Modeling JSC-1A Simulant Flow and Heat Transfer for the Helium Extraction & Acquisition Testbed

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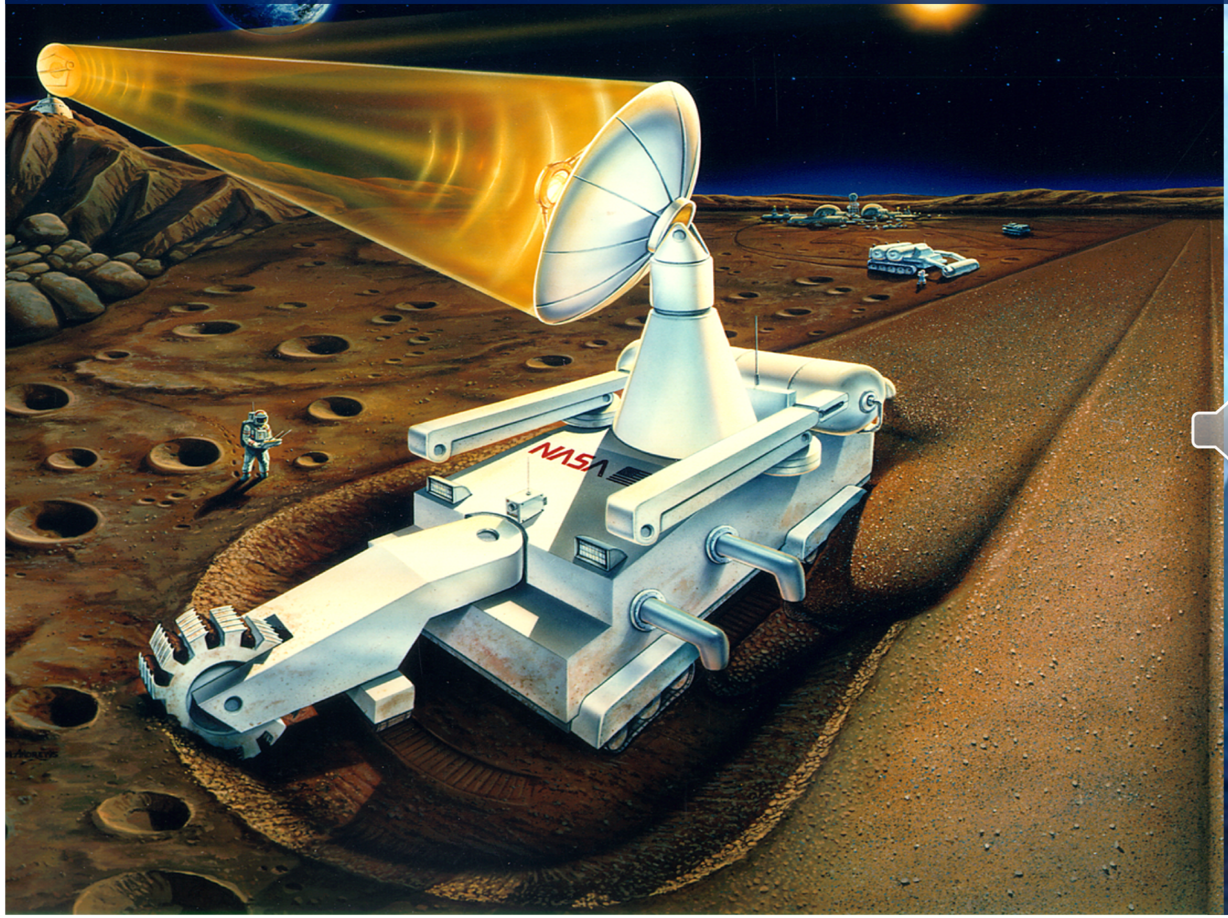
Outline

- Background: Research at the Fusion Technology Institute
- Overview of the Helium Extraction and Acquisition Testbed (HEAT)
- Granular Flow and Heat Transfer Modeling Approach
- Modeling Results
- Summary and Conclusion

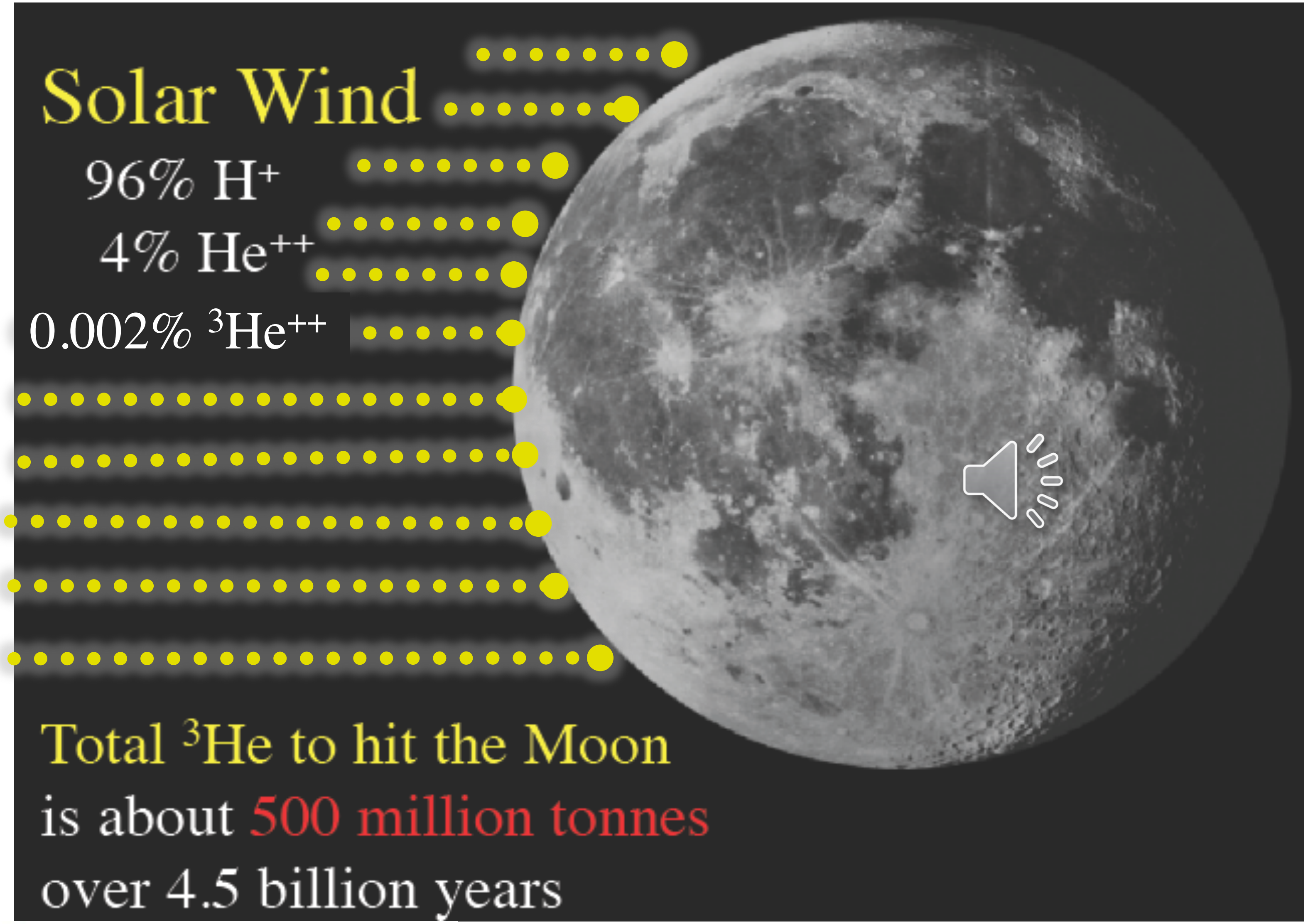
The FTI First Proposed Using Lunar Helium-3 For Fusion

