Mars Water Well Performance: Experimental Heat Transfer Results Supporting Simulations

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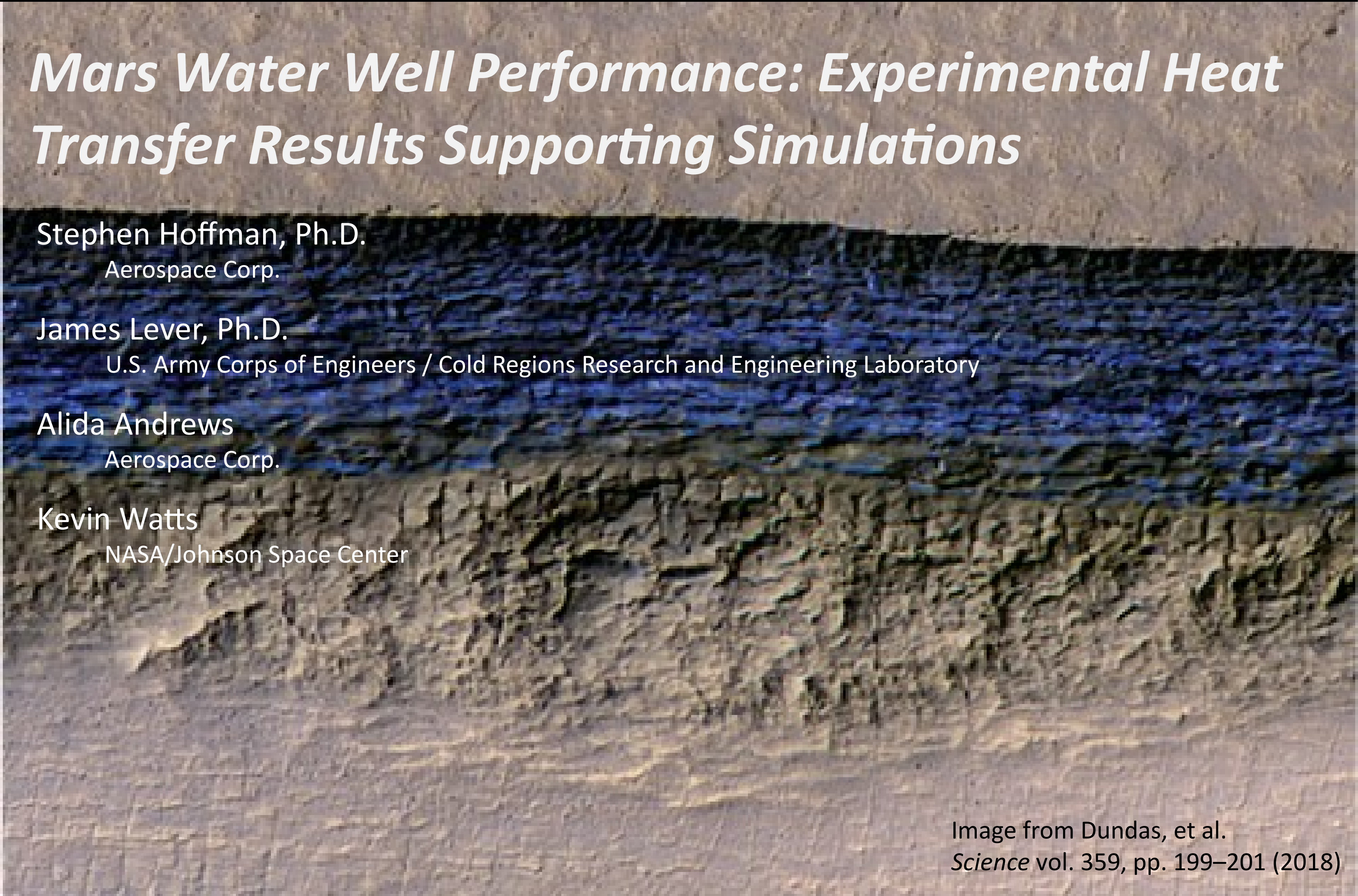
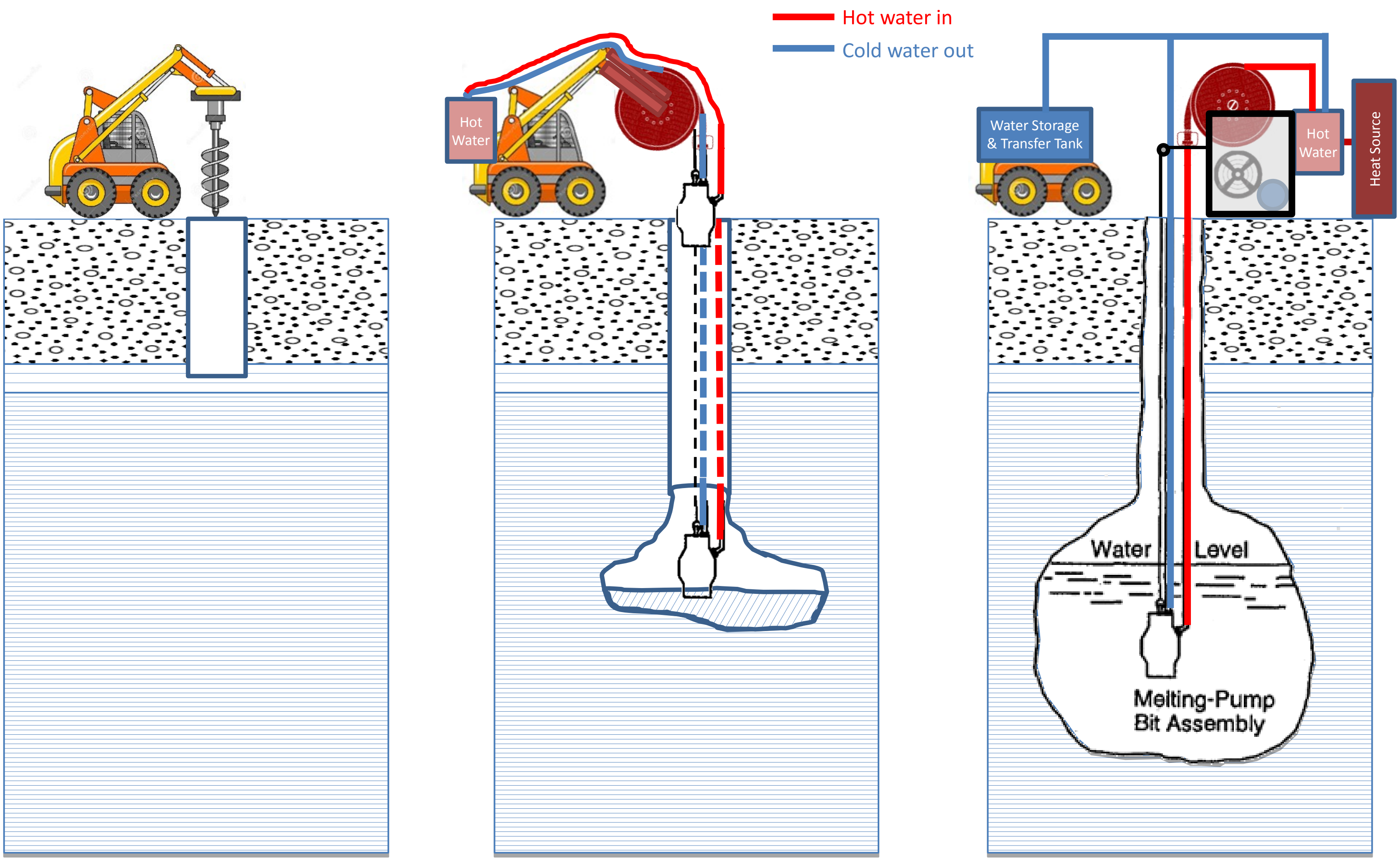


Image from Dundas, et al.
Science vol. 359, pp. 199–201 (2018)

What Is Motivating This Experiment?

- Using local resources for future human missions to Mars means reduced transportation requirements from Earth and a larger source of materials than might otherwise be available
- Of the many resources available on Mars, perhaps the most valuable is water
- One facet of NASA's current Mars Exploration Program is a search for the locations and quantities of water in various forms.
  - Subsurface liquid water aquafers
  - Surface and subsurface water ice and icy soils
  - Hydrated minerals
  - "Average regolith"
- Access to massive quantities of water could change surface mission concepts of operation and drive site selection
- A "Rodriguez Well" is one well-established technique for acquiring water from ice here on Earth
- A computer simulation developed by the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) is used to estimate Rodriguez Well performance
- ***This simulation incorporates empirical terms for heat transfer based on terrestrial environmental conditions – terms specific to Mars are needed***

