Demonstration of an Energy Efficient Lunar ^{3}He and Volatiles Extraction System

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Canadian Institute of Mining Convention

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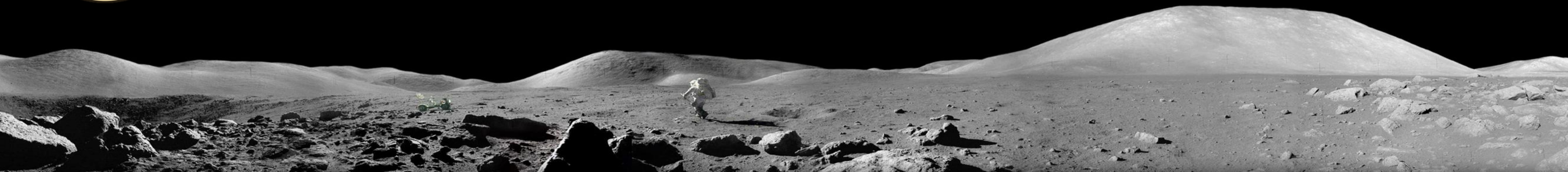


This Research is Supported by a NASA Fellowship

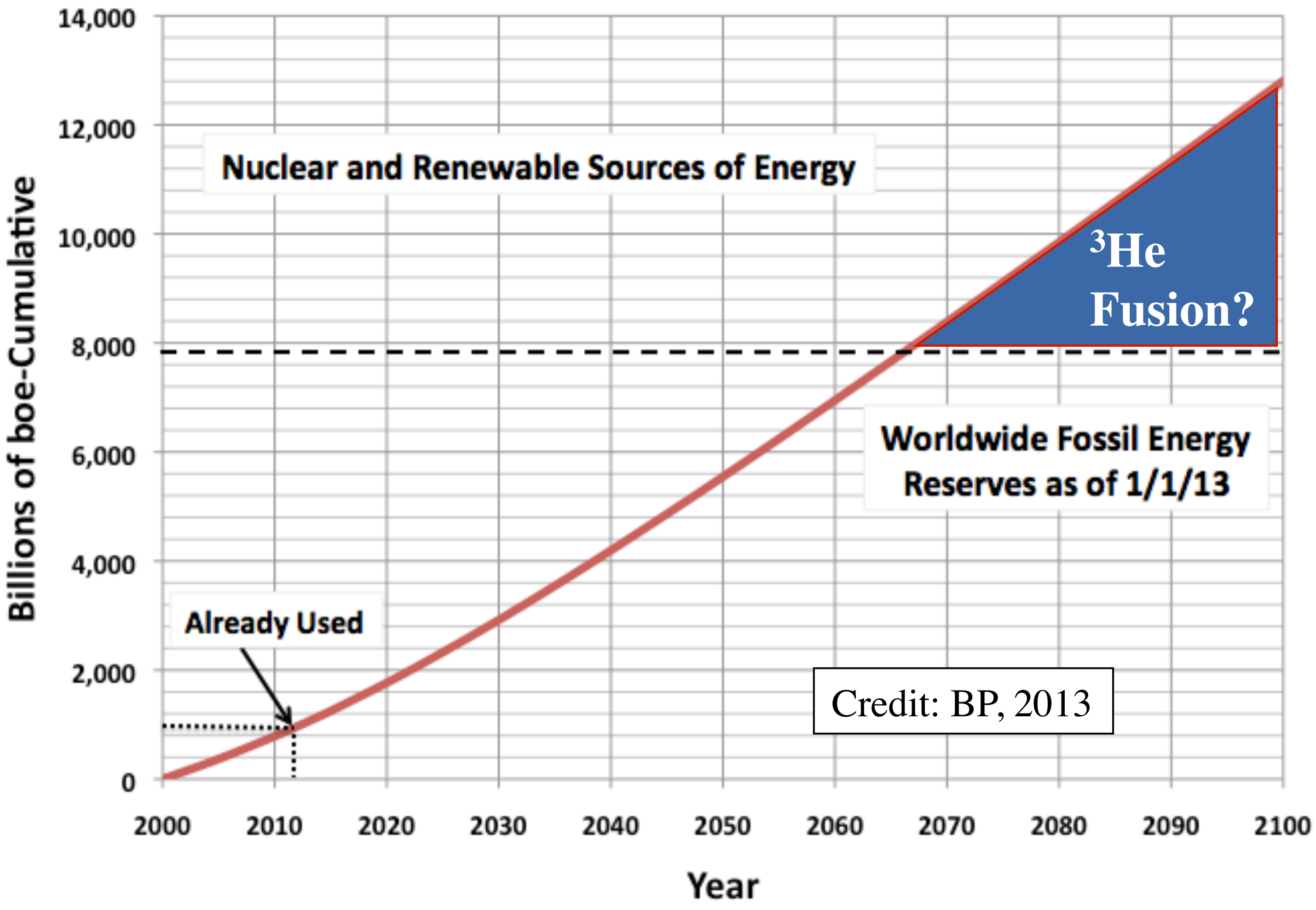
- Space Technology Research Fellowship (NSTRF)
- Class of 2014
- Collaboration with Kennedy Space Center

Outline

- Motivation for using Helium-3 (^{3}He) for Fusion Power
- How can ^{3}He be acquired from the Moon
- Ongoing Research to Demonstrate Lunar ^{3}He Extraction
- Conclusion, Expected Outcomes and Future Work

Motivation: ${}^3He$ Fusion Could Help Satisfy Future Energy Needs

- World population is increasing
- Energy usage per capita is increasing
- Nuclear and renewable energy will be key in meeting our future needs
- ${}^3He$ fusion can be a part of the solution



^{3}He Fusion Reactors Could Produce Nuclear Power With Little to No Nuclear Waste

Deuterium-Helium-3

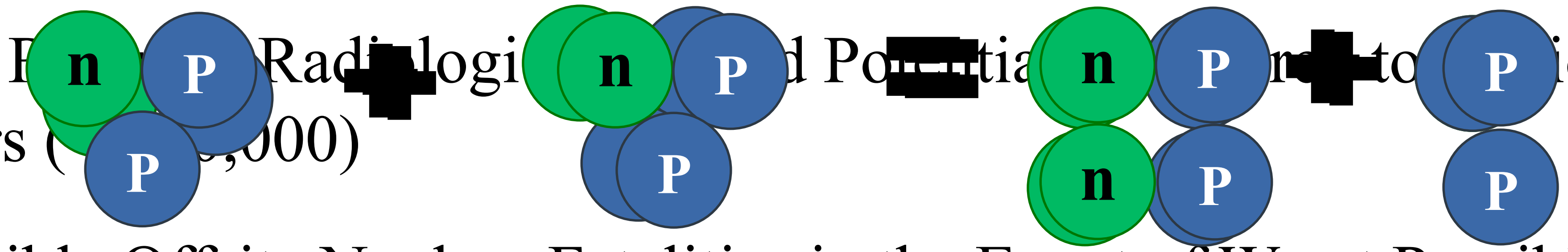
Helium-3 and Helium-3

- No Greenhouse or Acid Gas Emissions

$D + {}^{3}He \rightarrow {}^{4}He\ (3.67\ MeV) + p\ (14.68\ MeV)$

${}^{3}He + {}^{3}He \rightarrow {}^{4}He + 2p\ (12.86\ MeV)$

- Very High Efficiencies (>70%)
- Greatly R… Radiologi… d Potentia… …to… …ion Reactors (…,000)



- No Possible Offsite Nuclear Fatalities in the Event of Worst Possible Accident
- No Proliferation of Weapons Grade Material

^{3}He Fusion Reactors Could Produce Nuclear Power With Little to No Nuclear Waste

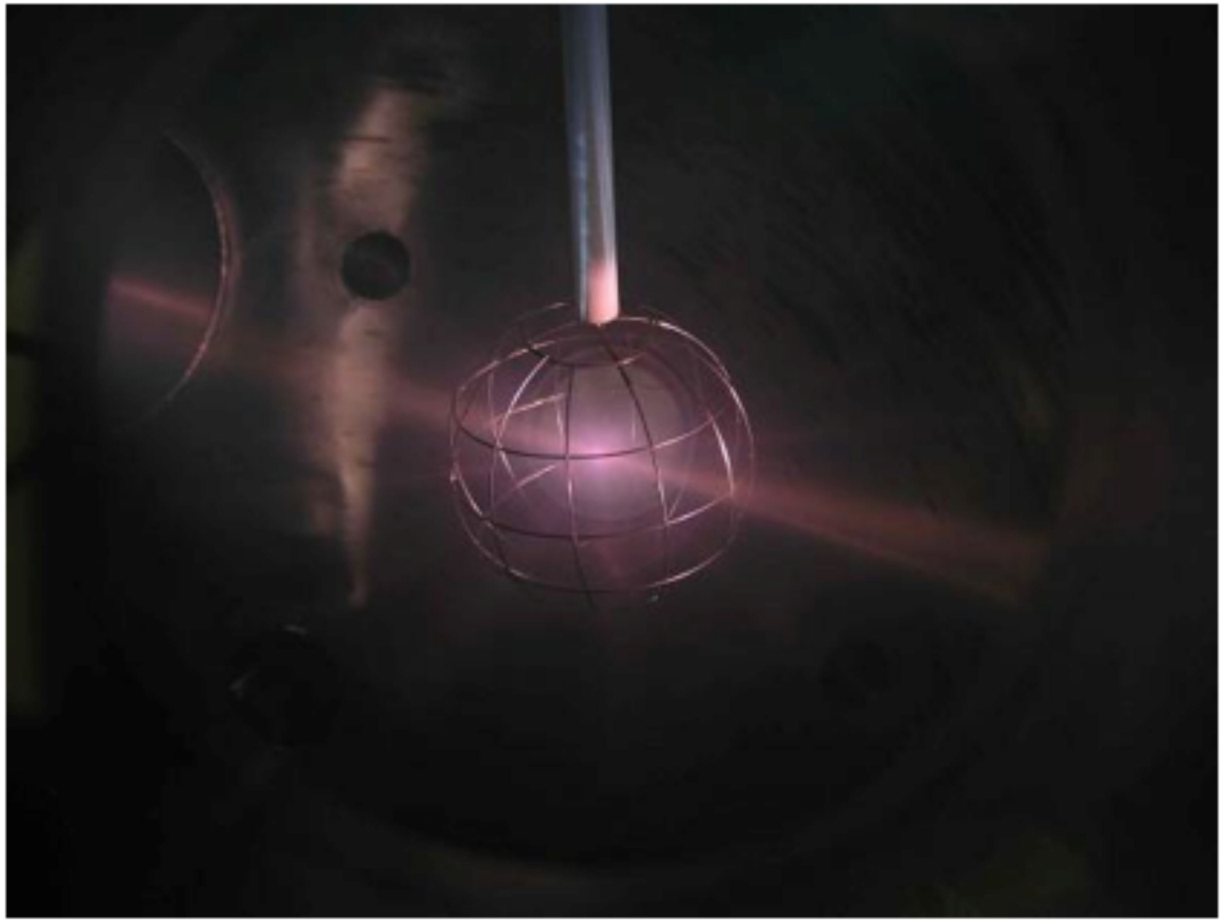
What Needs to be Done?

- ^{3}He Fusion Physics Experiments
- A Large Source of ^{3}He

Progress at Wisconsin Toward ^{3}He Fusion Reactors

D^{3}He fusion reactions in an IEC device demonstrated in 1999

First demonstration of ^{3}He^{3}He reactions in a plasma in 2005



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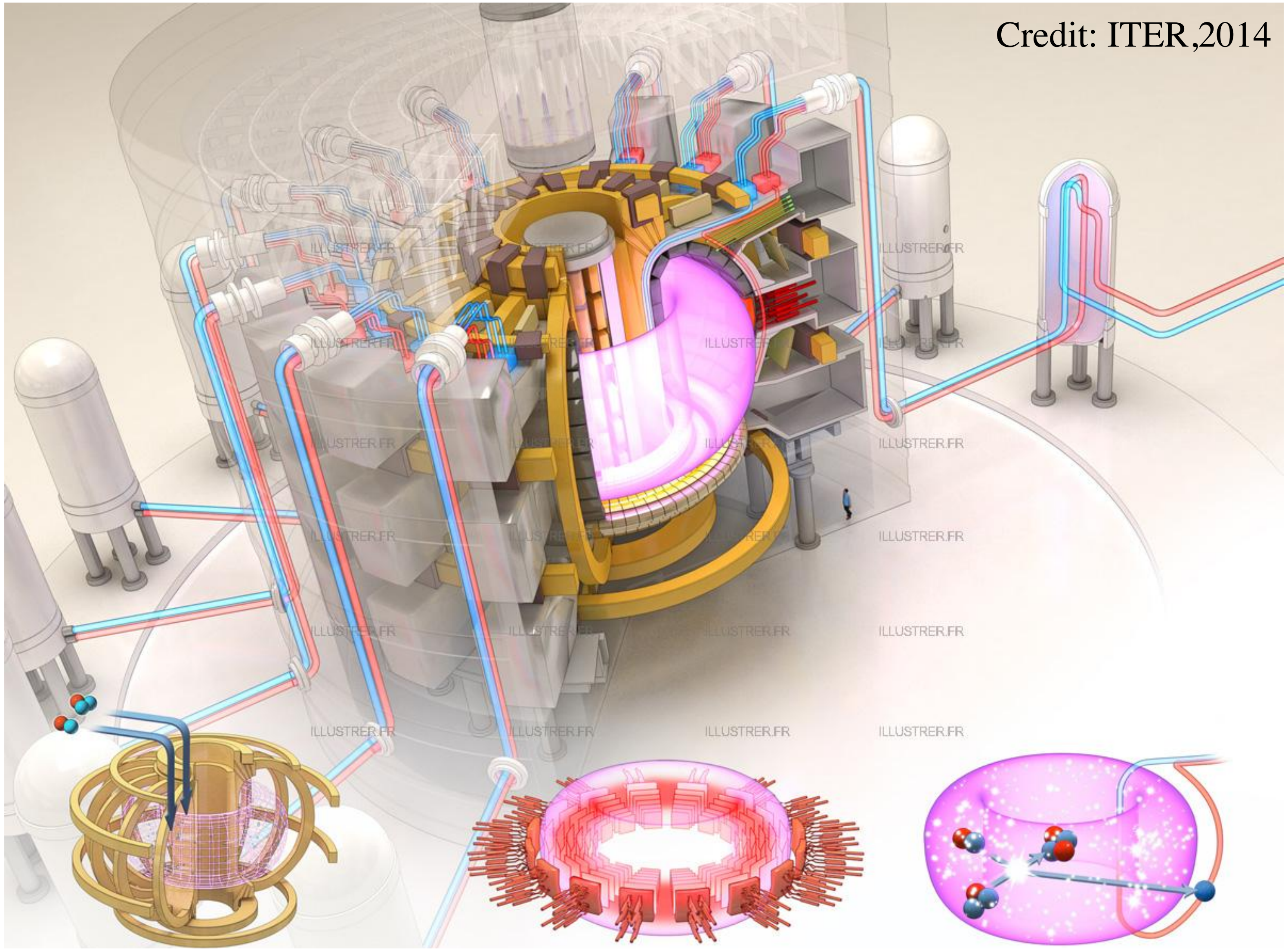
The ^{3}He on Earth is Insufficient to Support Fusion Power

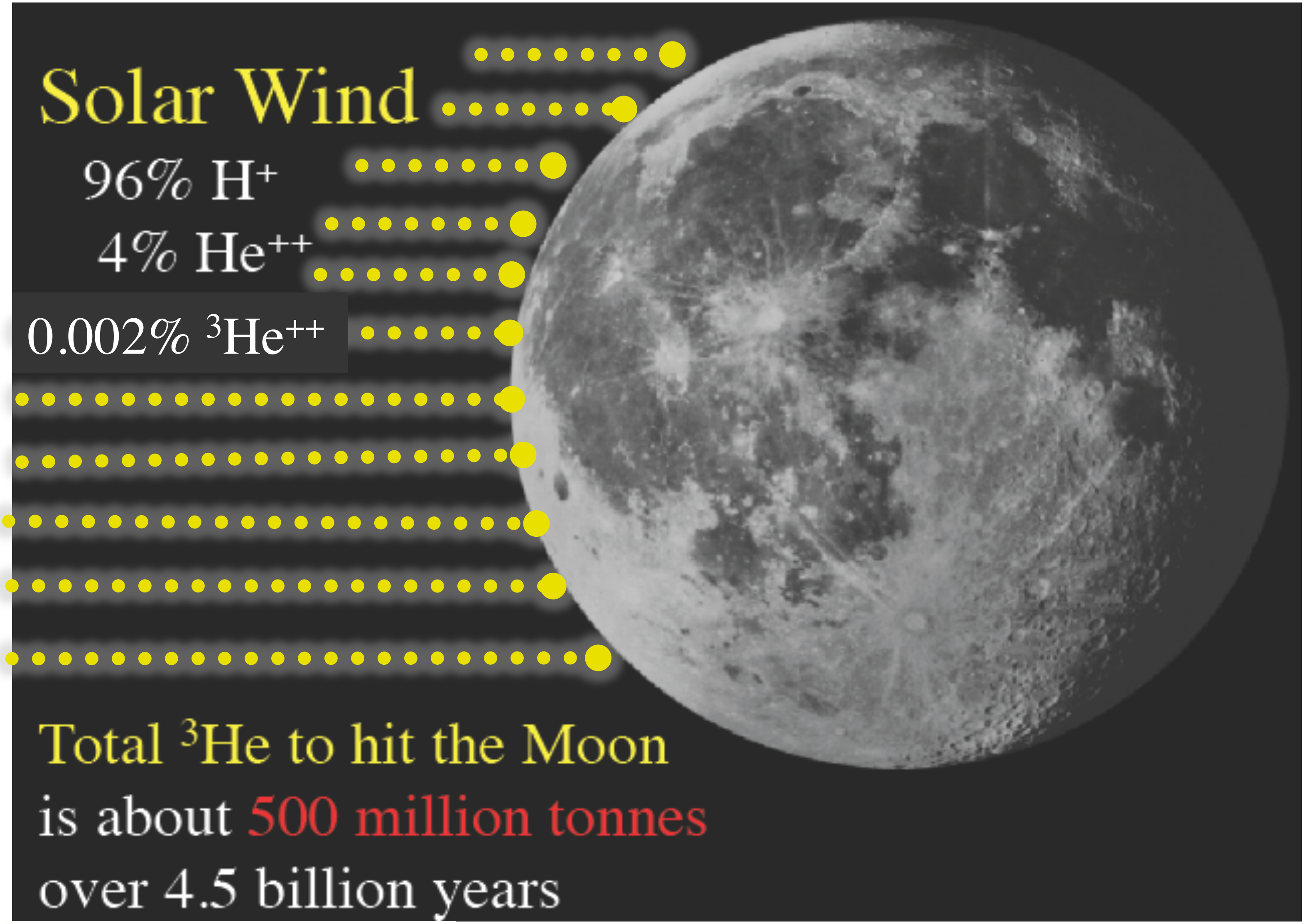
There is <100 kg of available terrestrial ^{3}He

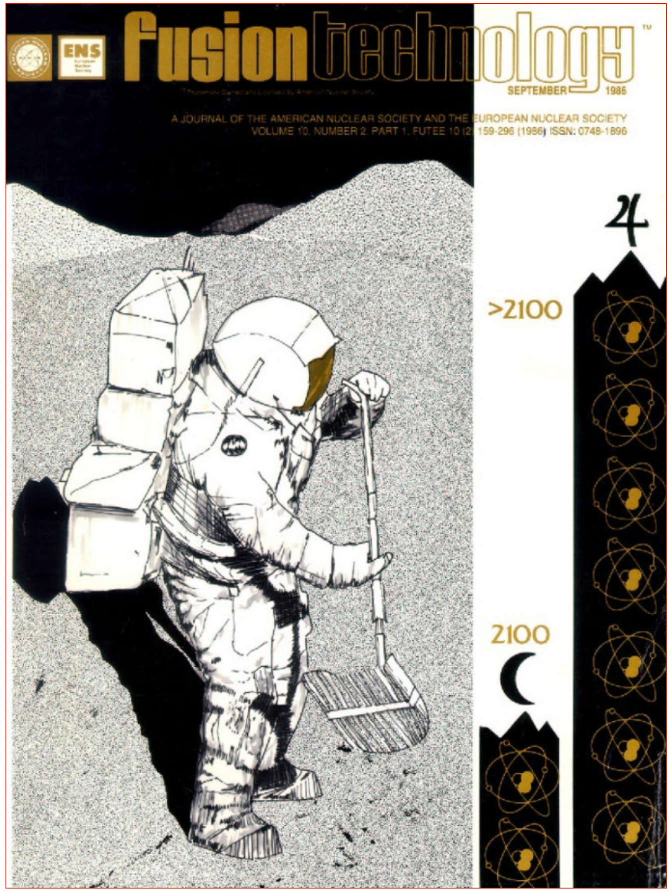
Only enough to operate a GWe fusion power plant for 1 year



Credit: ITER,2014

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





L.J. Wittenberg, J.F. Santarius, and G.L. Kulcinski, "Lunar Source of ^{3}He for Commercial Fusion Power," *Fusion Technology* **10**, 167 (1986).

