Planetary Volatiles Extractor (PVEx) for In Situ Resource Utilization (ISRU)

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HONEYBEE ROBOTICS
Spacecraft Mechanisms Corporation

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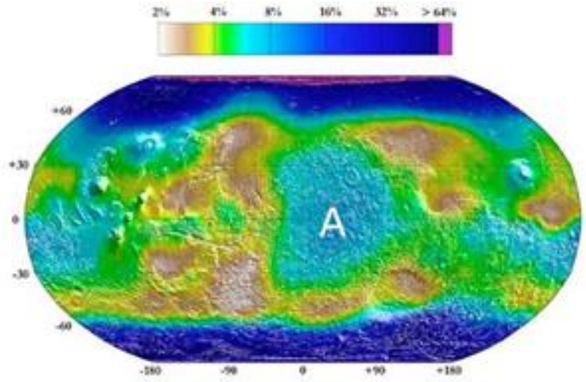
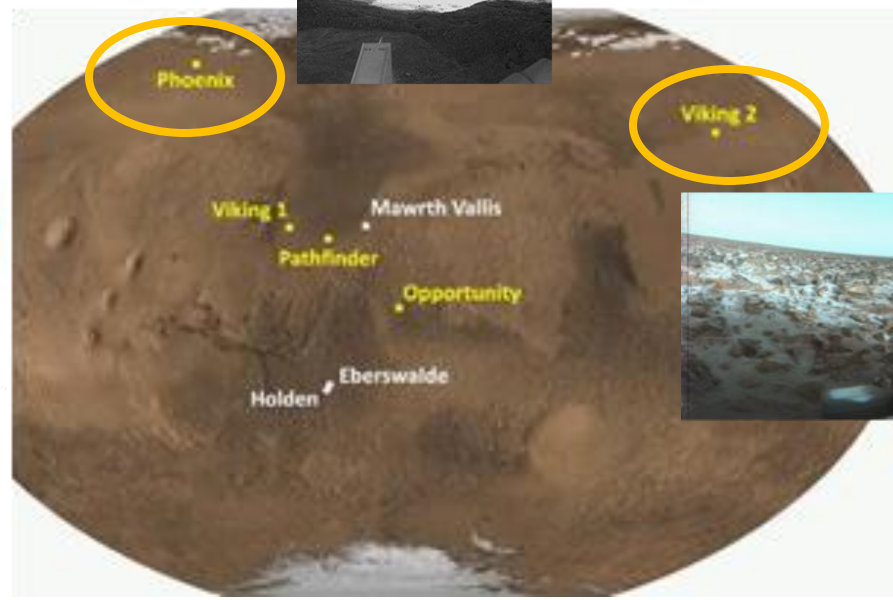
ISO 9001 CERTIFIED
AS9100 CERTIFIED

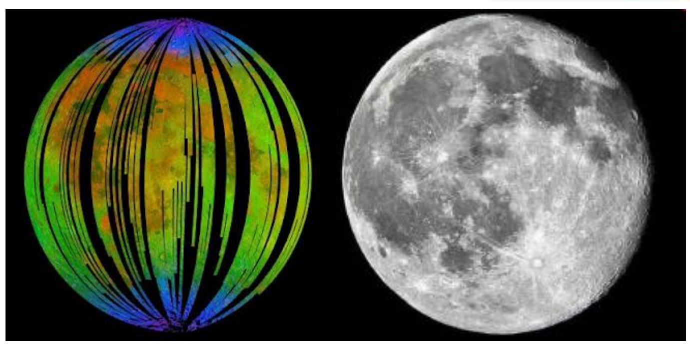
Water is Everywhere!