Subsurface Water Well Development: Rodwell Approach

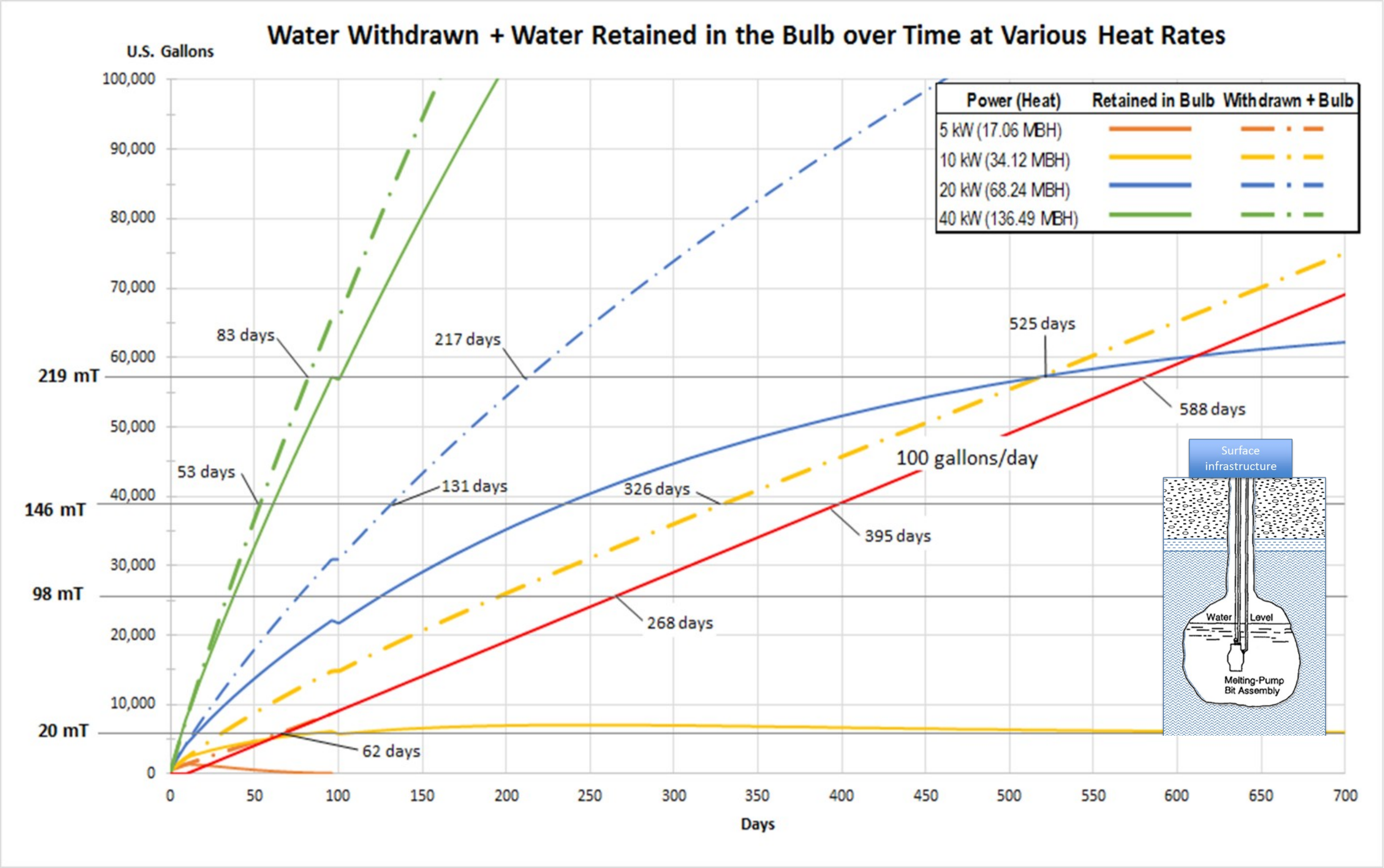


Phase 1: Drill through overburden into top of ice.

Phase 2: Melt into ice. Begin forming water pool.

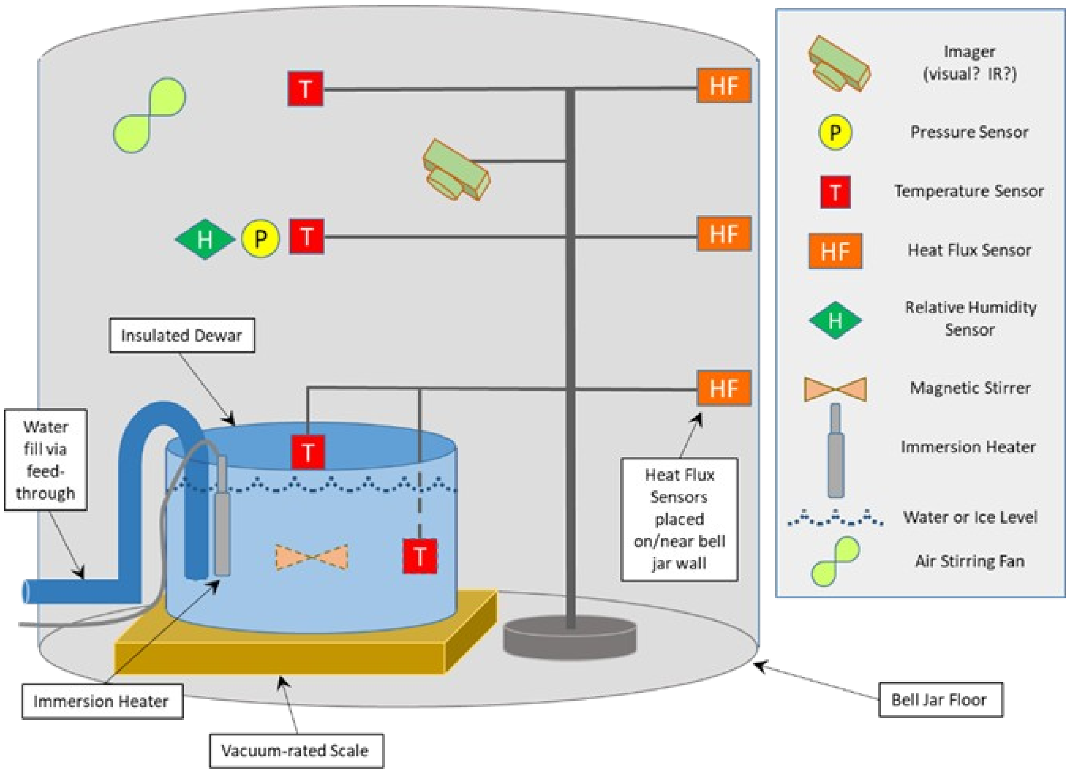
Phase 3: Steady state operation.

