A Water-Rich Mars Surface Mission Scenario

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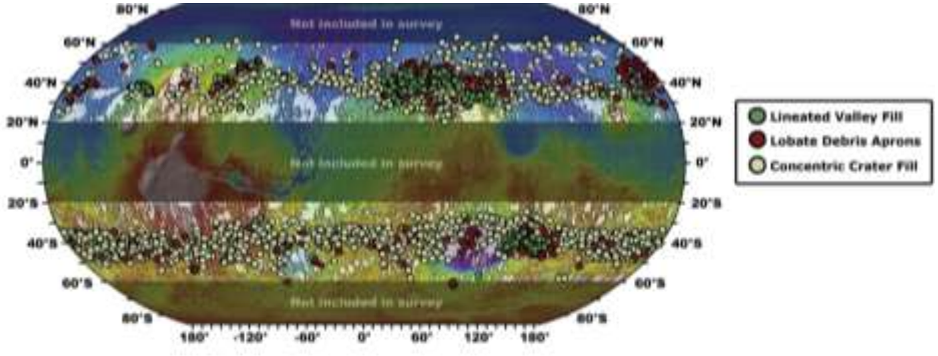
IEEE Aerospace Conference
Big Sky, Montana
March 4–11, 2017

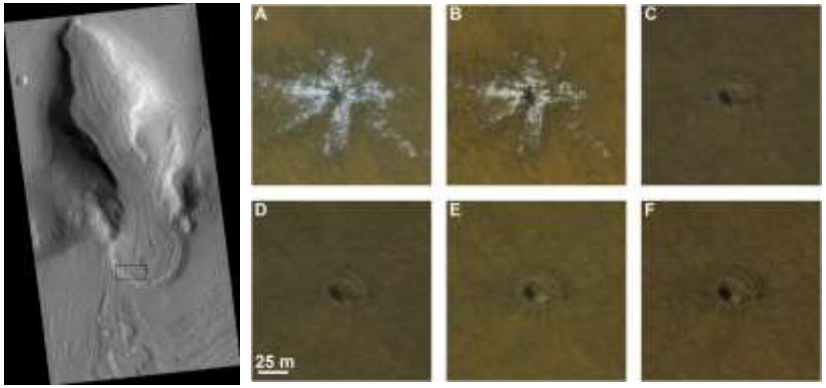
Introduction

- **Discoveries by Mars robotic missions have methodically indicated potential of accessible water on or near the non-polar Martian surface**
- **A pair of questions posed to those studying the Evolvable Mars Campaign (EMC): what are the implications of “unlimited” water on a human Mars mission and how would these quantities of water be acquired?**
- **This presentation will summarize work done to answer these questions**
  - The sources of water observed on Mars will be described
  - Uses for locally obtained water are identified and estimated quantities needed for each of these uses are presented
  - Methods for accessing local sources of Martian water are reviewed
  - Results from a simulation to estimate time and power required for one method are presented
- **Conclusions that can be drawn from these studies and recommendations for future work will be presented.**

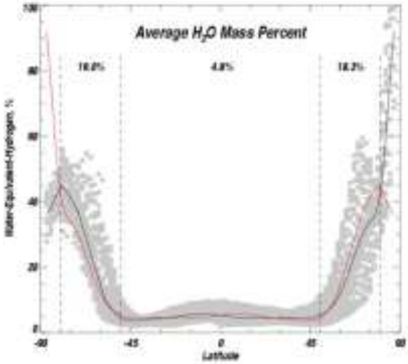
Martian Water Sources



From Dickson et. al. 2012.



From Dundas, et. al., 2014



From Feldman, et. al. 2004.

To date *Mars Express MARSIS and Mars Reconnaissance Orbiter (MRO) SHARAD radars* ***have failed to detect any indications of liquid groundwater within 200-300 m of the surface anywhere on Mars [Clifford, et. al. 2010]***

However:

- Martian geological features suggest evidence **for large-scale *mid-latitude* glaciation** ("ice ages"), potentially driven by changes in obliquity of planetary rotation axis
- MRO SHARAD radar took soundings of "lobate debris aprons" (LDAs) in southern and northern regions
- Radar properties completely consistent with **massive water ice (100s of m thick, >90% pure) covered by relatively thin (0.5 - 10 m) debris layer** [Holt, et. al. 2008]

- Fresh impacts detected by MRO HiRISE imager actually ***show* excavated, clean ice** (~1% regolith content), verified by CRISM spectrometer
- Majority of craters showing ice in mid-latitudes correspond to the suspected glaciers (LDAs), estimated **excavation ~2 m**

- Mars Odyssey gamma ray/neutron spectrometer confirmed previous predictions of extensive ground ice within *one meter* of surface
  - Poleward of 50°N and S
  - Concentration highly variable ~20-90%
  - Cryosphere estimated to be 5-15 km thick [Clifford, et. al. 2010]
- Predictions and orbital measurements confirmed by Phoenix Lander (68°N)
  - Ice excavated at 2-6 cm, up to 99% pure