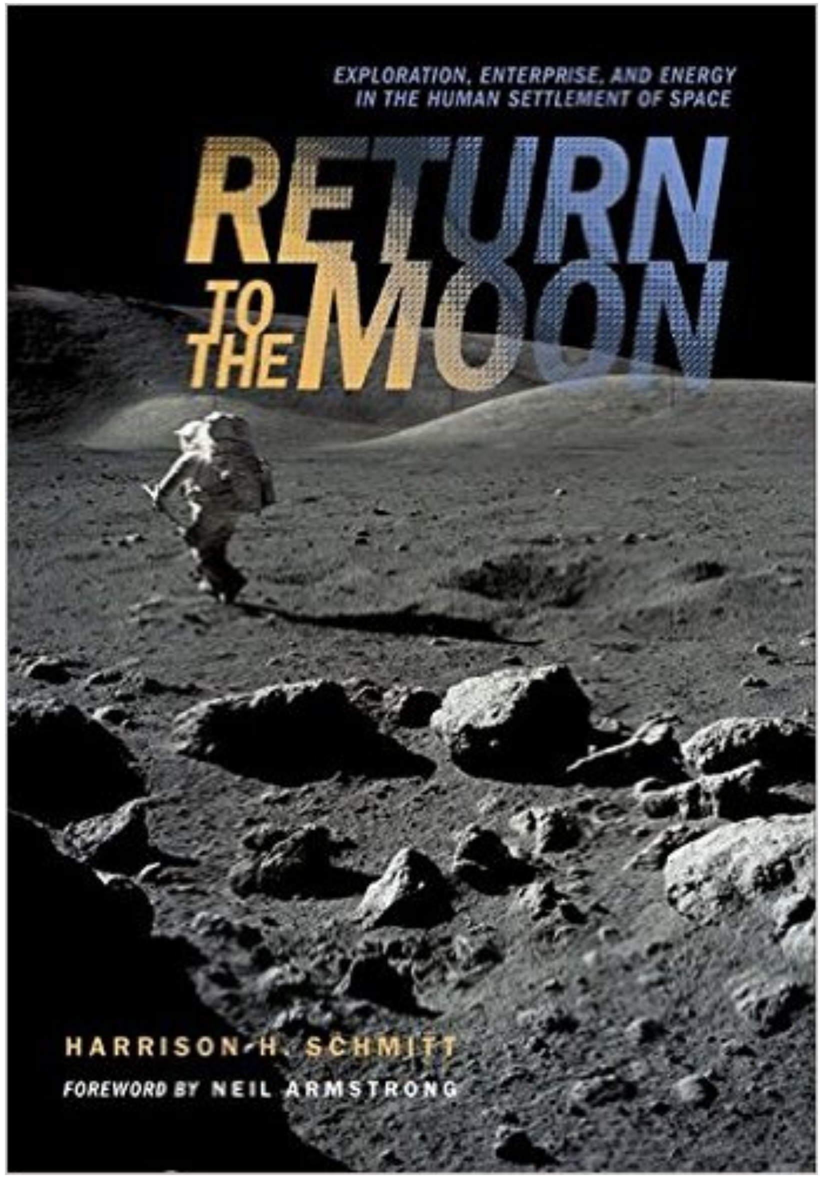
Helium-3 & Lunar Volatiles for Fuel & Life Support



Schmitt and Olson, 2013

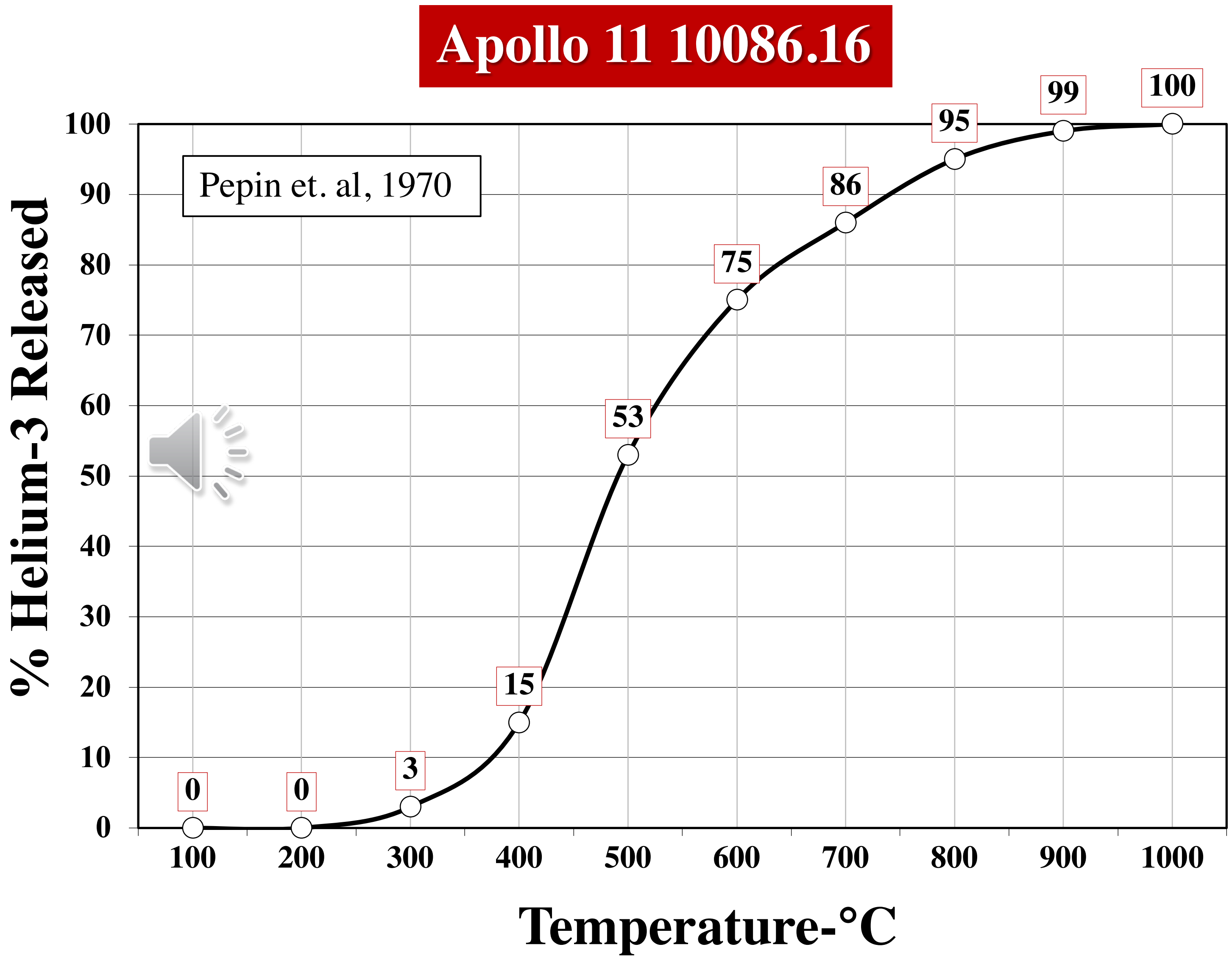
The Moon has retained over 1 million tonnes of ^{3}He





Heating Regolith Releases ^3He

- Heat to 700 °C to release 86% of embedded ^3He
- Peak release rate ~ 500 °C
- Agitation release – not yet quantified



There has been He-3 Miner Design Work at the FTI Since 1988

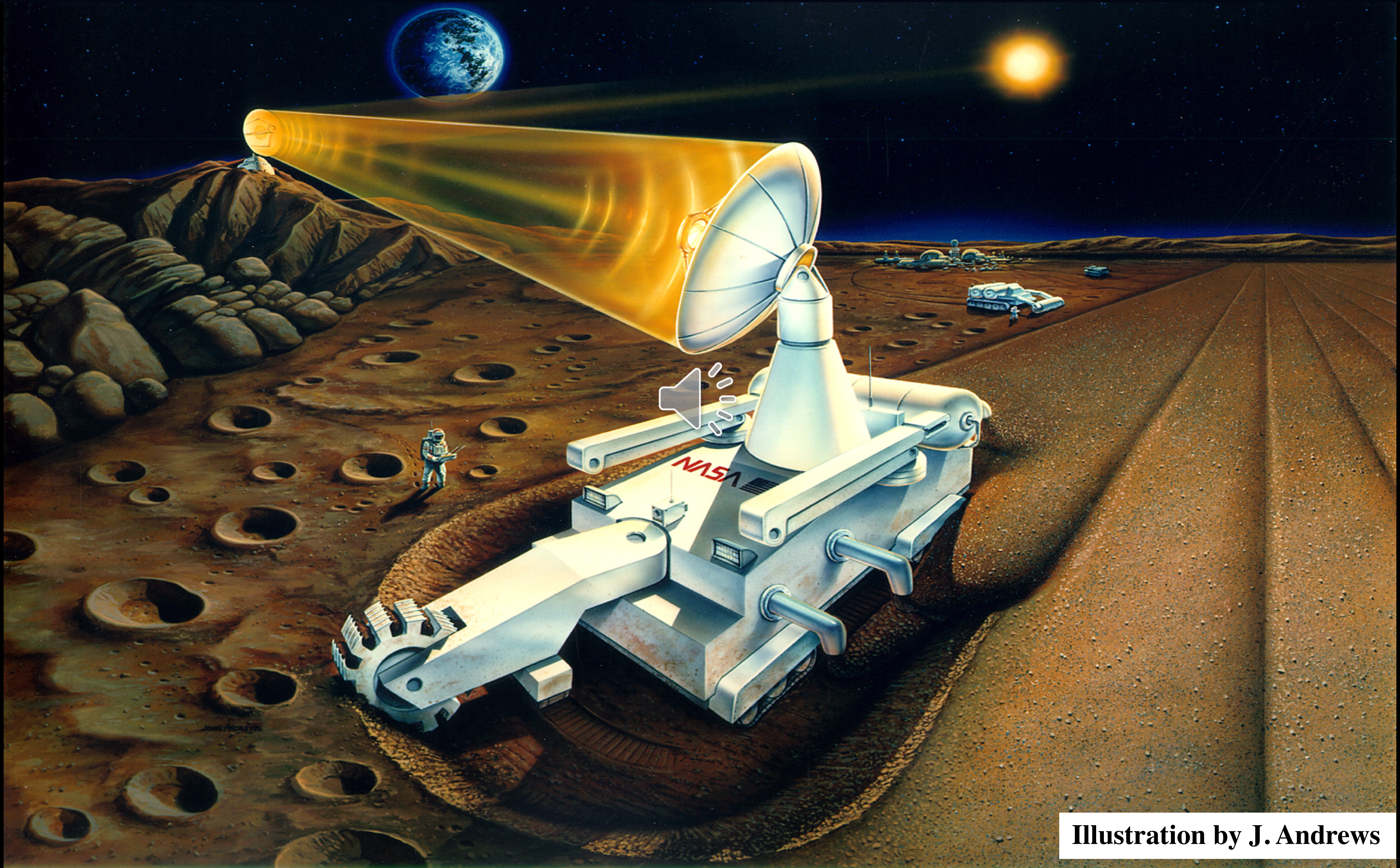
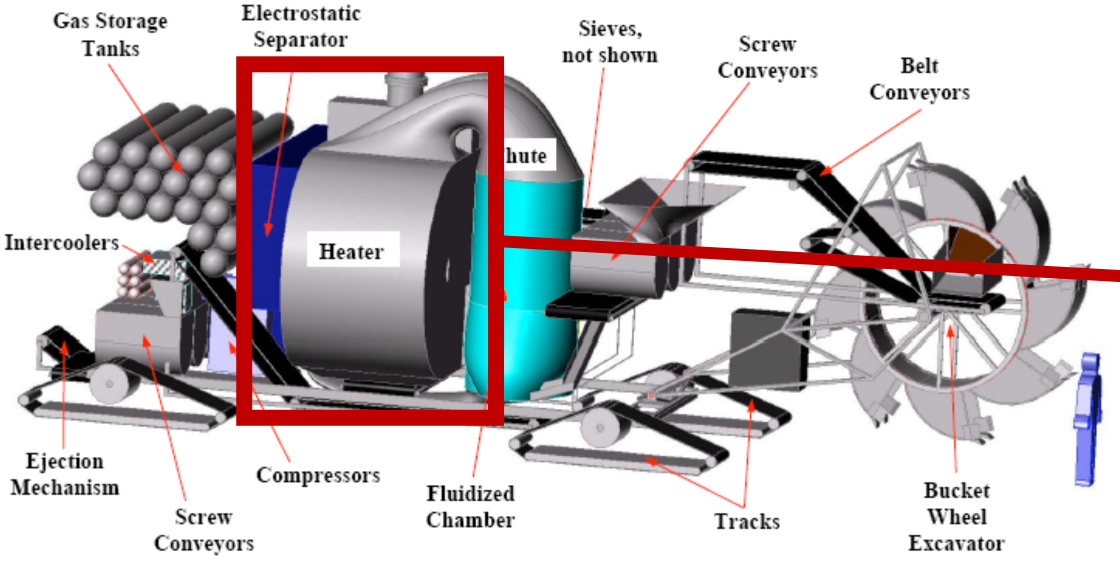