Mars
Free
Hydrated

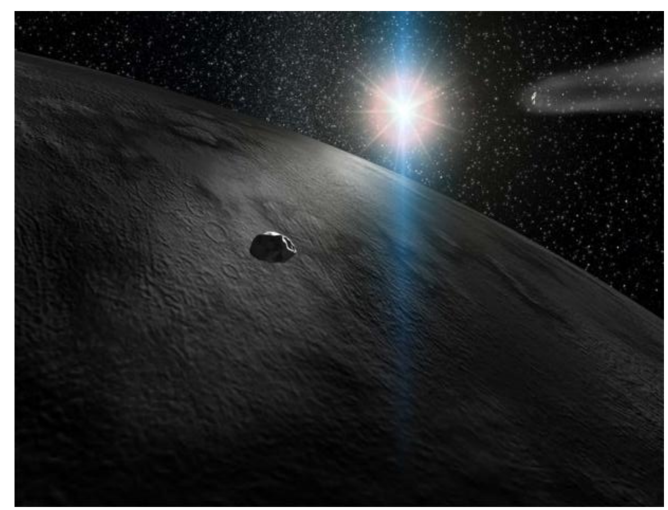




Moon
Free

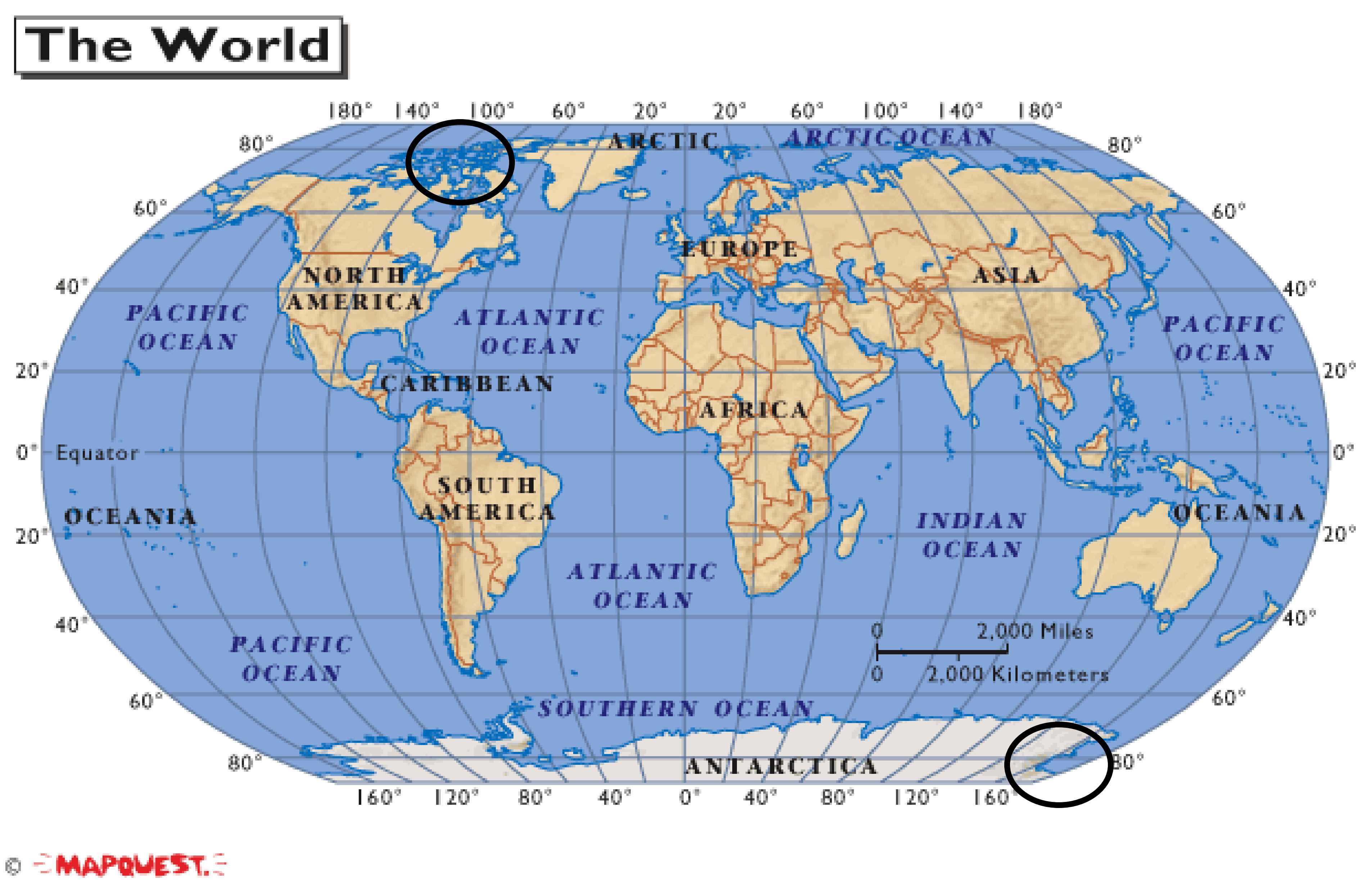


Asteroids
Hydrated



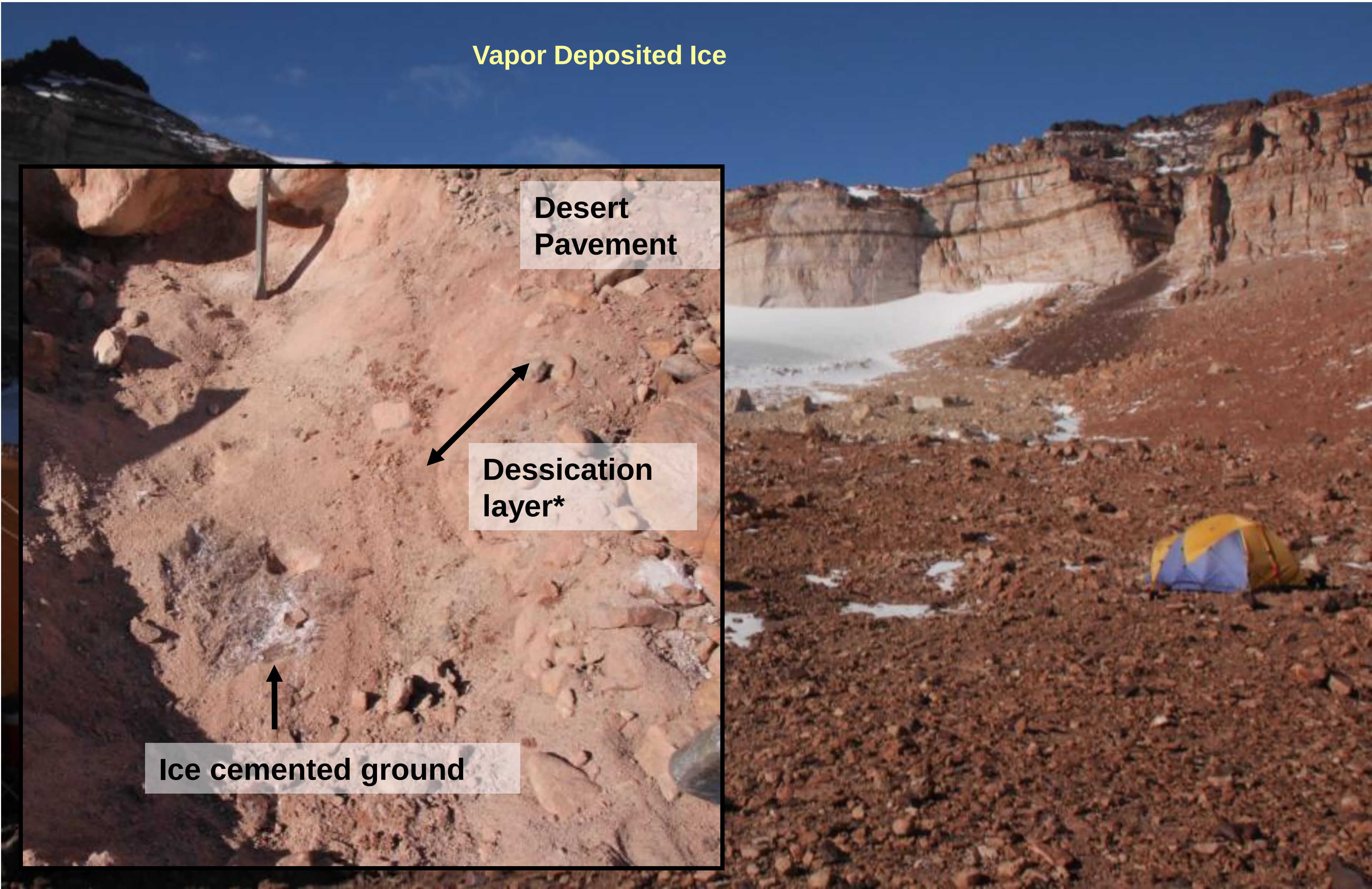
How to Mine Water-Ice?

Arctic and Antarctic



Devon Island, Arctic

Dry Valleys, Antarctica



Saturated JSC-1a at -20C

Strength of dense JSC-1 at 77K

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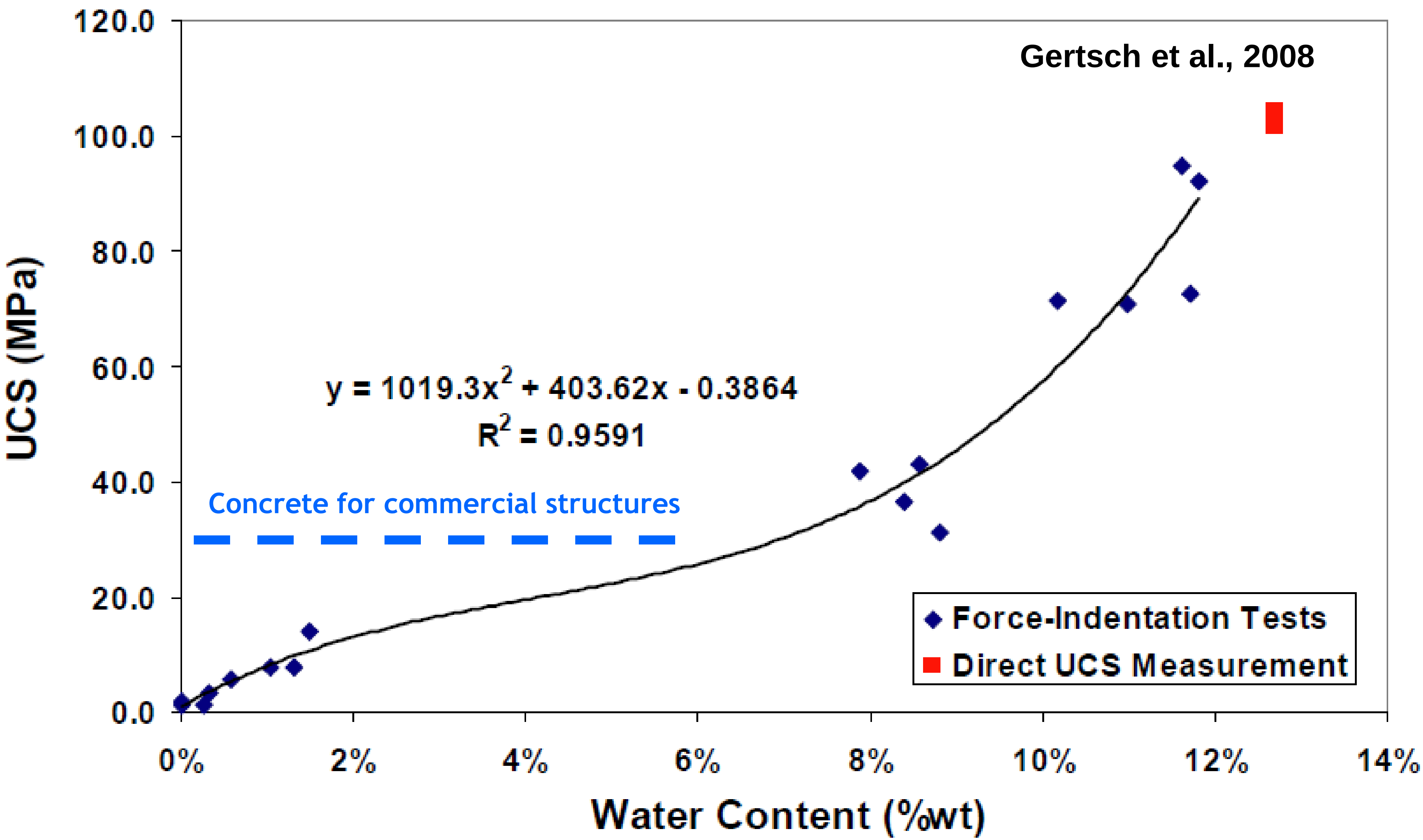
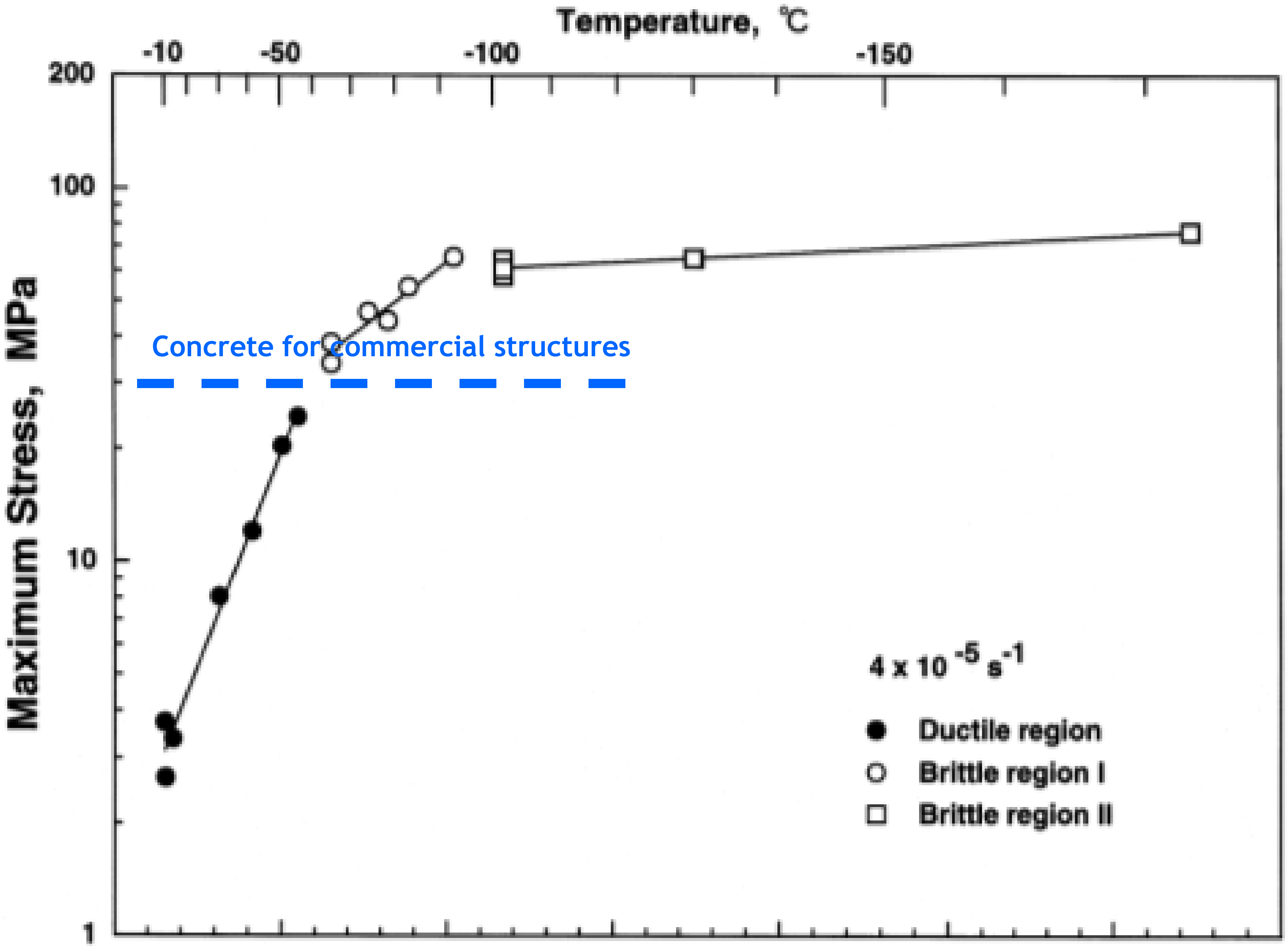
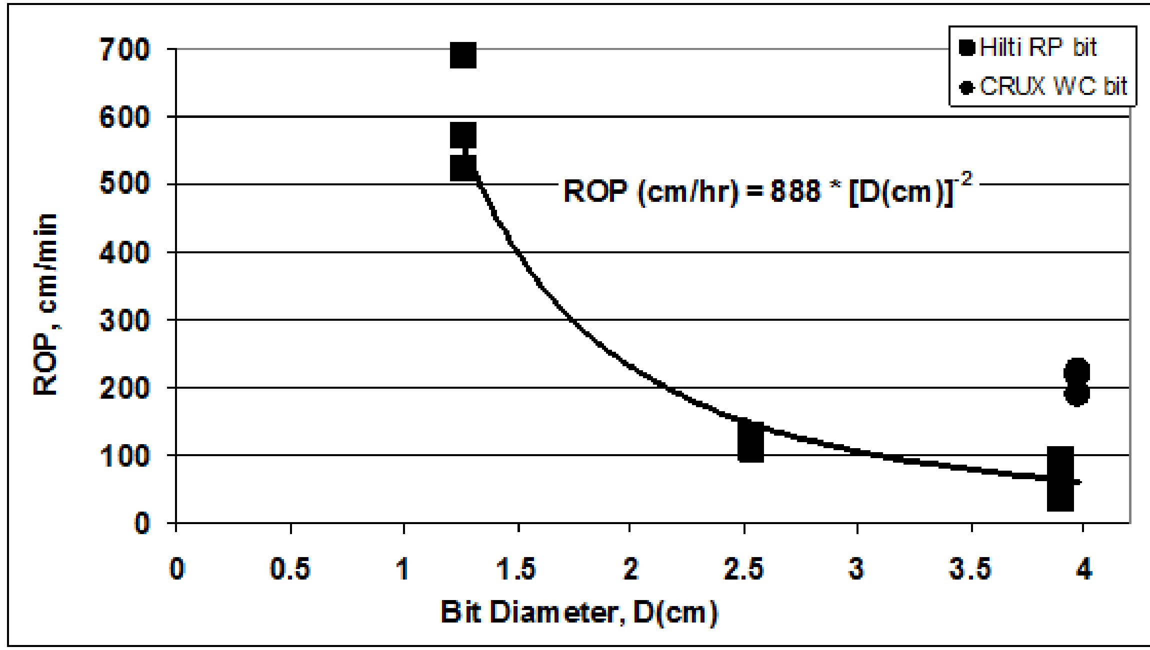


