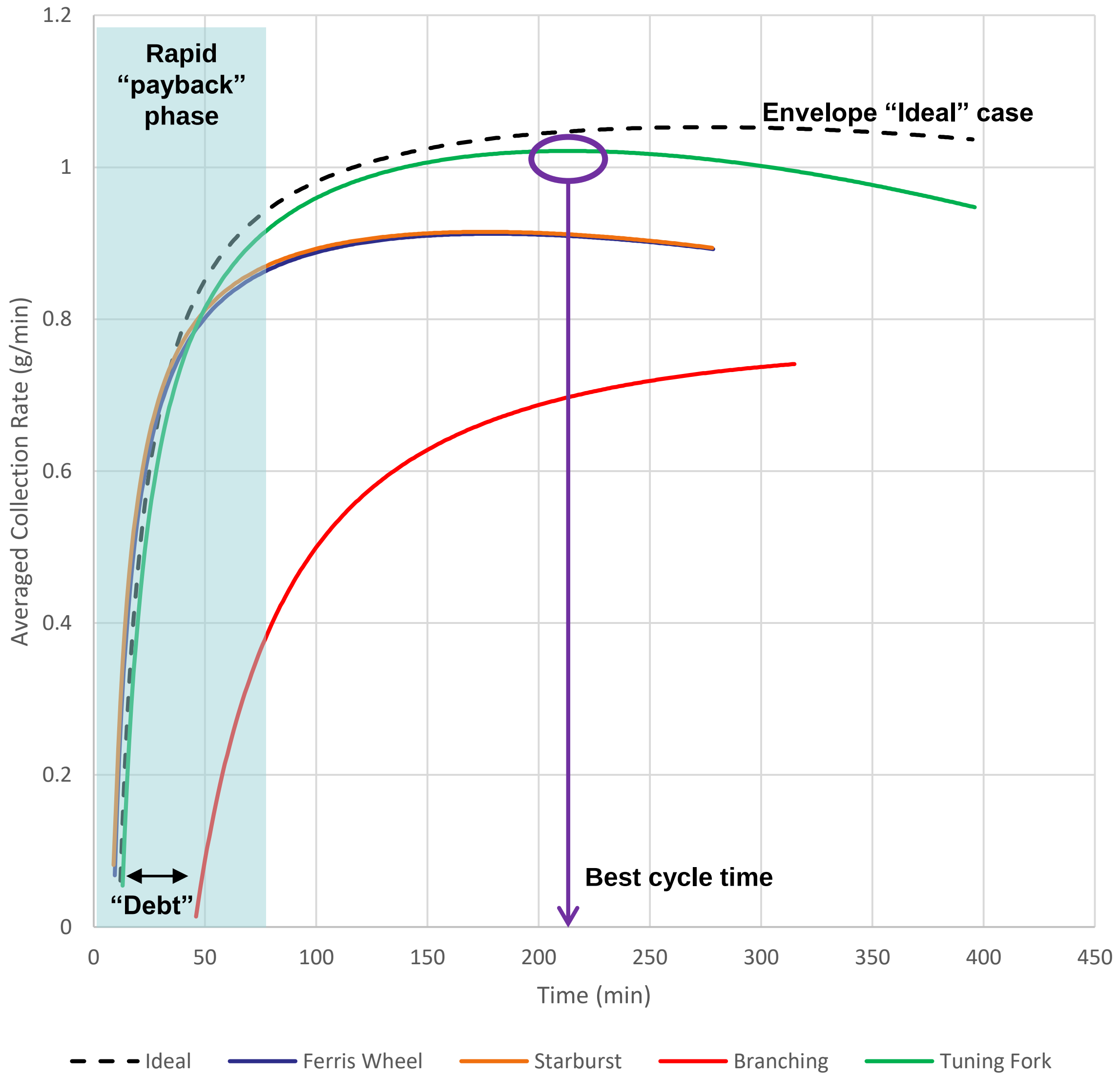
- Added data from legacy "Starburst" design
- Includes "Ideal" case meant to envelope possible designs
- Geometry can have measureable effect on collection performance
- Not a simple function of surface area



	Ferris Wheel	Branching	Tuning Fork
Volume [in^3]	1.74	6.67	2.37
Area [in^2]	64.35	157.38 (with lattice)	128.4