^{3}He on the Moon Could Become Extremely Valuable

One of today's SpaceX Dragon capsules could return a "payload" of ^{3}He worth around \$15 billion in energy.

40 Tonnes (12 Dragon capsules) of ^{3}He Could Provide all the Electricity Used in North America in 2014

At today's oil prices (\$8.5/million BTU or \$50/ barrel) the energy content in one tonne of ^{3}He would be worth \$4.4 billion

Credit: SpaceX, 2012

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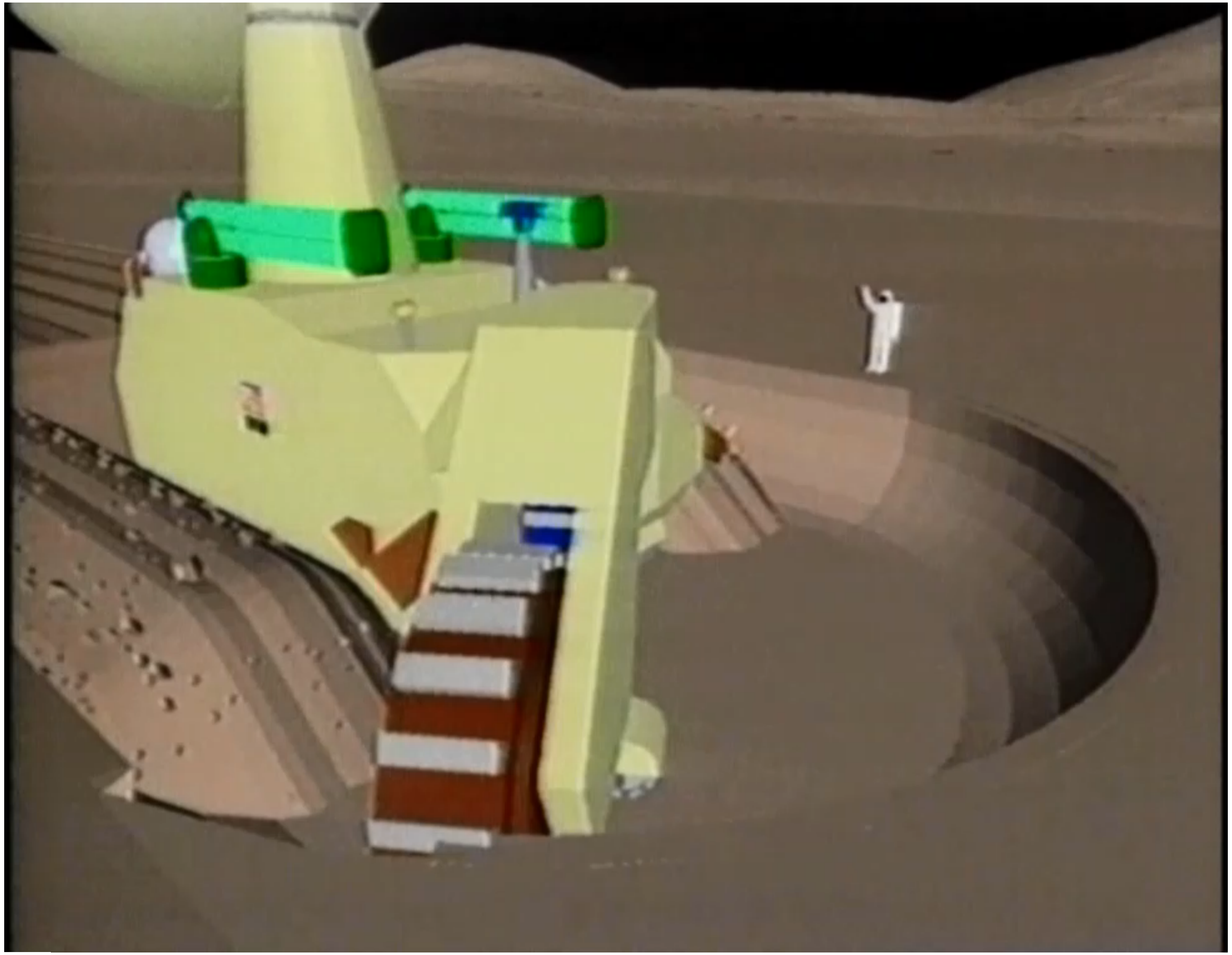
There are Three Wisconsin Lunar ^{3}He Miner Designs

Excavation rate (tonnes/hr)	1258
Processing rate (tonnes/hr)	
Thermal process power (MW)	
^{3}He extraction (kg/yr)	66

TAKRAF SR 8000 bucket-wheel excavator can excavate > 16,000 tonnes/hr of bituminous coal and has a mass of 14,200 tonnes


Credit: Tenova TAKRAF

There are Four Main Processes in a ^{3}He Miner



Credit: Bechtel, 1992

Excavate and Convey

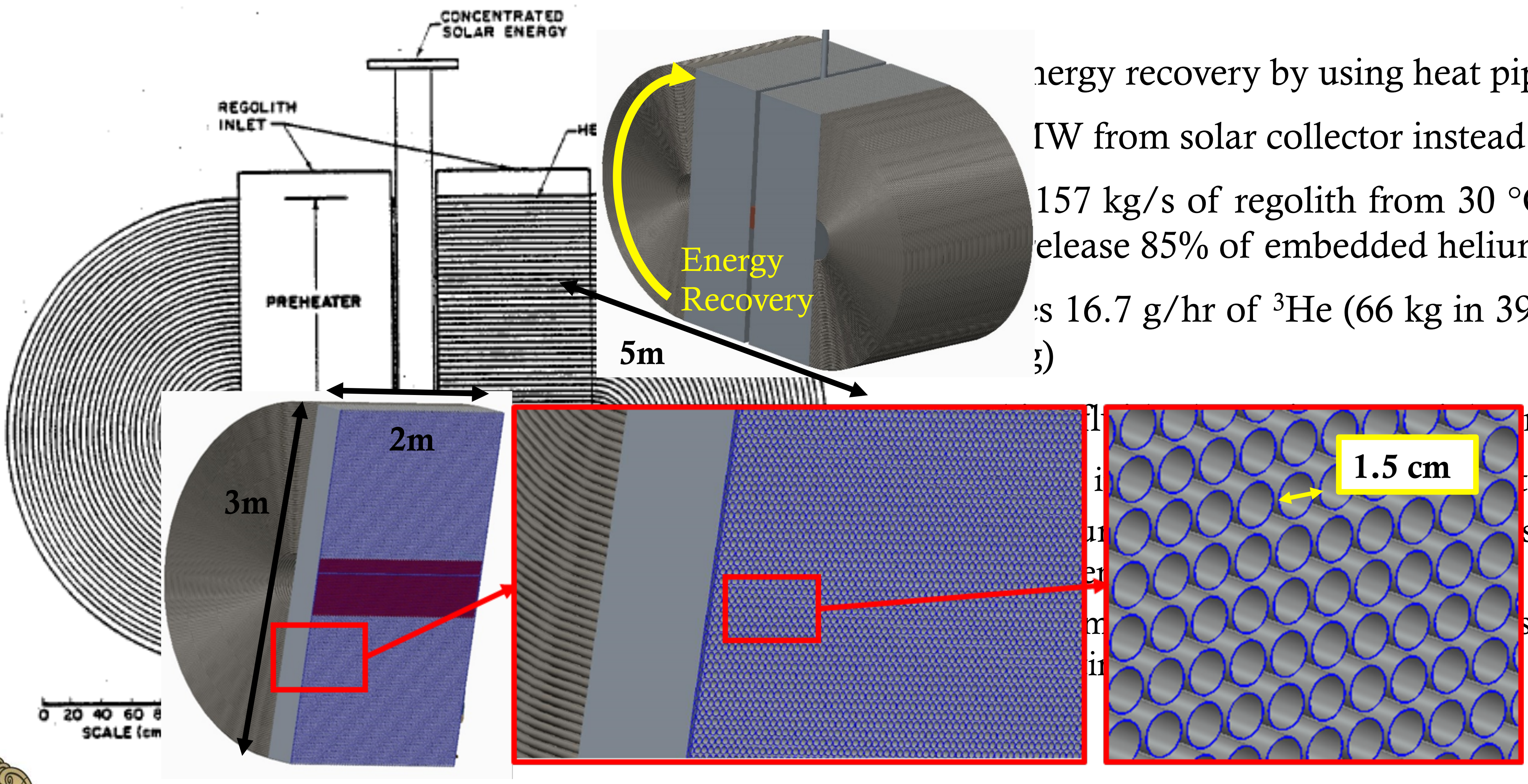
Beneficiate

Heat Regolith and Evolve Volatiles

Collect Volatiles


NASA

The Heat Pipe Heat Exchanger is the Key Part of the Miner

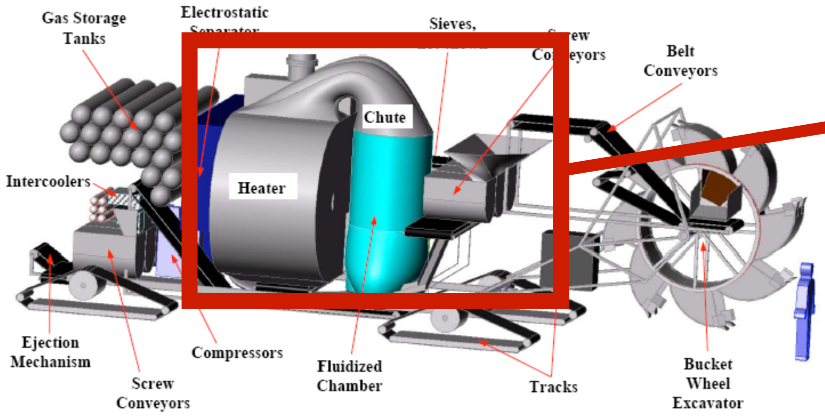


- nergy recovery by using heat pipes
- IW from solar collector instead of 82 MW
- 157 kg/s of regolith from 30 °C up to 700 elease 85% of embedded helium-3
- s 16.7 g/hr of ^{3}He (66 kg in 3942 hours of g)
- mbinations
- o ~250 °C
- s: operating
- ss steel pipes:

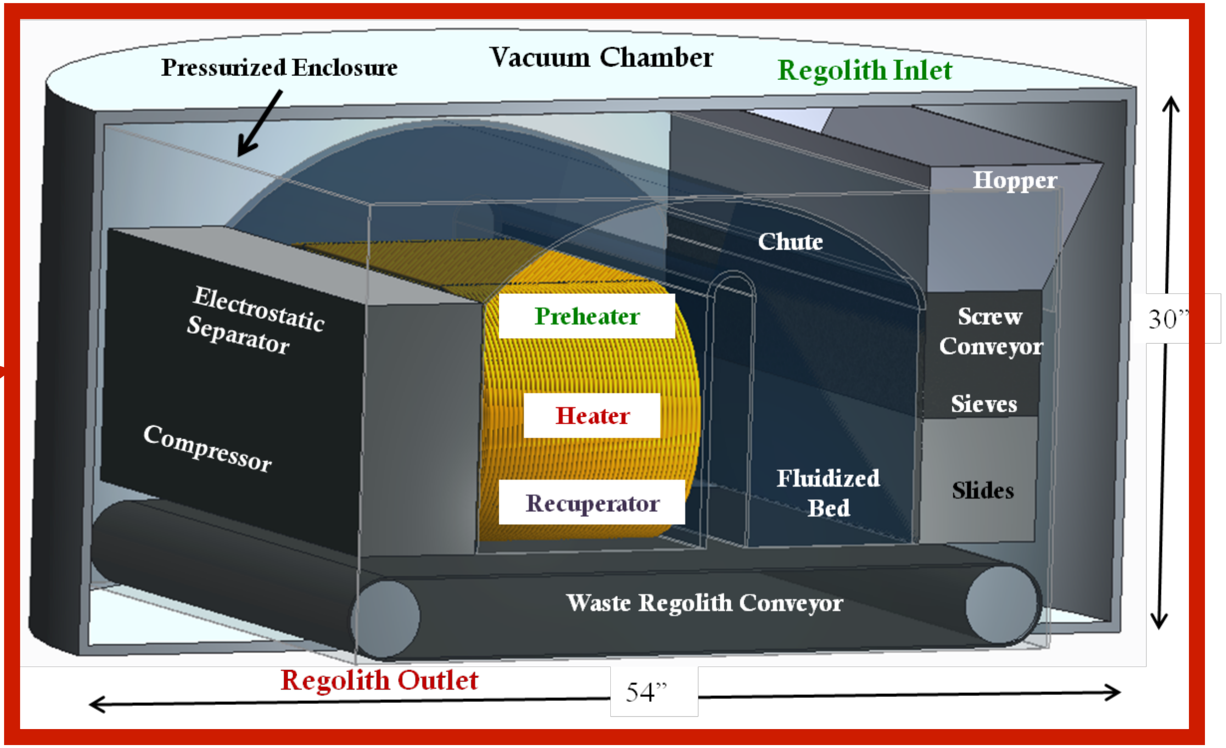
Research to Demonstrate the ^{3}He Miner Heating System

Main Research Question: How Effectively can ^{3}He be Extracted?

- First Demonstration of ^{3}He release inside of a heat pipe heat exchanger
- 1:1000 scale mass flow rate relative to M-3 (157 g/s)

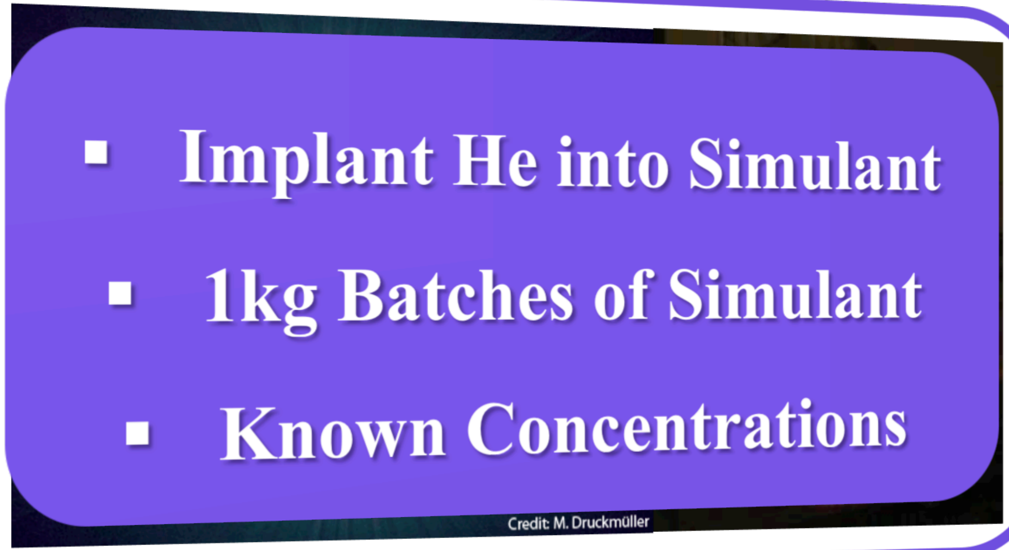


Helium Extraction and Acquisition Test bed (HEAT)



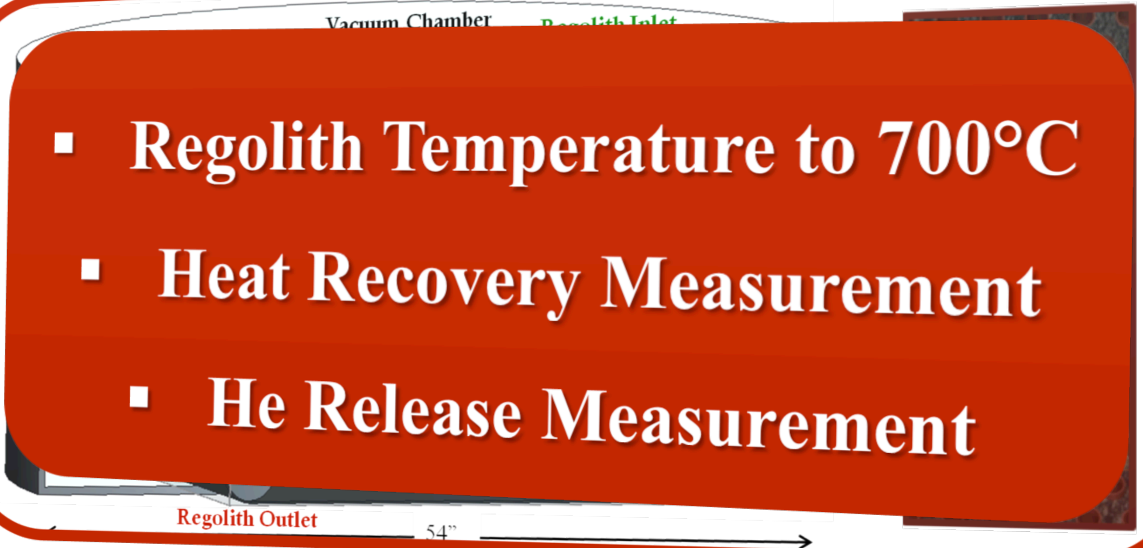
There are Two Main Areas to this Research

Small Scale Demonstration of Lunar ^3He Extraction



- Implant He into Simulant
- 1kg Batches of Simulant
- Known Concentrations

Helium Implantation



- Regolith Temperature to 700°C
- Heat Recovery Measurement
- He Release Measurement

HEAT

JSC-1A Lunar Regolith Simulant Will be Used

JSC-1A Merriam Crater Cinders (left) and ground regolith simulant (right). Credit: ORBITEC

Thanks to Dr. James Mantovani for 8kg of JSC-1A from NASA KSC

Den…		0 [k…	
Mea…		μm	
Mea…		μm	
Specific heat	700- 1400 [J/kg-K]	1047.41 log(Temp) – 1848.15 [J/kg-K]	
Thermal Conductivity @20 kPa	0.15 - 0.40 [W/m-K]	3.9e-4(Temp) + 0.1588 [W/m-K]	
Cohesion	1 kPa	1 kPa	
Angle of Internal Friction	40-55 degrees	45 degrees	

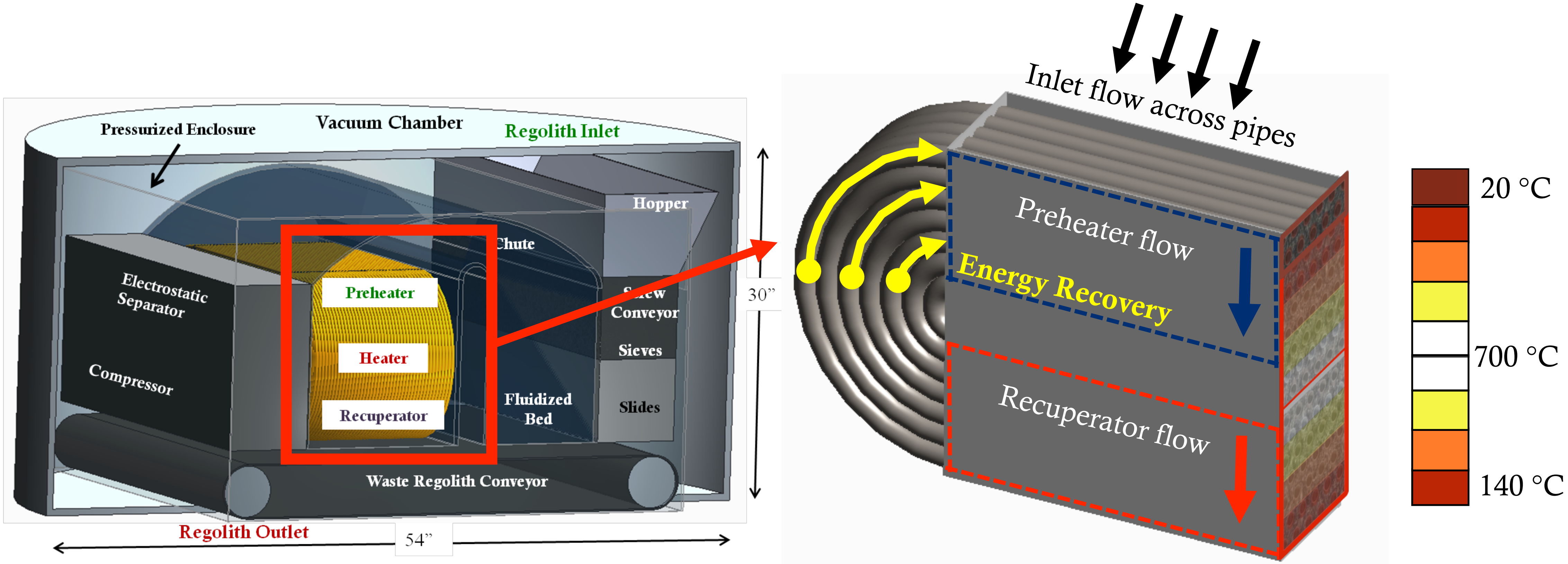
Minerals	JSC-1A
Plagioclase	37.83
Clinopyroxene	18.77
Orthopyroxene	0.66
Olivine	12.44
Glass	26.67
Magnetite	0.01
Chromite	0.00
Ilmenite	0.11
Sulphides	0.17
Iron	0.00
MgFeAl Silicate	3.06
K Feldspar	0.07
Quartz	0.01
Calcite	0.11
Others	0.07
Total	100.00