Illustration by J. Andrews

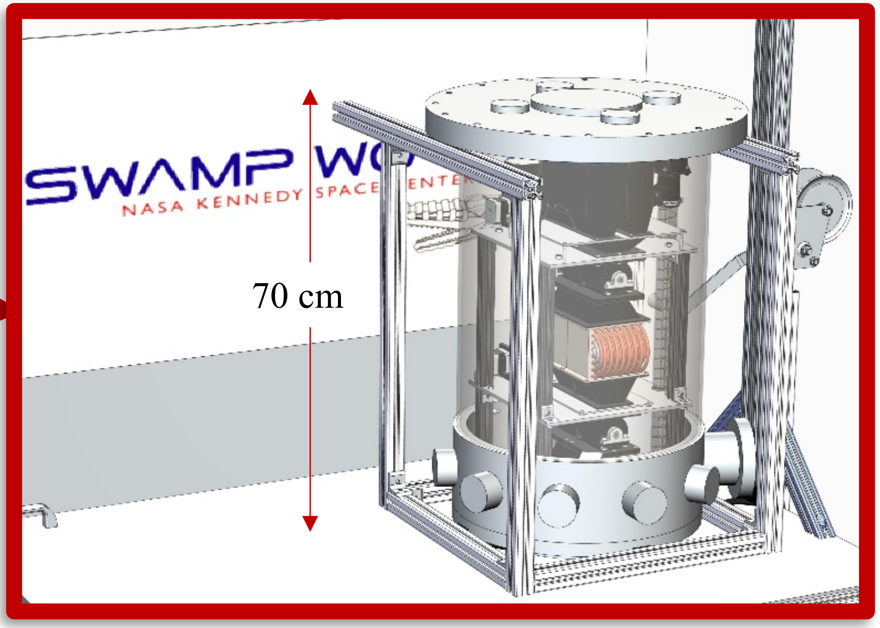
Research is Ongoing to Test a Scalable Version of the Volatiles Extraction System

Helium Extraction & Acquisition Test bed (HEAT)

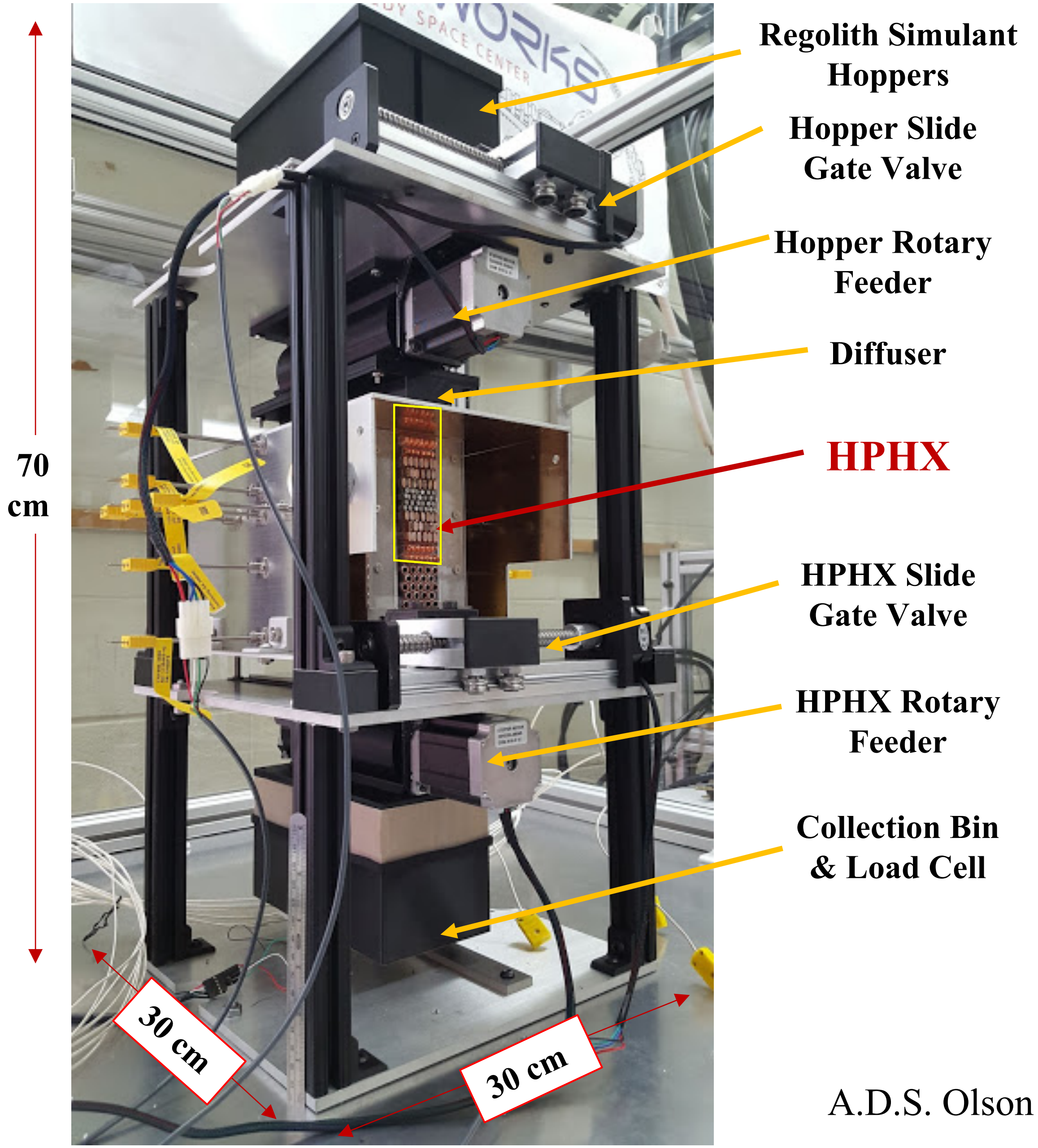
- Testbed for:
  - Thermal recuperation with a heat pipe heat exchanger
  - Volatiles extraction in a heat exchanger
- Laboratory scale (Technology Readiness Level – TRL 4)



Mark 3 Lunar Miner, Credit: M. Gajda



HEAT Can Test Volatile Extraction in a Heat Pipe Exchanger



- Heat Pipe Heat Exchanger (HPHX)
- Maximum mass flow rate (0.62 kg/s) (1:250 scale of Mark II)
- Heats regolith from ~20 °C up to 450 °C to release 30-50% of embedded helium
- Design for <100 μm JSC-1A regolith simulant
- Instrumentation
  - IR Imager, Thermocouples (K), Load Cell & RGA Instrumentation