Mars Mission Water Economy

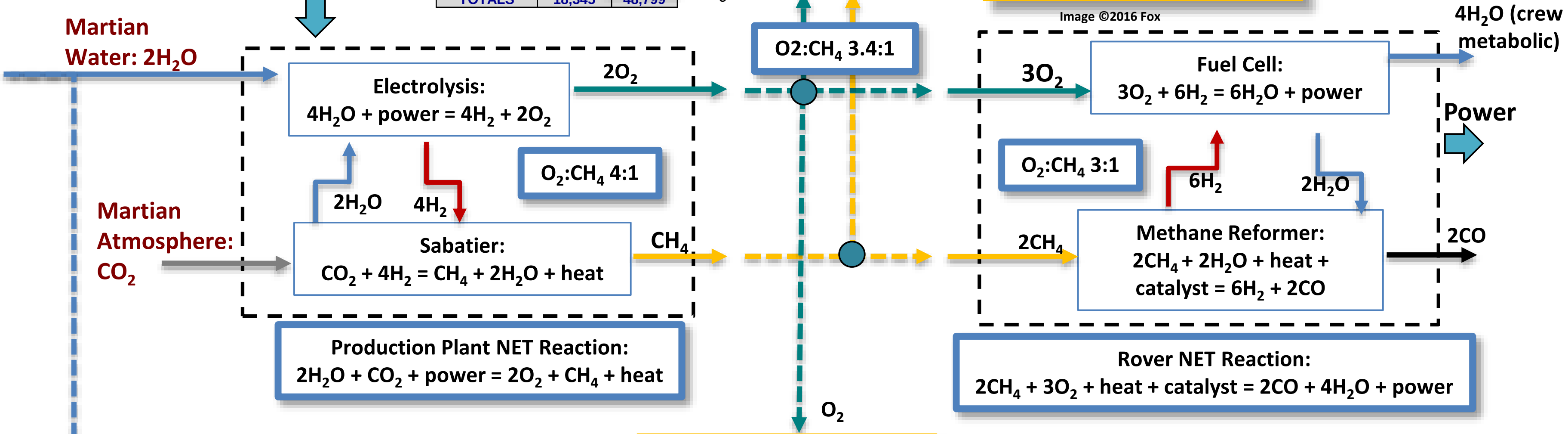
Subsystem	Mass (kg)	
	MDM Payload	Mars Liftoff
Crew Cabin	**3,427**	**4,122**
Structures	881	881
Power	377	377
Avionics	407	407
Thermal	542	542
ECLS	502	502
Cargo	422	1,117
Non-Prop. Fluids	295	295
1st Stage	**9,913**	**31,432**
Dry Mass	3,605	3,605
LO2	0	21,519
LCH4	6,308	6,308
2nd Stage	**5,006**	**13,245**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


Image ©2016 Fox


Image ©2016 Fox

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

Power



Electrolysis:
$4H_2O + power = 4H_2 + 2O_2$

Sabatier:
$CO_2 + 4H_2 = CH_4 + 2H_2O + heat$

$O_2:CH_4$ 4:1

$O2:CH_4$ 3.4:1

Fuel Cell:
$3O_2 + 6H_2 = 6H_2O + power$

$O_2:CH_4$ 3:1

Methane Reformer:
$2CH_4 + 2H_2O + heat + catalyst = 6H_2 + 2CO$

Production Plant NET Reaction:
$2H_2O + CO_2 + power = 2O_2 + CH_4 + heat$

Rover NET Reaction:
$2CH_4 + 3O_2 + heat + catalyst = 2CO + 4H_2O + power$

O_2

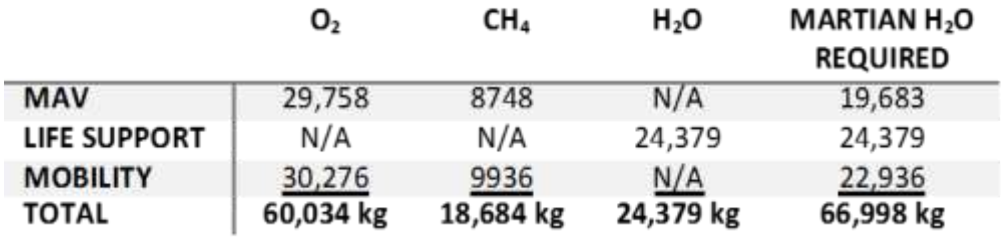
H_2O


Image ©2016 Fox

	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**

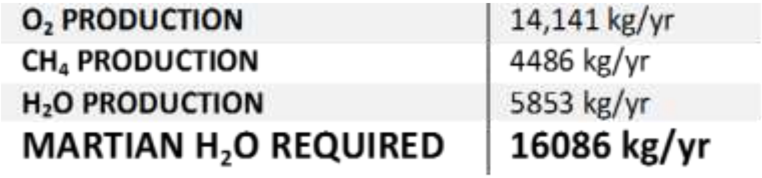
Crew of 4, 500 days

Water Extraction Requirements



	O_2	CH_4	H_2O	MARTIAN H_2O REQUIRED
MAV	29,758	8748	N/A	19,683
LIFE SUPPORT	N/A	N/A	24,379	24,379
MOBILITY	30,276	9936	N/A	22,936
TOTAL	**60,034 kg**	**18,684 kg**	**24,379 kg**	**66,998 kg**

Products and Required Feedstock per mission (4 crew, 500 days)



O_2 PRODUCTION	14,141 kg/yr
CH_4 PRODUCTION	4486 kg/yr
H_2O PRODUCTION	5853 kg/yr
MARTIAN H_2O REQUIRED	**16086 kg/yr**

Production and Water Extraction Rates to support one mission every 4 years

- Large quantities of water ice are available within 0.5 – 10 meters of the Martian surface poleward of 30° latitude in both hemispheres
- 20 tons of water provides ascent fuel & oxidizer
- 25 tons of water provides robust *open-loop* life support for crew of four for 500 days
- 23 tons of water provides rover reactants for robust surface mobility
- 16 tons/year of water extraction provides on-going exploration crew support (500-day mission every 4 years)