Strength of ice



Where diggers fail, drill works

Drilling in the Arctic



Drilling In the Antarctic

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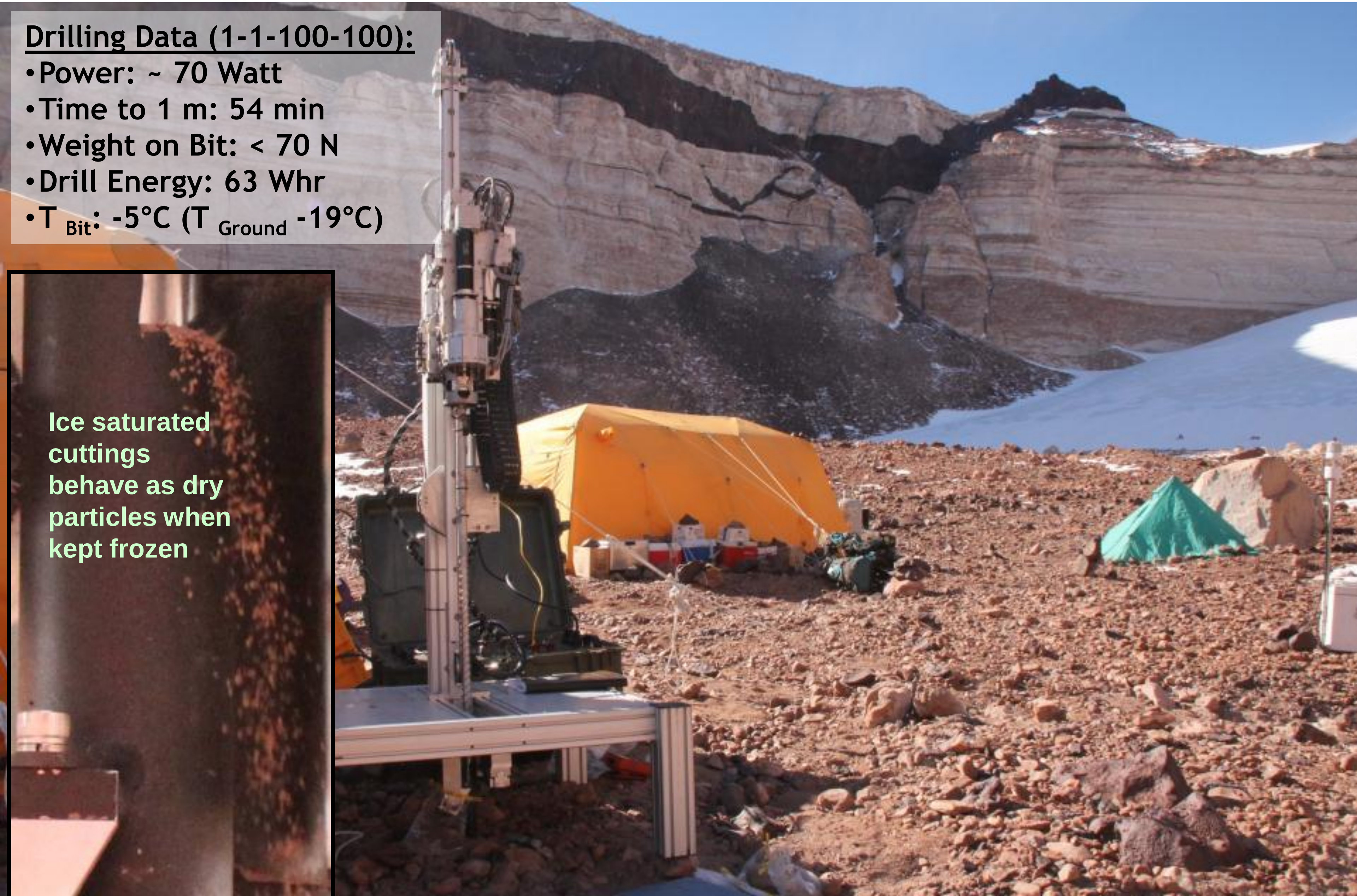


Drilling Data (1-1-100-100):

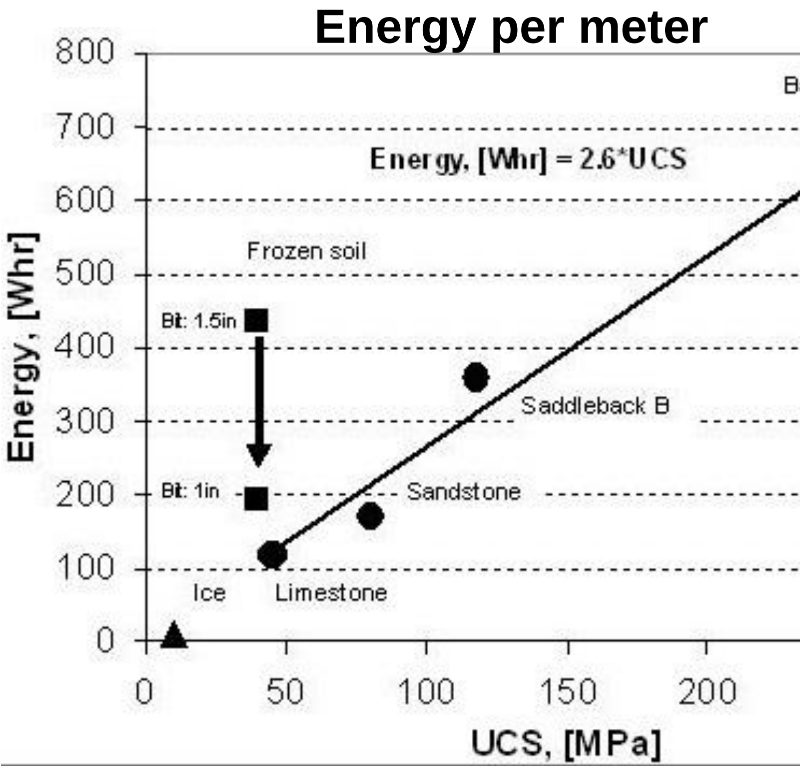
- Power: ~ 70 Watt
- Time to 1 m: 54 min
- Weight on Bit: < 70 N
- Drill Energy: 63 Whr
- T_{Bit}: -5°C (T_{Ground} -19°C)