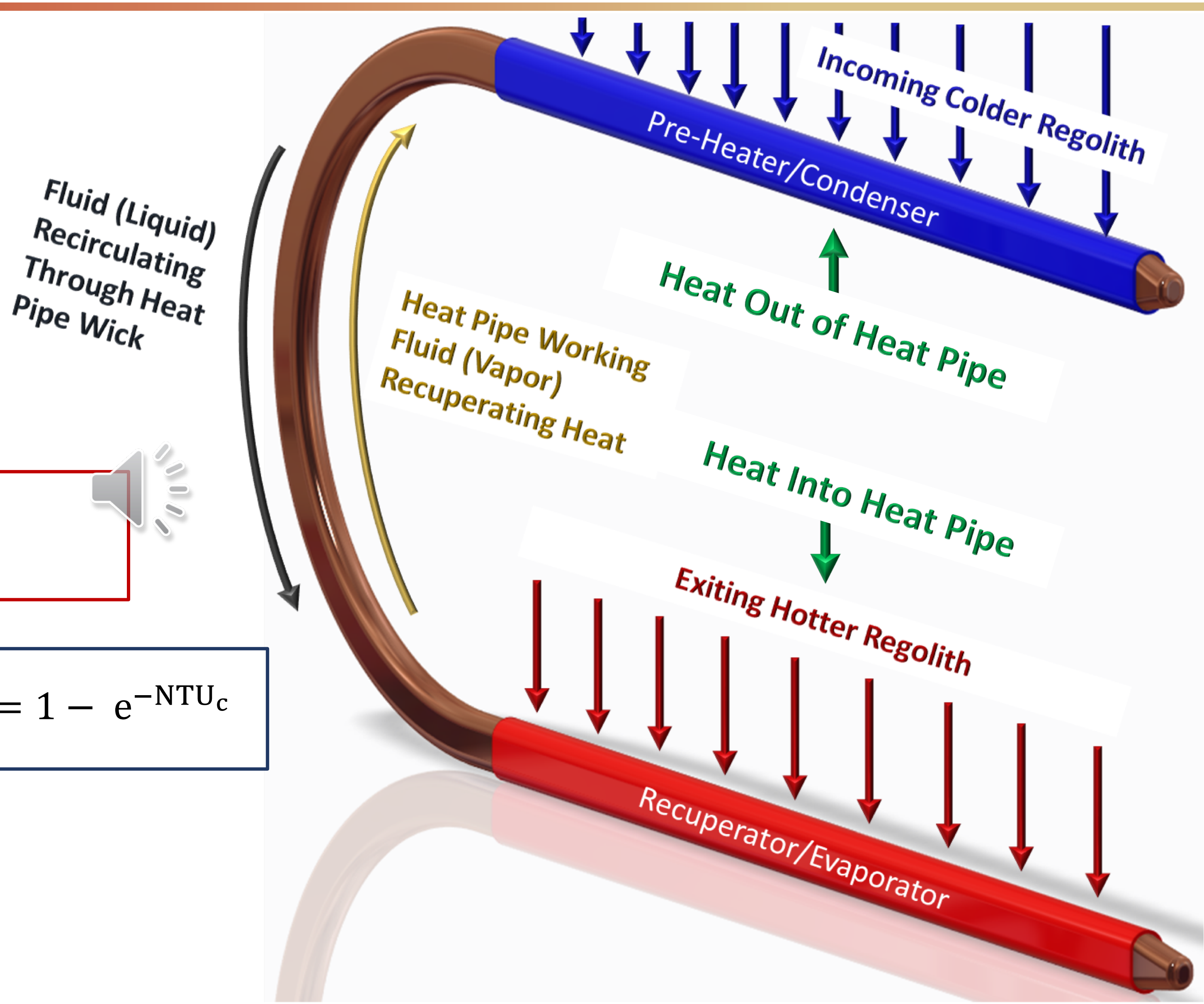
The Heat Pipe Analysis is Based on a Counterflow HX Model

- Energy balance of cold & hot regolith flow
- Effectiveness – NTU method
- Heat pipe effectiveness - function of thermal conductance regolith flow capacitance rate
- Thermal conductance - product of heat transfer coefficient and surface area

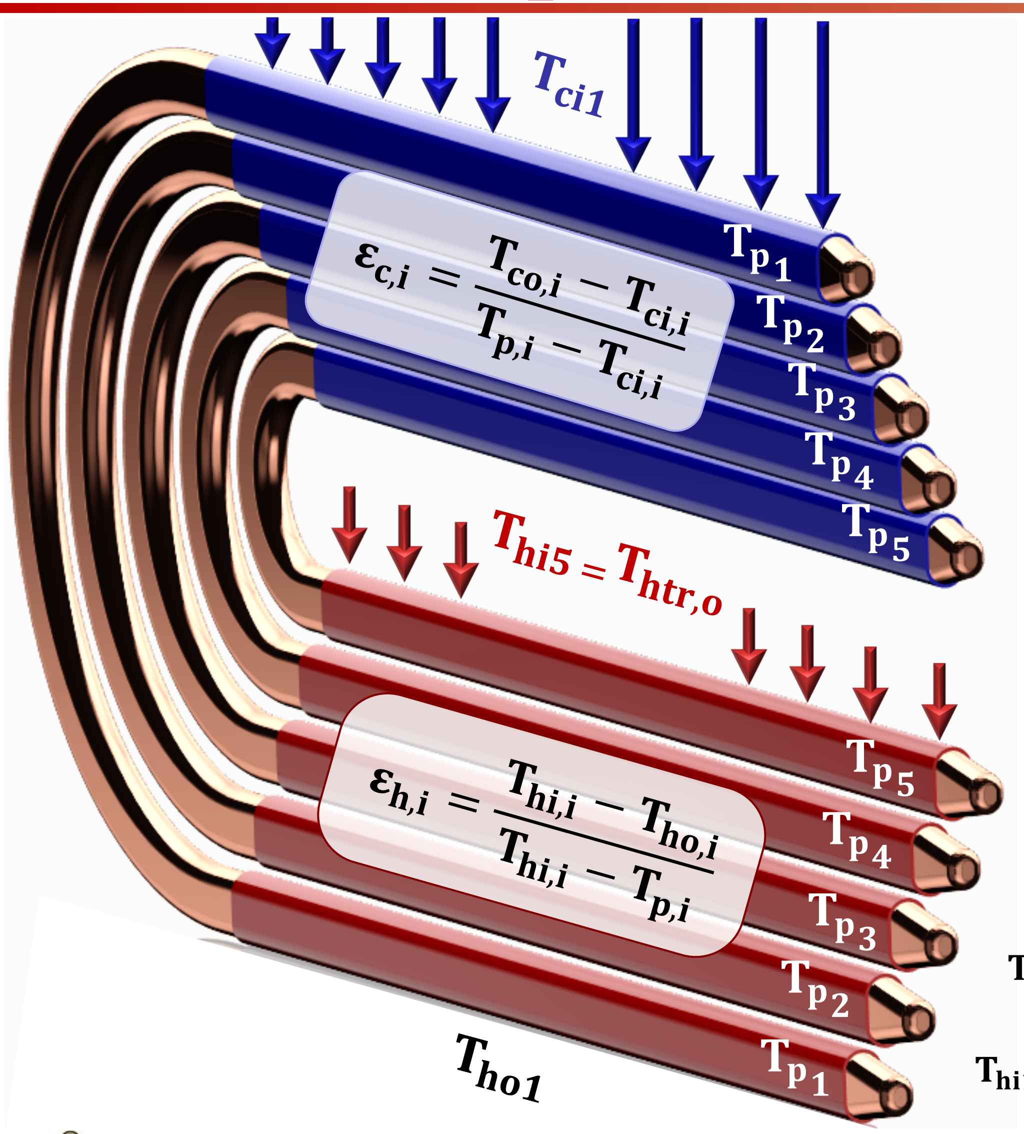
$$Q = C_h(T_{hi} - T_{ho}) = C_h\varepsilon_h(T_{hi} - T_p)$$
$$= C_c(T_{co} - T_{ci}) = C_c\varepsilon_c(T_p - T_{ci})$$

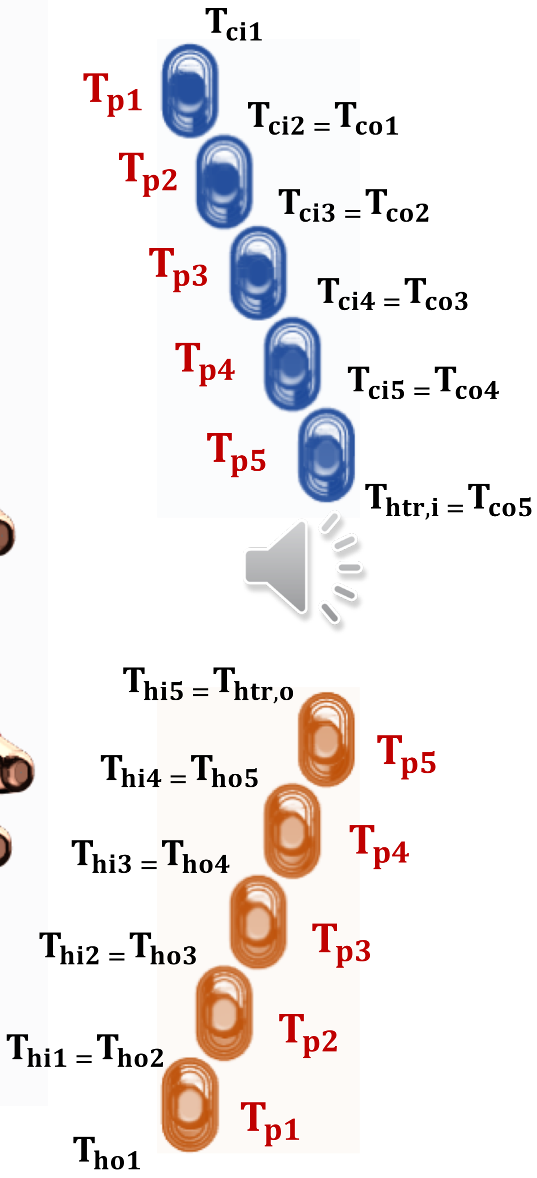
$$\varepsilon_h = \frac{T_{hi} - T_{ho}}{T_{hi} - T_p} = 1 - e^{-NTU_h} \qquad \varepsilon_c = \frac{T_{co} - T_{ci}}{T_p - T_{ci}} = 1 - e^{-NTU_c}$$