Predicted Time Needed to Withdraw Water at a 100 gal/day Rate



Note: assumes -80° C ice

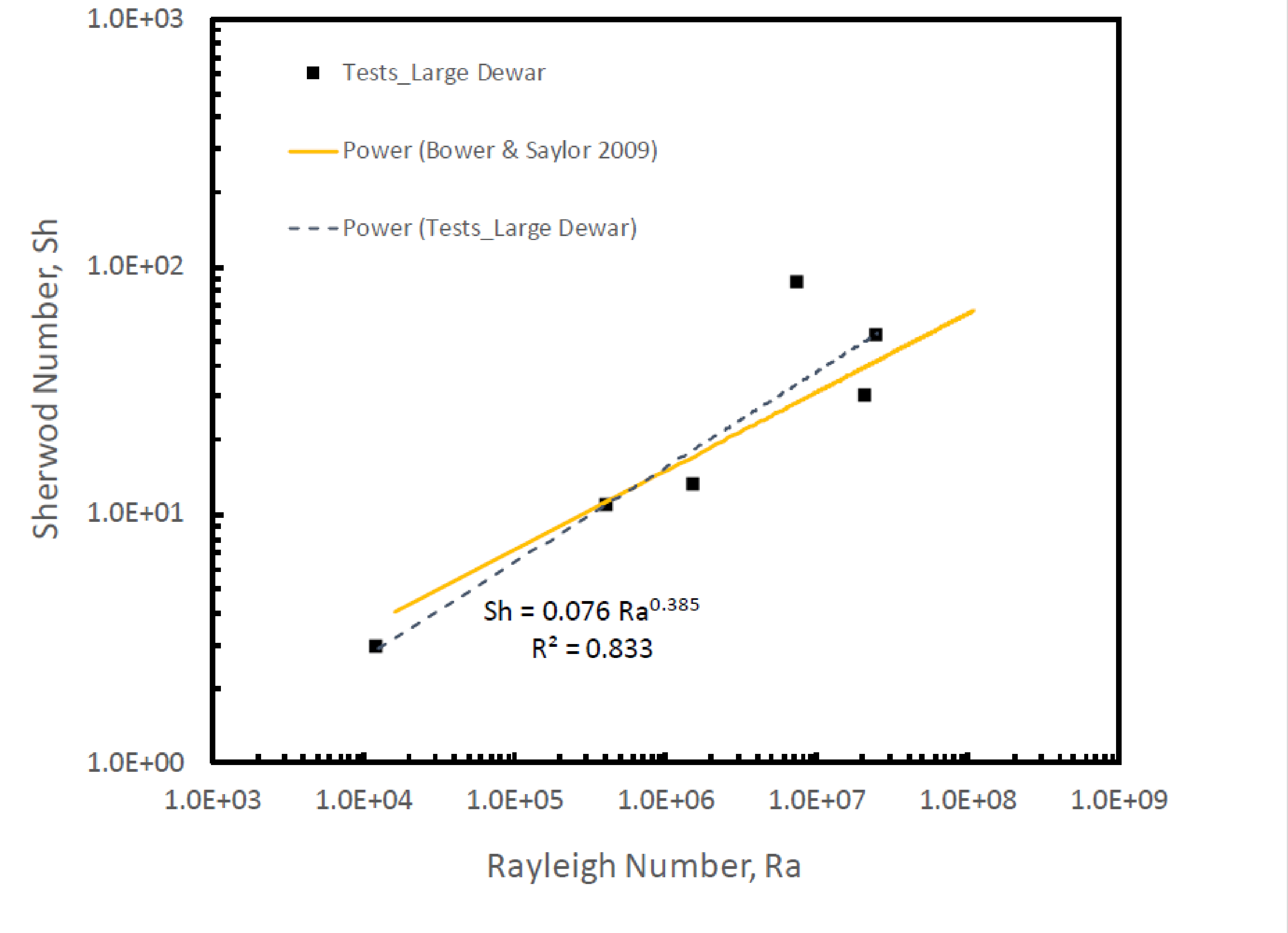
Experiment Equipment and Layout



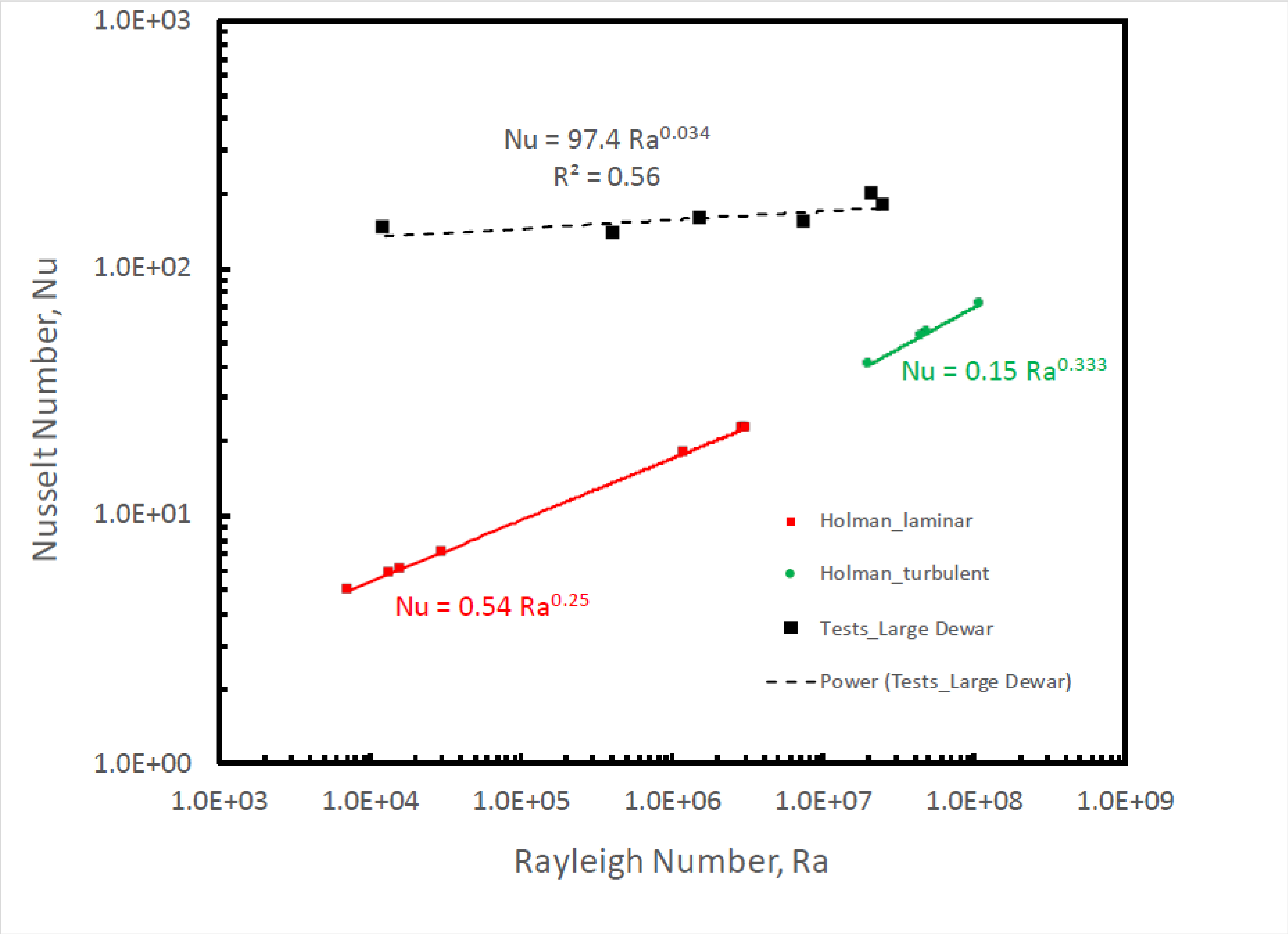
- Twelve test points – combinations of
  - Two dewar diameters (4.5 and 6.0 in)
  - Six chamber pressure (1000 – 8 mb)
  - Two chamber temperatures (-20 C and -40 C)
- Evaporative loss measured using a load cell
- Total heat transfer measured via immersion heater power

JSC 2-foot bell jar

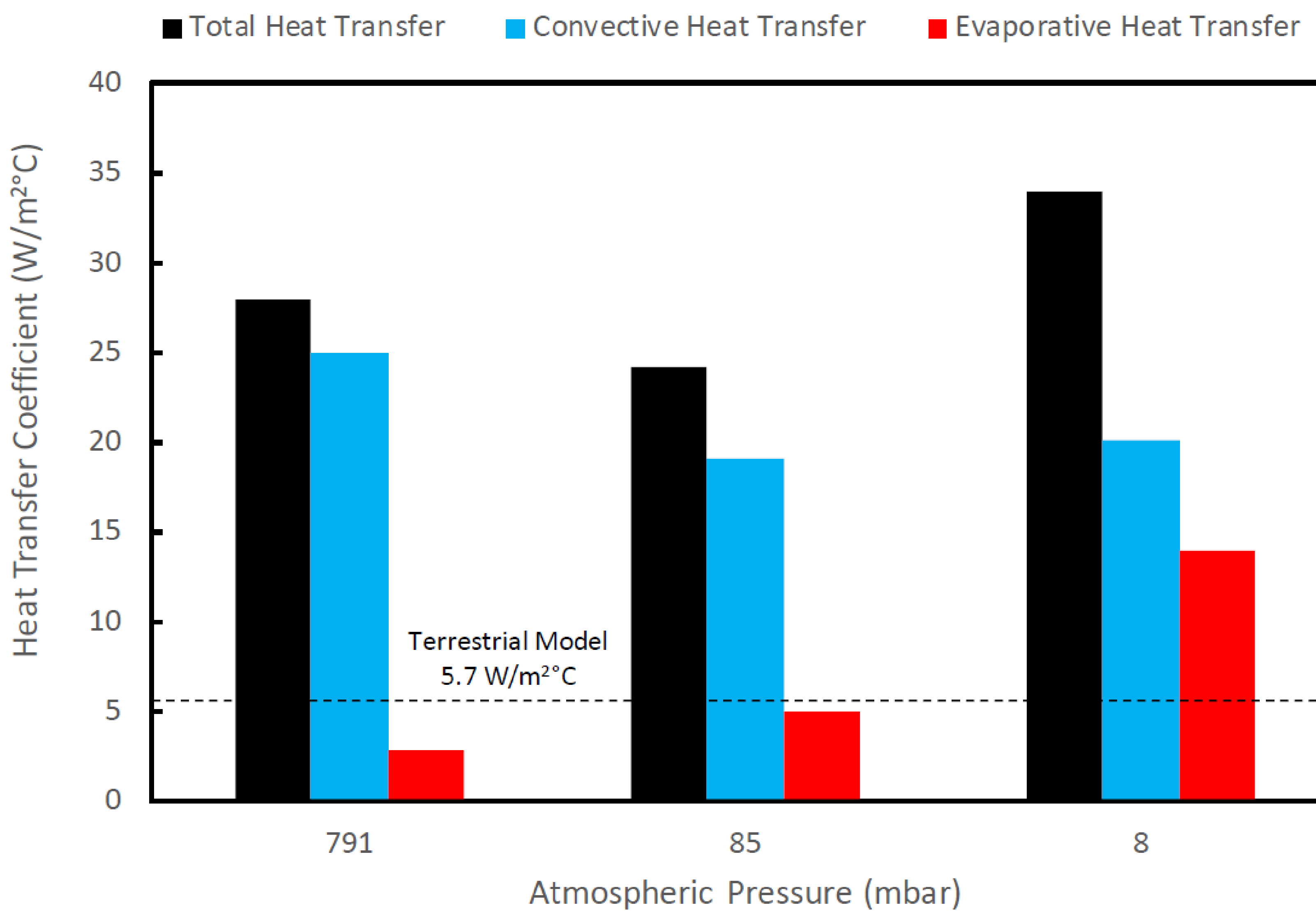
Sherwood–Rayleigh Relation for Water Undergoing Natural Convection-Driven Evaporation



Convective Heat Loss from Water to a Gas



Components of Heat Transfer, Water to CO_2 at T = -45°C



Summary

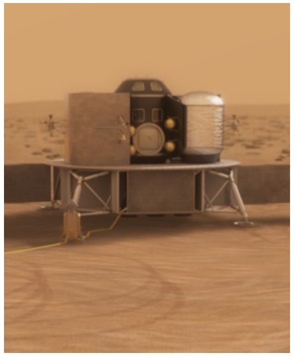
- Water will likely be an important resource for future human missions to Mars
- Recent discoveries of exposed ice sheets on Mars supports the theory that extensive buried ice sheets exist at mid latitude locations
- The Rodriguez Well technique offers one means for extracting significant quantities of water from these ice sheets
  - Extensive history of use in terrestrial applications
- Recent experiments at the NASA Johnson Space Center indicate these wells can be formed under ambient surface conditions on Mars
  - Water pools can be sustained with water held near freezing conditions
    - This approach is used in terrestrial Rodwells
  - Water pools under these Martian conditions found to exhibit structural characteristics similar to terrestrial Rodwells
    - For example: ice shelf formation
  - Evaporation follows power law trends observed for terrestrial water pools at Earth ambient conditions
- Total heat loss rates will be used to adapt CRREL simulation models for use in predicting Martian Rodwell performance

Backup

How Would a Human Mars Mission Use Abundant Water?