C…on

…% …e)

Si… Ti… Al… Fe… Fe… M… M… Ca… Na… K_2… P_2… LO… To…

The Heat Pipe HX (HPHX) is the Key Part of HEAT



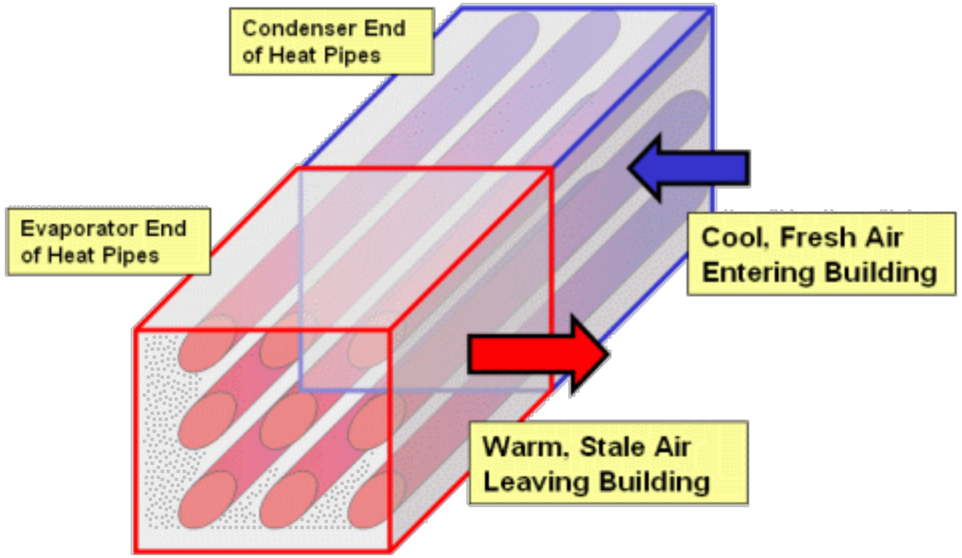
HPHX Design: Staged Counterflow HX Analysis

- Energy balance on cold and hot streams of regolith
- Effectiveness – NTU method
- Stage temp., effectiveness, conductance determined
- Stage change in regolith temperature determined
- HX surface area determined

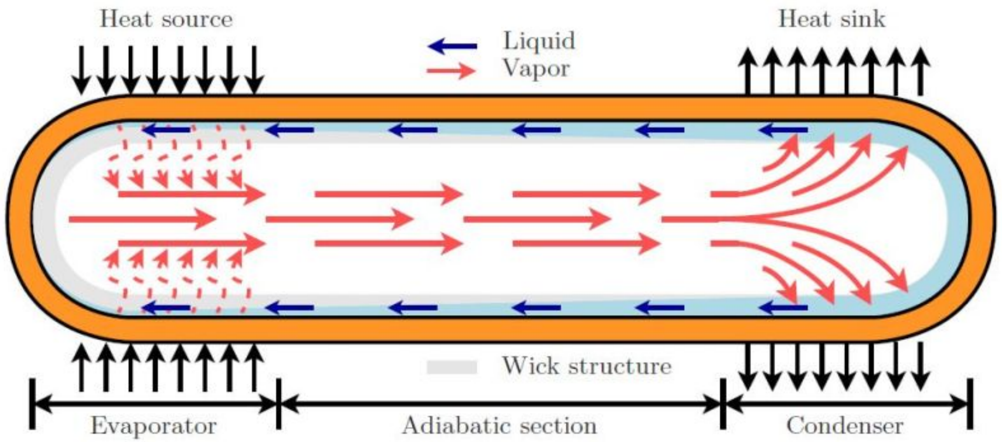
$$Q = C_h (T_{hi} - T_{ho}) = C_h \varepsilon_h (T_{hi} - T_p) = C_c (T_{co} - T_{ci}) = C_c \varepsilon_c (T_p - T_{ci})$$

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

$$NTU_h = h_h A_h / C_h \qquad NTU_c = h_c A_c / C_c$$

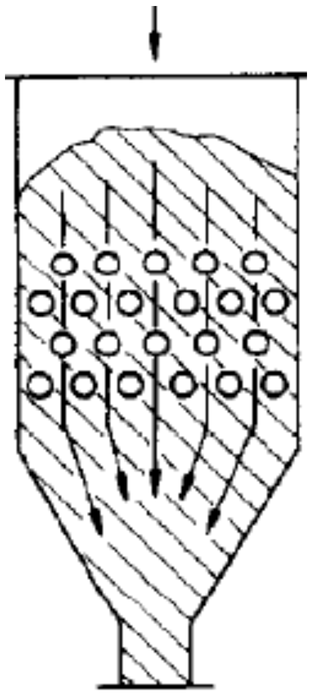


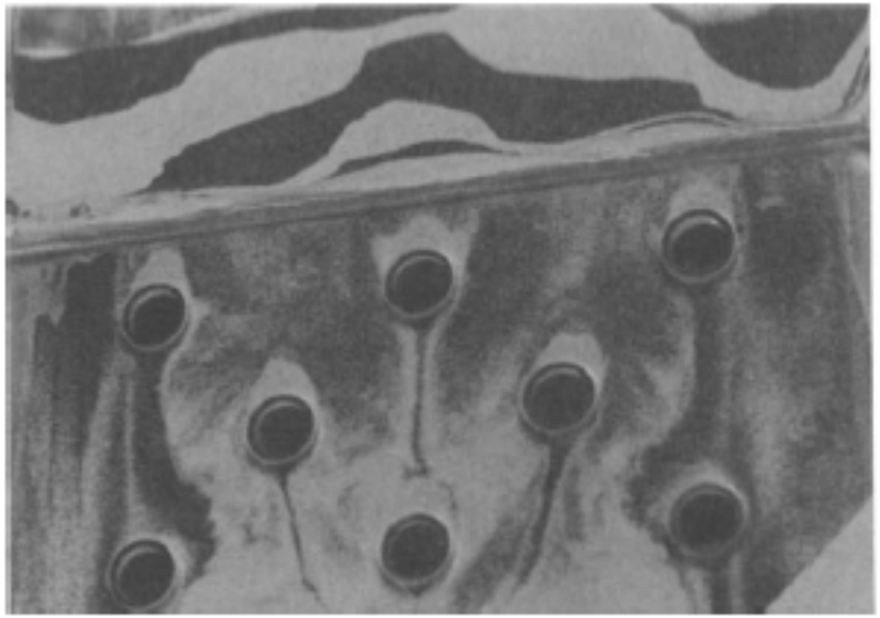
Credit: Des Champs Labs,1993



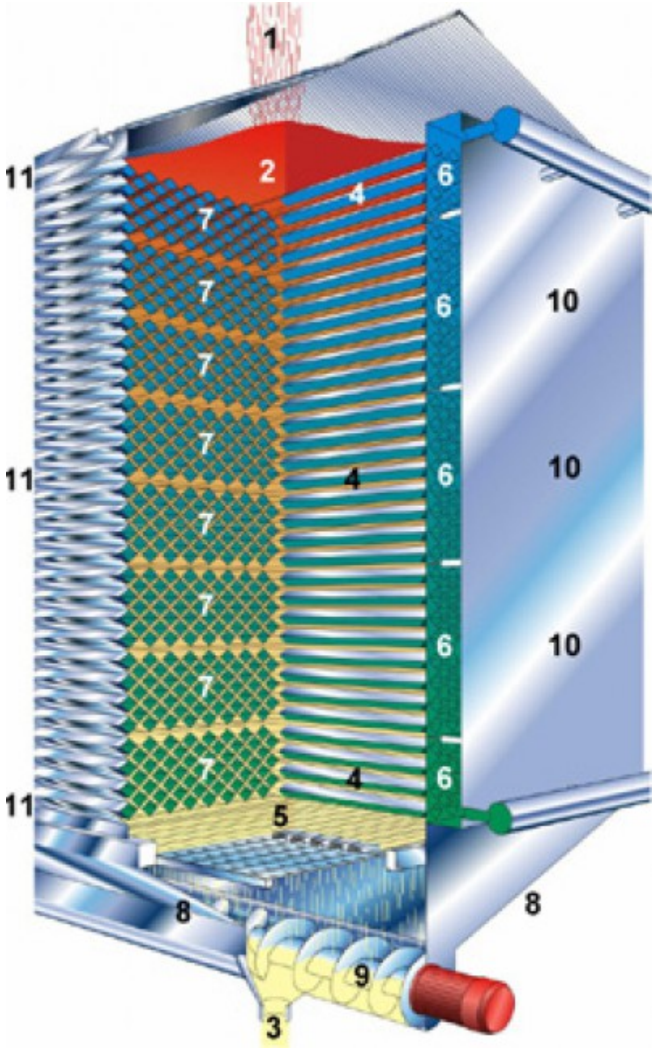
HPHX Design: Moving Bed Flow and Heat Transfer

- Moving Bed Heat Exchangers
  - Thermal Energy Storage
  - Heat recovery from bulk solids

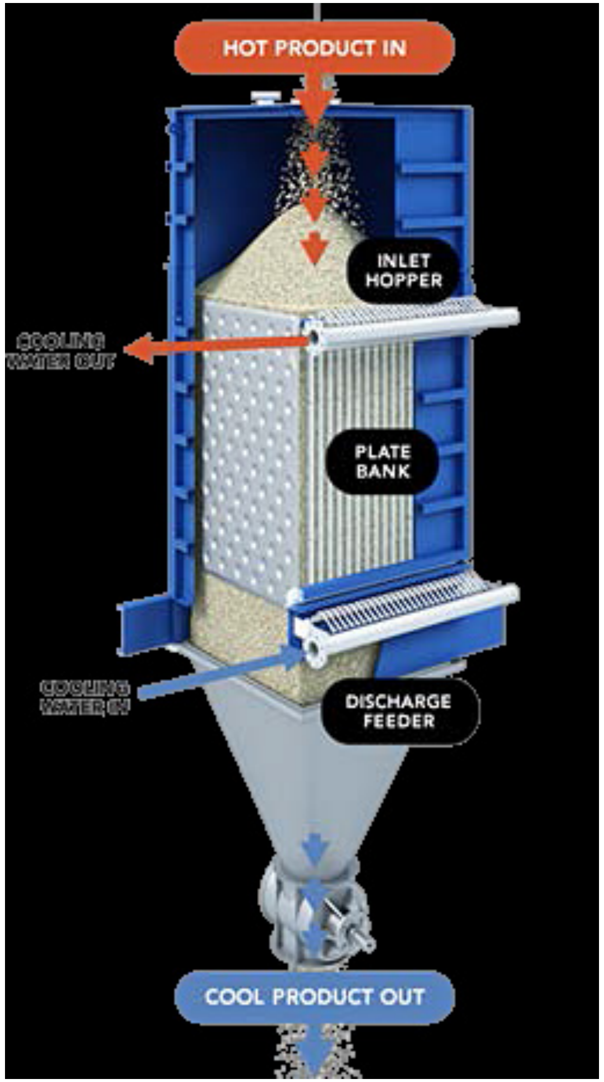




Credit: Niegsch et al.,1994



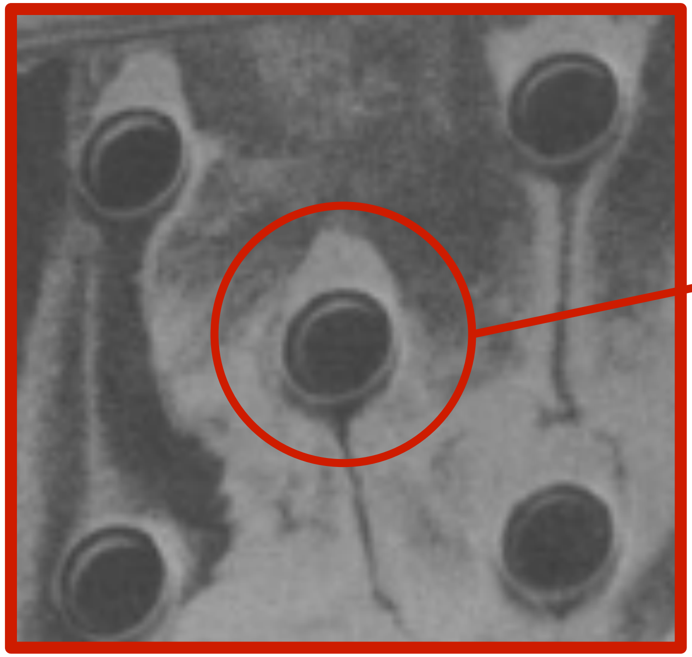
Credit: Grenzebach Group



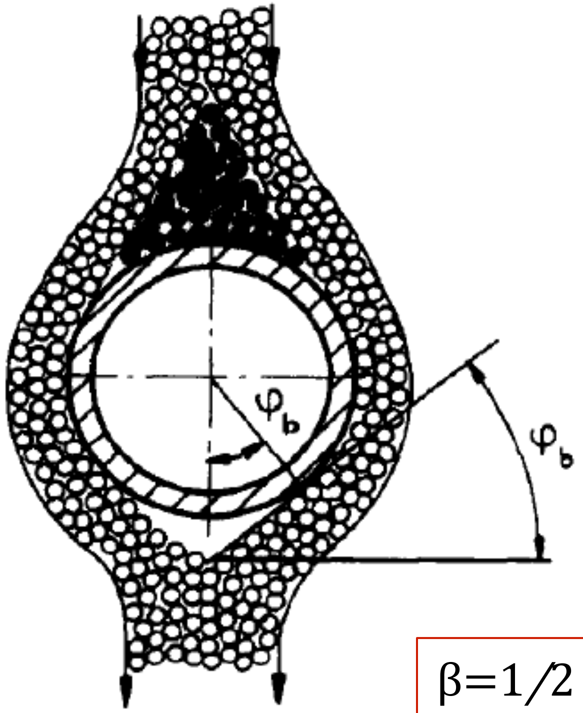
Credit: NETL/DOE, 2014

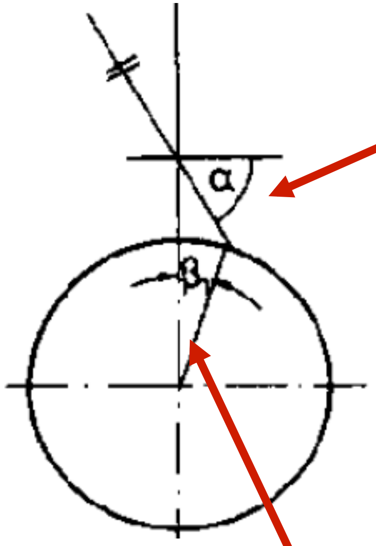
HPHX Design: Moving Bed Flow Model

- 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

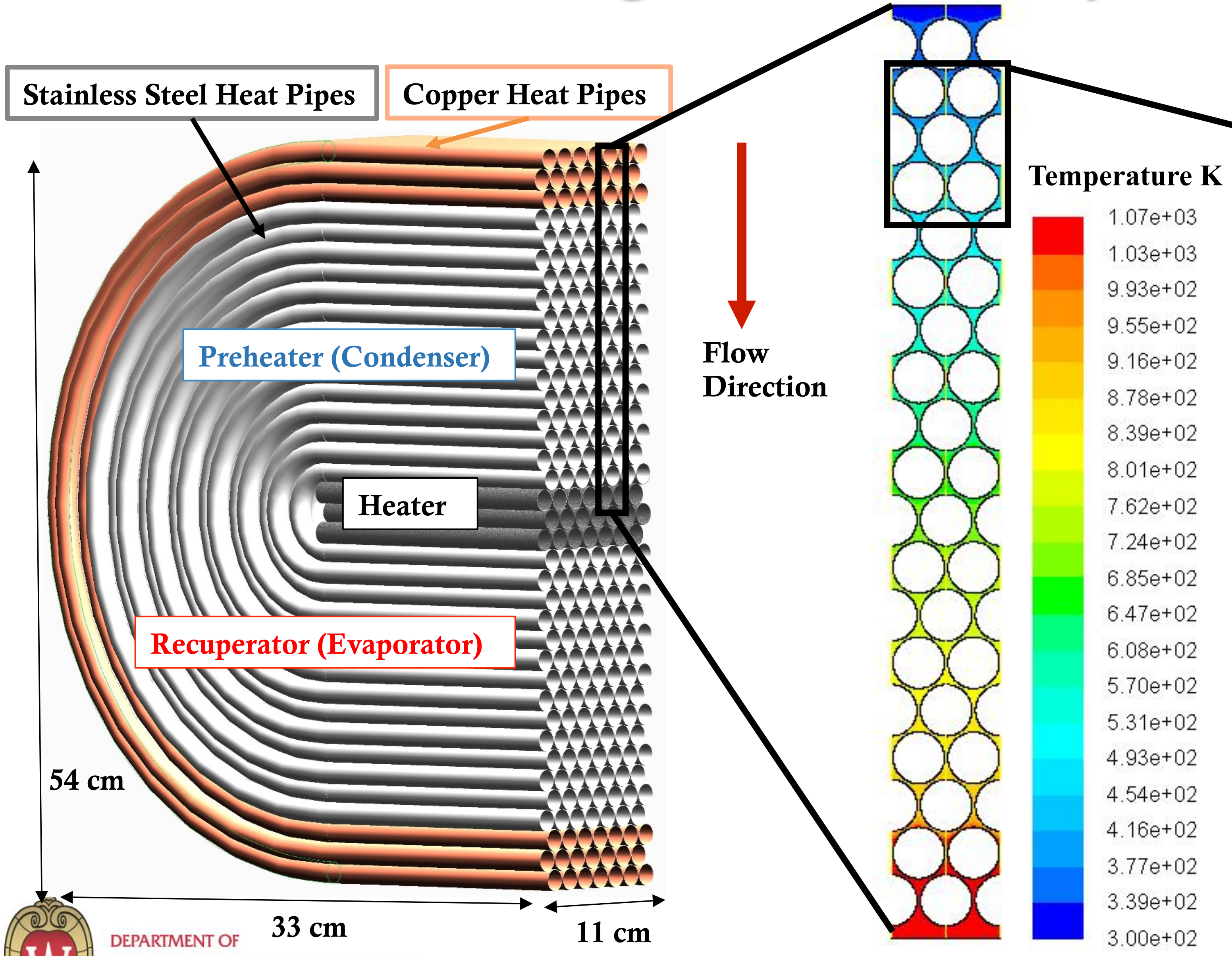




$$\alpha = \pi/4 + \varphi_e$$

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

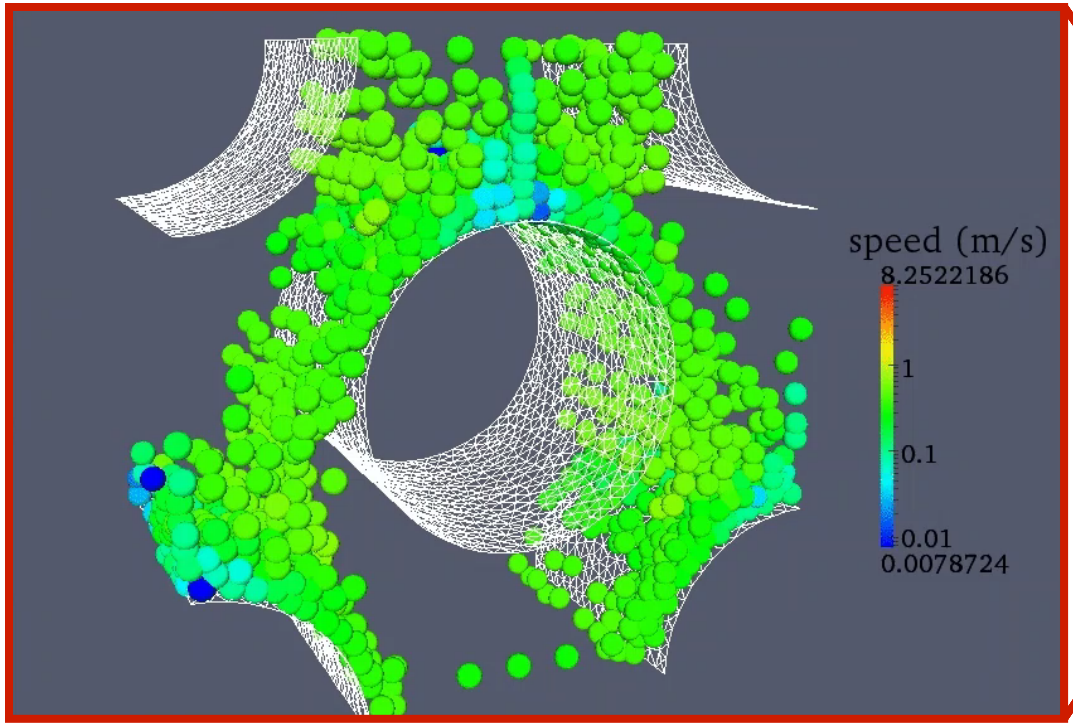
HPHX Design: Preliminary Thesis Design Work