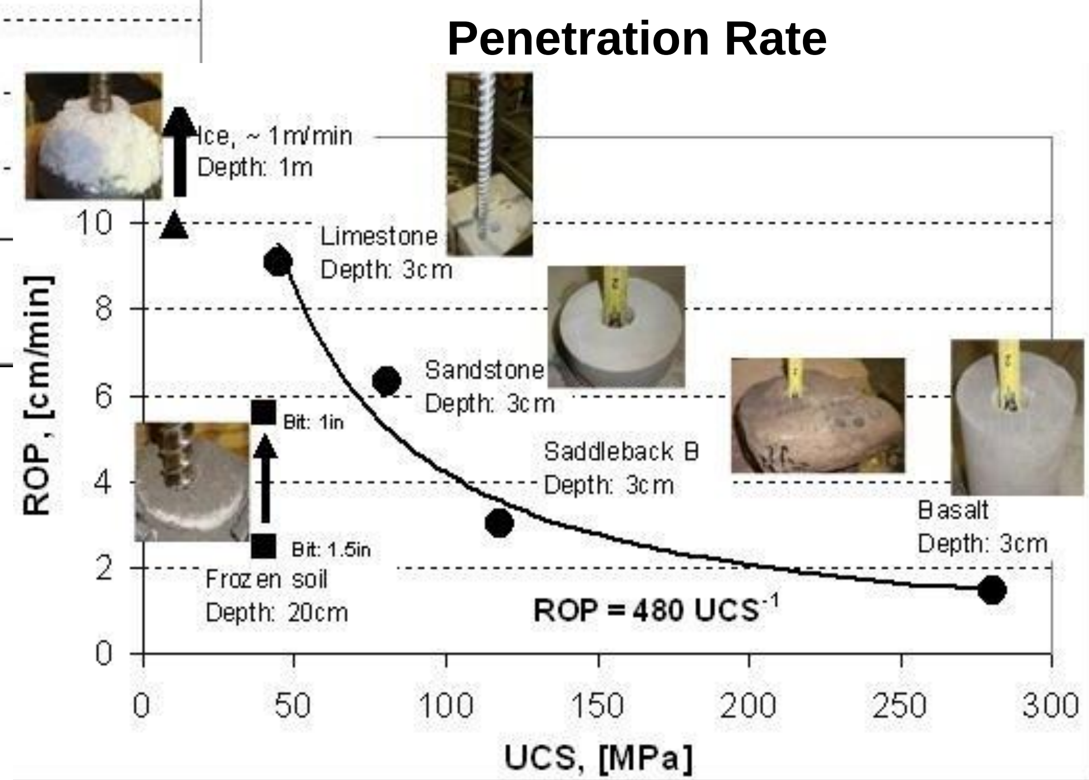
Ice saturated cuttings behave as dry particles when kept frozen

Drilling in JSC-1a

Energy and Power vs. Strength

Drilling performance is a strong function of formation strength (UCS)

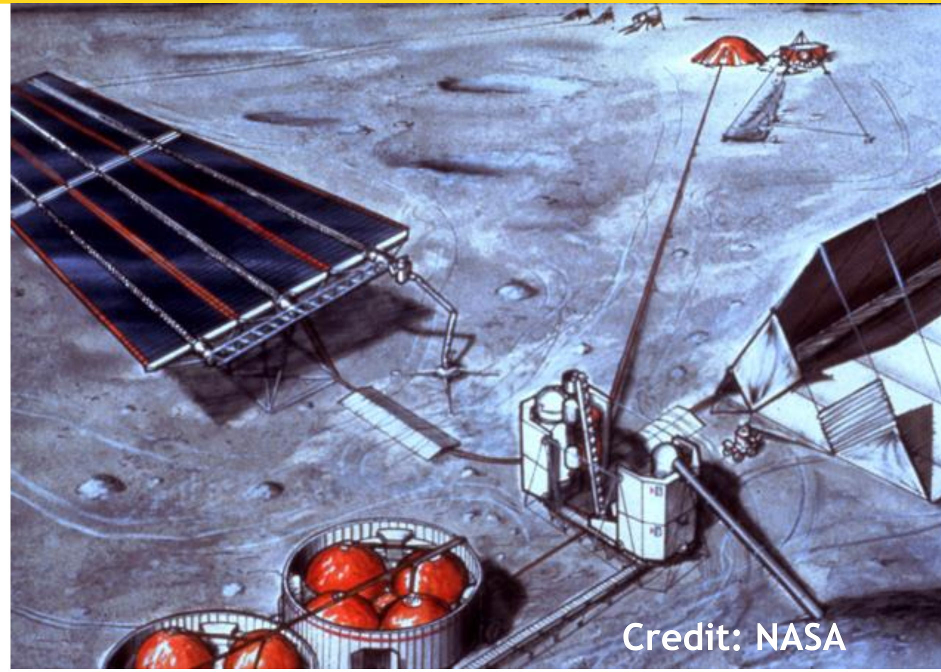




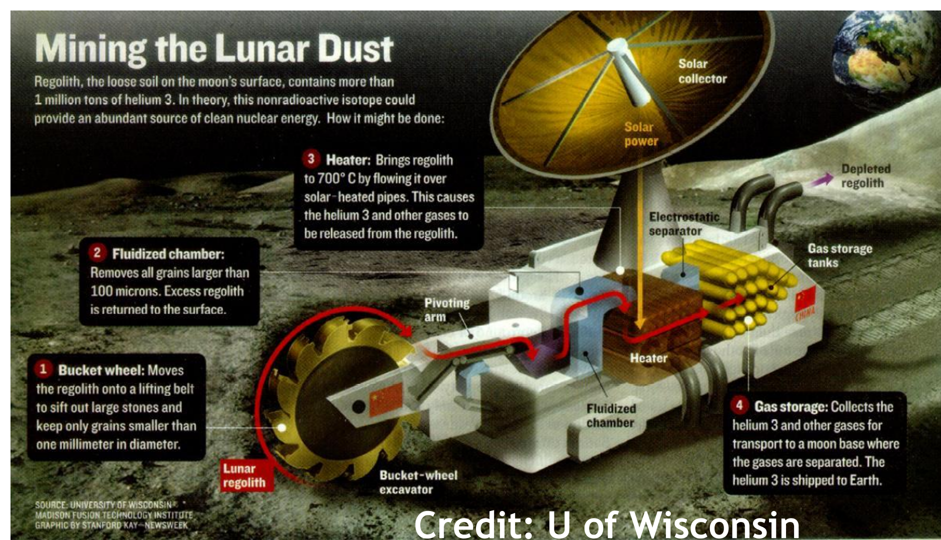
PVEx Approach and Options

Two Possible ISRU Architectures

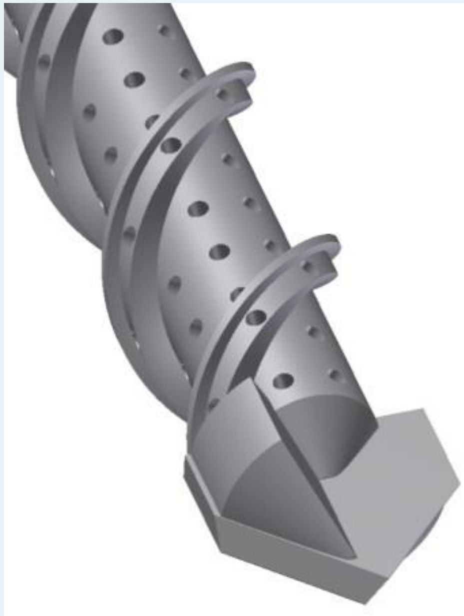
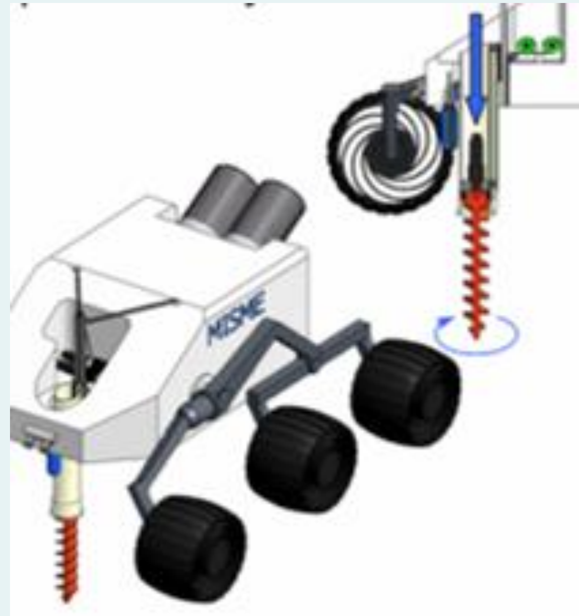
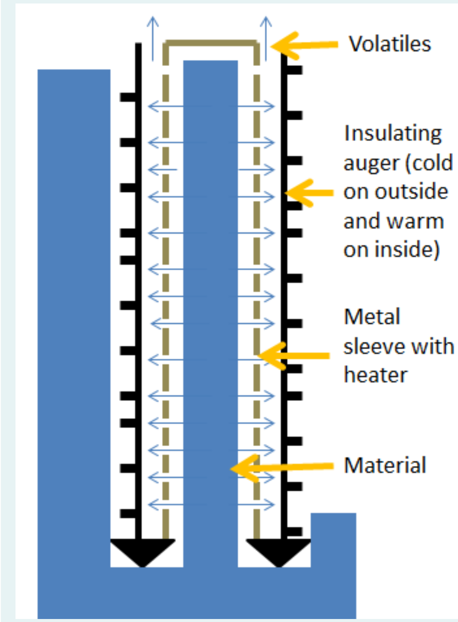
- Central processing station:
  - Mine
  - Transport
  - Process/extract
  - Dump tailings