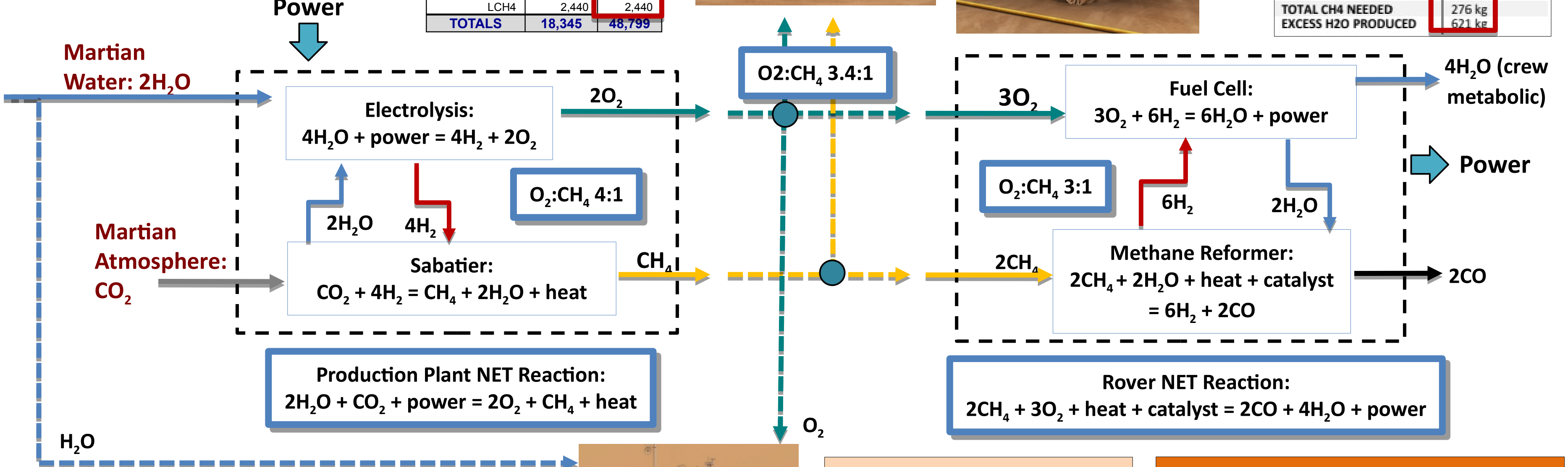
20 tons of water (plus CO_2) provides ascent fuel and oxidizer for one MAV

Subsystem	Mass (kg)	
	MDM Payload	Mars Liftoff
Crew Cabin	3,427	4,122
Structures	881	881
Power	377	377
Avionics	407	407
Thermal	542	542
ECLS	502	502
Cargo	422	1,117
Non-Prop. Fluids	295	295
1st Stage	9,913	31,432
Dry Mass	3,605	3,605
LO2	0	21,519
LCH4	6,308	6,308
2nd Stage	5,006	13,245
Dry Mass	2,566	2,566
LO2	0	8,239
LCH4	2,440	2,440
TOTALS	18,345	48,799

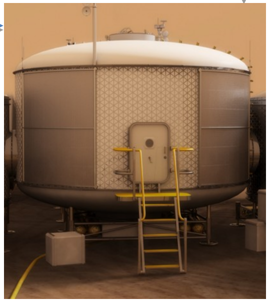


23 tons of water provides rover reactants for robust surface mobility

TRIP DURATION	14 sols
NO. OF DAYS DRIVING	9 sols
CREW	2
ROVER DRIVE TIME/DAY	9 hours
TOTAL ENERGY NEEDED	1564 kW-hrs
TOTAL O2 NEEDED	841 kg
TOTAL CH4 NEEDED	276 kg
EXCESS H2O PRODUCED	621 kg



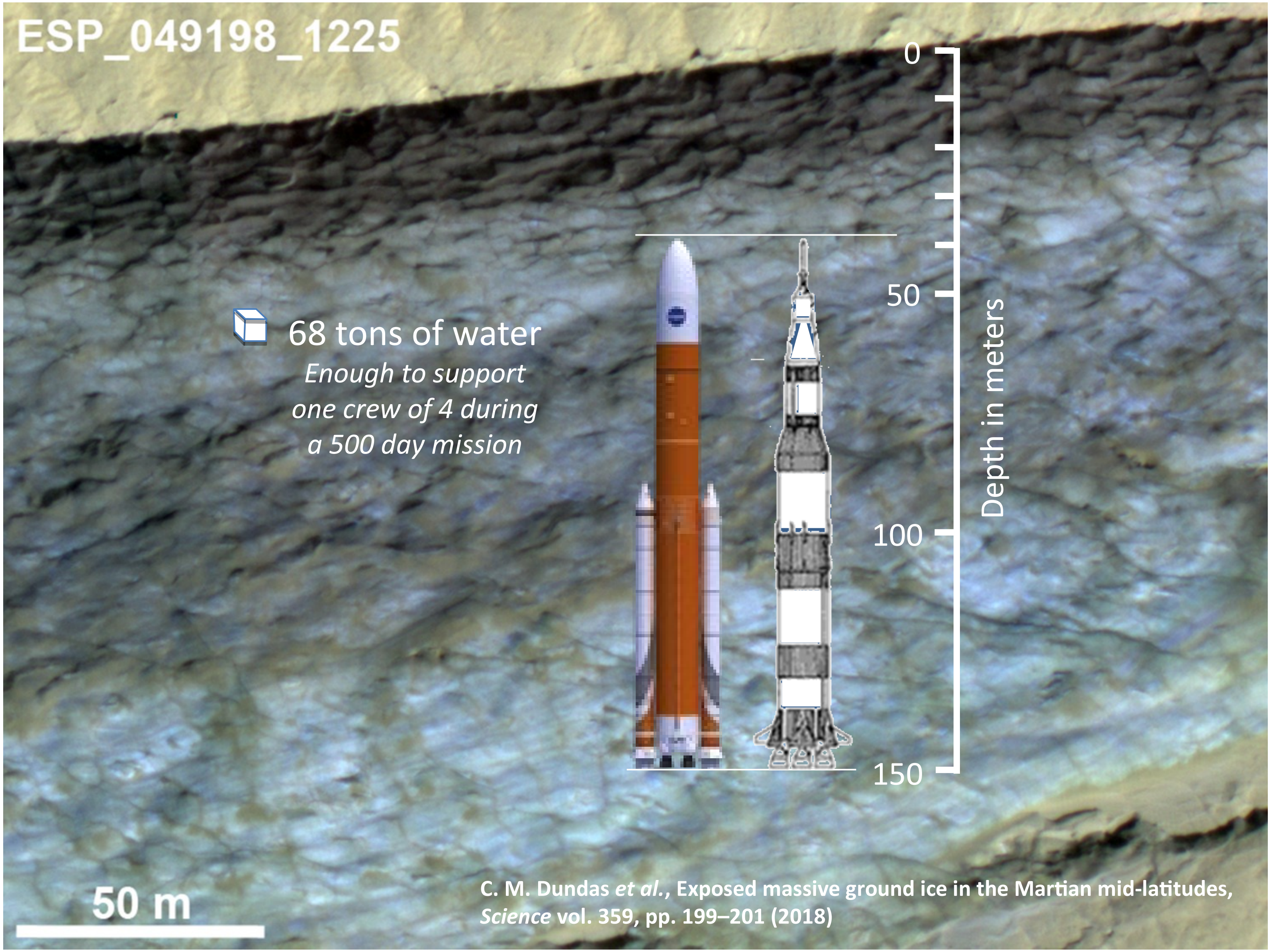
	CLOSED-LOOP H_2O, O_2	OPEN-LOOP H_2O, O_2	OPEN-LOOP + LAUNDRY
H_2O CLOSED-LOOP MAKEUP	970	0	0
O_2 CLOSED-LOOP MAKEUP	2480	0	0
LAUNDRY	0	0	14660
EVA	0	3072	3072
FOOD REHYDRATION	0	1070	1070
MEDICAL	0	107	107
DRINK	0	4280	4280
FLUSH	0	134	134
HYGIENE	0	856	856
TOTAL	3450 kg	9519 kg	24379 kg



25 tons of water provides robust open-loop life support for a crew of 4 for 500 days