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)

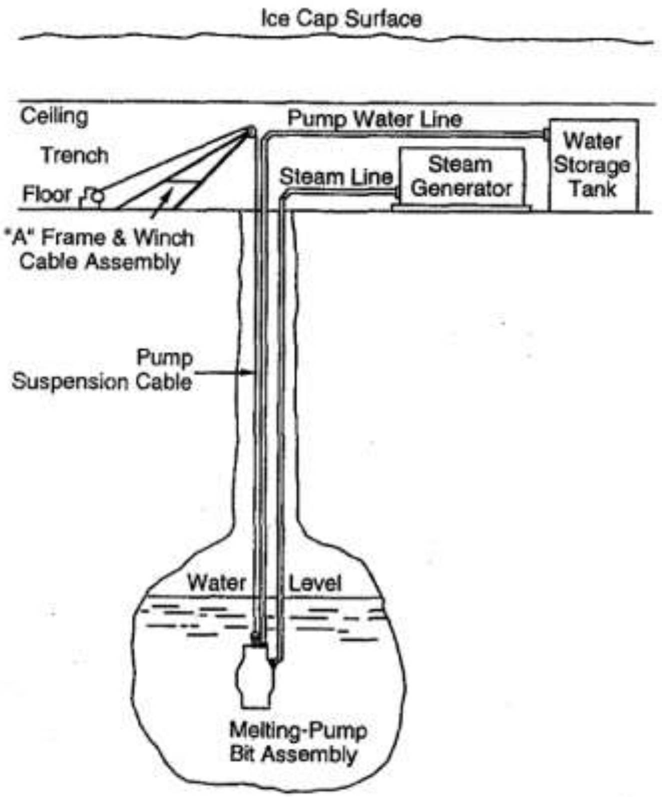


Figure 1. Camp Century water well equipment (from Clark 1965).

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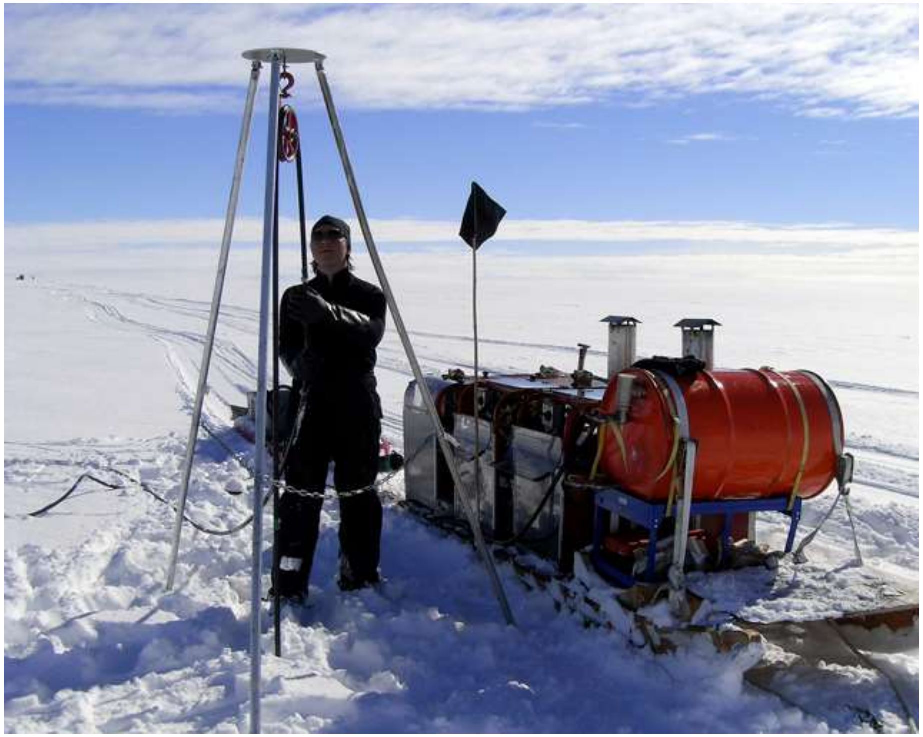
*Lunardini, V.J. and J. Rand (1995). Thermal Design of an Antarctic Water Well. *CRREL Special Report 95-10*.

Mechanical Drills with “Icebreaker” drill example

- **A study of available mechanical drill options for future human missions was completed in 2013**
    - Results documented in “Drilling System Study; Mars Design Reference Architecture 5.0,” JSC 66635, September 30, 2013
    - This study captured results from a drilling workshop for robotic mission, also completed in 2013
        - Planetary Drilling and Sample Acquisition (PDSA) held at the NASA Goddard Space Flight Center in May, 2013