- In-Situ processing
  - Mine
  - Process/extract/dump



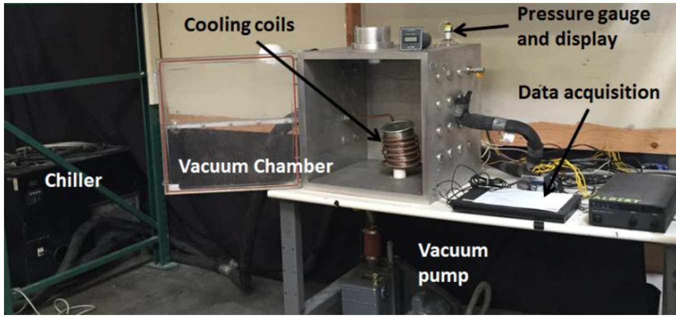
Volatile Extraction Options

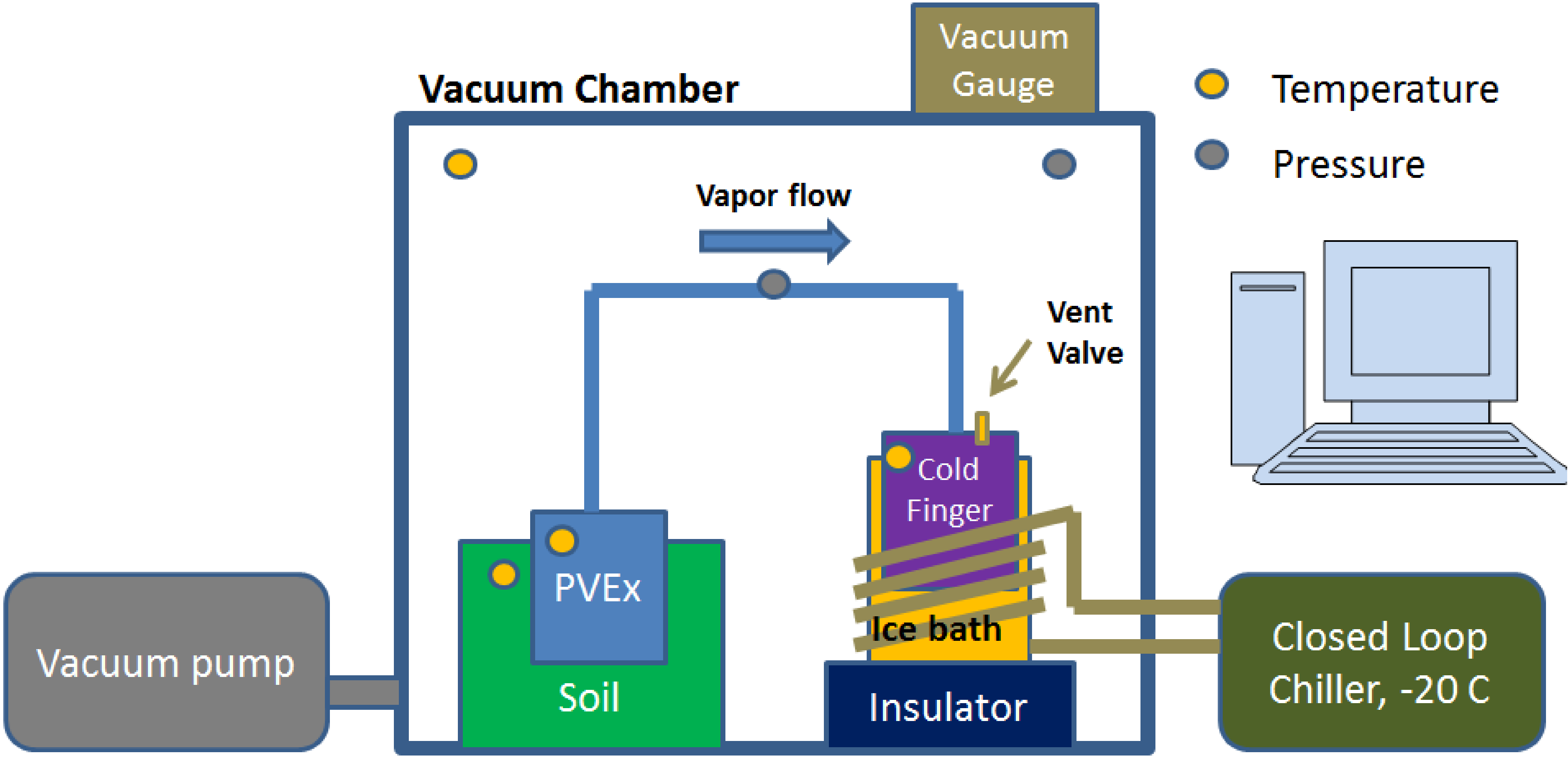
	Sniffer	MISWE	Corer
			
Description	Deep fluted auger with perforated stem. Material is heated up, volatiles flow through holes up the hollow auger stem to the cold trap.	Deep fluted auger captures sample and retracts into tube. The tube/auger is preload against the ground. Auger is heated and volatiles flow through the holes, up the annular space and into a cold trap.	Double wall corer with outer insulating auger and inner perforated and conductive tube. Material within inner tube is heated, volatiles flow through holes and up the annular space into a cold trap.
Efficiency	Low	High	V. High
Complexity	Low	Medium	Low
Risks	Auger freezes Holes clog with material	Material does not fall off the flutes	Cannot empty the corer Holes clog with material

Experiments

Experimental Setup

- **Tests done at 5 torr (Mars) vacuum**
- **JSC-1A**

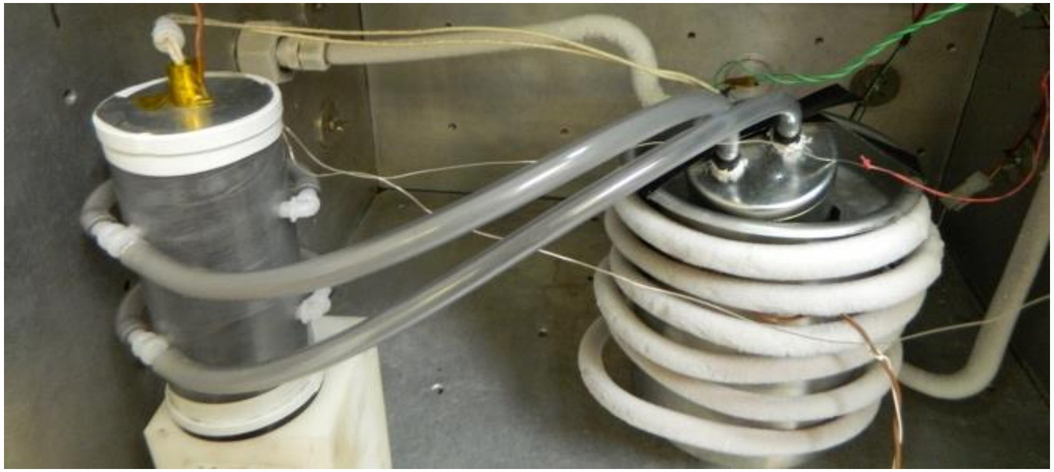




Cold Finger

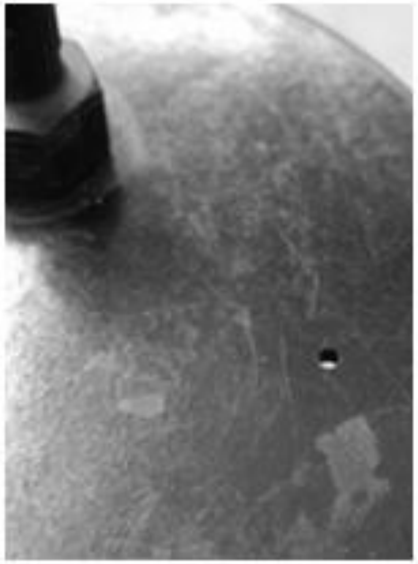
Variables:

- Number of lines
- Surface area
- Material
- Vent hole



Glass jar with 2 ports and Al foil. The ping pong ball floated as water level rose- this was a visual cue.