$$NTU_h = \frac{h_h A_h}{\dot{C}_h} \qquad NTU_c = \frac{h_c A_c}{\dot{C}_c}$$



The Heat Pipe HX is Modeled like a Staged Counterflow HX





System of equations solved in EES

Key Inputs

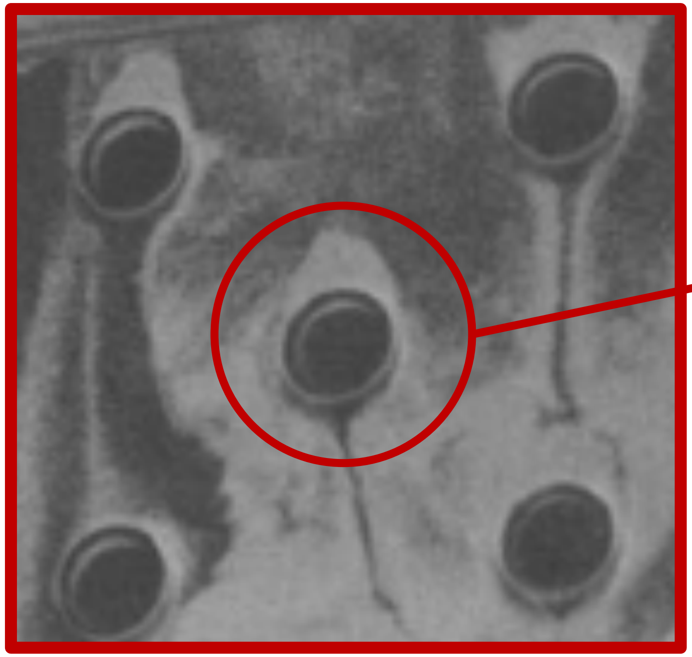
- Regolith and pipe friction and thermal properties
- Heat transfer coefficient functions
- Regolith inlet temperature (**T_{ci1}**)
- Regolith maximum temperature (**T_{hiN}**)

Outputs

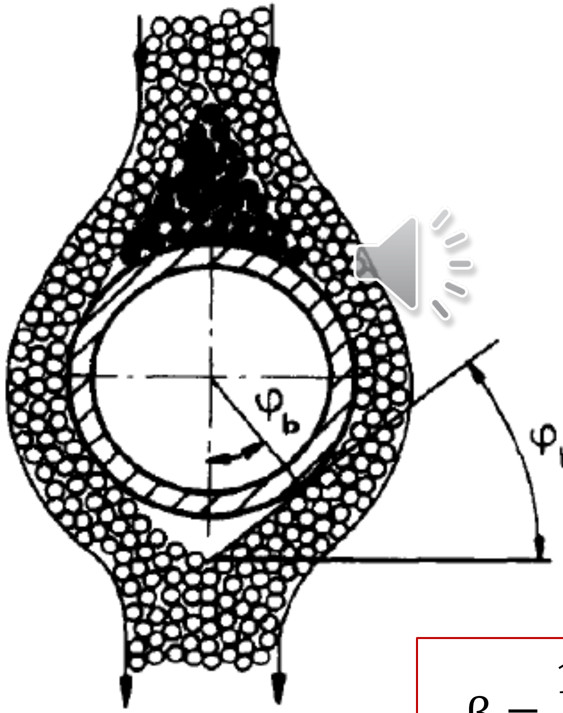
- Heat pipe stage temperatures (N)
- Heat pipe heat transfer
- Regolith temperature vs. heat pipe stage
- Heater section inlet temperature
- Heater power and heat flux requirements

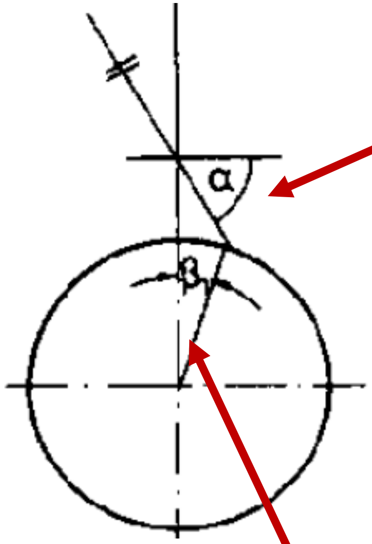
This Research Effort Focuses on an Analytical Flow Model

- The granular friction properties influence the flow channel shape
- The Niegsch model (Niegsch et al., 1994) incorporates the stagnation and void areas of flow