Photos courtesy of Brian Glass

Hot Water Drill with Small (i.e., EMC-scale) Example



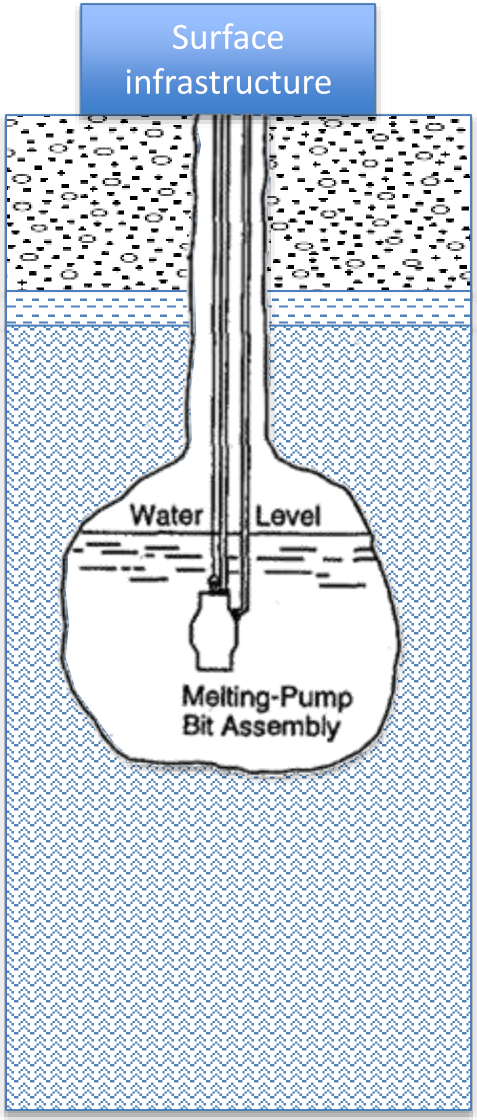
NSF Ice Drilling Development Office (IDDO) portable hot water drill. Image from: http://icedrill.org/equipment/portable-hot-water-drills.shtml

- **NSF Ice Drilling Development Office (IDDO) developed a "portable" hot water drill.**
  - Transportable by light aircraft and helicopter
  - Mass data of pictured system is listed below
- **Primary use is for shot holes for seismic work, but they have been used also for access holes through a thin ice shelf.**
- **Can be rapid to operate.**
  - During one 3-month Antarctic season, drilled nearly 170 shot holes and completed four seismic transects

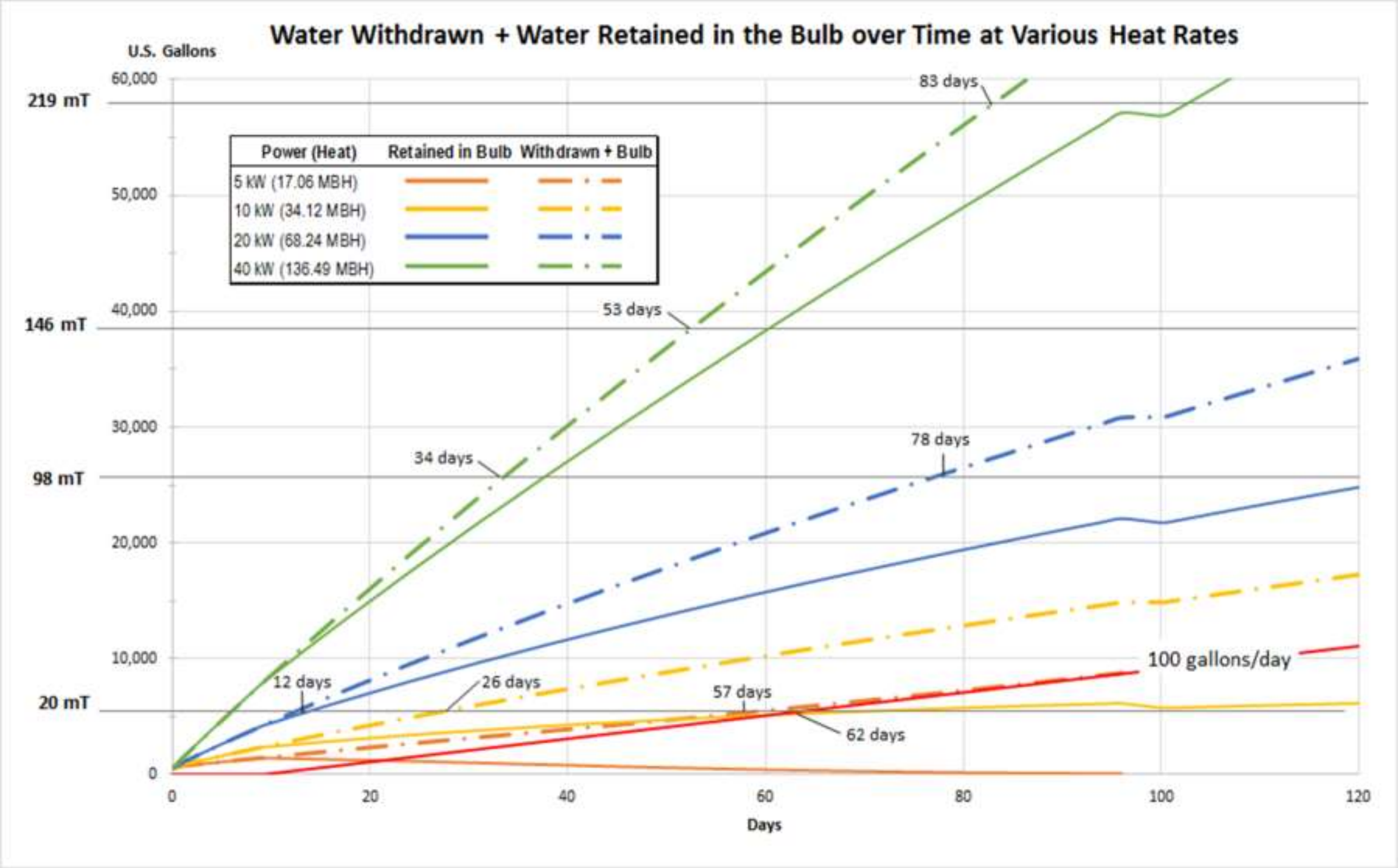
Type:	**Non-coring**
Number in Inventory:	**2**
Max. Depth Possible:	**Reliable and efficient to a depth of 25-30 m**
Shipping Weight:	**1590 kg (3500 lbs)**
Comments:	**Assembled for operation w/o fuel: 1000 kg (2200 lbs)**