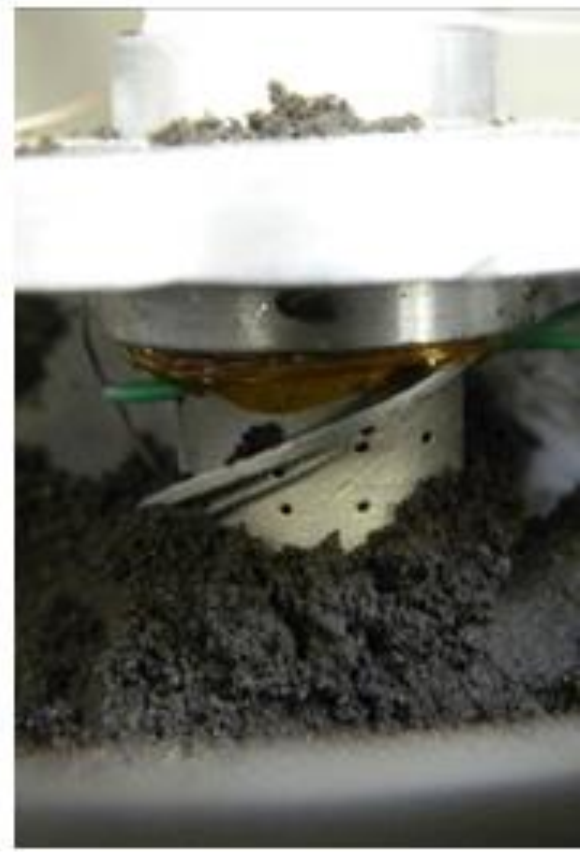
Steel jar with one port. Aluminum foil curtain is seen on the inside.



Close up of vent valve in its open state.

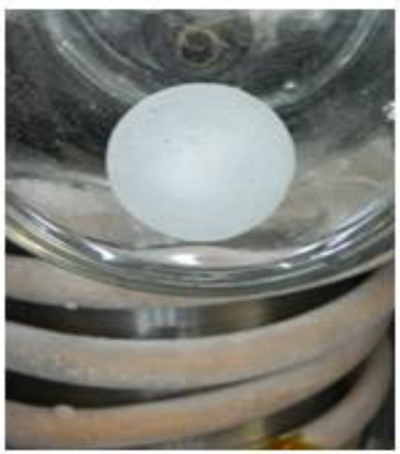
Sniffer: Setup

- Used 3D printer auger with several holes
- 2.5 cm diameter and 15 cm long
- Placed inside a frozen JSC-1A with 6wt% and 12wt%
- Varied Power and Time



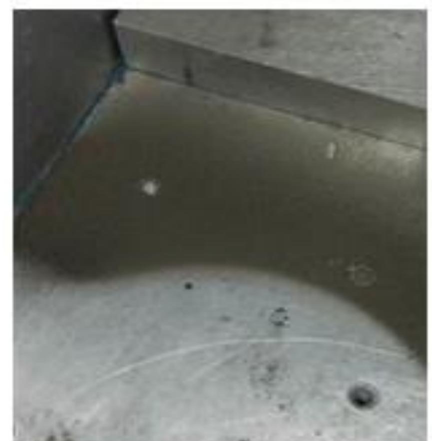
Sniffer: Results

Test #	Wt %	Power (W)	Time (min)	Captured Water (g)	% Water Extracted	Whr/g	Notes
1	6	20	30	5.5	4.58	1.82	Particulates in water
2	6	20	30	0.0	0.00	-	
3	6	34	20	0.8	0.67	14.17	
4	6	34	30	0.0	0.00	-	
5	6	50	20	0.3	0.25	55.56	Particulates in water
6	6	50	20	0.0	0.00	-	Short due to >200°C
7	12	20	30	0.0	0.00	-	
8	12	20	30	0.0	0.00	-	
9	12	20	40	0.5	0.21	26.67	½ inch tube
10	12	20	40	0.0	0.00	-	½ inch tube
11	12	34	30	0.0	0.00	-	
12	12	34	2	0.0	0.00	-	Sparks from short
13	12	50	20	0.2	0.08	83.33	½ inch tube



The best result: 5.5 g. Could not be repeated.

Majority of heat went to heat up and sublime surrounding soil

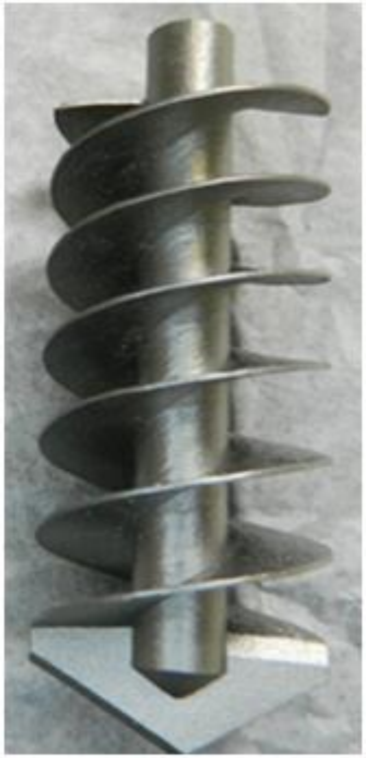


Sublimation caused lofting of soil particles which fell around circular bin.

High temp caused insulation melting

MISWE: Setup

- Conventional and with Pins (heat spreader)
- Direct metal laser sintered 316 Stainless
- Diameter: 6.4 cm, Length: 13 cm long
- Initial observations:
  - Metal jar is better than a glass jar (collects more water)
  - Inserting an aluminum curtain into the metal jar increases efficiency.



Conventional auger.

Alternative auger with pins

Chamber setup.

MISWE: Results

Type	Power	Bottom	Vent	Time	Water Extracted		Eff.
	Watt			min	g	%	Whr/g
Orig	75	C	C	10	3.7	21	3.4
Orig	50/75	C	O	10/10	6.1	35	3.4
Orig	50	C	O	25	6.5	41	3.2
Orig	50/75	P	C	10/10	2.8	16	7.4
Orig	20	P	C	60	2.9	15	6.9
Orig	50/75	P	O	10/10	5.1	28	4.1
Orig	20	P	C	30	3.3	18	3.0
Alt	50/75	C	C	25/10	14.6	78	2.3
Alt	75	C	C	10	8.3	45	1.5
Alt	75	C	C	10	9.8	54	1.3
Alt	50	C	C	25	10.9	61	1.9
Alt	50	C	C	30	4.6	27	5.4
Alt	50/75	C	C	10/10	13.9	71	1.5
Alt	50/75	C	O	10/10	9.8	53	2.1
Alt	50	C	O	20	7.3	38	2.3
Alt	50/75	P	C	10/10	5	27	4.2
Alt	20	P	C	60	10	50	2.0
Alt	50/75	P	O	10/10	8.1	41	2.6
Alt	20	P	O	30	3.1	18	3.2
Alt	50	P	C	20	5.7	29	2.9
Alt	50	P	C	20	7.1	38	2.4
Alt	75	P	C	20	8	42	3.1
Alt	75	P	C	10	4.8	27	2.6

Trade: Repeatability (Average and Std Dev).

- Performed two sets of tests with exactly the same parameters
- Results are relatively repeatable with approx. 10% standard deviation

Type	Power	Bottom	Vent	Time	Water Extracted		Eff.
	Watt			min	g	%	Whr/g
Alt	75	C	C	10	8.3	45	1.5
Alt	75	C	C	10	9.8	54	1.3
						50±5	**1.4±0.1**
Alt	50	P	C	20	5.7	29	2.9
Alt	50	P	C	20	7.1	38	2.4
						34±5	**2.7±0.25**

Trade: Original vs. Alternative Auger Design

- Alternative auger design with pins is better

Type	Power	Bottom	Vent	Time	Water Extracted		Eff.	Better?
	Watt			min	g	%	Whr/g	
Orig	75	C	C	10	3.7	21	3.4	
Alt	75	C	C	10	8.3	45	1.5	
Alt	75	C	C	10	9.8	54	1.3	
Alt	75	P	C	10	4.8	27	2.6	
					RATIO Alt/Orig	**2.0**	**0.5**	**Alt**
Orig	50/75	C	O	10/10	6.1	35	3.4	
Alt	50/75	C	O	10/10	9.8	53	2.1	
					RATIO Alt/Orig	**1.5**	**0.6**	**Alt**
Orig	50	C	O	25	6.5	41	3.2	
Alt	50	C	O	20	7.3	38	2.3	
					RATIO Alt/Orig	**0.9**	**0.7**	**Alt**
Orig	50/75	P	C	10/10	2.8	16	7.4	
Alt	50/75	P	C	10/10	5	27	4.2	
					RATIO Alt/Orig	**1.7**	**0.6**	**Alt**
Orig	20	P	C	60	2.9	15	6.9	
Alt	20	P	C	60	10	50	2.0	
					RATIO Alt/Orig	**3.3**	**0.3**	**Alt**
Orig	50/75	P	O	10/10	5.1	28	4.1	
Alt	50/75	P	O	10/10	8.1	41	2.6	
					RATIO Alt/Orig	**1.5**	**0.6**	**Alt**

Trade: Bottom preloaded vs. Closed

- Energy and water extraction efficiency is higher when the auger tube (reactor) is closed at the bottom.

Type	Power	Bottom	Vent	Time	Water Extracted		Eff.	Better?
	Watt			min	g	%	Whr/g	
Orig	50/75	C	O	10/10	6.1	35	3.4	
Orig	50/75	P	O	10/10	5.1	28	4.1	
					RATIO: C/P	**0.8**	**1.2**	**C**
Alt	75	C	C	10	8.3	45	1.5	
Alt	75	C	C	10	9.8	54	1.3	
Alt	75	P	C	10	4.8	27	2.6	
					RATIO: C/P	**0.5**	**2.0**	**C**
Alt	50/75	C	C	10/10	13.9	71	1.5	
Alt	50/75	P	C	10/10	5	27	4.2	
					RATIO: C/P	**0.4**	**2.8**	**C**
Alt	50/75	C	O	10/10	9.8	53	2.1	
Alt	50/75	P	O	10/10	8.1	41	2.6	
					RATIO: C/P	**0.8**	**1.2**	**C**

Trade: Heating Time/Energy Input.