Credit: Niegsch et al.,1994

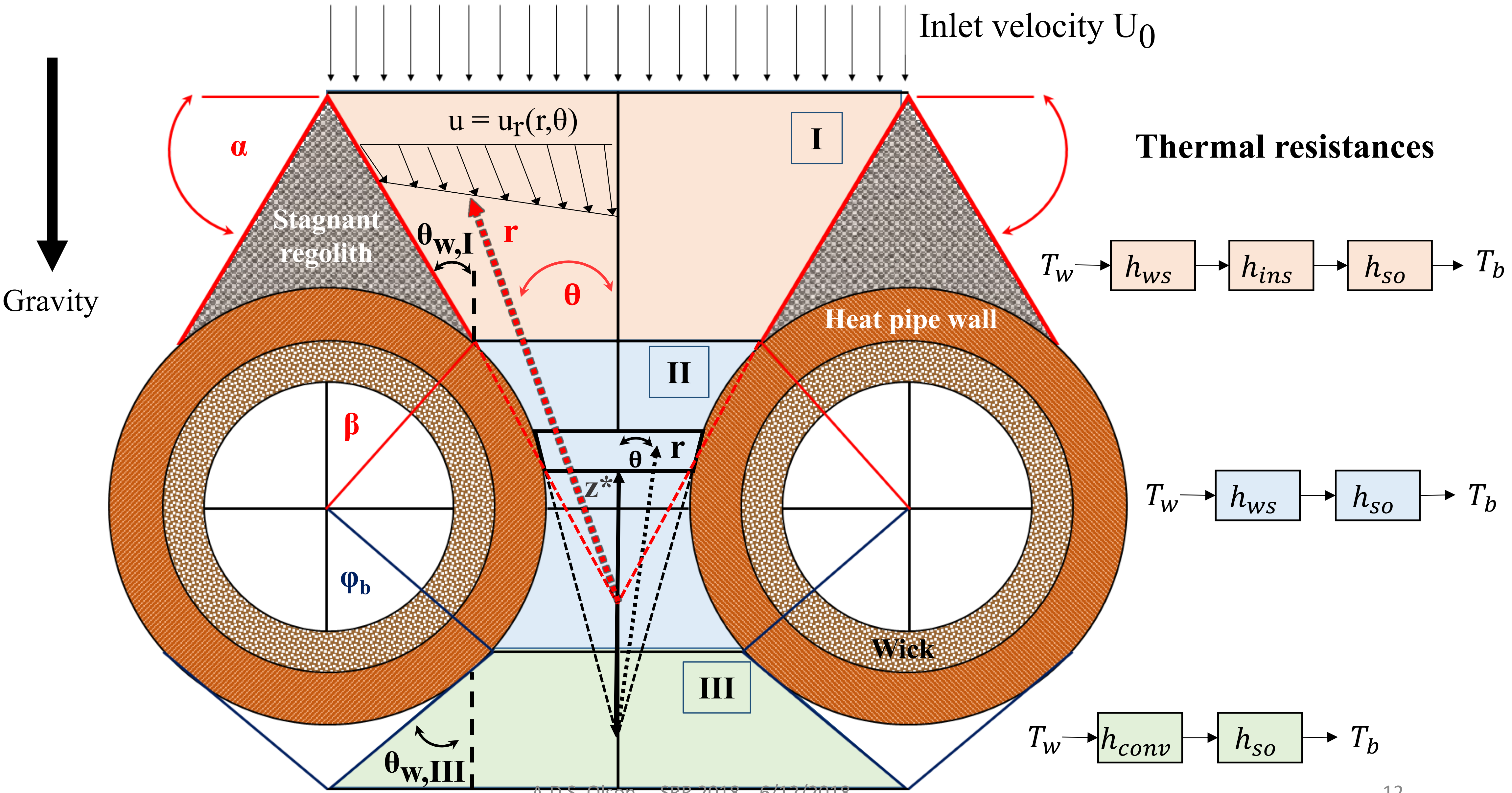




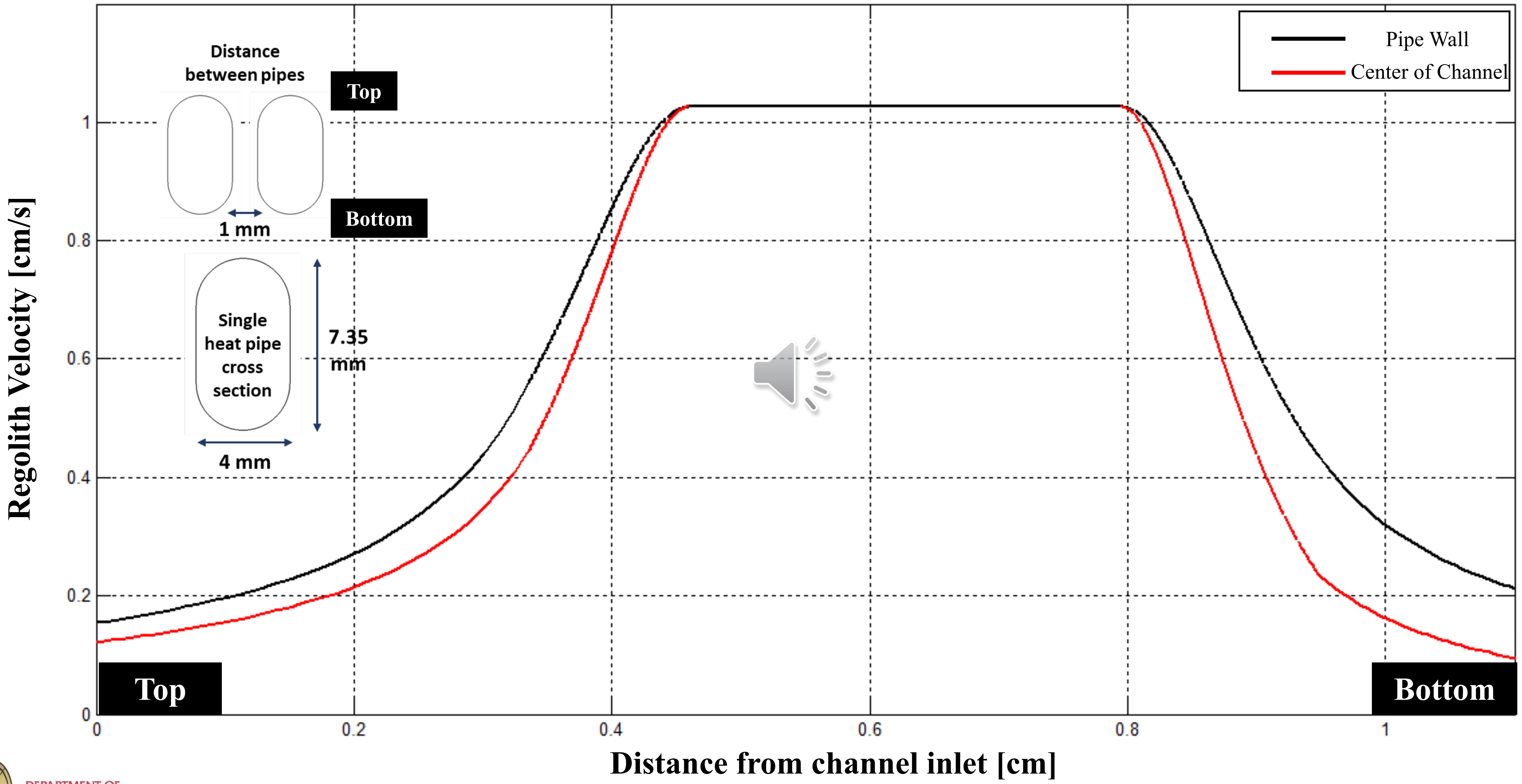
$$\alpha = \frac{\pi}{4} + \varphi_e$$

$$\beta = \frac{1}{2}\left[\cos^{-1}\left(\frac{1-\sin(\varphi_e)}{2\sin(\varphi_e)}\right) + \sin^{-1}\left(\frac{\sin(\varphi_w)}{\sin(\varphi_e)}\right) + \varphi_w\right]$$

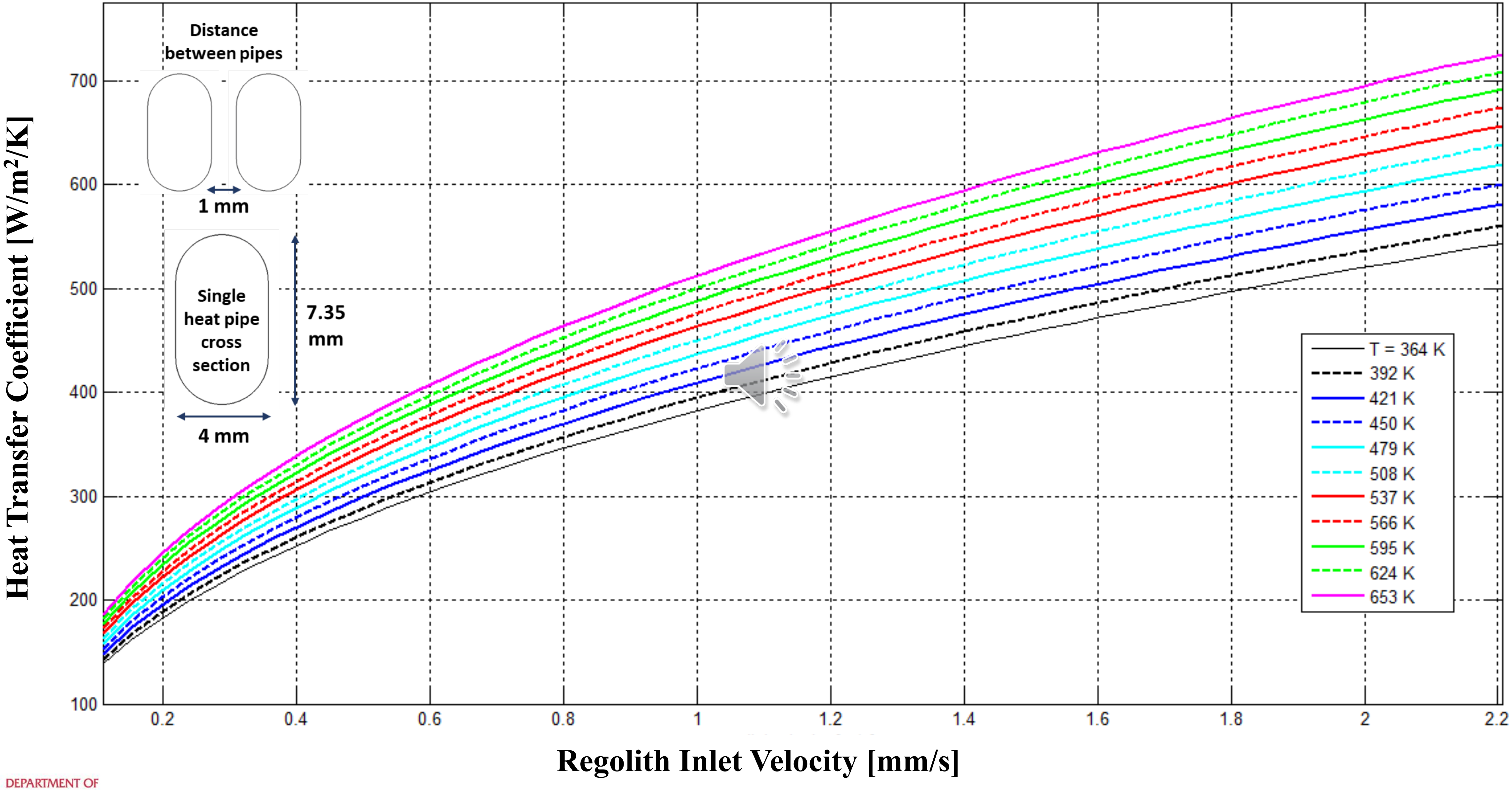
The Flow Model Produces A Velocity Field & Surface Heat Transfer Coefficient