Concept for Assessment

- **Based on the previous discussion, a Rodwell approach appears to provide a viable means of extracting water that should be assessed**
- **This approach will require drilling through the overburden layer and far enough into the ice layer so that the resulting cavity will not collapse due to the weigh of the overburden**
- **A cased hole through at least the overburden and possibly the upper ice layer will be required so that the cavity can be sealed and pressurized to some TBD level to minimize water sublimation**
- **To assess this option, the following elements must be identified and characterized:**
  - A drill that can penetrate the overburden layer and emplace a casing
  - A drill that can penetrate the ice layer (may or may not be the same as the overburden drill)
  - A concept to melt and recirculate water within the Rodwell "melt pool"



Predicted Time Needed to Withdraw Water for a 100 gal/day Case

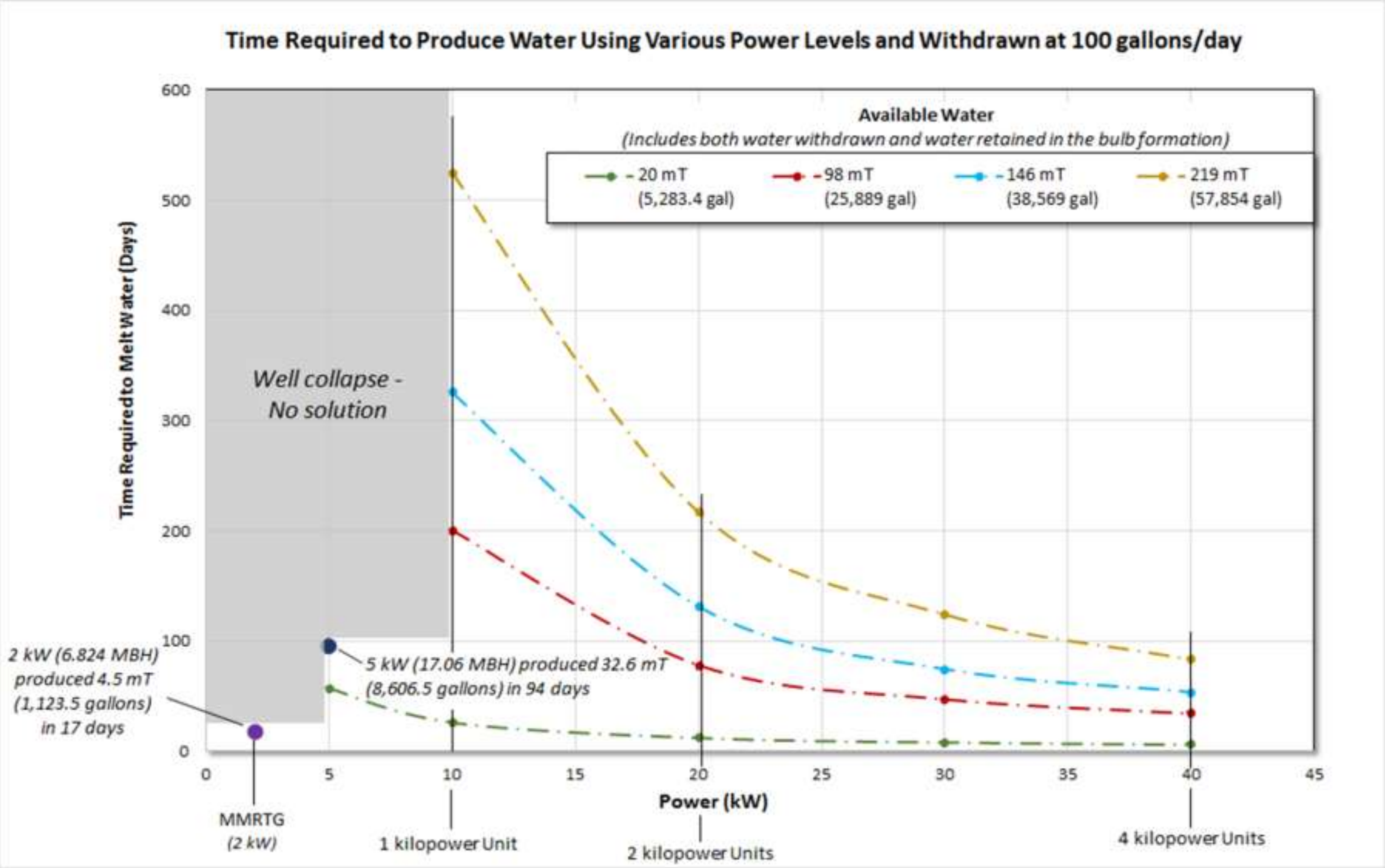


Note: assumes -80° C ice

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 could be withdrawn before the well “collapses” but little additional water would be made

Impact of Power Input for a 100 gal/day Withdrawal Rate



Time Required to Produce Water Using Various Power Levels and Withdrawn at 100 gallons/day