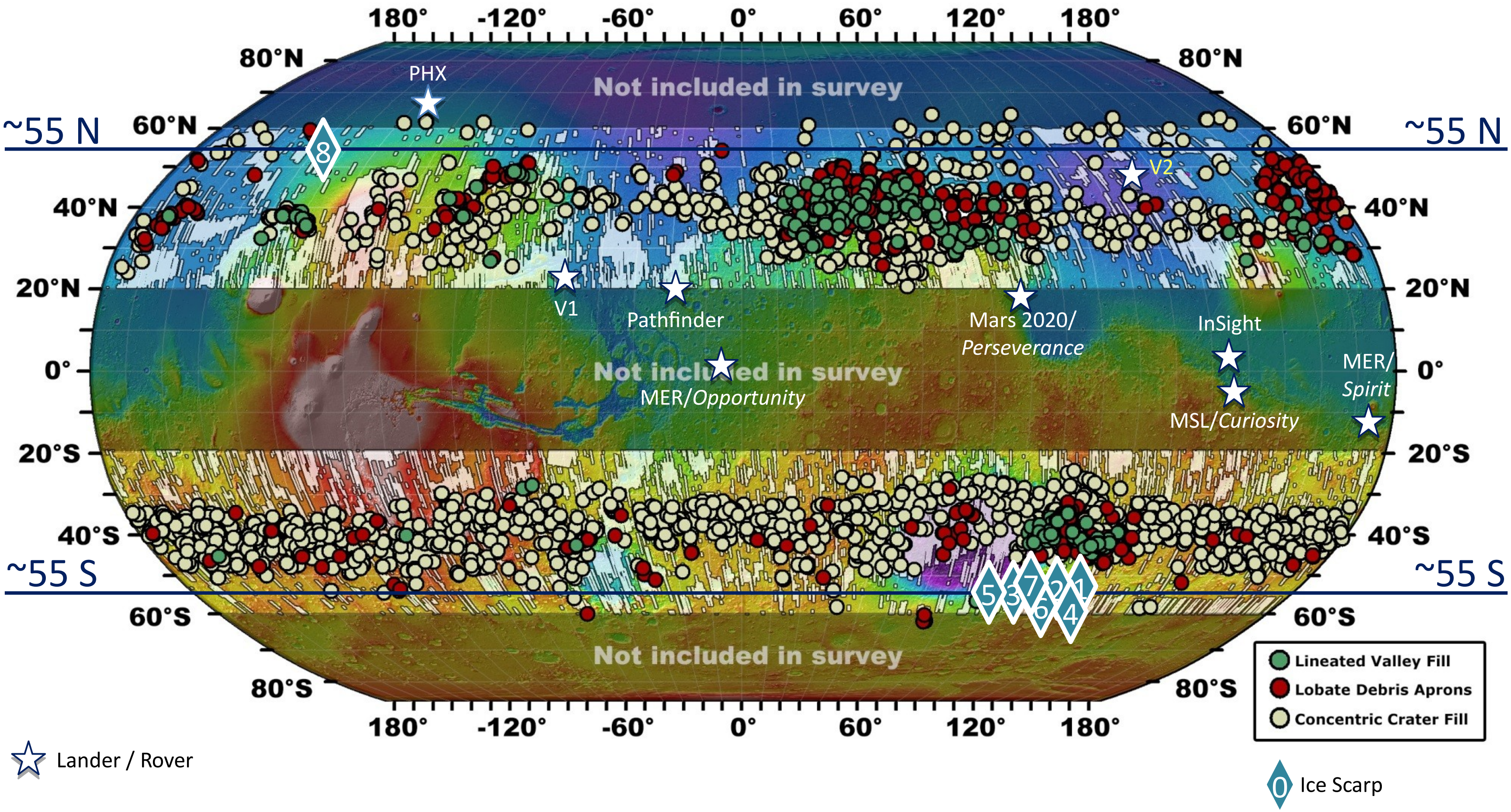
A total of 68 tons of water supports one crew of 4 during a 500 day mission

How Much Water Ice Could Be In These Formations?



Where are these Scarps Located?

- Seven of the scarps "… are located in the southern hemisphere, and the eighth location is a cluster of scarps in Milanković Crater in the northern hemisphere."



Test Points: Liquid Water at ~1°C

Test Number	Dewar Size	Air Temp (deg C)	Air Pressure (mbar)	Rayleigh Number
1	4.5 in (11.4 cm)	-40	8	4.6E+03
2	4.5 in (11.4 cm)	-40	240	1.0E+06
3	4.5 in (11.4 cm)	-40	1000	1.7E+07
4	4.5 in (11.4 cm)	-20	8	2.5E+03
5	4.5 in (11.4 cm)	-20	370	1.0E+06
6	4.5 in (11.4 cm)	-20	1000	7.0E+06
7	6.0 in (15.2 cm)	-40	8	2.5E+04
8	6.0 in (15.2 cm)	-40	95	9.9E+05
9	6.0 in (15.2 cm)	-40	1000	9.1E+07
10	6.0 in (15.2 cm)	-20	8	1.3E+04
11	6.0 in (15.2 cm)	-20	250	2.6E+06
12	6.0 in (15.2 cm)	-20	1000	3.8E+07

Green values – in range of published data. Red numbers – outside range of published data

Terrestrial Polar Operations: The Rodriguez Well*

- In situ water reservoirs were first designed and built by the U.S. Army Cold Regions Research and Engineering Laboratory (USACRREL) in the early 1960s for several U.S. Army camps located in Greenland (Schmitt and Rodriguez 1960; Russell 1965).
  - commonly referred to as Rodriguez Wells or Rodwells
- Snow or ice is melted and stored in place at some depth below the surface of the ice cap, eliminating the need for mechanical handling of snow and for fabricated storage tanks
- Water wells or Rodwells have been used at:
  - Camp Fistclench (Greenland, 1957)
  - Camp Century (Greenland, 1959 and 1960)
  - Camp Tuto (Greenland, 1960)
  - South Pole Station (Antarctica, 1972-73 and 1995-present; currently using third Rodwell)
  - IceCube drilling operation (2004 – 2011; seasonal only)

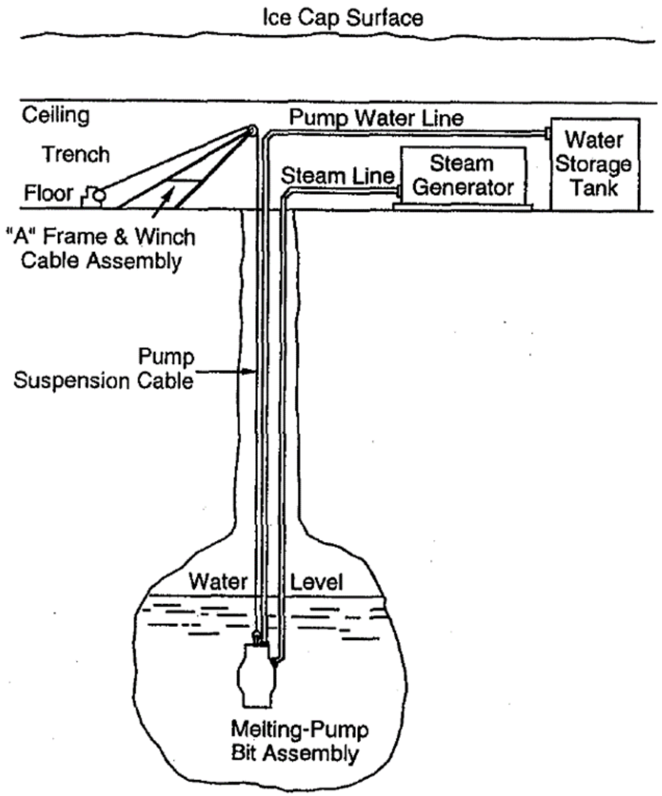
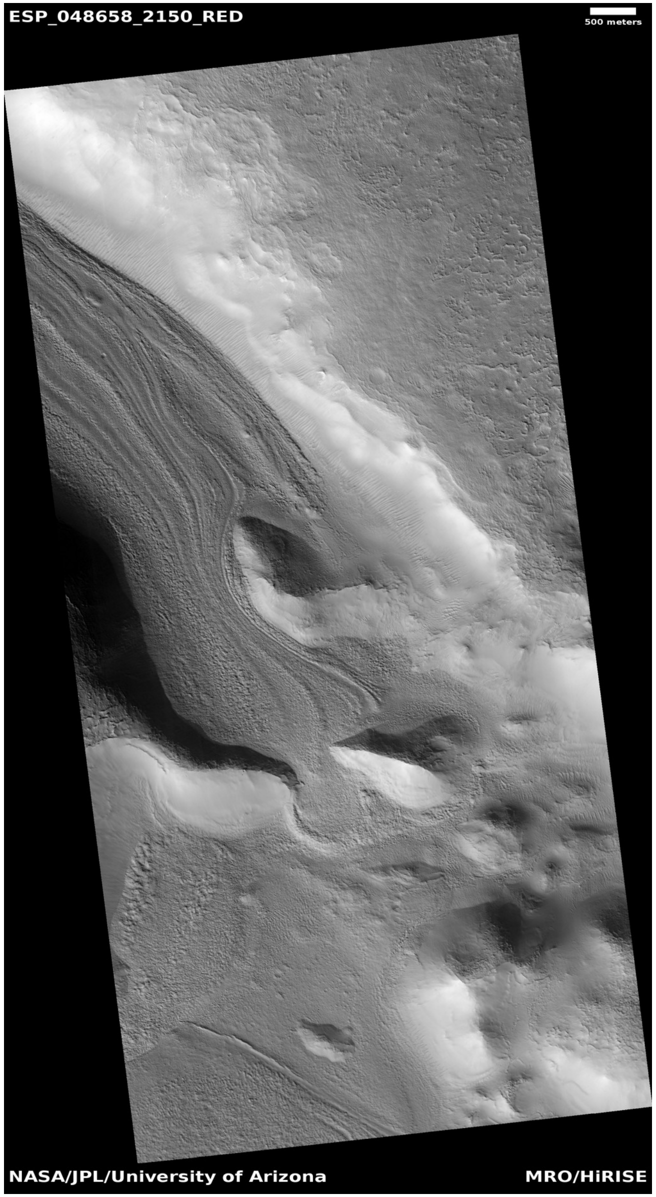


Figure 1. Camp Century water well equipment (from Clark 1965).

*Lunardini, V.J. and J. Rand (1995). Thermal Design of an Antarctic Water Well. *CRREL Special Report 95-10*.

What is Lineated Valley Fill?