Regolith Velocity vs. Position Between Heat Pipes

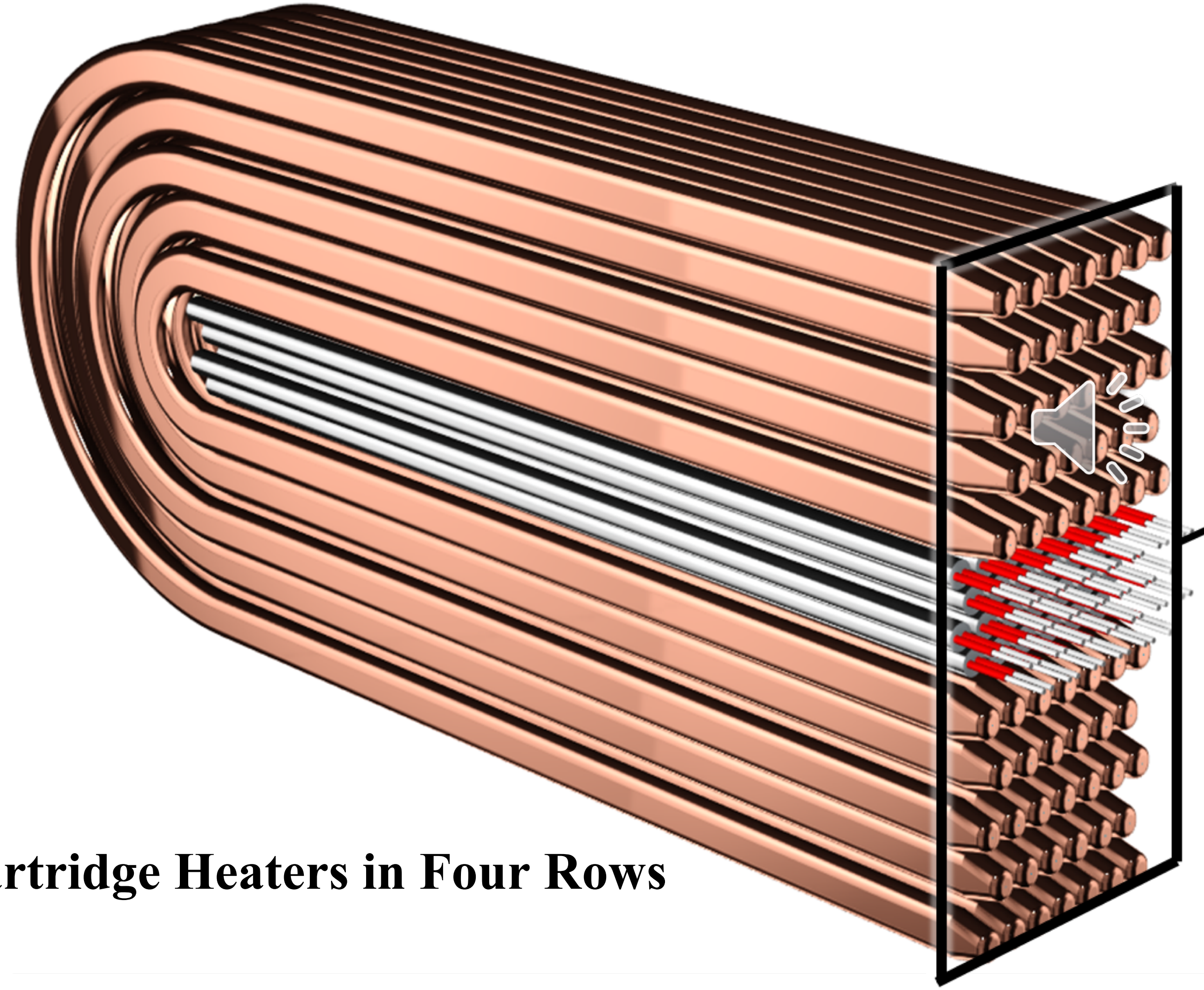


JSC-1A to Heat Pipe Heat Transfer Coeff. vs. Velocity and Regolith Temp.