2 kW (6.824 MBH) produced 4.5 mT (1,123.5 gallons) in 17 days

5 kW (17.06 MBH) produced 32.6 mT (8,606.5 gallons) in 94 days

Note: assumes -80° C ice

Summary of Key Observations from this Assessment

- **Ice sources**
  - Broad subsurface layers
  - Localized remnant deposits
- **Multiple existing technologies identified to drill through debris and ice layers**
  - Mechanical drills for debris layer and ice
    - Small devices under development for robotic space missions
    - Wide variety of terrestrial devices in use (operational experience)
    - Device characteristics documented in several locations
  - Several technologies for drilling ice
    - Electro-thermal
    - Hot water
    - Hybrid
  - Terrestrial examples of these technologies are mature and commonly used in analogous polar operations
- **At least one existing technique – the Rodriguez Well – identified to melt and store water in large bodies of ice**
- **These technologies and techniques were used to assess an approach to address a gap in the initial M-WIP study to access and extract water from buried ice deposits**

Known unknowns

- **There are still many unknowns regarding the quantity and distribution of ice sources at high Martian latitudes**
- **This assessment focused on bodies of ice that would be typical of the Lobate Debris Apron (LDA) and Lineated Valley Fill (LVF) categories of glacier-like forms**
- **A better understanding of glacier-like forms on Mars is needed**
  - A general understanding of these Martian formations and how closely they compare to similar formations on Earth
  - Better resolution and characterization of the vertical profile of these formations
    - Thickness and particle size distribution of debris layer – this drives how much casing and drill string is needed
    - Vertical profile of the ice layer
      - Is there a firn layer?
      - Are there cracks, crevasses, or voids?
      - Temperature profile
  - Surveying capabilities (e.g., ground penetrating radar) to select the “best” site(s) to establish this type of water well
- **Where and how to store water above ground – long term storage still a problem on ISS; e.g., chemicals leaching out of containers over time**

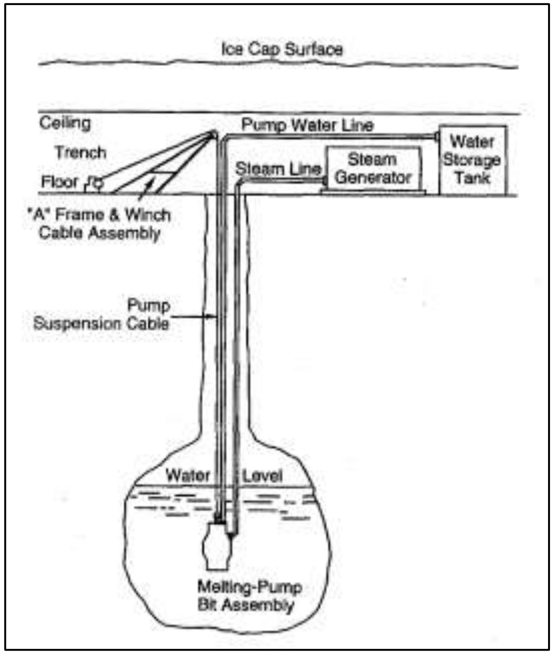
Recommendations for Future Work

- **This analysis indicates that use of terrestrial ice drilling and Rodriguez Well techniques to generate a source of liquid water from presumptive Martian glaciers has promise for an operational system at Mars. However, the heat input available and water withdrawal rates for a representative Mars surface mission are small compared to most terrestrial experience. Tests using a functional prototype of such an operational system could provide useful data to validate or refute the analytical results.**
- **Is a Rodwell the best approach to extracting water for a periodic, but extended duration, Mars surface mission? What are the alternatives? What factors tip the "best" approach to one solution or another?**
- **What combination of mechanical, thermal, and hot water drilling is (most likely) needed to establish the access shaft for a Rodwell or other water melting/extraction approach given the likely vertical profile associated with glacier-like features on Mars?**
- **What thickness of ice is needed to support an overlying layer of debris that could be somewhere between 0.5 m and 10 m thick?**
- **What remote sensed data is most useful or needed for site selection? What on-site data is needed for site selection?**

Backup

Contemporary Terrestrial “Mining” of Snow and Ice

- **Two approaches typically used in terrestrial polar regions to “mine” snow and ice for potable and utility water**
  - “Harvesting” surface snow/ice and using snow melters (typically using waste heat from diesel power generators) to make water
  - Drilling into ice layers to create in-situ water reservoirs
- **Harvesting ice on Mars**
  - Surface ice not accessible at latitudes included in the EZ zone
  - M-WIP assessment indicates accessing buried ice become increasingly unattractive as overburden depth increases (e.g., at lower latitudes)
- **In situ water reservoirs were first designed and built by the U.S. Army Cold Regions Research and Engineering Laboratory (USA CRREL) 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
  - *Rodwell-like concept identified but not assessed in M-WIP*