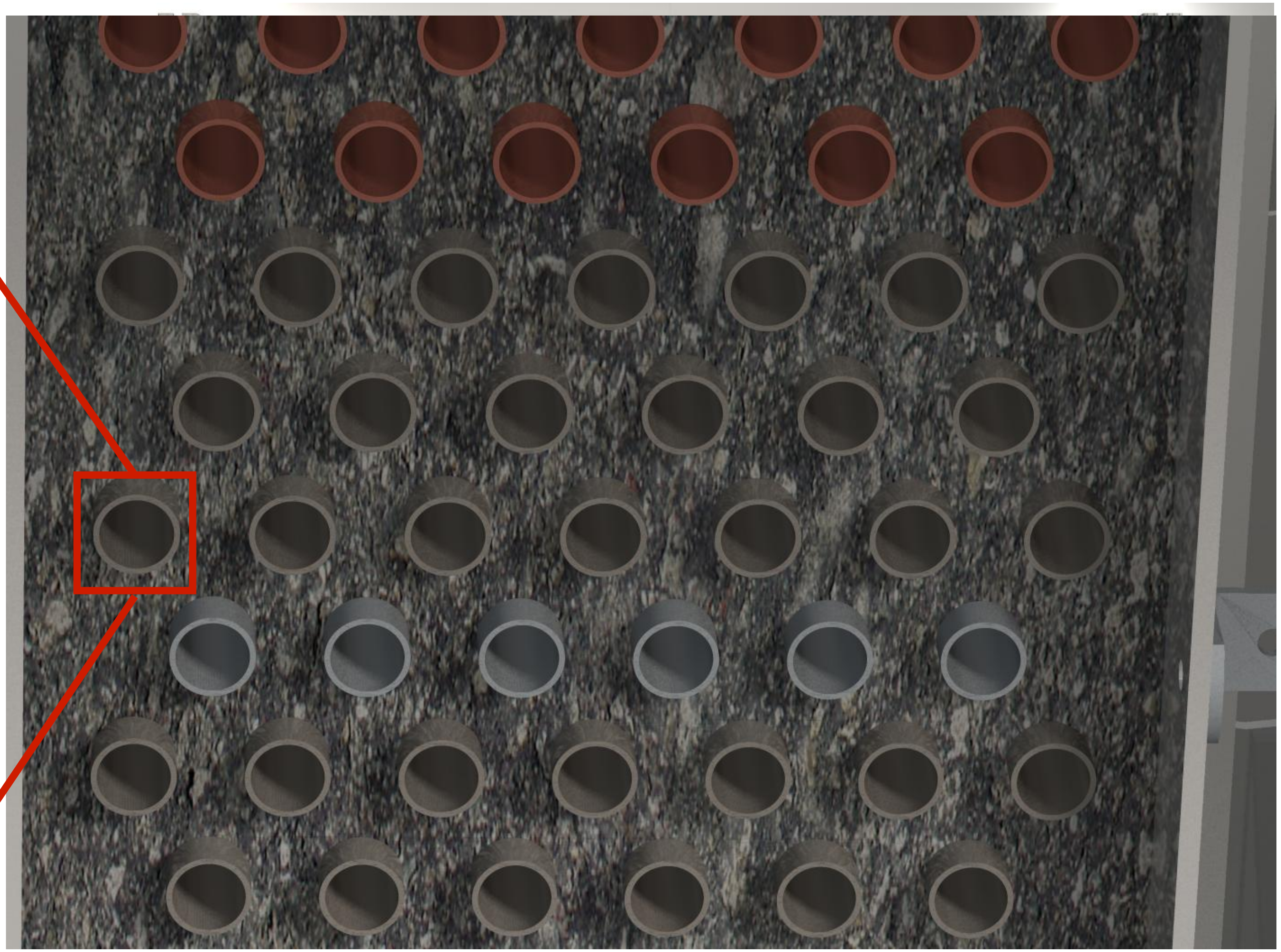


Heat pipes	119
Columns	7
Rows	17
Pipe outer diameter	1.5 cm
Pipe heat exchanging length	22.3 cm
Heater rows	3
Distance between pipe columns	1 mm
Heat exchanger mass	6 kg
Heat exchanger height	54 cm
Heat exchanger width	10.7 cm

Verify HPHX Design: Testing of Flow and Heat Transfer

- **Pipe to Regolith Heat Transfer Coefficient**
- **Minimum pipe spacing**
- **Verification of Analysis**





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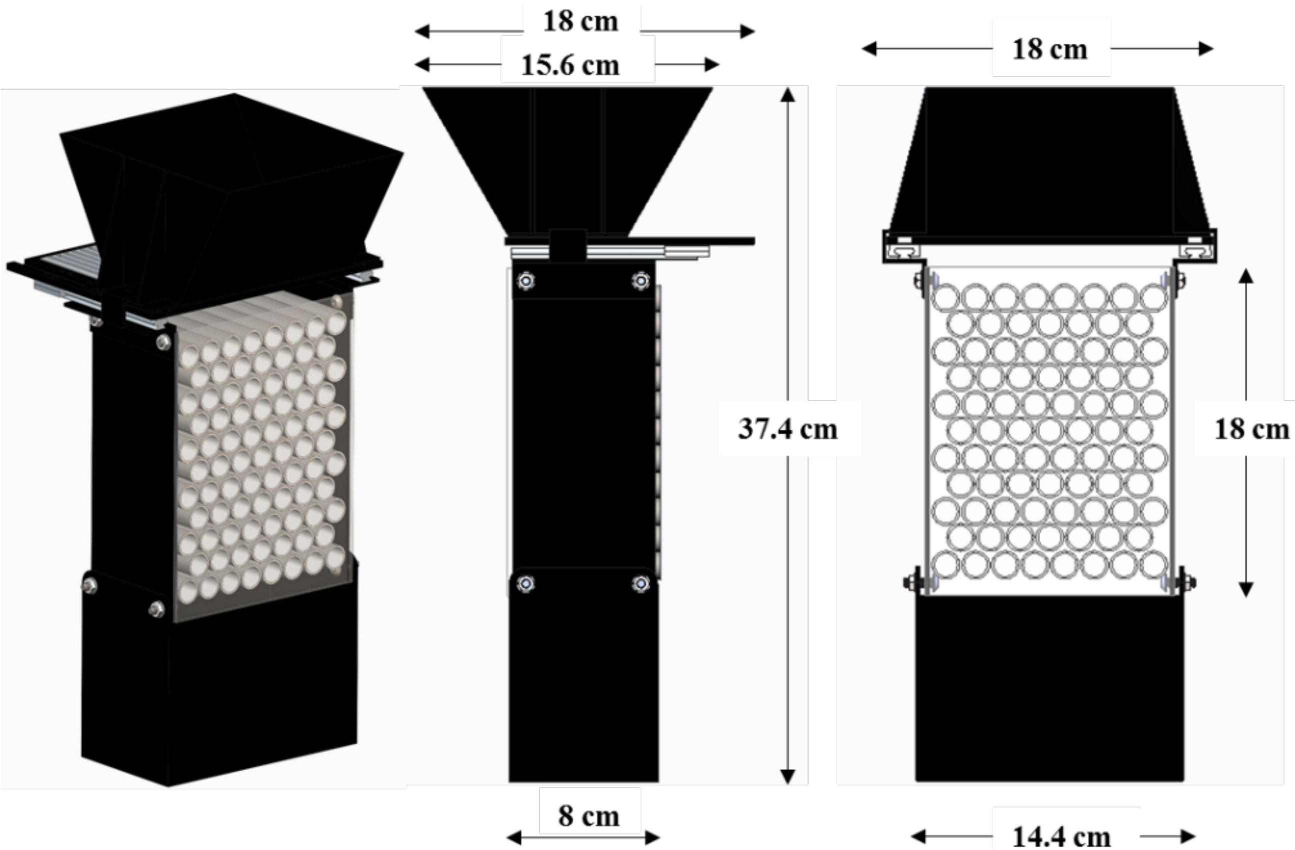
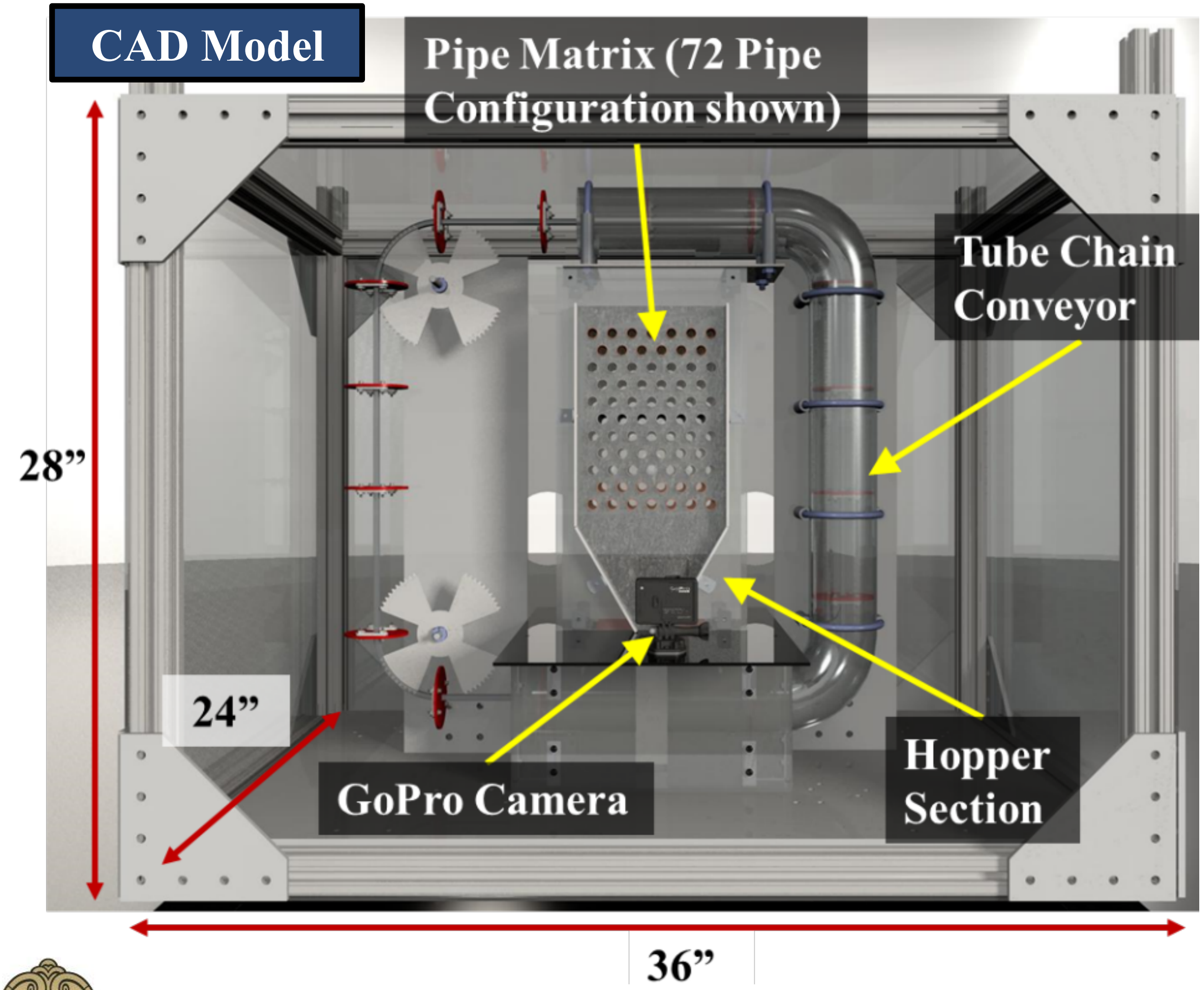
Verify HPHX Design: Granular Flow Experiment (GFX)

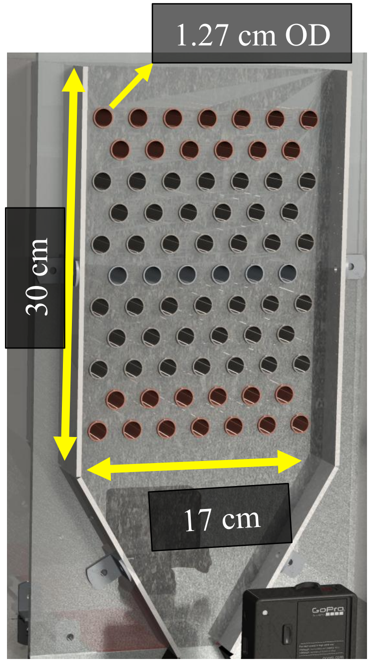
- The first iteration of testing allowed for a better second iteration
- Particle Image Velocimetry (PIV) to be used as with other studies

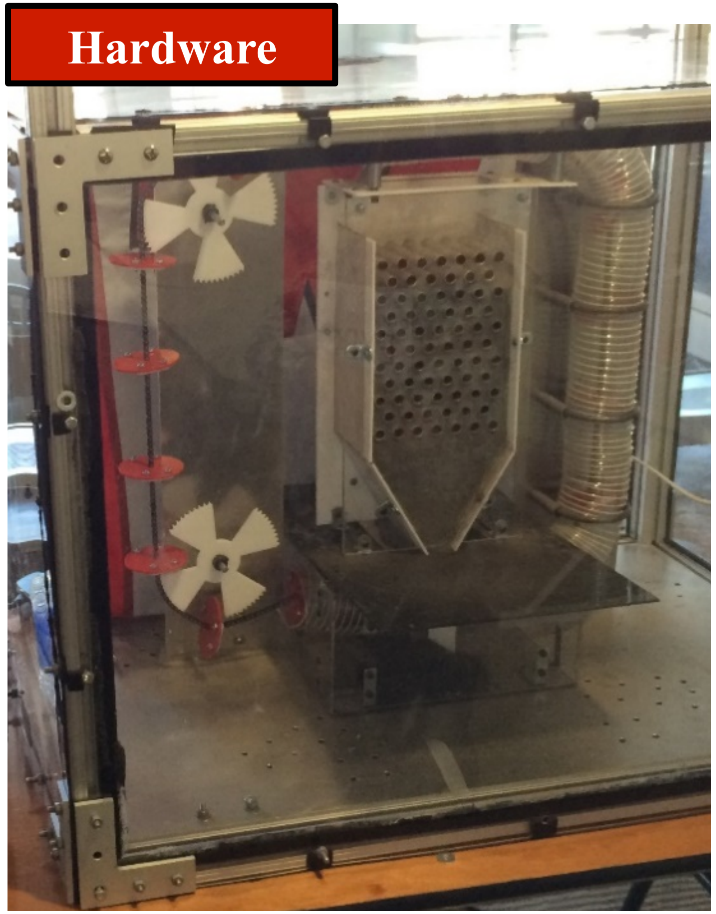


Credit: Olson, Strange, Atruktsang

Verify HPHX Design: GFX V.2 Nearly Complete



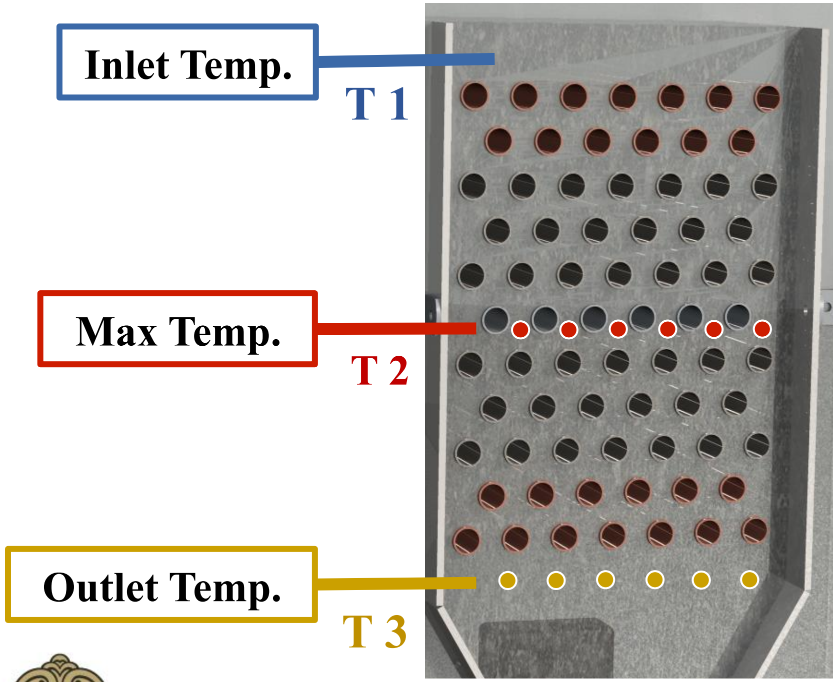




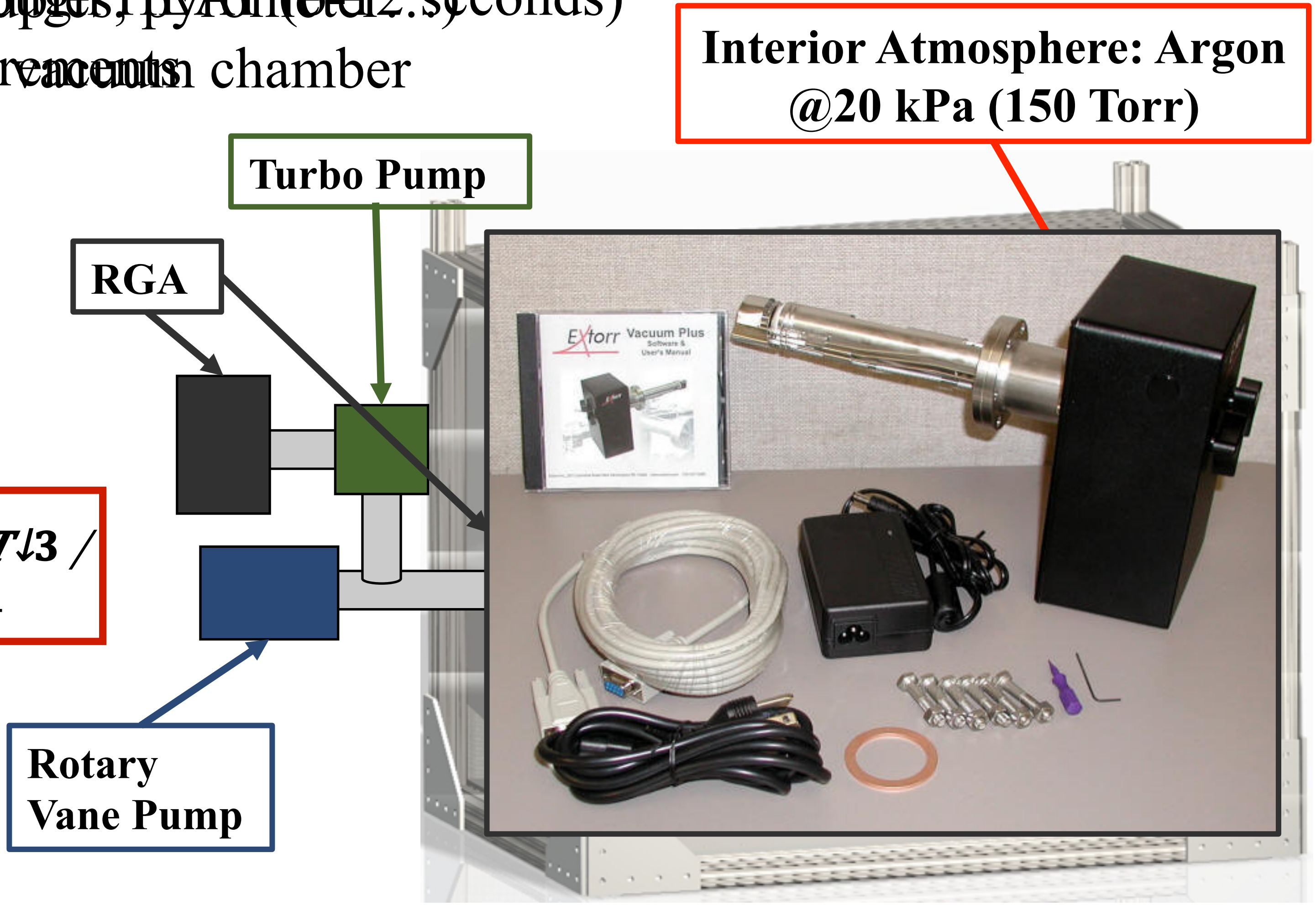
Build and Test HPHX : High Temp, Instrumentation, Procedure