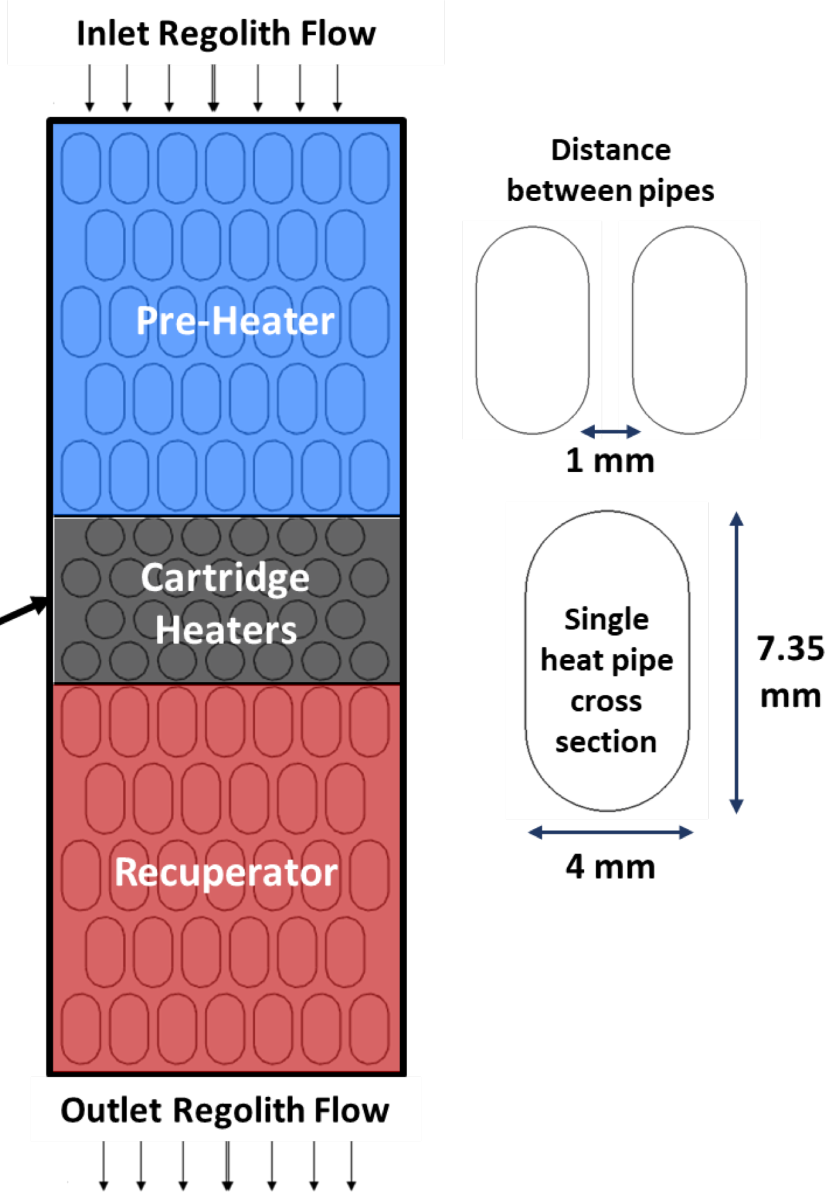


The HPHX Nominal Design Uses Five Stages of Flattened Heat Pipes

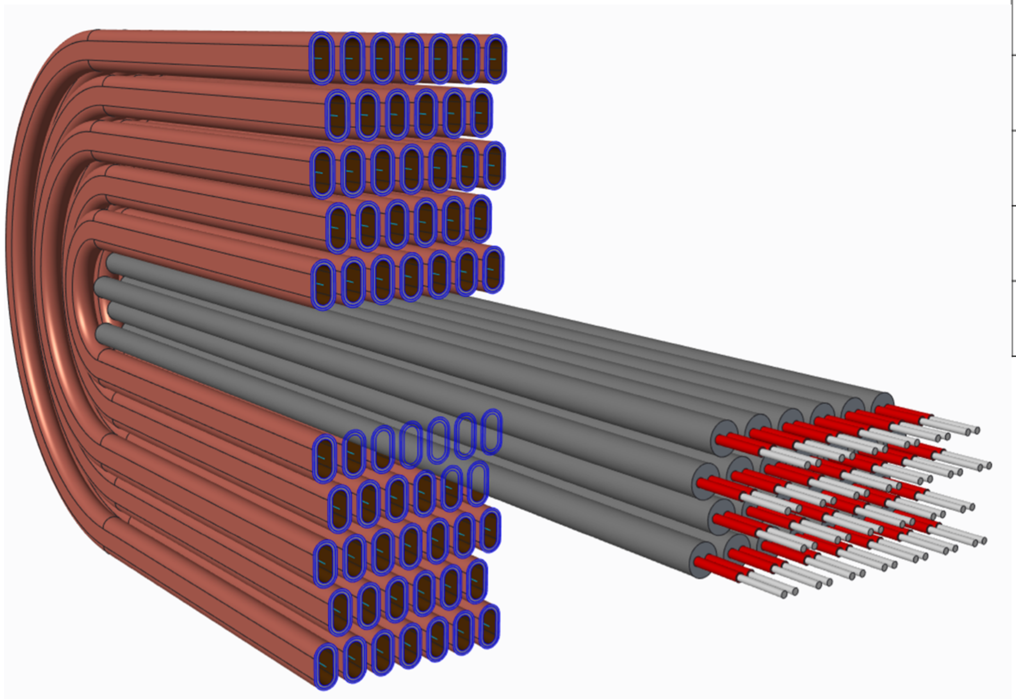
33 Heat Pipes in Five U-shaped stages



26 Cartridge Heaters in Four Rows

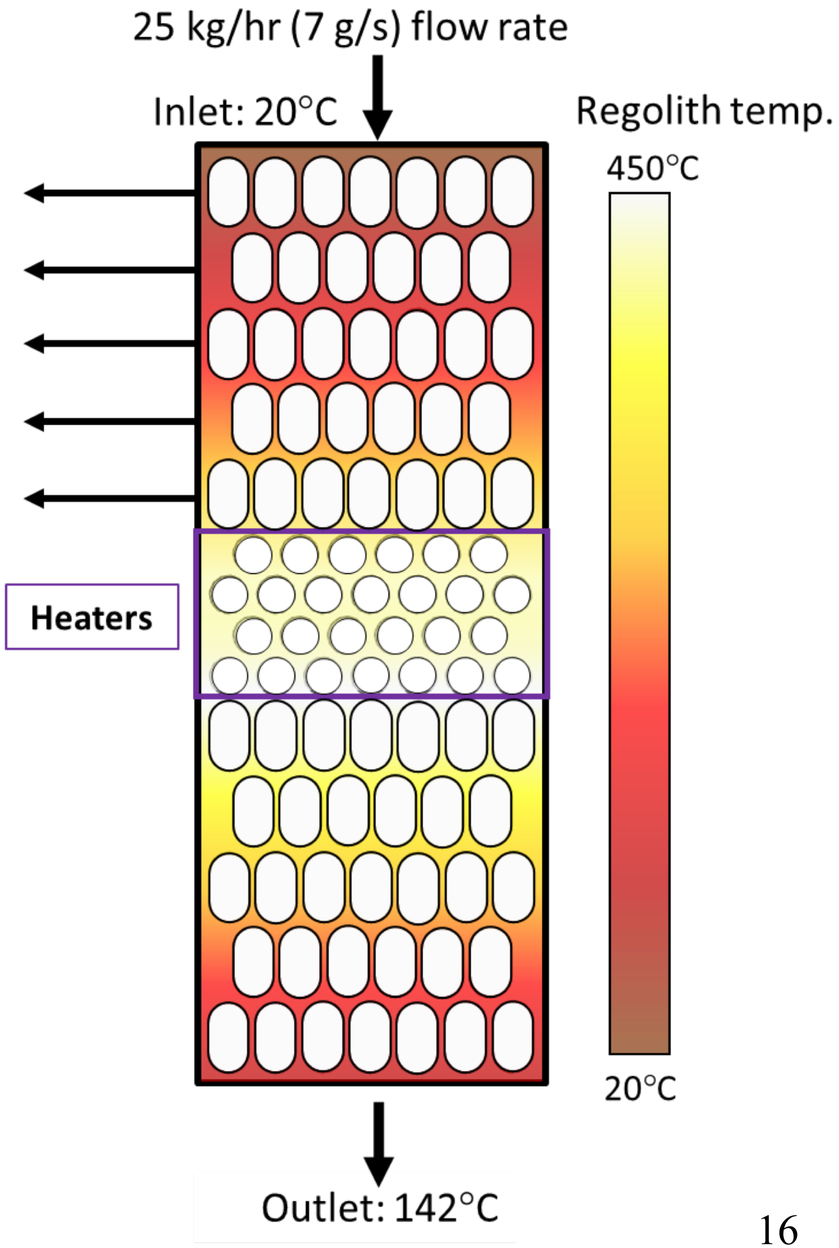


HPHX Predicted to Recuperate 72% of JSC-1A Thermal Energy



Fluid	HP Temp.	HP Heat	Stage
Water	101°C	34 W	1
Water	147°C	54 W	2
Dowtherm A	207°C	66 W	3
Dowtherm A	275°C	80 W	4
Dowtherm A	349°C	86 W	5

Input Power	922 W
Recoup. Efficiency	72 %
Cartridge Power	42 W
Heater Heat Flux	2.2 W/cm^2
Heater Surf. Temp.	460 °C
Total Residence	78 seconds
Heater Residence	14 seconds



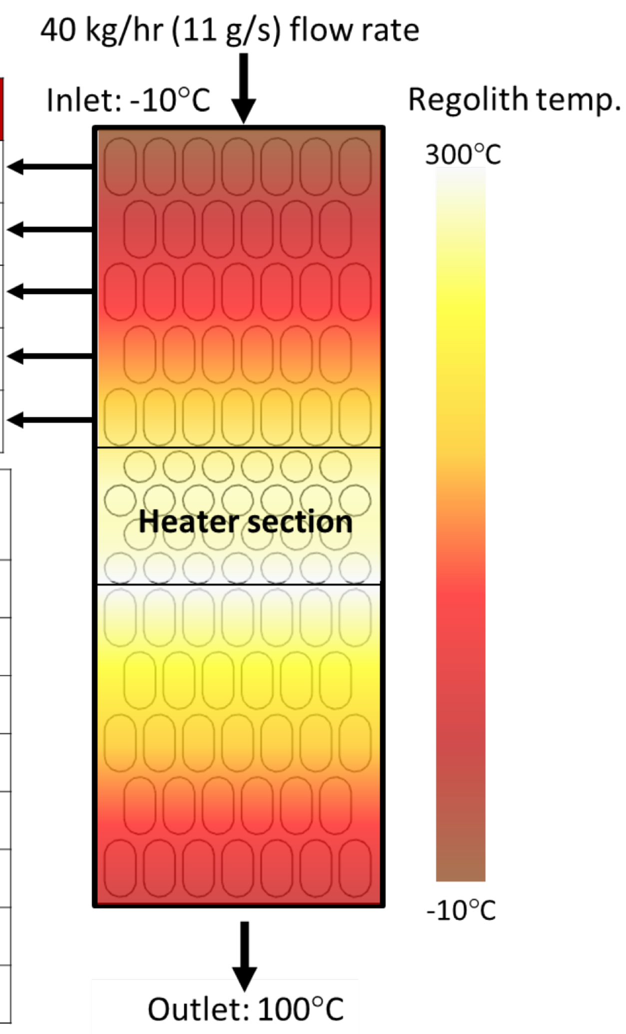
Summary

- Modeling approach developed to design heat pipe heat exchangers for regolith
- Modeling results will be compared against experimental results in the Helium Extraction and Acquisition Testbed (HEAT) device
- Demonstration of volatile extraction in a heat pipe heat exchanger before the end of this research effort
- The modeling approach for heat pipe heat exchangers could useful for the extraction of water from hydrated and/or icy regolith

Modeling for Water Extraction on Mars (Ice or Hydrated)

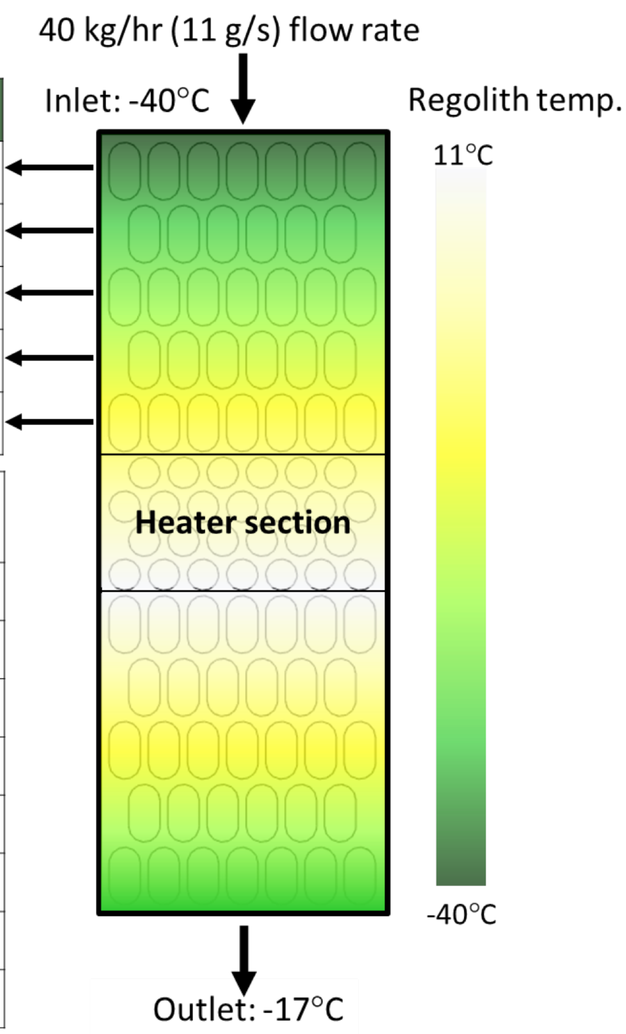
Fluid	Temp.	Stage
Water	66°C	1
Water	104°C	2
Water	143°C	3
Water	184°C	4
Dowtherm	225°C	5

Water Extraction (12% Concentration)	**3.8 kg/hr**
Power/Water Rate	1.1 MJ/kg
Input Power	1.1 kW
Recoup. Efficiency	66 %
Cartridge Power	43 W
Heater Heat Flux	2.3 W/cm^2
Heater Surf. Temp.	301 °C
Total Residence	41 seconds
Heater Residence	7.5 seconds



Fluid	Temp.	Stage
Methanol	-26°C	1
Methanol	-20°C	2
Methanol	-16°C	3
Methanol	-10°C	4
Methanol	-5°C	5

Water Extraction (10% Concentration)	**3.2 kg/hr**
Power/Water Rate	3.3 MJ/kg
Input power	4.6 kW
Recoup. Efficiency	53 %
Cartridge Power	141 W
Heater Heat Flux	7.4 W/cm^2
Heater Surf. Temp.	121 °C
Total Residence	41 seconds
Heater Residence	7.5 seconds



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Lunar Volatiles Extraction Technology for Future Fusion Power and Multi-Outpost Scale Human Space Exploration

December 8, 2014

Aaron Olson
University of Wisconsin, Madison

The proposal is for the development of a prototype lunar volatiles extraction system the will demonstrate a process for acquiring helium-3 and volatile gases that can be used for life support. Helium-3 could be used in future fusion reactors that would produce no radioactive waste. The process of acquiring helium-3 produces far more life supporting volatile gases than helium-3, and incorporates many of the technologies that may be required in the future for supporting multiple in space outposts from lunar resources. The prototype system will be based on a past lunar volatiles miner design, developed at the University of Wisconsin Fusion Technology Institute, and will be a scaled down version that will investigate issues of system optimization for volatile production, component degradation due to continuous exposure to regolith simulant and thermal energy efficiency of the prototype's heat pipe heater system.

Aaron Olson