Lunardini and Rand – full ref on p. 46

Drilling Options Identified

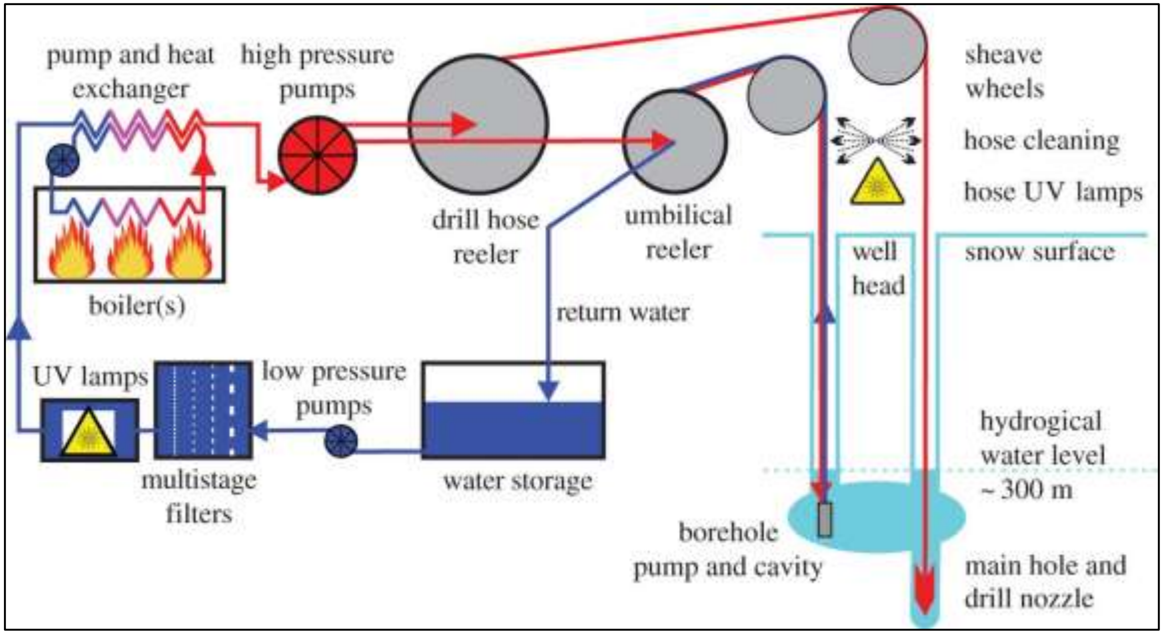
- **Mechanical drills**
  - Must be used for overburden; can be used for ice
  - Many design put forward for both coring and drilling on robotic missions
- **Electrothermal drills**
  - Can only be used for ice
  - Many design exist for both coring and drilling
- **Hot water drills**
  - Can only be used for ice
  - Many design exist for both coring and drilling
  - This technology is easily scalable to create larger diameter and/or deeper holes.

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

"Clean Hot Water Drilling" already implemented in terrestrial applications – addressing planetary protection considerations

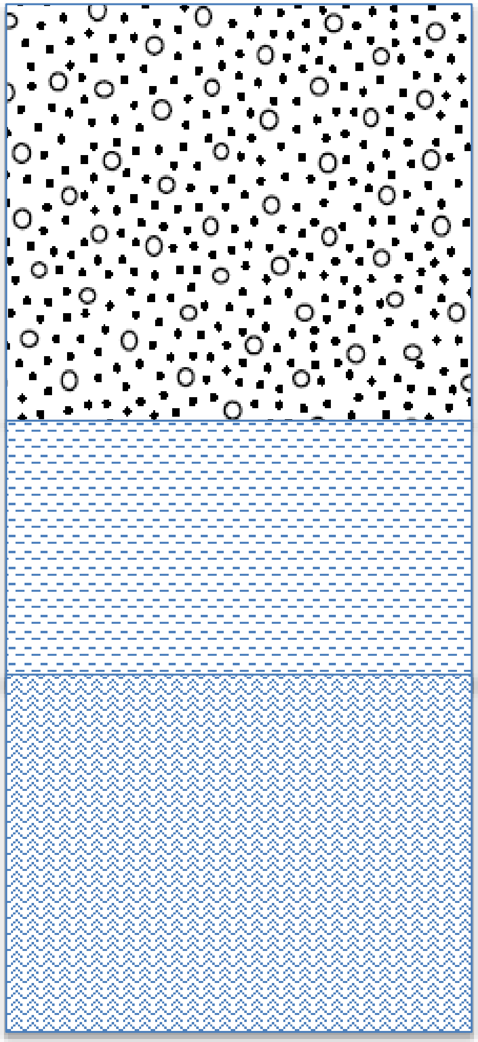
- **The Scientific Committee on Antarctic Research (SCAR) has issues a formal Code of Conduct on the exploration of subglacial aquatic environments**
  - Adopted at the XXXIV Antarctic Treaty Consultative Meeting (Buenos Aires, 2011)
- **This Code of Conduct is comparable to Planetary Protection policies likely to be adopted for Mars subsurface access**
- **Terrestrial experience likely to provide guidance for Mars**



Schematic of the optimized Clean Hot-Water Drill (CHWD) water circulation system*

***Clean subglacial access: prospects for future deep hot-water drilling**
Keith Makinson, David Pearce, Dominic A. Hodgson, Michael J. Bentley, Andrew M. Smith, Martyn Tranter, Mike Rose, Neil Ross, Matt Mowlem, John Parnell, Martin J. Siegert
Phil. Trans. R. Soc. A 2016 374 20140304; DOI: 10.1098/rsta.2014.0304. Published 14 December 2015

Possible Vertical Profile Through Glacier-Like Forms



Debris/Sublimation Till Layer. Likely to resemble terrestrial glacial till - an unsorted collection of rocks, cobbles, sand, and fine sedimentary material. From Plaut et al*, this debris layer on Mars "… can be constrained as greater than 0.5 meters, based on the lack of a strong hydrogen signature in gamma ray and neutron data, and less than ~10 meters, based on the lack of a detection of a shallow soil-ice interface in SHARAD data."