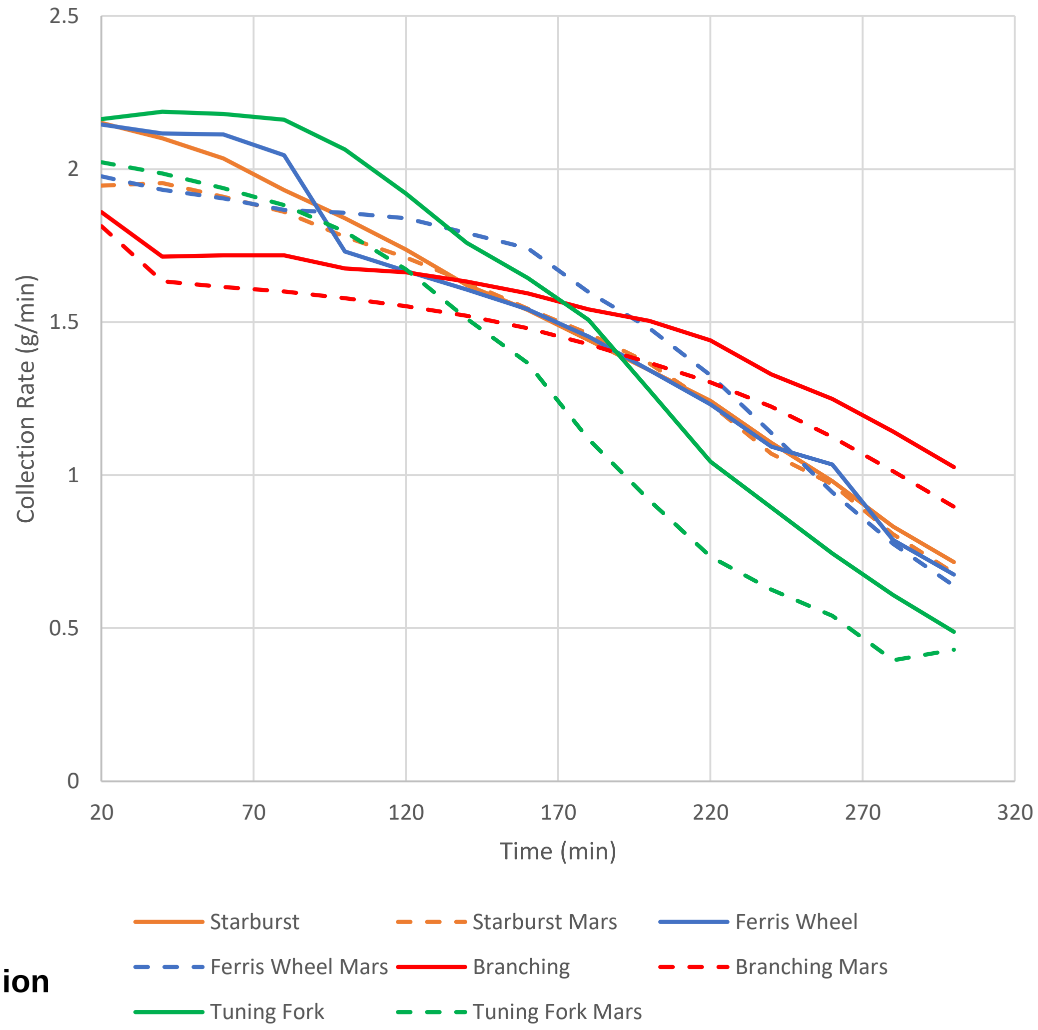
Cycle Optimization

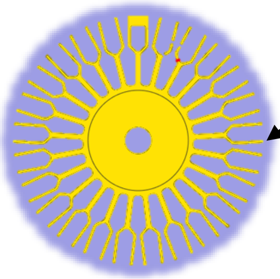
- Integrate collection performance curves
  - Assuming equal duration freezing / sublimation phases
    - Paired cryofreezer design
    - Sublimation rate determined by method
  - Starting offset determined by cool-down time
- Peak of curve indicates highest average collection rate
- Late cycle performance (Branching) never "pays back" initial time "debt"
- Best cycle times are much shorter than prior experiments
  - Given performance plateau, can trade collection rate vs. power efficiency, reduced on/off cycles, etc.
- Tuning Fork design superior
  - ~217 min cycle, ~100 min freezing



Non-condensable Gas Effects

- Ar and N_2 remains after freezing, low temperatures and density limit diffusion rate
  - Previous work (Clark 2001) points this out and indicates importance of recirculation blower
- Differing impact on designs indicates geometry may be important
  - Tuning fork seemingly most affected
  - Ferris Wheel, Starburst most affected early in cycle
  - Branching least affected, likely due to lower overall rate
  - Additional cuts to open “pockets”?
  - More open fin spacing, larger size?

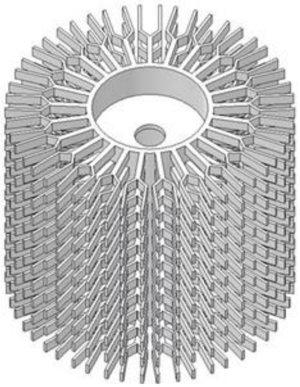




CO_2 depleted region

Conclusions

- Coldhead geometry does matter for performance
  - Tuning Fork ~11% improved cycle-averaged collection rate relative to Ferris Wheel / Starburst
    - But bounding “Ideal” case shows practical limitations
      - Only ~15% better than Ferris Wheel
      - Only 3% better than Tuning Fork
    - Worth trying harder?
- Cycle optimization is important
  - Impacts goals of coldhead geometry design
  - Allows trades with energy efficiency, system reliability, etc.
- Computational modeling is difficult
  - Multi-phase, multi-material, conduction and convection, 3D, transient, diffusion
  - Phase change energy storage analogy seems promising
- Novel concepts?
  - Self-cleaning / scraping coldhead
  - Other materials



Tuning Fork v2.0 Concept

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