- Time and Power input should be varied to determine optimum efficiency.
- In some cases, we were applying more power for too long than needed.
- A T sensor needs to be used to determine the point at which soil is dry
  - soil temperature during drying process will stay the same and will increase when soil is fully dry and heat no longer is used by the latent heat of water.

Type	Power	Bottom	Vent	Time	Water Extracted		Eff.	Better?
	Watt			min	g	%	Whr/g	
Orig	20	P	C	60	2.9	15	6.9	
Orig	20	P	C	30	3.3	18	3.0	
						Same	**Shorter**	**Shorter**
Alt	50/75	C	C	25/10	14.6	78	2.3	
Alt	50/75	C	C	10/10	13.9	71	1.5	
						Same	**Shorter**	**Shorter**
Alt	50	C	C	30	4.6	27	5.4	
Alt	50	C	C	25	10.9	61	1.9	
						Shorter	**Shorter**	**Shorter**
Alt	75	P	C	20	8	42	3.1	
Alt	75	P	C	10	4.8	27	2.6	
						Longer	**Shorter**	**Shorter**

MISWE-Results

- MISWE with pins, 50 W/75W heating cycle for 10 minutes per power setting.
- Both the auger tube and the vent hole closed.
- Water extraction efficiency: 71%
- Extraction energy: 1.5 Whr/g (yielding an efficiency of 67%)



Corer: Setup

- Double-wall coring augers (2.5 cm and 5 cm in diameter)
- Direct metal laser sintered copper for the perforated conductive tube
- 3D printed VeroClear PolyJet plastic for the insulating auger surface

Corer: Results

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Power	Bottom Seal	Time	Hose dia.	Water Extracted		Energy
Watt		min	Inch	g	%	Whr/g
50	Closed	20	0.25	4.7	17	3.6
50	Closed	40	0.25	9.9	37	3.4
50/75	Closed	10/10	0.25	7.8	28	2.7
50/75	Closed	20/20	0.25	6.8	25	6.1
50	Closed	40	0.25	2.5	8	13.3
50	Closed	20	0.25	1.8	6	9.3
50	Closed	40	0.25	2.2	7	15.2
75	Closed	20	0.25	3.7	14	6.8
75	Closed	40	0.25	3.7	14	13.5
50	Closed	40	0.25	6.1	22	5.5
60	Closed	40	0.25	19.6	72	2.0
60	Closed	40	0.25	12	44	3.3
60	Closed	30	0.25	11.2	39	2.7
60	Closed	40	0.5	17.6	67	2.3
50	Closed	40	0.5	18.4	63	1.8
60	Preloaded	40	0.5	24.5	84	1.6
60	Preloaded	40	0.5	24.2	87	1.7
60	Preloaded	40	0.25	9	31	4.4
60	Preloaded	40	1	21	76	1.9
60	Preloaded	40	1	22	77	1.8
60	Closed	40	1	16.4	59	2.4
60	Preloaded	30	0.5	13.7	47	2.2
60	Preloaded	30	0.5	18	62	1.7
50	Preloaded	40	0.5	21.5	85	1.6
50	Preloaded	40	0.5	22.1	76	1.5

Trade: Repeatability (Average and Std Dev).

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- Performed seven sets of tests with exactly the same parameters
- Results are relatively repeatable with low standard deviation

Power	Bottom Seal	Time	Hose dia.	Water Extracted		Energy
Watt		min	Inch	g	%	Whr/g
50	Closed	20	0.25	4.7	17	3.6
50	Closed	20	0.25	1.8	6	9.3
				Avg and Std Dev	**12±6**	**6.5±2.9**
50	Closed	40	0.25	9.9	37	3.4
50	Closed	40	0.25	6.1	22	5.5
				Avg and Std Dev	**30±7.5**	**4.5±1.1**
60	Closed	40	0.25	19.6	72	2.0
60	Closed	40	0.25	12	44	3.3
				Avg and Std Dev	**58±14**	**2.7±0.7**
60	Preloaded	40	0.5	24.5	84	1.6
60	Preloaded	40	0.5	24.2	87	1.7
				Avg and Std Dev	**86±1.5**	**1.7±0.05**
60	Preloaded	40	1	21	76	1.9
60	Preloaded	40	1	22	77	1.8
				Avg and Std Dev	**77±0.5**	**1.9±0.05**
60	Preloaded	30	0.5	13.7	47	2.2
60	Preloaded	30	0.5	18	62	1.7
				Avg and Std Dev	**55±7.5**	**2±0.2**
50	Preloaded	40	0.5	21.5	85	1.6
50	Preloaded	40	0.5	22.1	76	1.5
				Avg and Std Dev	**81±4.5**	**1.6±0.1**

Trade: Bottom Closed vs. Preloaded

- Given limited data set, there is no clear winner.

Power	Bottom Seal	Time	Hose dia.	Water Extracted		Energy	Better?
Watt		min	Inch	g	%	Whr/g	
60	Closed	40	0.25	19.6	72	2.0	
60	Closed	40	0.25	12	44	3.3	
60	Preloaded	40	0.25	9	31	4.4	
				RATIO: P/C	**0.5**	**1.7**	**Closed**
60	Closed	40	0.5	17.6	67	2.3	
60	Preloaded	40	0.5	24.5	84	1.6	
60	Preloaded	40	0.5	24.2	87	1.7	
				RATIO: P/C	**1.3**	**0.7**	**Preloaded**
50	Closed	40	0.5	18.4	63	1.8	
50	Preloaded	40	0.5	21.5	85	1.6	
50	Preloaded	40	0.5	22.1	76	1.5	
				RATIO: P/C	**1.3**	**0.9**	**Preloaded**

Trade: Hose Diameter: 0.25 inch-0.5 inch-1 inch

- 0.5 inch tube diameter offers least resistance for volatiles transfer and as such the system has much greater water extraction efficiency at much lower extraction energy.
- Data suggests that system needs to be fine-tuned for best results.

Power	Bottom Seal	Time	Hose dia.	Water Extracted		Energy
Watt		min	Inch	g	%	Whr/g
60	Closed	40	0.25	19.6	72	2.0
60	Closed	40	0.25	12	44	3.3
60	Closed	40	0.5	17.6	67	2.3
				RATIO: 0.5 / 0.25	**1.2**	**0.9**
50	Closed	40	0.25	9.9	37	3.4
50	Closed	40	0.25	6.1	22	5.5
50	Closed	40	0.5	18.4	63	1.8
				RATIO: 0.5 / 0.25	**2.1**	**0.4**
60	Preloaded	40	0.25	9	31	4.4
60	Preloaded	40	0.5	24.5	84	1.6
60	Preloaded	40	0.5	24.2	87	1.7
60	Preloaded	40	1	21	76	1.9
60	Preloaded	40	1	22	77	1.8
				RATIO: 0.5 / 0.25	**2.8**	**0.4**
				RATIO: 1 / 0.5	**0.9**	**1.1**

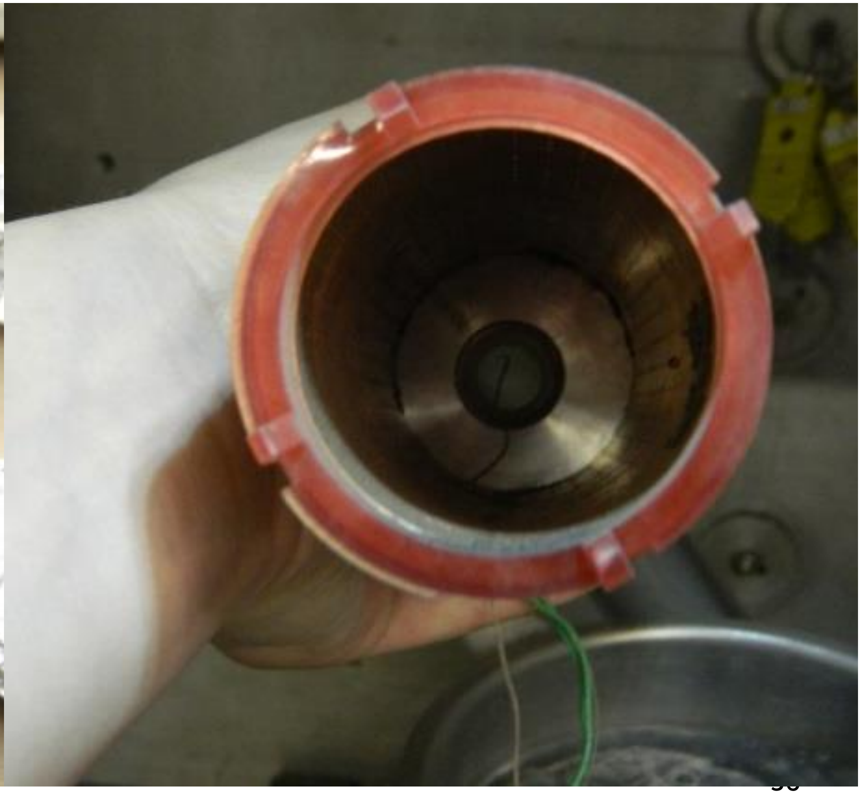
Trade: Heater Power/Energy.

- Heating power and time affects extraction efficiency and also energy efficiency.
- Soil temperature should be directly or indirectly monitored in real time to determine at what stage the soil is completely dry and the extraction process can stop.