- Run co-implanted JSC-1A regolith until HPHX is at steady state
- Flow 1-2 kg of implanted regolith through HEAT (6-12 seconds)
- Analyze temperature and RGA measurements

- HEAT components to be constructed for high temperature (900 °C)
- Temperature measurement (thermocouples, pyrometer...)
- Residual gas analyzer attached to low vacuum chamber



$$\varepsilon = \frac{T_2 - T_3}{T_2 - T_1}$$



There are Two Aspects to Implantation into JSC-1A

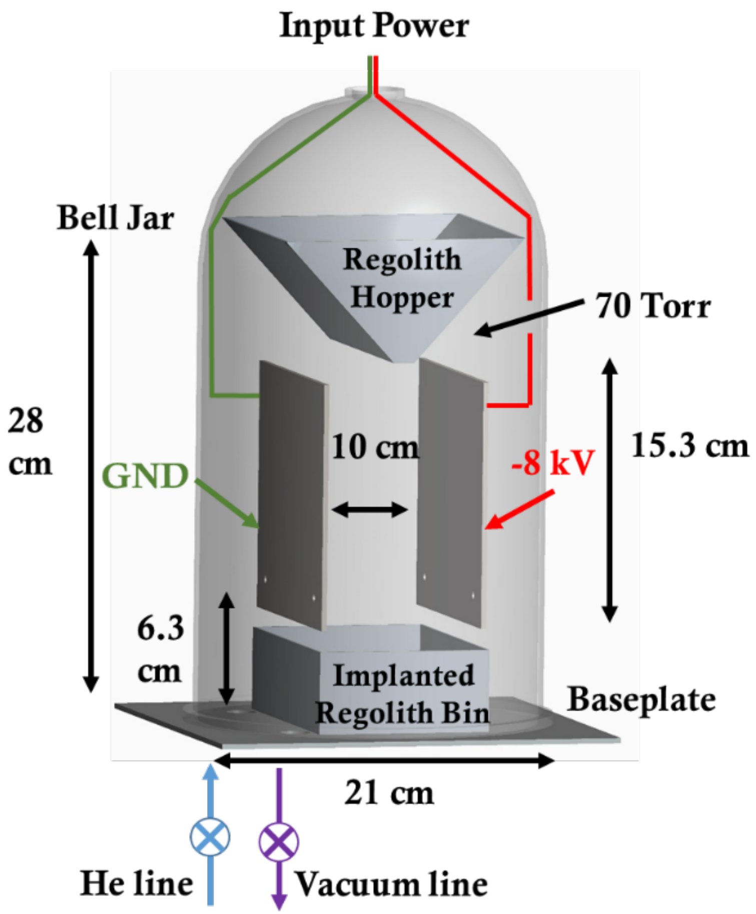
- Implantation energy: 1 keV/amu
- Aim for 20 ppb concentration
- ^{4}He diffuses out of regolith like ^{3}He (use ^{4}He for cost)

Implant ^{4}He

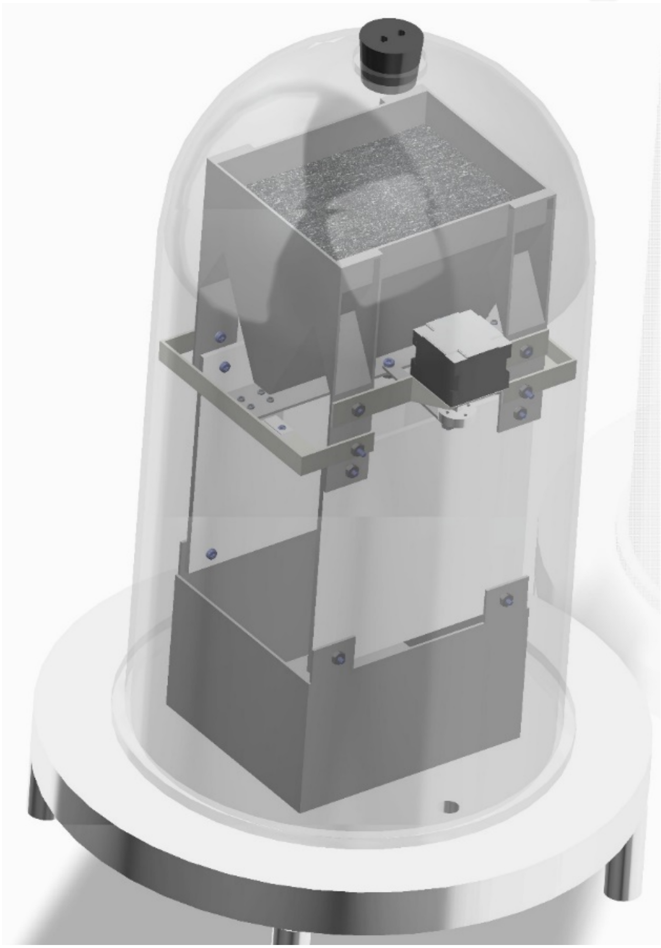
- Heat several ~1 g samples from ~1 kg batches to 1000°C
- Vacuum tube furnace, RGA
- Background ^{4}He concentration

Measure Concentration

Implant Helium: From Concept to Construction



Concept: DC Plasma Discharge



Preliminary DC Plasma Discharge Design

KSC Swampworks Lab Dust Tolerant Vacuum Chamber

Conclusion

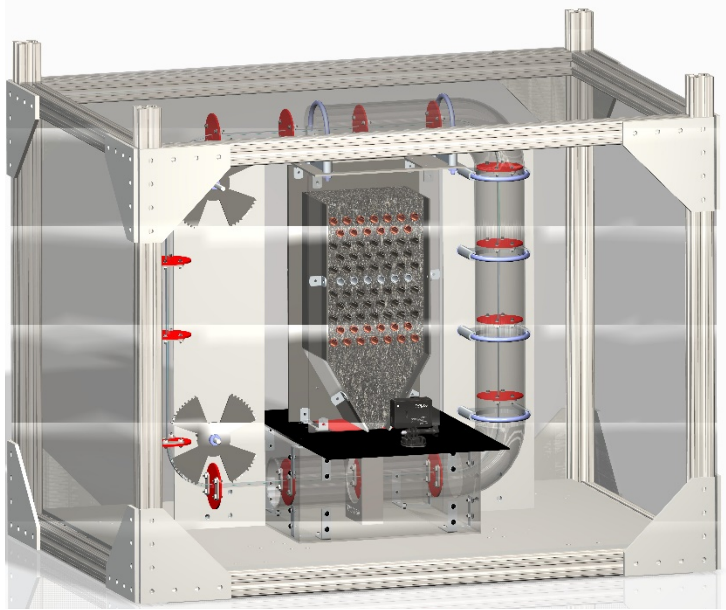
- First Demonstration of ^3He release inside of a heat pipe heat exchanger
- Requires development of HEAT and an Implantation device

Goal	Evaluation Criteria
^3He release rate of 5 μg/s (1/1000th of Mark series designs)	RGA measurements of atmosphere inside of the HEAT system
Achieve 85% thermal energy recovery efficiency	Change in temperature of the regolith simulant throughout the HEAT system as measured by thermocouples
Recommendations to improve the system for a future lunar pilot scale miner	Design alterations to increase the ^3He release rate and the energy recovery efficiency

Wisconsin ^{3}He Extraction Research Roadmap

Lab Prototypes

- Heating System Optimization
- Evolved ^{3}He Measurement



(UW HEAT GFX)

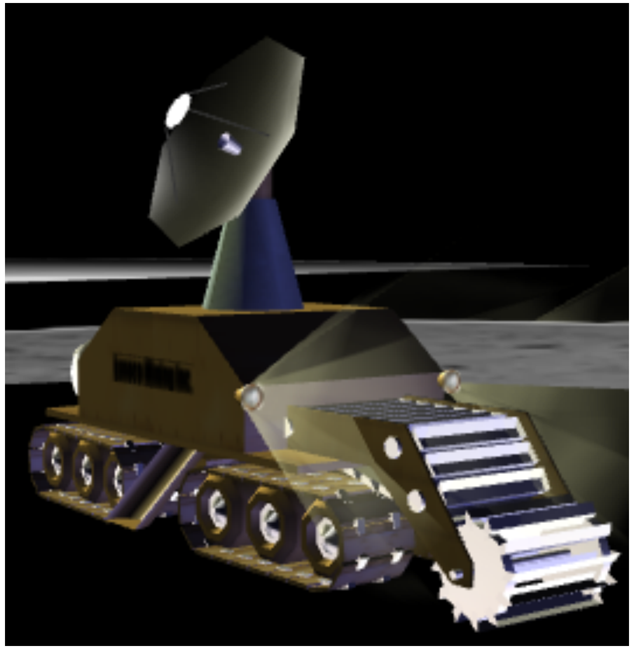
Lunar Gravity Testing

- Regolith Flow through Heating System in Lunar Gravity

(Lunar G HEAT)

Small Scale Lunar Mission

- INTERLUNE 1 Concept
- Use of GLXP Provider(s)?



(Micro ^{3}He Miner)

A Potential Roadmap for Lunar Helium-3

Prospecting and Research ~2015-2025

- Government missions
- **Research at UW-Madison**
- Google Lunar X-Prize

(NASA RESOLVE)

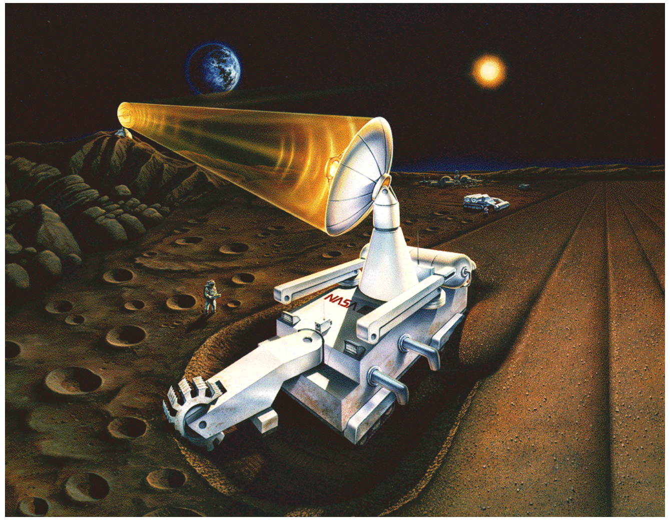
Small Scale Mining ~2025-2035

- First small test lunar miners
- Start of lunar outposts
- Other mining activities starting

(Small scale concept)

Established Mining Industry ~Post 2035

- Large lunar miners
- Established Moon-Earth shipping
- **^{3}He Fusion Reactors**



(UW Mark-II concept)

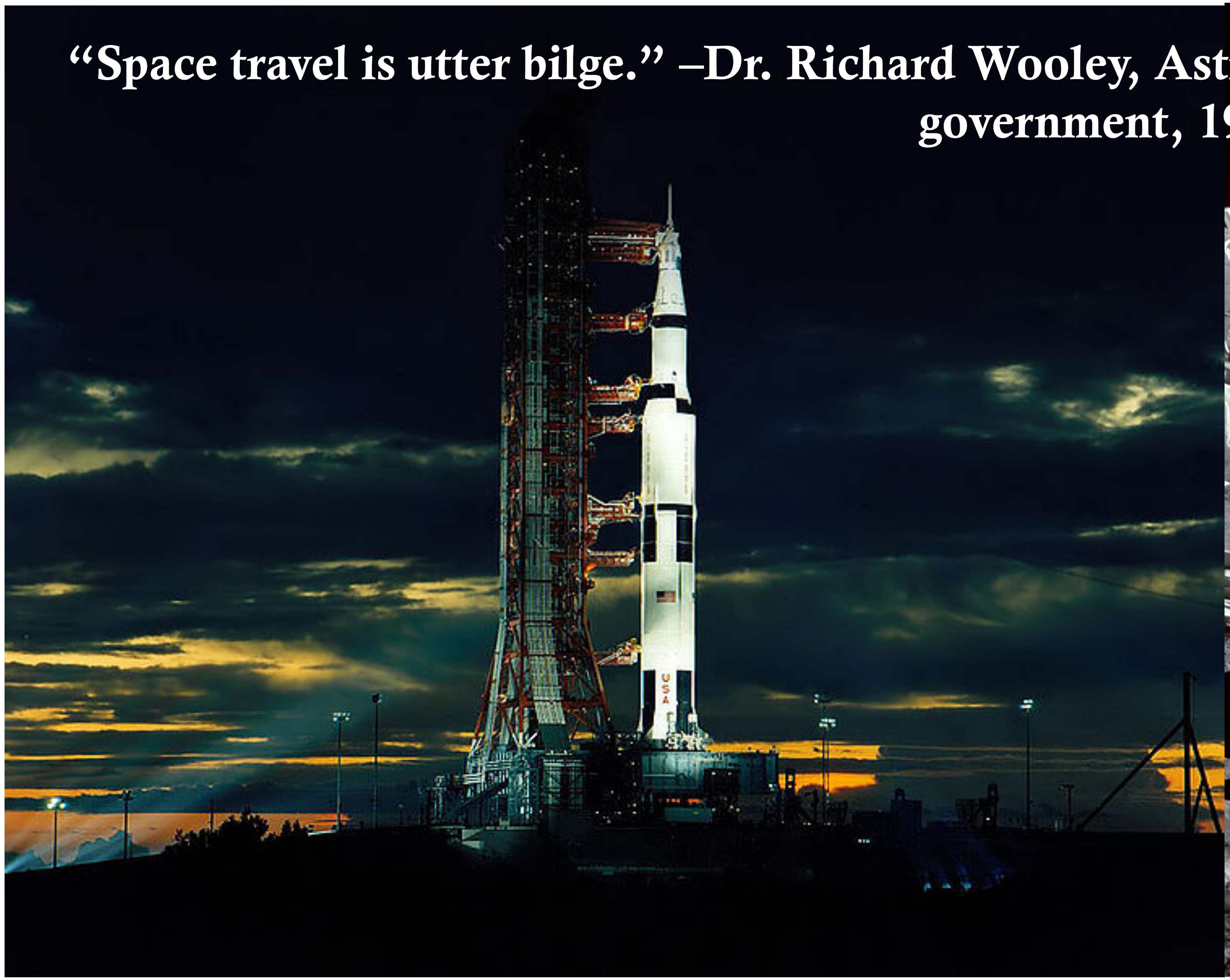
Questions?

Acknowledgments

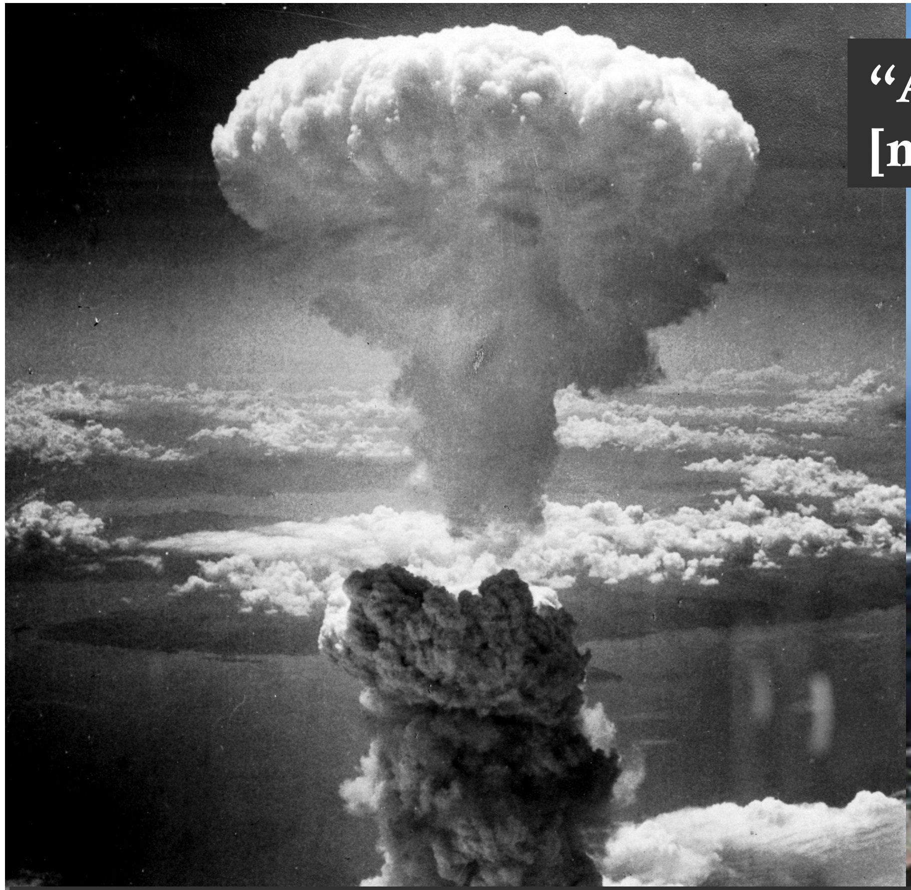
- NASA Space Technology Research Fellowship Program
- Greatbatch Foundation
- Grainger Foundation
- Wisconsin Space Grant Consortium

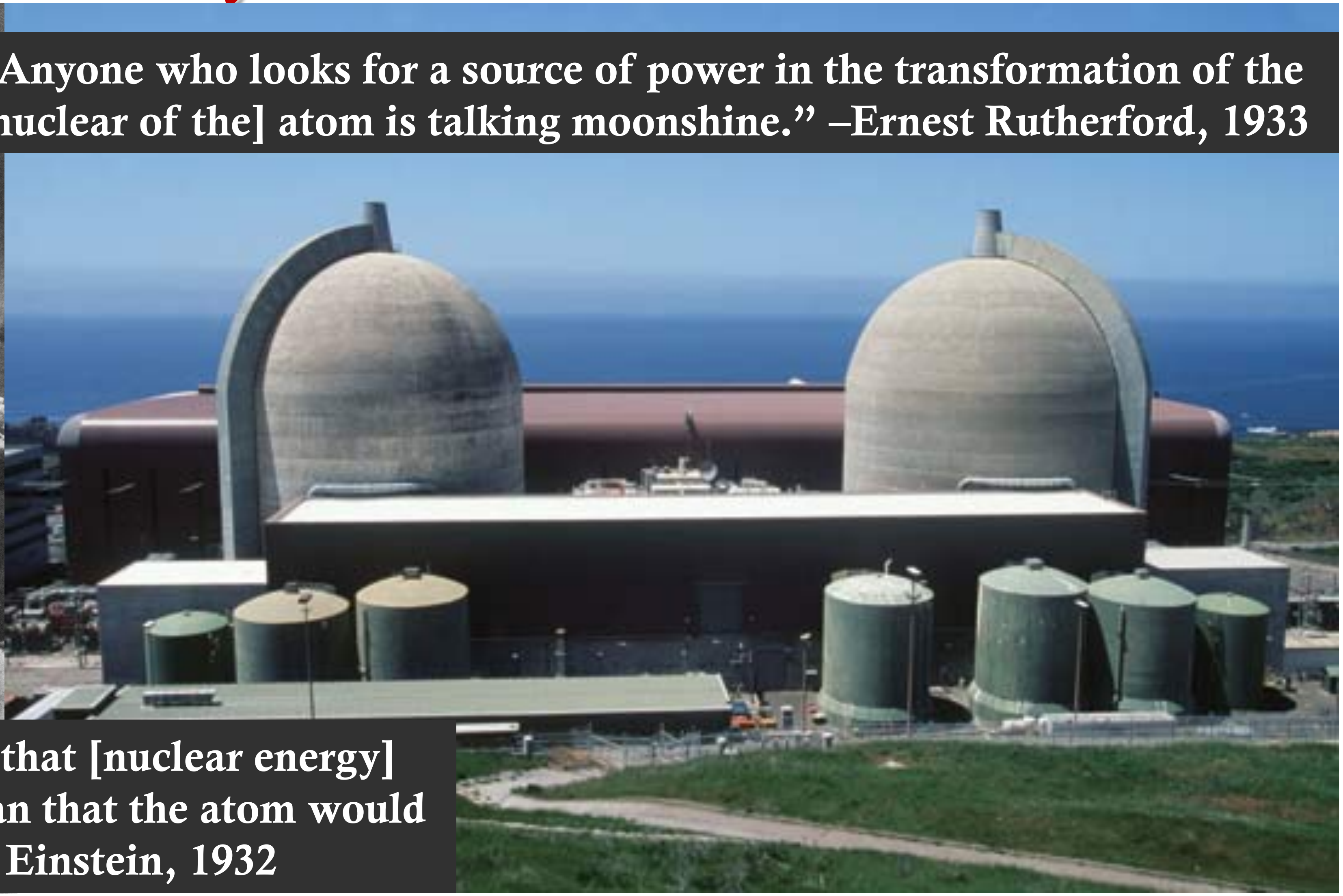
Mining ^{3}He and using it for Fusion Could Happen Sooner than you Think