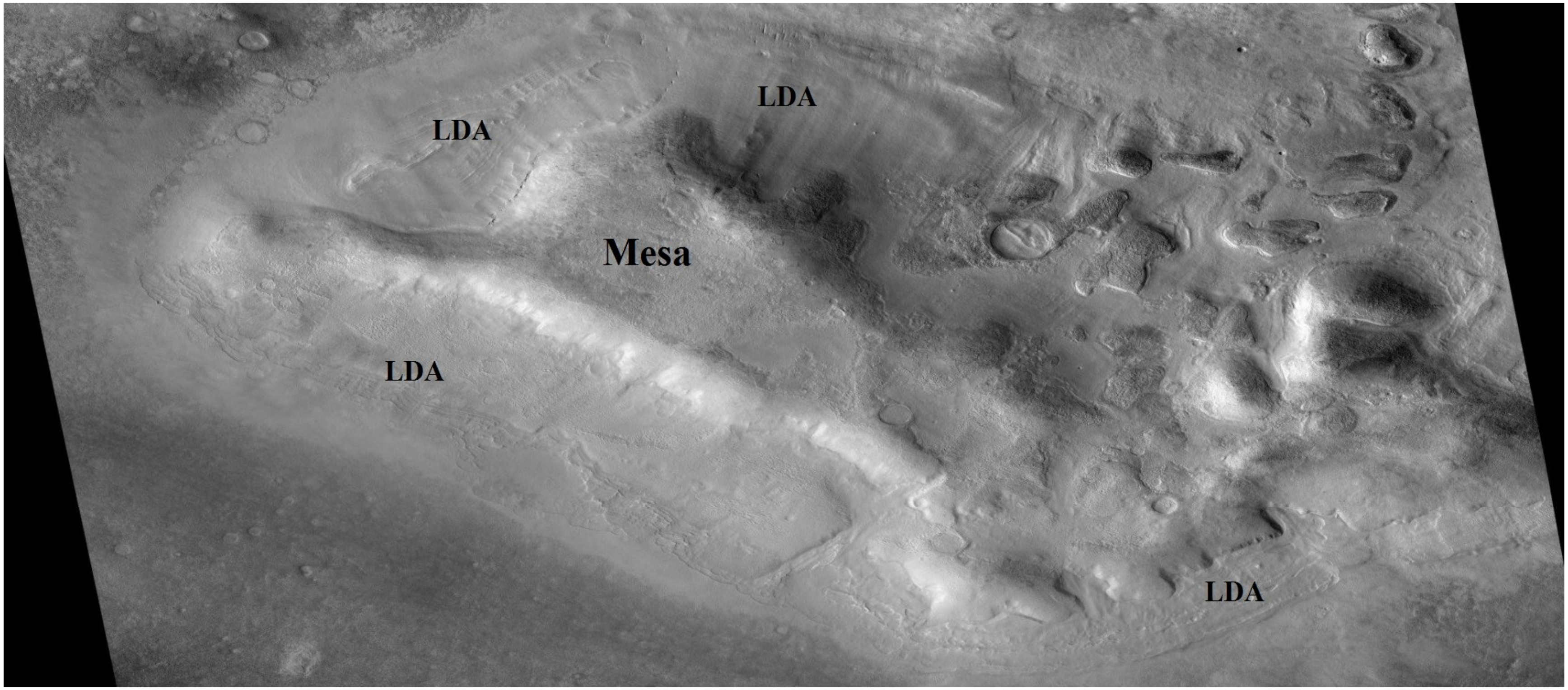


Lineated Valley Fill is a feature seen on the floors of some channels on Mars, exhibiting ridges and grooves that seem to flow around obstacles. These features bear a strong visual resemblance to some terrestrial glaciers.

The Heimdal Glacier in southern Greenland. Credit: NASA/John Sonntag

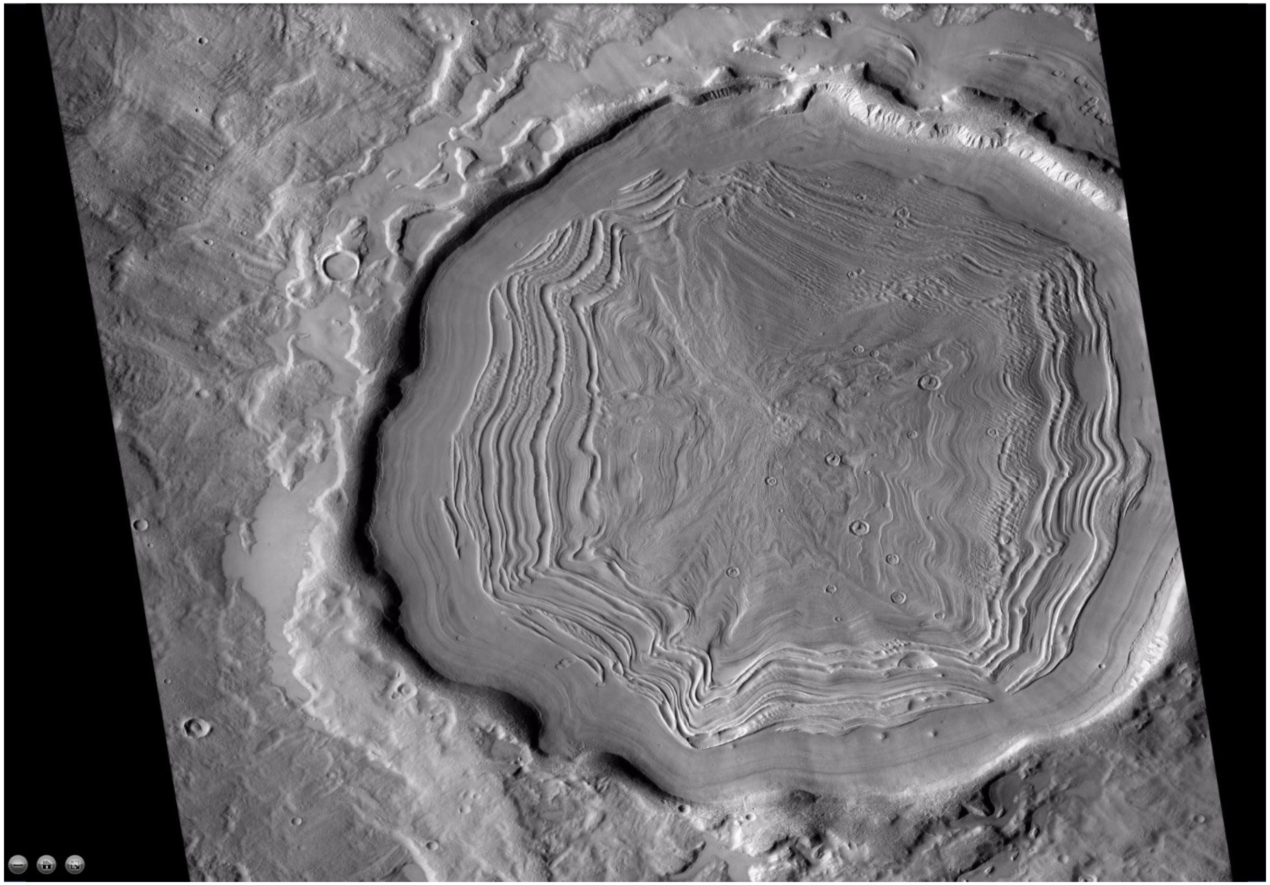
What are Lobate Debris Aprons?

Lobate debris aprons (LDAs) are geological features on Mars, consisting of piles of rock debris below cliffs. These features, first seen by the Viking Orbiters, are typically found at the base of cliffs or escarpments. They have a convex topography and a gentle slope, suggesting flow away from the steep source cliff.



What is Concentric Crater Fill?

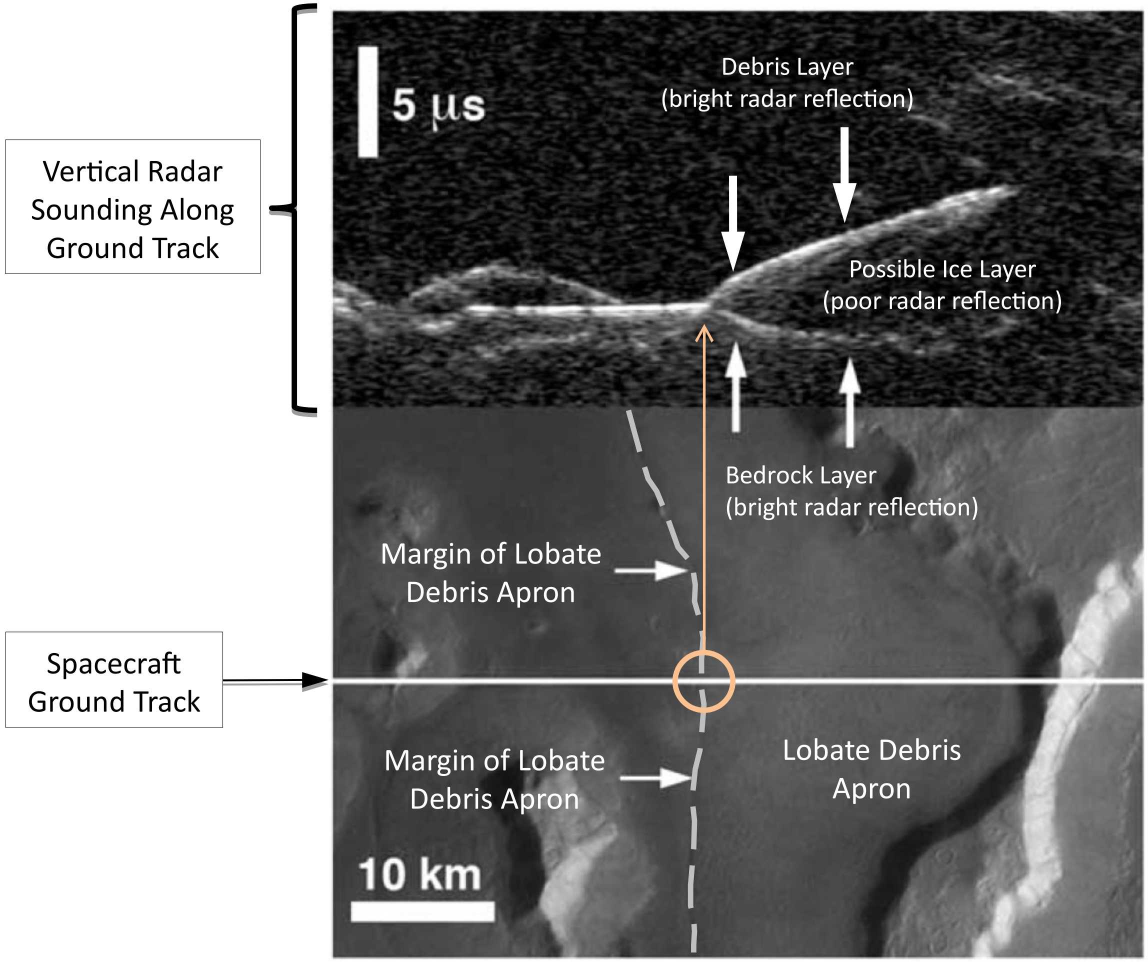
Concentric crater fill is a terrain feature where the floor of a crater is mostly covered with a large number of parallel ridges.