Power	Bottom	Time	Hose dia.	Water Extracted		Energy	Better?
Watt		min	Inch	g	%	Whr/g	
50	Closed	20	0.25	4.7	17	3.6	
50	Closed	20	0.25	1.8	6	9.3	
75	Closed	20	0.25	3.7	14	6.8	
				RATIO 75/50	**1.2**	**1.1**	**Same**
50	Closed	40	0.25	9.9	37	3.4	
50	Closed	40	0.25	2.5	8	13.3	
50	Closed	40	0.25	2.2	7	15.2	
50	Closed	40	0.25	6.1	22	5.5	
60	Closed	40	0.25	19.6	72	2.0	
60	Closed	40	0.25	12	44	3.3	
75	Closed	40	0.25	3.7	14	13.5	
				RATIO: 60/50	**3.1**	**0.3**	**60 W**
				RATIO 75/60	**0.2**	**5.1**	**60 W**
50	Preloaded	40	0.5	21.5	85	1.6	
50	Preloaded	40	0.5	22.1	76	1.5	
60	Preloaded	40	0.5	24.5	84	1.6	
60	Preloaded	40	0.5	24.2	87	1.7	
				RATIO 60/50	**1.1**	**1.1**	**Same**

Corer: Results

- The Corer can extract up to 87% of water at 1.7 Whr/g.
- The needed Power is 60 watt for 40 min.
- The Corer can be Preloaded against the hole bottom (regolith).
- The volatile transfer hose diameter is 0.5 inch



PVEx Final Trade: Volatile Extraction

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		Sniffer	MISWE (Org)	MISWE (Alt)	Corer
Data Points		5	7	16	15
Energy Efficiency [Whr/g]	**Min**	1.8	3	1.3	1.5
	Max	83	7.4	5.4	4.4
	Average	**36**	**4.5**	**2.6**	**2.2**
	Std. Dev	**30**	**1.7**	**1.0**	**0.8**
Water Recovery [%]	**Min**	0.1	15	18	31
	Max	4.6	41	78	87
	Average	**1.2**	**25**	**44**	**65**
	Std. Dev	**1.7**	**9**	**16**	**17**
Rankings		**4**	**3**	**2**	**1**

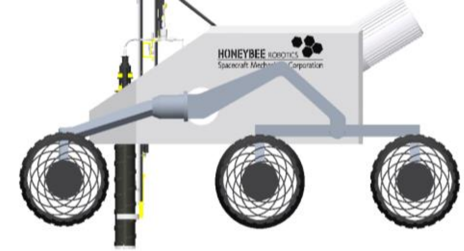
PVEx Final Trade: Excavation

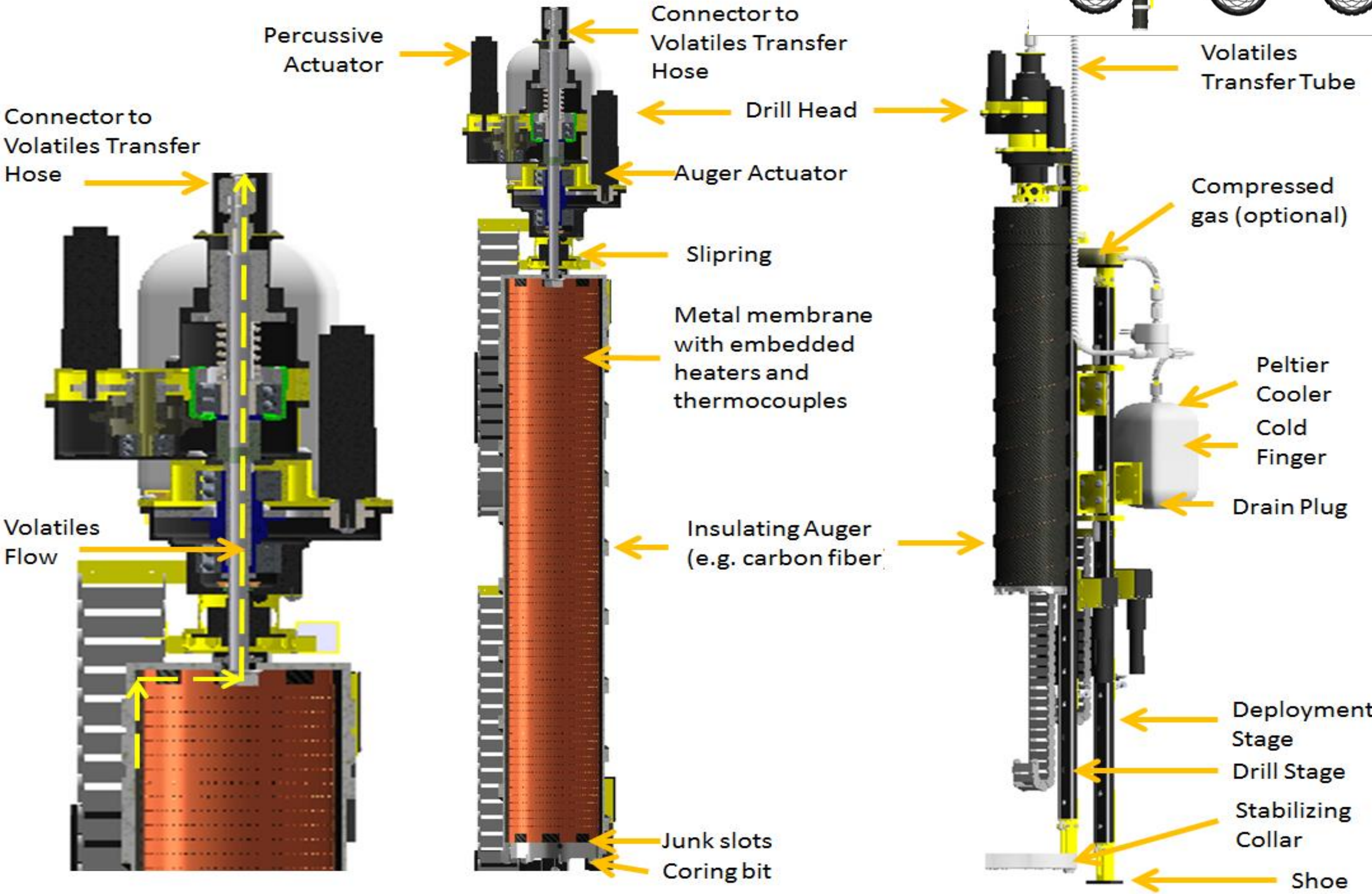
	PVEx-Corer	MISWE
Drill Name	Autogopher1	AMNH DeepDrill
Bit Picture		
Bit OD/ID, mm	71/70	64/0
Bit Kerf, mm	5.5	0
ROP, cm/min	2.6	0.4
Avg. Power, Watt	225	300
Energy, Whr/m	150	1250
Weight on Bit, N	~100	500-1000

PVEx Extraction Efficiency Study

	Parameters	MISWE	Corer	Recommended Corer
Inputs	Water concentration (wt%)	12	12	12
	Required Production Rate, kg/day	30	30	30
	Mission Duration, days	480	480	480
	Actual Production Time, hrs/day	10	10	10
Drill	Drill Outside Diameter, cm	6.4	7.1	15
	Drill Inside Diameter, cm		6	13
	Drill Stem Diameter, cm	3		
	Drill Length, cm	75	75	75
	Drill Power, Watt	300	225	400
	Drill Penetration Rate, cm/min	0.4	2.6	2.6
	Drill Energy, Whr	1250	144	256
Water Extraction	Volume of Soil Captured, cc	1882	2120	9950
	Density of Soil Captured, g/cc	1.5	2	2
	Mass of soil, g	2822	4239	19900
	Mass of water in the soil, g	339	509	2388
	Extraction Efficiency, %	44	65	65
	Mass of water extracted, g	149	331	1552
	Extraction Specific Energy, Whr/g	2.6	2.2	2.2
	Extraction Energy, Whr	387	727	3415
	Heater Power required, W	387	727	3415
Output	Total cycle time, hours	5.2	1.6	1.6
	Water Extraction Rate, g/hour	29	201	946
	Water Extraction Rate, kg/day, for 10 hour day	0.3	2	9
	Total Energy per 1 g water, Whr/g	11	3	2
	Total Heat Energy/ day, kWhr	78	66	66
	Total Energy per day, kWhr	330	79	71
	Number of rovers to reach 30 kg/day	**26**	**4**	**1**
	Number of PVEx Systems/rover	**4**	**4**	**4**

PVEx Corer Design





PVEx Corer: Power System

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PVEx Corer would need 2 MMRTGs to provide needed electrical and thermal energy for drilling and water extraction

Parameter	Value	Notes
Total Energy per day, kWhr	**71**	
Drill Energy/day, kWhr	**5**	
Heat Energy/day, kWhr	**66**	
Battery Energy Density, kWhr/kg	0.180	
Battery mass assuming 4 charge/discharge cycle per day, kg	100	Required energy: 71/4=18 kWhr
MMRTG Heat Generation, kW	2	MSL-type
MMRTG Heat Generation per 24 hr day, assuming 25% losses	36	
MMRTG Electrical Power Generation, kW	0.1	MSL-type
MMRTG Electrical Energy Generation per 24 hrs, kWhr	2.4	
MMRTG Mass, kg	**40**	
Number and mass of MMRTGs for all Electrical and Heat per day	**2** **80 kg**	2x36 kWhr of heat 2x2.4 kWhr of Electrical Energy

Summary

- Investigated 3 volatile extraction methods: Sniffer, MISWE, Corer
- Corer was the best from drilling and volatile extraction stand point.
- The PVEx-Corer would need a MSL-size rover with 2 MMRTGs to provide needed 30 kg of water per day
- Heating sample is relatively easier task than volatiles capture

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