"Space travel is utter bilge." –Dr. Richard Wooley, Astronomer Royal, space advisor to the British government, 1956



Mining ^3He and using it for Fusion Could Happen Sooner than you Think





"Anyone who looks for a source of power in the transformation of the [nuclear of the] atom is talking moonshine." –Ernest Rutherford, 1933

"There is not the slightest indication that [nuclear energy] will ever be obtainable. It would mean that the atom would have to be shattered at will." –Albert Einstein, 1932

Upcoming Lunar ^{3}He Fusion Book

Lunar Helium-3 Fusion: The Earth's Energy Future

Follow-on to *Return to the Moon* by Dr. Harrison Schmitt, to be published in 2015

Discusses

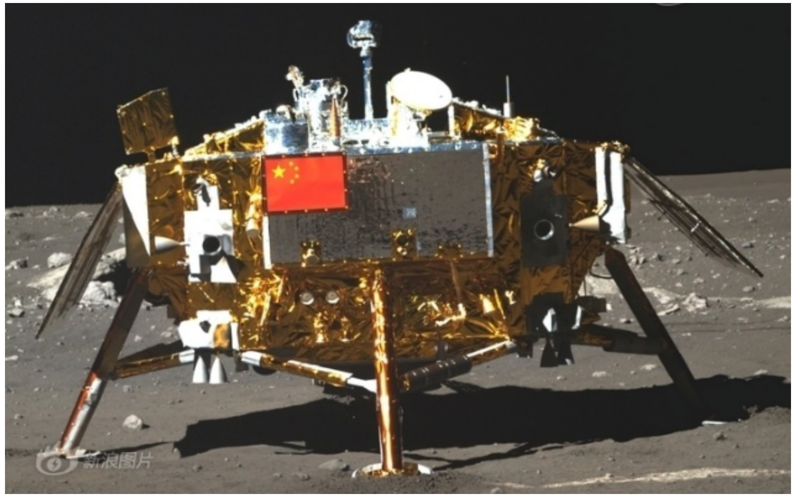
- Increasing need for power worldwide
- Potential role of ^{3}He fusion technology
- Lunar bases and resources
- Legal regimes for lunar mining
- Economics of ^{3}He procurement
- Terrestrial fusion power plants
- Space applications of ^{3}He fusion
- Current lunar initiatives around the world

Authors: Dr. Harrison Schmitt, Dr. Gerald Kulcinski, Dr. John Santarius, Aaron Olson

Lunar Mining and Prospecting Systems are Being Developed

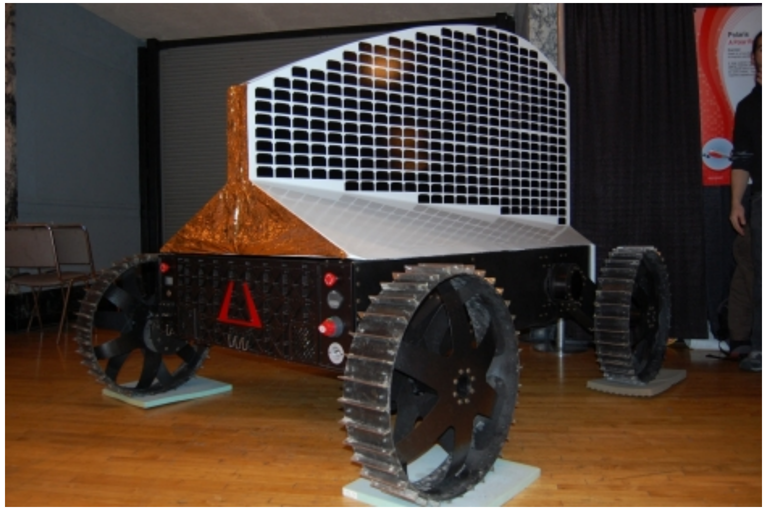
Credit: Lockheed Martin, 2010

Credit: NASA KSC, 2012

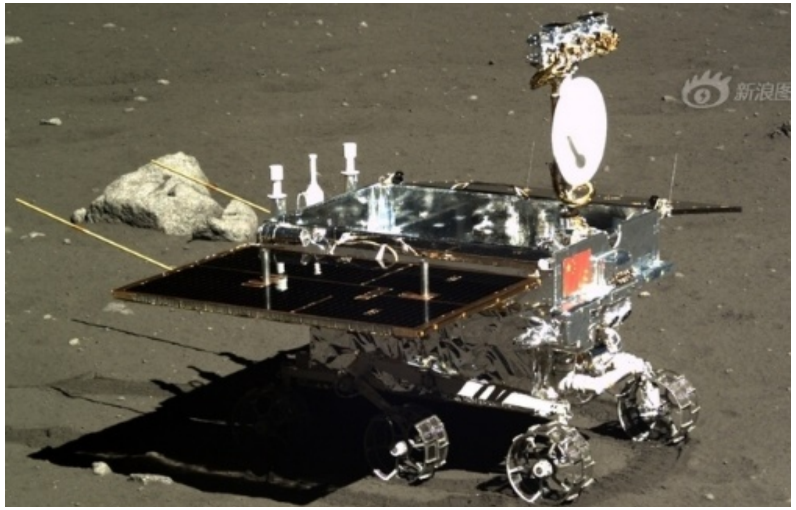


Credit: CNSA/CLEP, 2013

Credit: Laurentian U., 2011



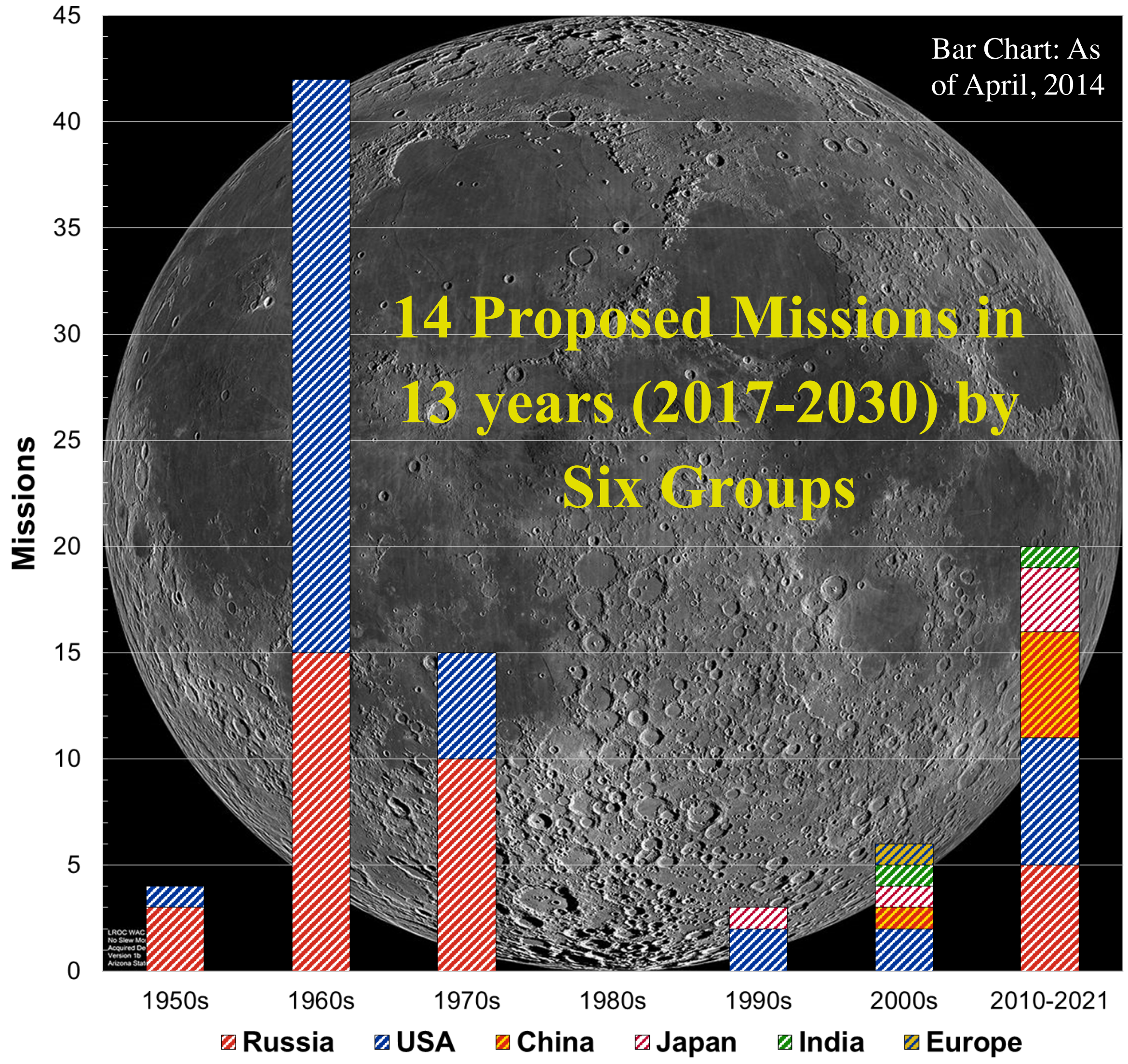
Credit: Astrobotic, 2013



Credit: CNSA/CLEP, 2013

Interest in Lunar Exploration is Ramping Up

Lunar Mission Manifest			
Launch Date	**Organization**	**Country**	**Mission**
2015-2018	Google Lunar XPrize (GLXP)		GLXP
2017	CNSA	China	Chang'e-5
2017	JAXA	Japan	SELENE-2
2018	ISRO	India	Chandrayaan-2
2018	NASA	USA	RP
2018	NASA	USA	EM-1
2020	CNSA	China	Chang'e-6
2021	NASA	USA	EM-2
2020s	Roscosmos	Russia	Luna-25
			Luna-26
			Luna-27
			Luna-28
			Luna-29
	JAXA	Japan	SELENE-3



There are Three Key Steps for HEAT

HPHX Design

- Regolith ΔT
- Mass Optimization
- Heat Recovery

Verify HPHX Design

- Testing
- Regolith flow
- Heat transfer

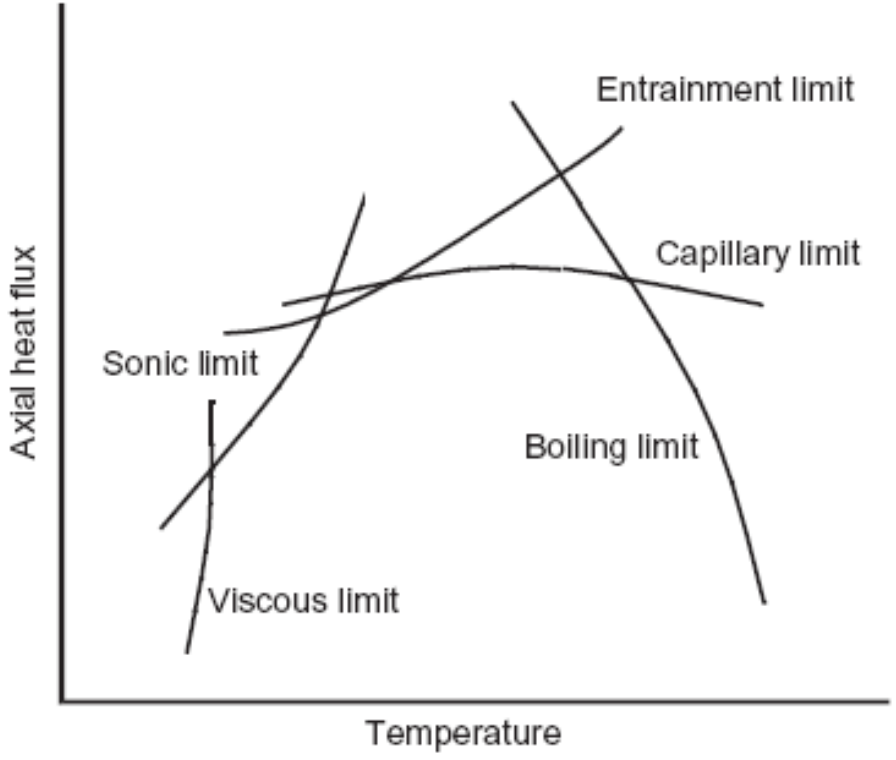
Build and Test HEAT

- Heat Pipes
- High Temp. System
- Instrumentation

HPHX Design: Heat Pipe Design Considerations

Temperature Range (°C)	Working Fluid	Vessel Material
5-230	Water	Copper, Cu-Ni alloys
190-550	Mercury	Stainless steel
300-600	Cesium	Nickel, Ni-Cr alloys
400-800	Potassium	Stainless steel, Nickel
500-900	Sodium	Stainless steel, Nickel

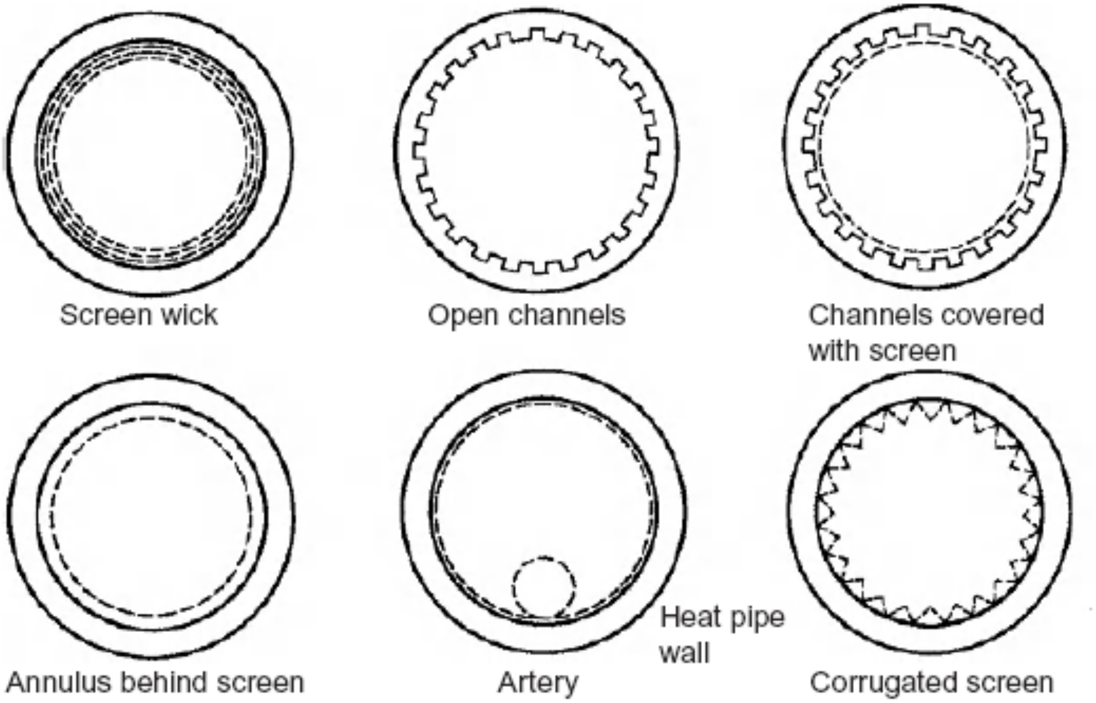
Heat Pipe Limit	Description
Capillary	Capillary pressure of the wick cannot overcome the pressure drops
Viscous	Vapor flow is inhibited by viscous forces at the inner wick surface
Sonic	The vapor velocity maxes out at Mach 1 (speed of sound)
Entrainment	The prevention of liquid return flow
Boiling	Film boiling starts at the evaporator section



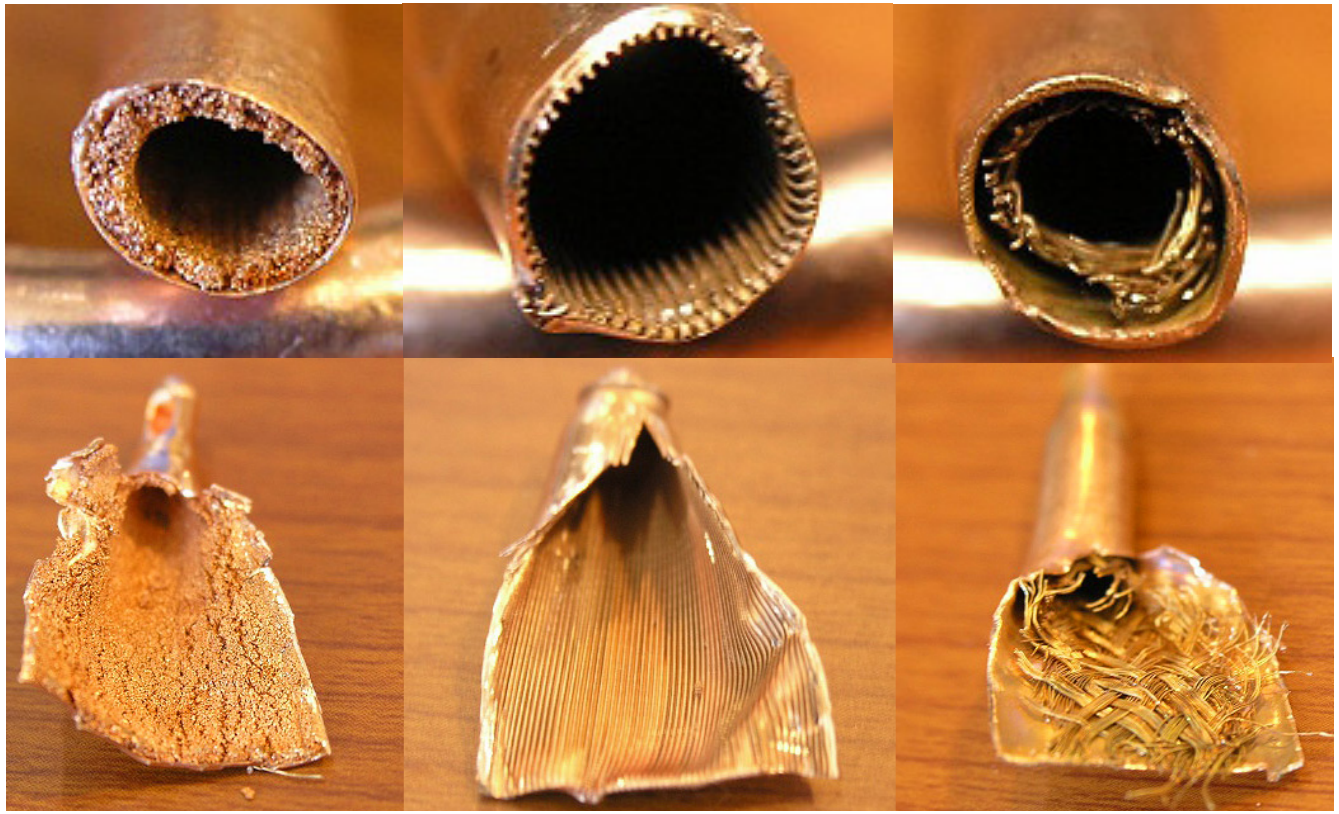
Credit: D.Reay (Heat Pipes, 2005)