Modeling suggests that concentric crater fill developed over many cycles in which snow is deposited, then moved into the crater. Once inside the crater, shade and dust preserved the snow. The snow was gradually compressed into ice. The many concentric lines are created by many cycles of snow accumulation, at a time when the Mars environment could support snowfall.

What is the Radar Evidence for Debris Covered Water Ice?

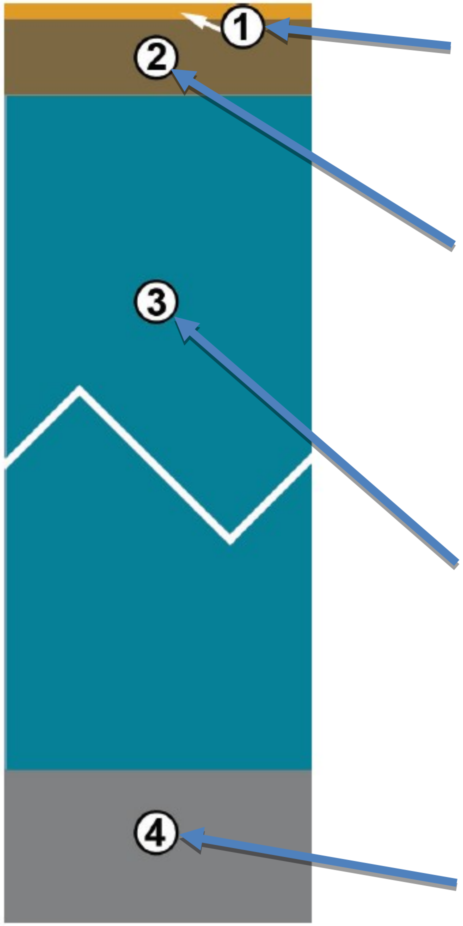
While searching for subsurface aquafers, the MARSIS (Mars Advanced Radar for Subsurface and Ionosphere Sounding; on *Mars Express*) and SHARAD (SHAllow RADar; on *Mars Reconnaissance Orbiter - MRO*) radars gathered data indicating these terrain features could be debris covered ice.



Radar evidence for ice in lobate debris aprons in the mid-northern latitudes of Mars
Jeffery J. Plaut, Ali Safaeinili, John W. Holt, Roger J. Phillips, James W. Head III, Roberto Seu, Nathaniel E. Putzig, and Alessandro Frigeri
Geophysical Research Letters Volume 36, L02203, 2009.

Debris Protects This Ice, But How Thick Is It?

Conceptual stratigraphy of the materials exposed in the scarps.*



1. Upper dry lithic layer (dust, rocks, regolith), with a thickness of about 10 centimeters at these locations [i.e., ~50 deg. Latitude; based on models]; this is too thin to be well-expressed in the scarps. The basal contact is likely to be sharp, as observed by Phoenix.
2. Ice-rich soil (ice filling the pores of lithic material). The thickness may be variable spatially and is ≤1–2 m in places. This could be locally absent if the uppermost massive ice is covered by mass-wasted debris; however, such a layer is possible based on the difference between the depth to visible ice and the predicted depth to the top of the ice table. If such a layer exists, vertical variations in ice content due to ice modification processes are possible.
3. Massive ice with low lithic content (≤ a few vol%). This is likely to be greater than 100 m thick but may be variable; it constitutes the bulk of the material exposed in the scarps. This unit contains some vertical structure (e.g. layers with variation in lithic fraction) and lateral heterogeneity (e.g., lens with less ice at Scarp 2). It may be locally covered by a surface lag deposit, especially on the lower parts of the scarps.
4. Basal unit (bedrock or underlying regolith materials); this may contain some ice in pore space.

***C. M. Dundas *et al.*, Exposed massive ground ice in the Martian mid-latitudes, *Science* vol. 359, pp. 199–201 (2018)**

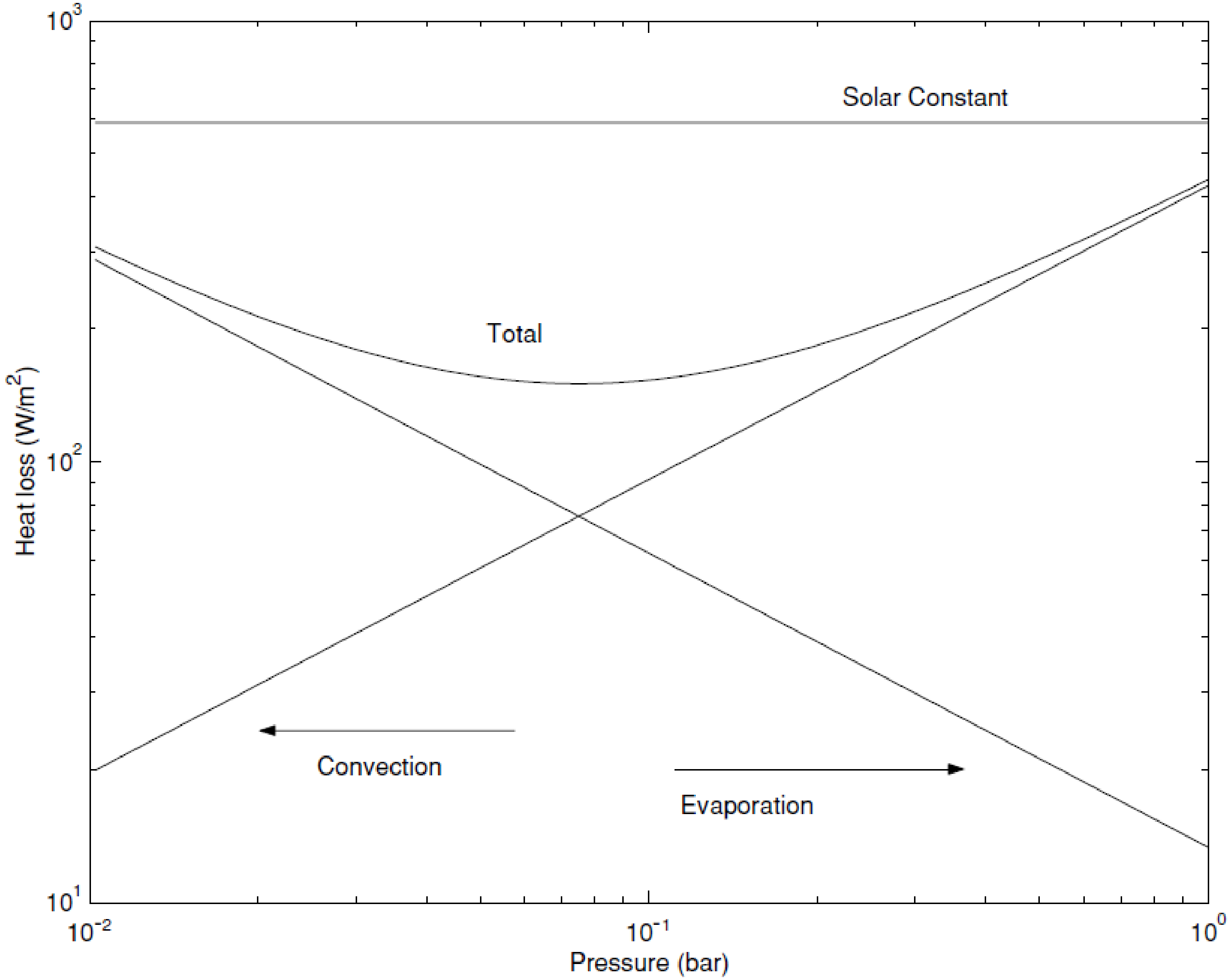
Conceptual System and Notional Conops

- Conduct a local site survey to identify the specific location for the Rodwell
  - Identify the thinnest debris depth
  - Determine the firn layer depth (if any) and identify cracks, voids, etc.
- Drill through the debris layer
  - Use mechanical drill
  - Case the hole to prevent debris from collapsing into the hole and to allow some TBD pressurization of the reservoir
- Drill into ice layer
  - Drill down to a depth sufficient for ice to support the overlying debris layer and bypass any firn, cracks, voids, etc.
  - Several technology options exist for this step; further evaluation/tests are needed to select "best" option
    - Mechanical, electro-thermal, hot water, hybrid
- Melt ice and store water in subsurface reservoir
  - Power needed to melt ice and water extraction rate are coupled and both are tied to the specific use scenario
- Options exist to cease operations between crews or to keep Rodwell in continuous operation
  - Dependent on surface mission scenario and overall campaign – future work required
- Option to store water above ground or use the Rodwell reservoir for storage
  - Future work required