HPHX Design: Heat Pipe Design Considerations

- Heat pipe wick to be determined, there are a number of options



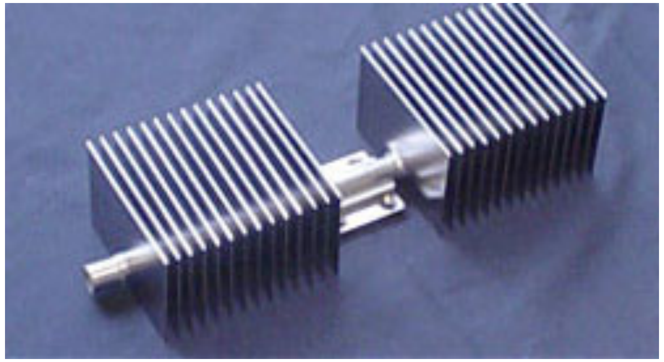
Credit: D.Reay (Heat Pipes, 2005)



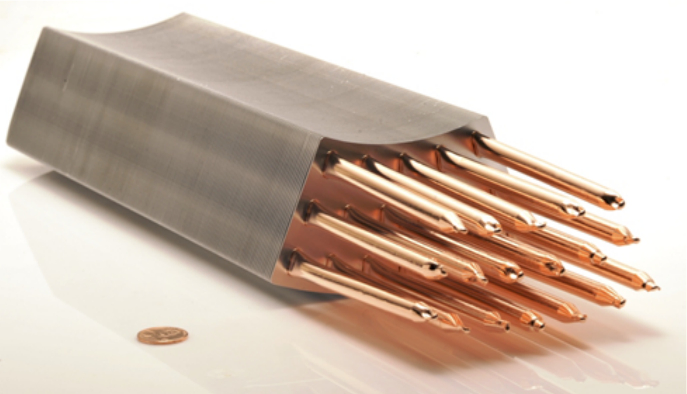
Credit: Thermolab

HPHX Design: Three Heat Pipe Manufacturers Identified

Credit: ACT



Credit: ACT



Credit: Thermacore

Credit: ACT

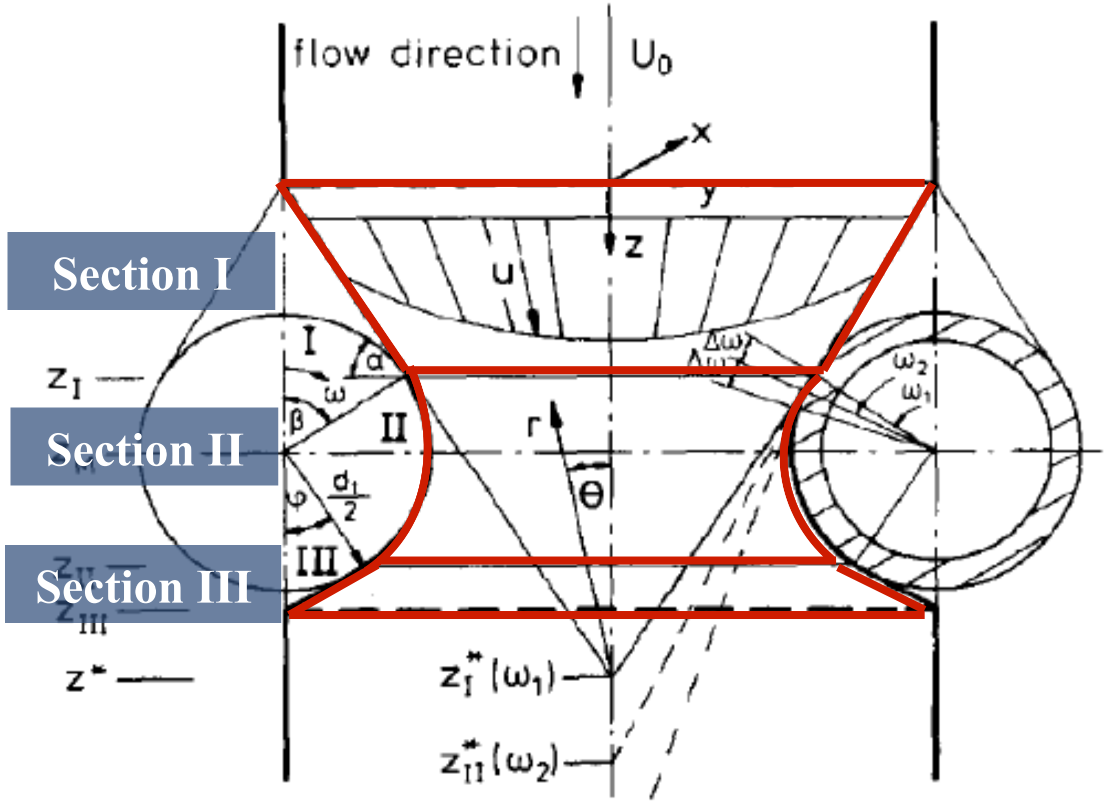
ACT
INNOVATIONS IN ACTION
The Thermal Management Experts

THERMACORE
Thermal Management Solutions

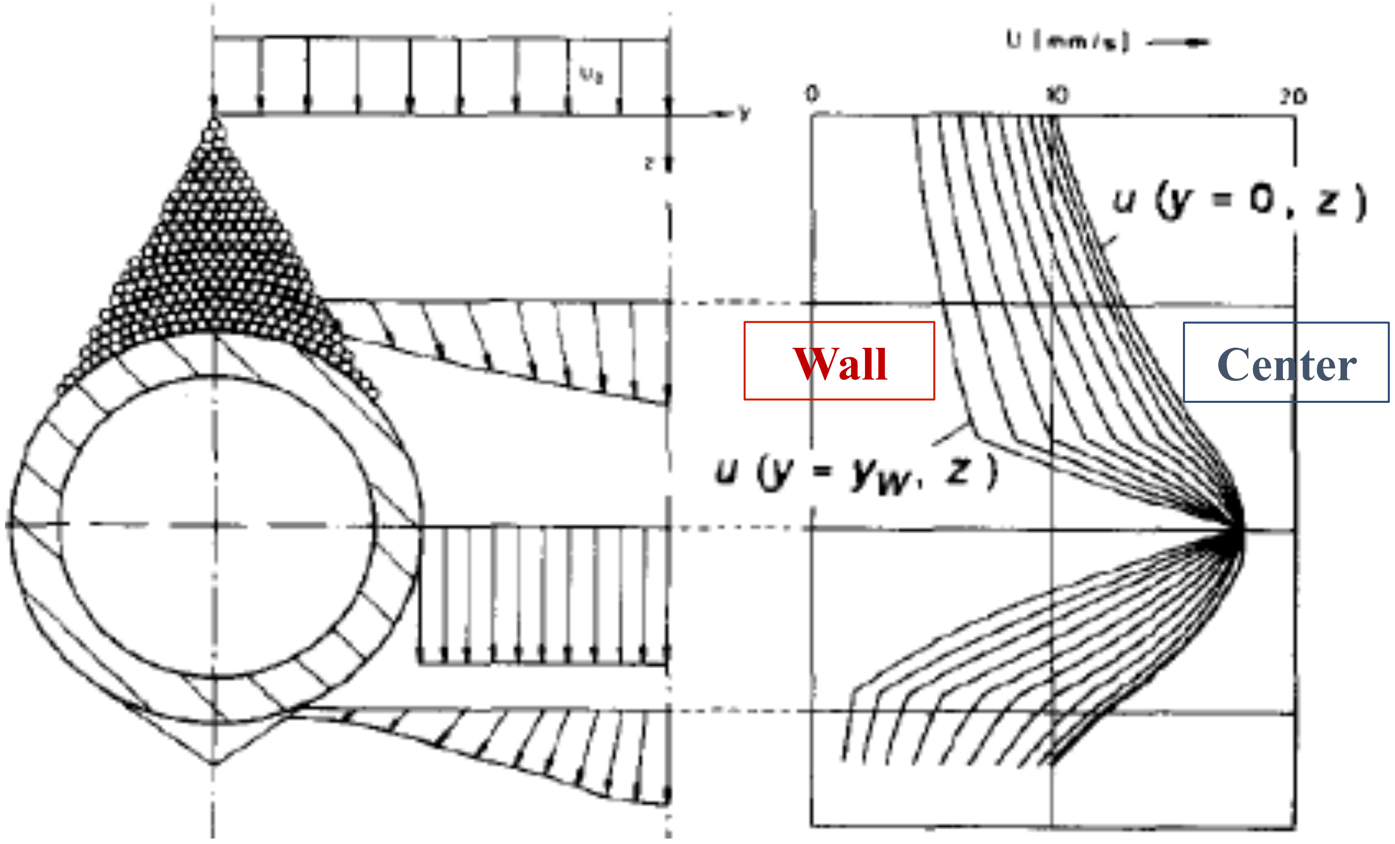
ENERTRON
TOTAL THERMAL MANAGEMENT SOLUTIONS

HPHX Design: Moving Bed Velocity Field Solution

- Steady 2D flow, material is described as an isotropic, incompressible continuum fluid



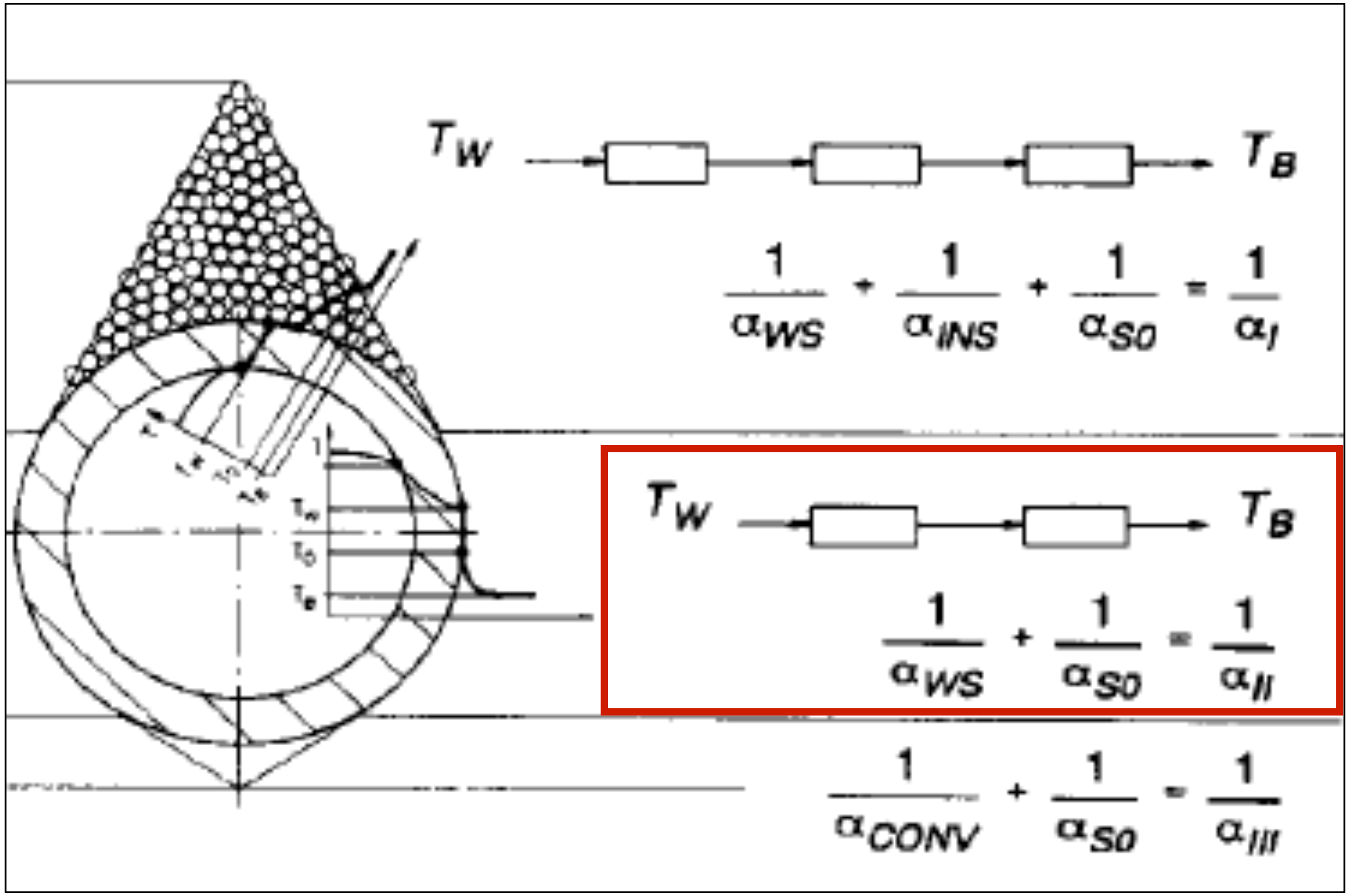
Credit: Niegsch et al.,1994



Credit: Niegsch et al.,1994

HPHX Design: Moving Bed Heat Transfer

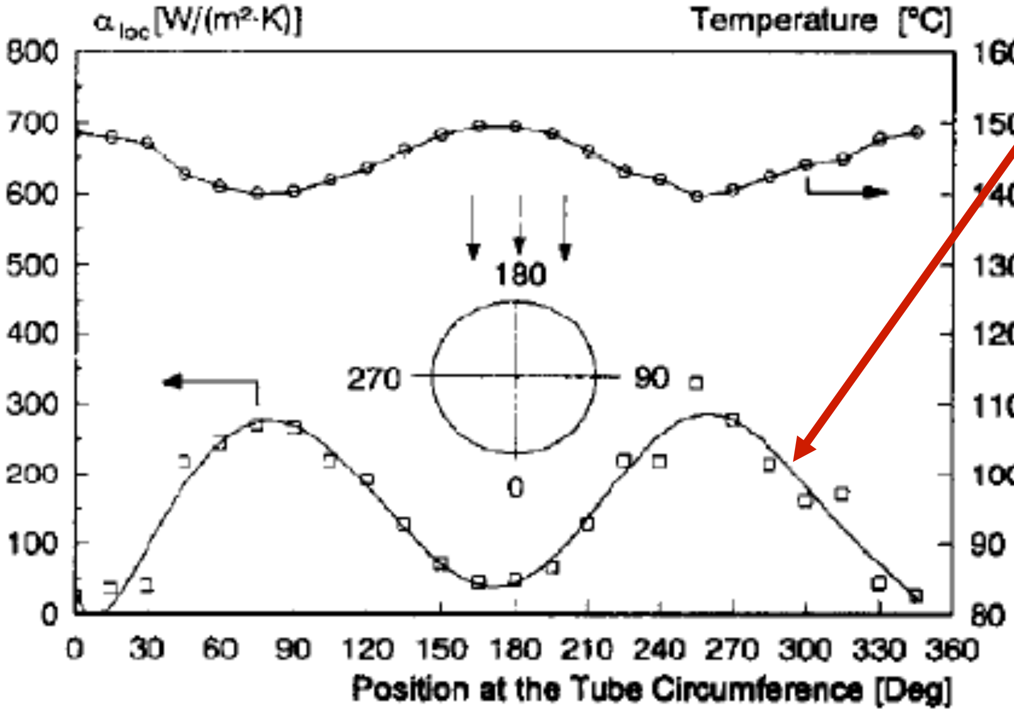
- Thermal resistances vary by section
- Section II has the greatest influence
- Surface heat transfer coefficient
- Heat penetration into the bulk



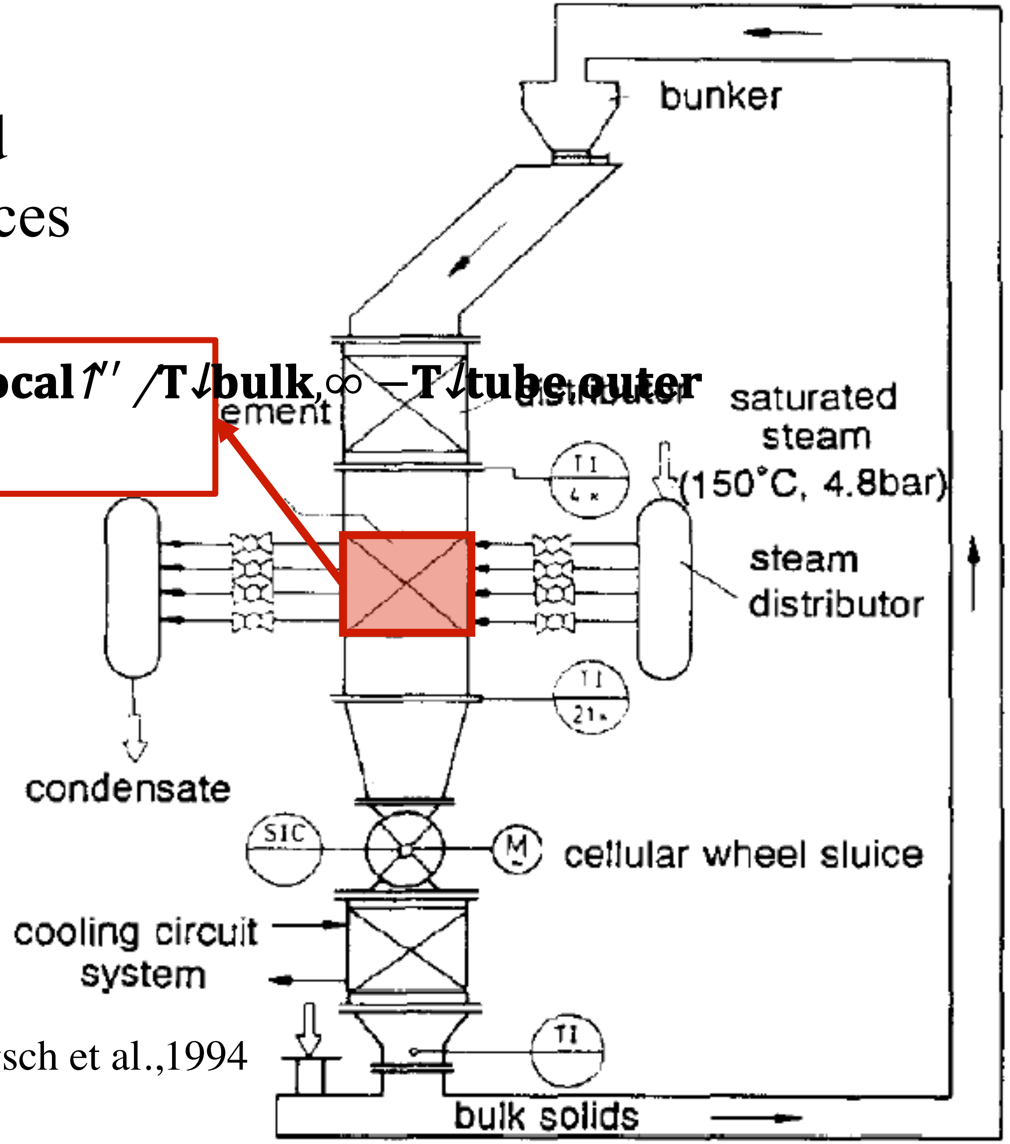
Credit: Niegsch et al.,1994

HPHX Design: Moving Bed Experimental Results

- Niegsch Model matches experimental results
- Heat transfer coefficients measured with a steam heated tube with thermocouples on its inside and outside surfaces



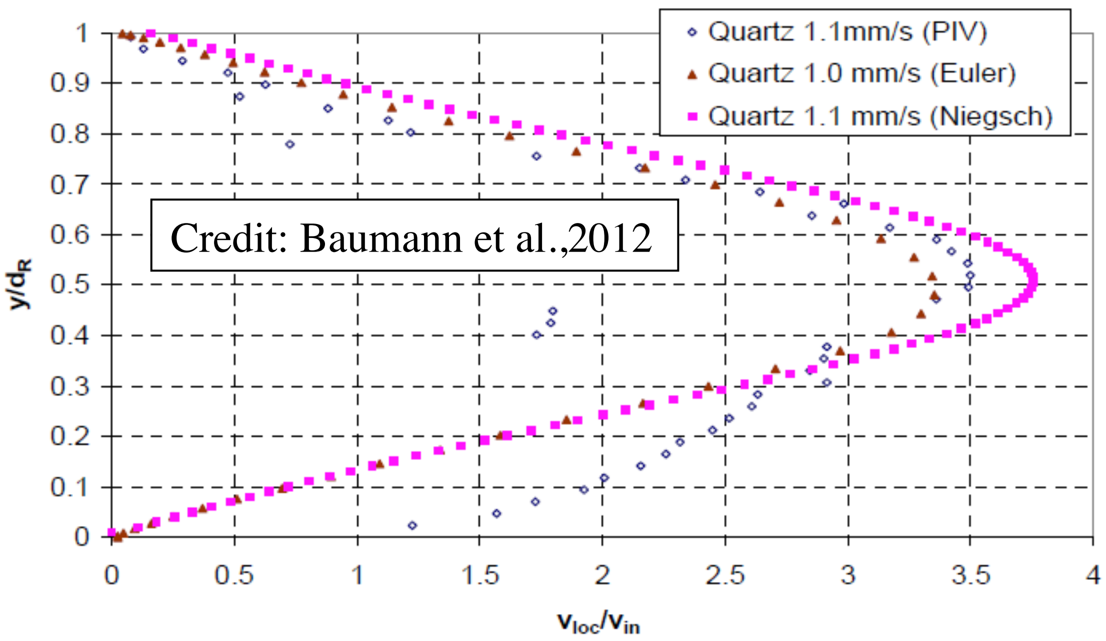
$$h_{local} = q''_{tube,local} / (T_{bulk,\infty} - T_{tube,outer})$$



Credit: Niegsch et al.,1994

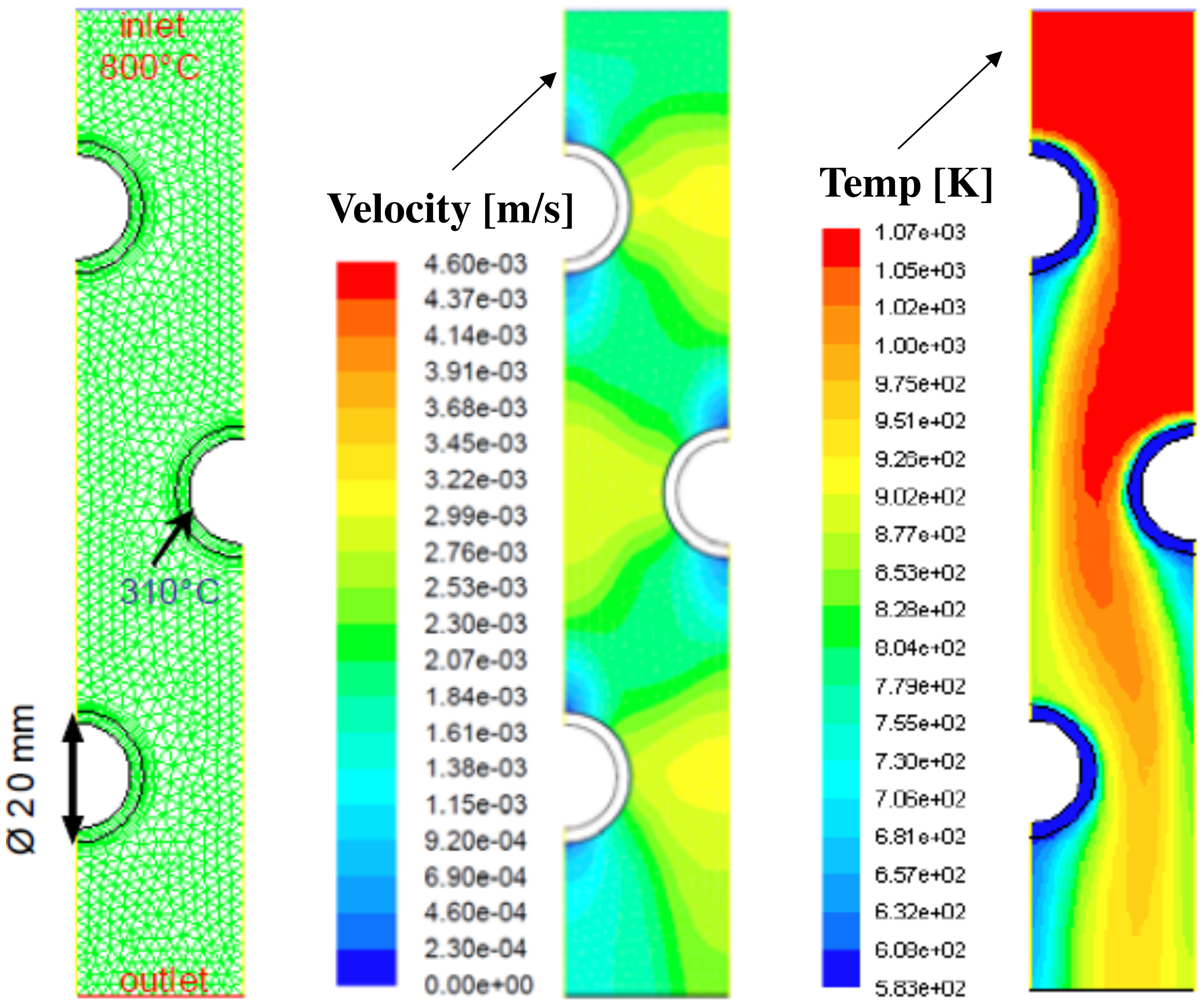
HPHX Design: CFD Can Effectively Describe Moving Bed Flow and Heat Transfer

- Euler-Euler Two Phase Granular CFD models match Niegsch results closely
- Particle Image Velocimetry (PIV) used to check against Niegsch model



Credit: Baumann et al.,2012

Done in ANSYS Fluent®

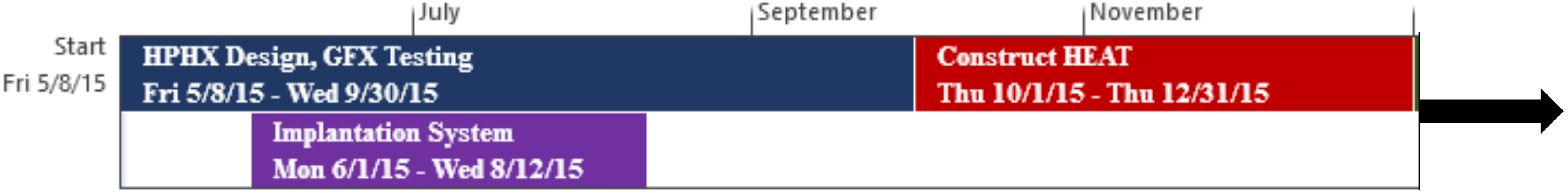


Credit: Baumann et al.,2014

Proposed Research Schedule

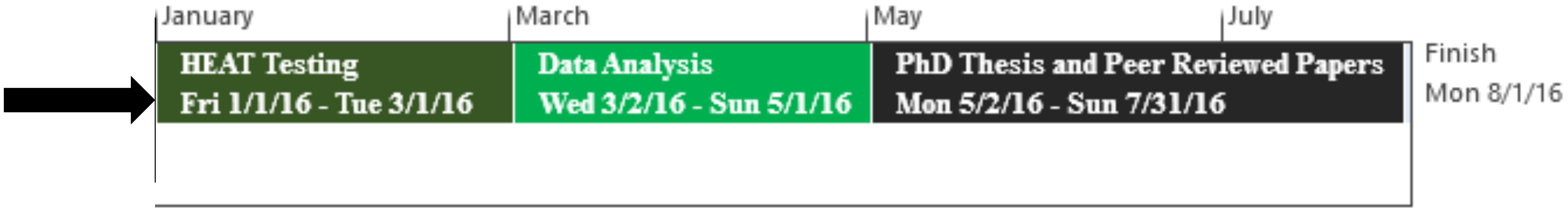
May - Dec. 2015

40-50% Complete



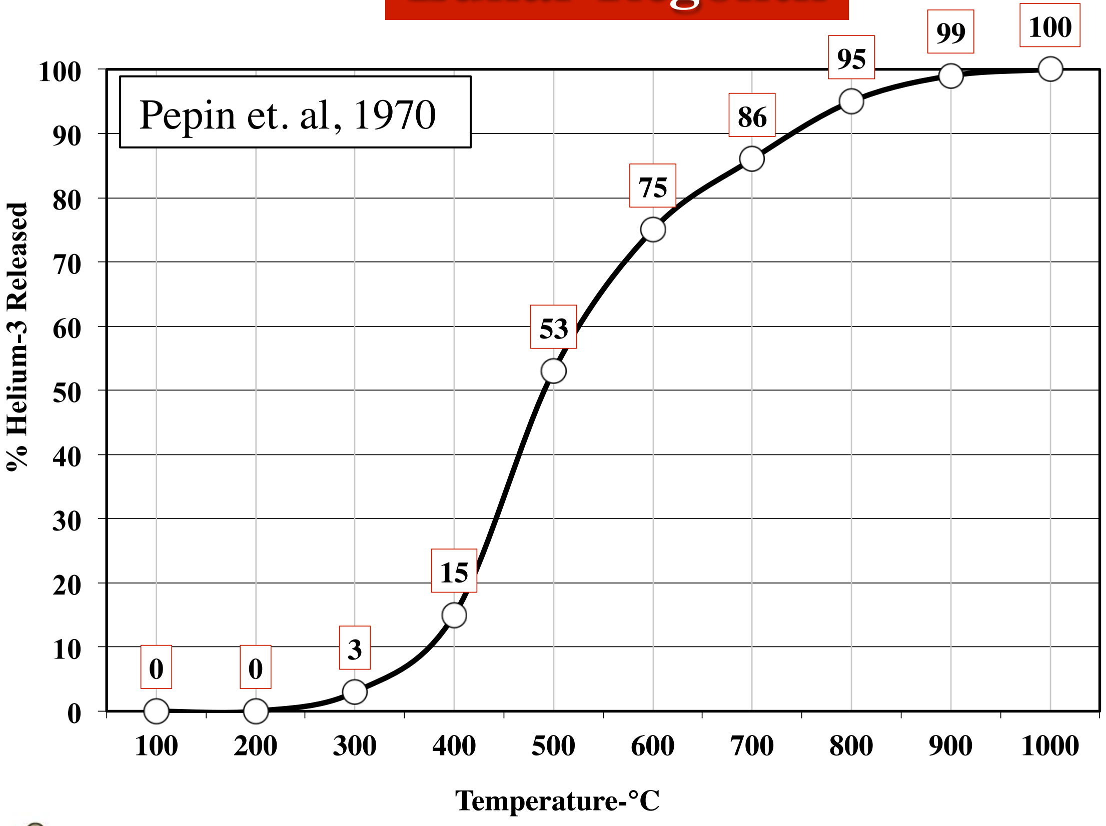
20% Complete

Jan. – Aug. 2016

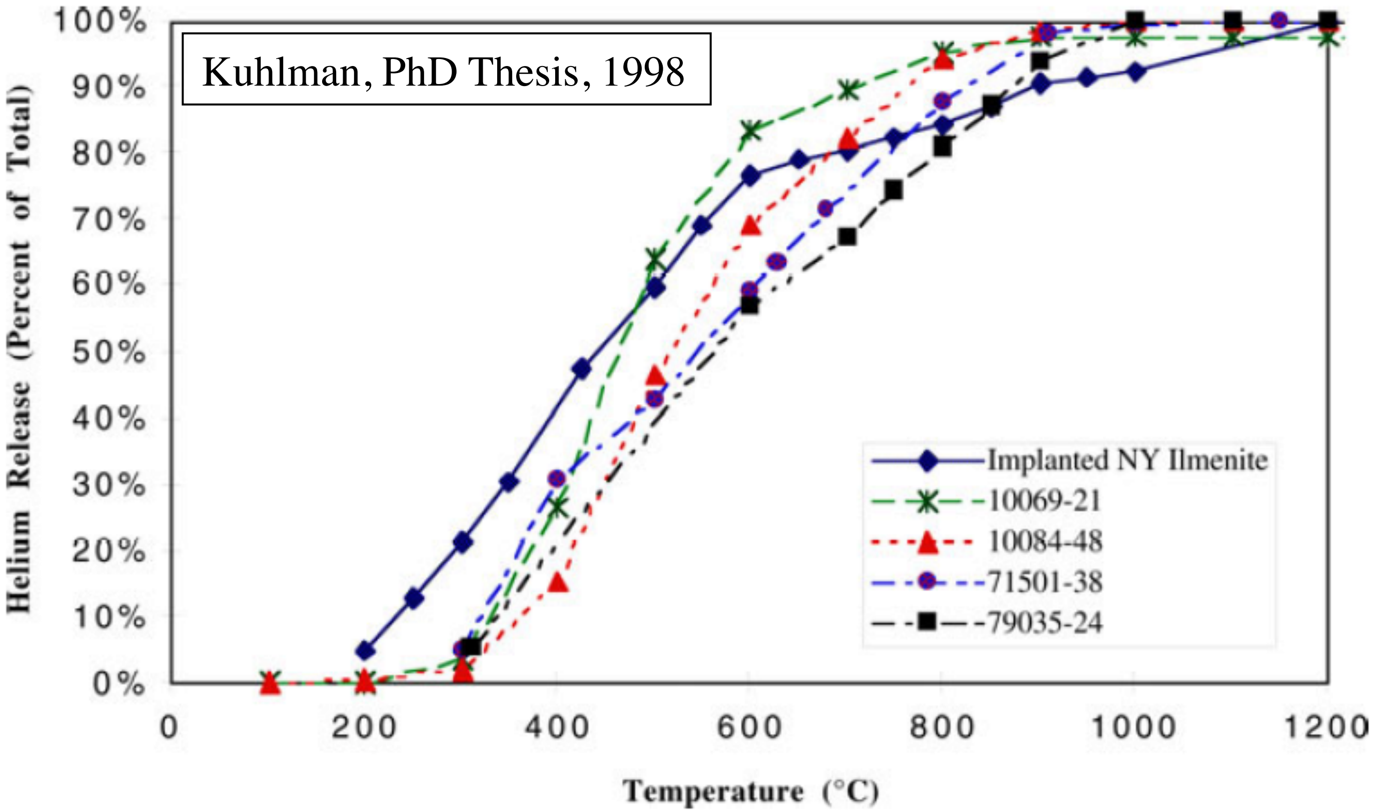


^{3}He Diffusion out of Lunar Regolith has been Studied

Lunar Regolith



Analog Regolith



HPHX Design: Analysis Simplifications

- Simplifications
  - Effectiveness ratio of unity
  - Capacitance ratio of unity

Stage effectiveness

$$\varepsilon_{st} = \frac{2\varepsilon}{N-(N-1)\varepsilon}$$

Stage temperature

$$T_p = \frac{T_{hi} + T_{ci}}{2}$$

Stage change in temp. of regolith

$$\Delta T_{st} = \varepsilon_{st} (T_p - T_{ci}) = \varepsilon_{st} (T_{hi} - T_p)$$

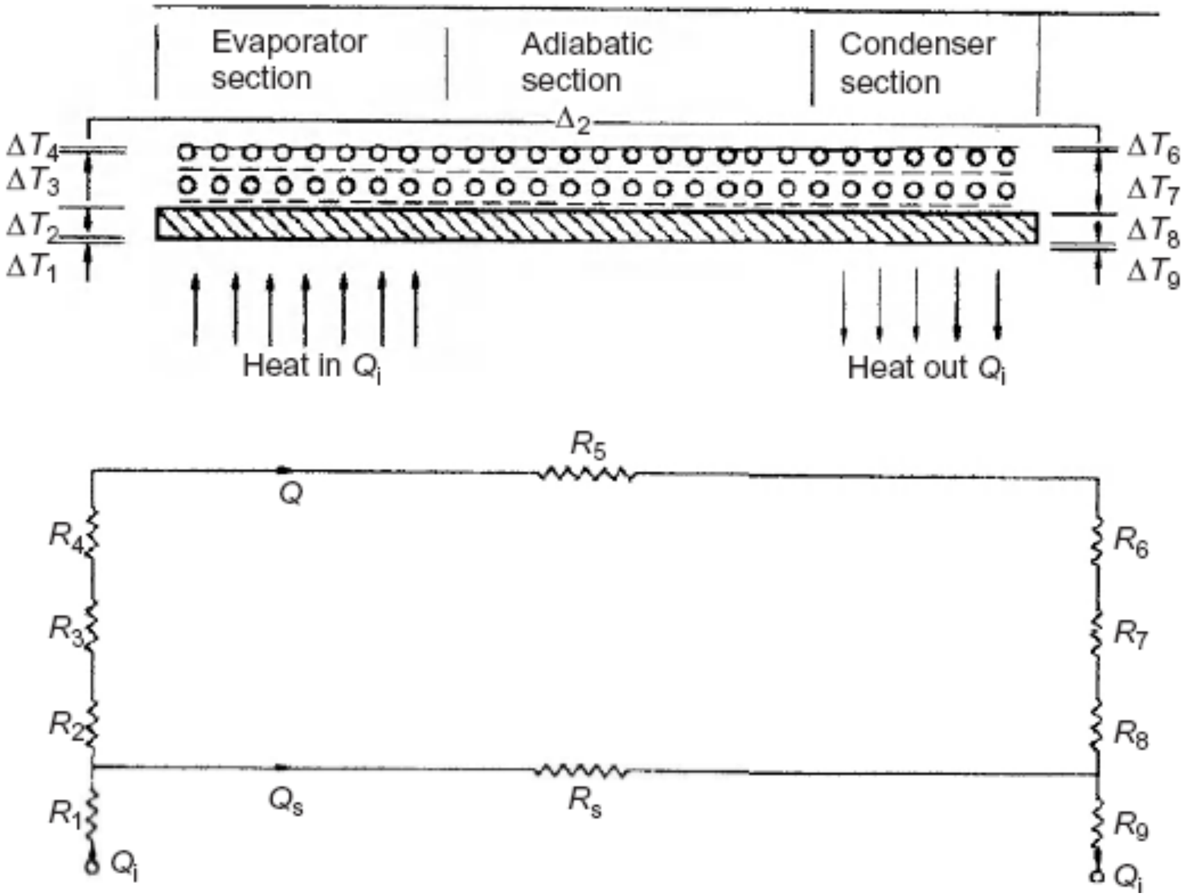
Heat pipe power

$$Q = \frac{C\, \varepsilon_{st}\, \Delta T_{st}}{N_{columns}}$$

Total surface area

$$A_t = N A_{st} = N(A_h + A_c) = \frac{NC\,(NTU_s)\left(1 + \frac{h_h}{h_c}\right)}{h_h}$$

HPHX Design: Heat Pipe Thermal Resistances



Credit: D.Reay (Heat Pipes, 2005)

- Heat pipes operate nearly isothermally
  - Temperature variation will have some effect on the overall HX

Thermal Resistance	Description	Typical order of magnitude (Kcm^2/W)
R1	Evaporator external surface area resistance	0.001-10
R2, R8	Heat pipe wall resistance	~0.1
R3, R7	Wick structure and liquid conduction resistance	~10
R4, R6	Vapor-liquid surface resistance	$\sim 10^{-5}$
R5	Vapor column resistance	$\sim 10^{-8}$
Rs	Heat pipe axial structure resistance	Usually neglected

Overview of lunar simulants

Simulant(s)	Type	Primary Reported Use	Manufacturer	feedstock	status
NU-LHT series	Highlands	General	NASA-MSFC and USGS	Stillwater mine (MT), commercial minerals	In production and use
OB-1	Highlands	Geotechnical	Norcat	Shawmere anorthosite, olivine slag glass	In production and use
JSC-1 (-1A, -1AF)	Mare, low-Ti	Geotechnical and lesser chemical	Orbitec, Inc.	Basalt ash, San Francisco volcanic field (AZ)	In production and use
FJS-1	Mare, low-Ti	Geotechnical	Japanese, (JAXA, LETO)	Mt. Fuji area basalt	No longer available
MLS-1	Mare, high-Ti	Chemical	University of Minnesota	Basalt sill, Duluth complex	No longer available

Slide 8

C.M. Schrader
6/2/2008

BAE SYSTEMS

^{3}He on the Moon Could Become Extremely Valuable

One of yesterday's U. S. shuttles could return a "payload" worth over $100 billion in energy.

One of today's SpaceX Dragon capsules could return a "payload" worth around $15 billion in energy.

40 Tonnes (12 Dragon capsules) of Helium-3 Could Provide all the Electricity Used in North America in 2014

The ^{3}He on Earth is Insufficient to Support Fusion Power

Three sources of helium-3 on the Earth

- **Atmosphere:**
  - helium-3 concentration in atmosphere is ≈ 7×10^{-12} by volume.
  - total amount in the entire atmosphere is ≈ 4,000 tonnes
- **Natural Gas:** potentially as much as 280 kg in reserves and speculative sources that are not being tapped
- **Decay of Tritium**: tritium decays into helium-3 with a 12.3 year half life and 2-4 kg/yr of helium-3 is produced from tritium in the U.S. and Canada

Shortage

- **Increased Usage:** supply depleted of helium-3 from tritium decay (down to < 10 kg in the U.S. as of 2010)
- **Increased Price:** from (~$1,000,000/kg) to (> $30,000,000/kg)
- **Available for Fusion R&D:** only ~10 kg ^{3}He (200 MW-y fusion energy) is accessible on Earth

Exhibit Earns First Place at the 2015 UW Engineering Expo

- Over 10,000 students and parents visited
- Graduate/group category
- Thank you to Abe Megahed for miner simulation work

"Fusion Fuel From the Moon"