Observations from the 100 gal/day Withdrawal Case

- The power values on the previous chart are ONLY for melting ice and maintaining a liquid pool of water in the subsurface cavity; *additional power* will be needed to pump water out of this cavity and to run other surface infrastructure elements.
- The withdrawal rate and input power are highly coupled
  - A different withdrawal rate will result in a different shape to these results
- For this 100 gal/day withdrawal rate
  - For power levels above approximately 10 kW, liquid water is being created at a much faster rate than it is being withdrawn, resulting in very large subsurface water pools that will not be used
  - A power level of approximately 10 kW generates liquid water at about the rate at which it is being withdrawn
    - The water pool remains at approximately a constant volume
    - The water pool will gradually sink to lower levels, which will drive the amount of power needed to pump water from these deeper levels
  - For power levels below approximately 10 kW, water is being withdrawn faster than it is being melted and the well eventually "collapses"
    - At a power level of approximately 5 kW, the 20 mT projected need for a single crew's MAV could be withdrawn before the well "collapses" but little additional water would be made

Example of Relevant Experimental Results



Convective heat transfer between a 273 K surface (water) and a 200 K atmosphere compared to evaporative cooling. The right-hand boundary reflects terrestrial conditions; the left reflects Martian conditions. For equivalent conditions, total heat loss is actually less on Mars than on Earth. (Hecht, "Metastability of Liquid Water on Mars")

Differences Between Existing Model and Mars Model

- Physical / Chemical Properties
  - Atmospheric constant pressure specific heat
  - Atmospheric gas constant
- Heat transfer
  - Air – water heat transfer
    - *Requires investigation owing to low-pressure conditions on Mars*
  - Air – ice heat transfer
  - Water – ice heat transfer (assumed to be the same on Earth and Mars)
- Air pressure effects
  - Atmospheric pressure ranges from slightly above the triple point of water to slightly below
- Gravity (impacts factors such as buoyancy)

Parameter	Earth		Mars	
	(SI/metric)	(SAE)	(SI/metric)	(SAE)
Atmospheric Pressure	1013 mb	14.7 psi	8.0 mb	0.116 psi
Gas Constant	287 J/(kg-K)	53.4 ft-lbf/(lbm-R)	189 J/(kg/K)	35.1 ft-lbf/(lbm-R)
Atmospheric Specific Heat	1.01 kJ/(kg-K)	0.240 Btu/(lb-R)	0.834 kJ/(kg-K)	0.199 Btu/(lb-R)
Heat Transfer – Water to Air	5.67 W/(m^2-K)	1.00 Btu/(h-ft^2-R)	4.11 W/(m^2-K)	0.725 Btu/(h-ft^2-R)
Heat Transfer – Ice to Air	5.67 W/(m^2-K)	1.00 Btu/(h-ft^2-R)	4.11 W/(m^2-K)	0.725 Btu/(h-ft^2-R)

Baseline value used in CRREL Rodwell simulation

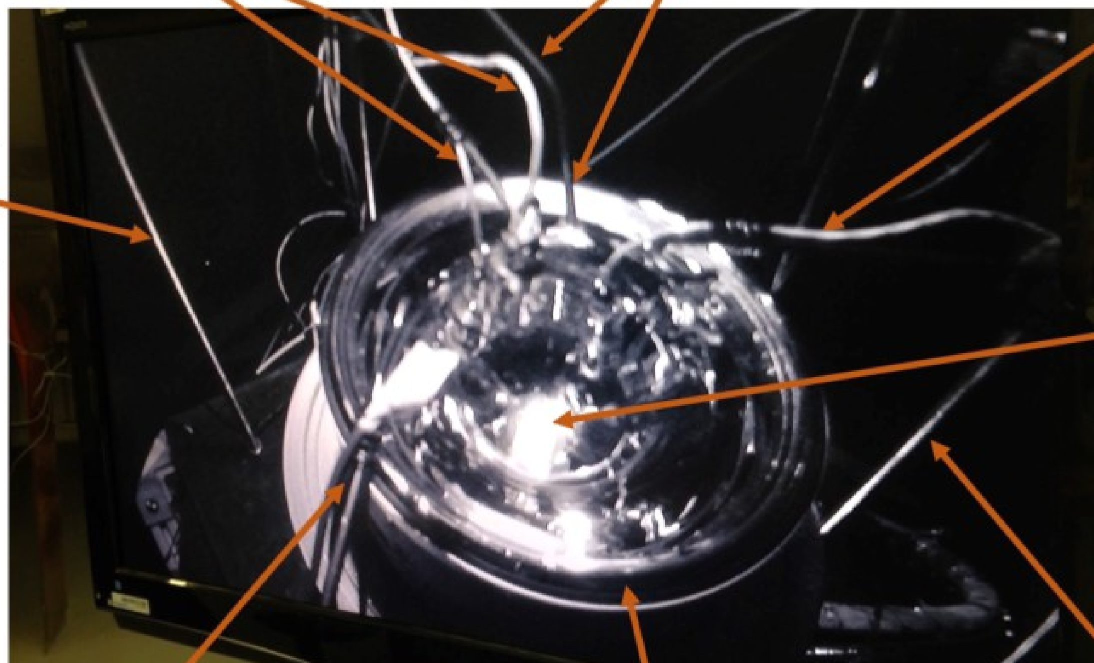
Key Items Appearing in Video

2 RTDs – one in water (primary for water temp) and one just above water surface

Water supply line to dewar

RTD in water (backup for water temp)

Circulating fan support



Rotating stirrer bar

Heater power and heater temp thermocouple

Dewar with hemispherical bowl and mirrored inner surface

LED illumination source support

Short video

Test conditions:

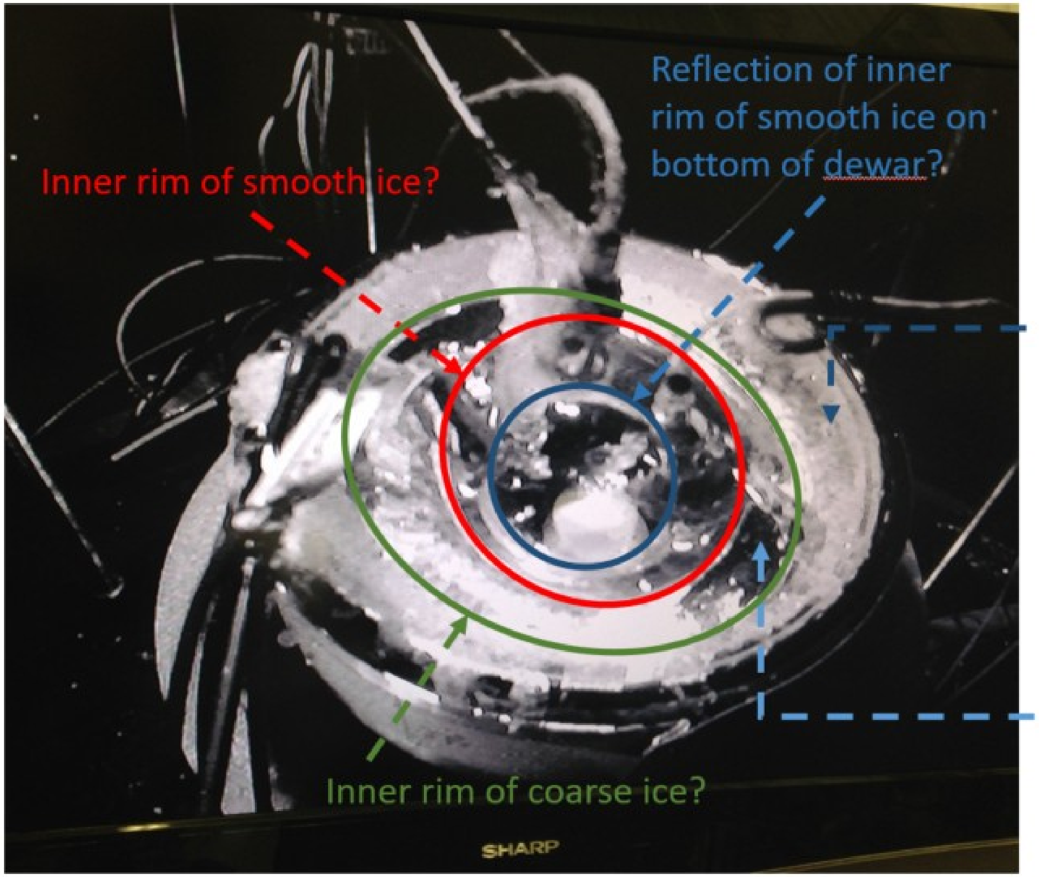
Chamber pressure = 8 mb (6 torr)

Chamber temperature = -20 C

Chamber gas = CO_2

Ice and Water Formation Visible in Video

“Coarse” ice
from rim inward about 0.50-0.75 in



“Smooth” ice
from edge of coarse ice inward about 0.75 in