Firn Layer. Typically found on terrestrial glaciers and ice sheets - a layer of granulated snow and ice crystals that is gradually being compressed into solid ice. Because of the granular/porous nature of this layer, any liquid water will move to lower levels until a solid interface is encountered. Due to the lack of snowfall and the overlying debris layer it is thought that any firn on Mars will have been compressed into solid ice long ago (i.e., the firn layer has zero thickness).

Ice Layer. Solid layer of water ice; likely to contain debris gathered as the body of ice was formed as well as fractures of varying sizes due to a variety of causes. Depending on the size of the fracture, these could be "self healing" in the presence of liquid water. This layer could be 100's to 1000's of meters thick.

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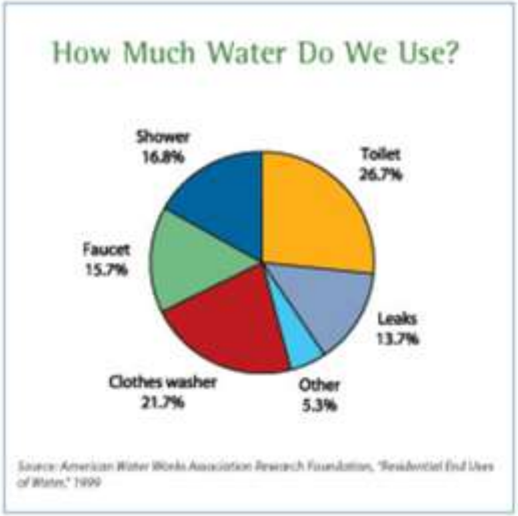
*Plaut et al, "Radar evidence for ice in lobate debris aprons in the mid-northern latitudes of Mars," Geophysical Research Letters, Vol. 36, L02203.

Example Water Usage Rates

- **“Typical” U.S. family of four:**
  100 gallons/person/day (379 kg/person/day)
  - This is both indoor and outdoor usage; 70% indoor and 30% outdoor
  - Source: U.S. EPA; https://www3.epa.gov/watersense/pubs/indoor.html
- **“Typical” U.K. family of four:**
  30 gallons/person/day (112 kg/person/day)
  - Source: http://www.ccwater.org.uk/savewaterandmoney/averagewateruse
- **Summit Station, Greenland (winter):**
  ~18 gallons/person/day (68 kg/person/day)
  - Based on an average population of four people
  - Source: Haehnel and Knuth “Potable water supply feasibility study for Summit Station, Greenland”
- **Summit Station, Greenland (summer):**
  ~9.4 gallons/person/day (36 kg/person/day)
  - Based on an average population of 30 people
  - Source: Haehnel and Knuth “Potable water supply feasibility study for Summit Station, Greenland”
- **Mars Surface Crew (with laundry):**
  ~3.5 gallons/person/day (13.3 kg/person/day)
  - Based on a population of four crew
- **Mars Surface Crew (without laundry):**
  ~1.6 gallons/person/day (6.0 kg/person/day)
  - Based on a population of four crew

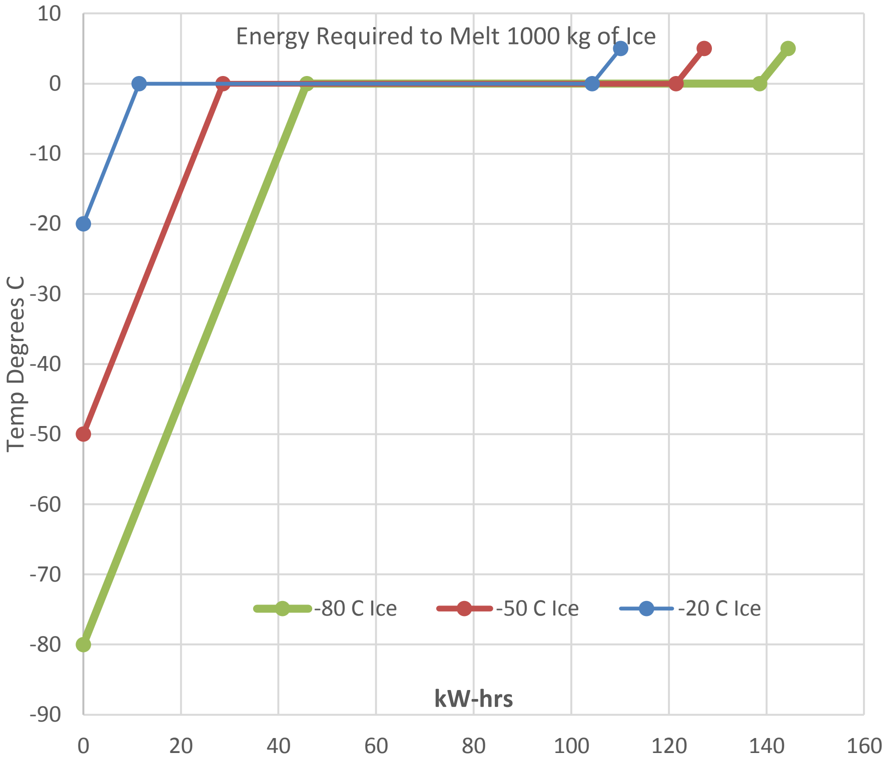


Source: American Water Works Association Research Foundation, “Residential End Uses of Water,” 1999

U.S. Family Water Usage

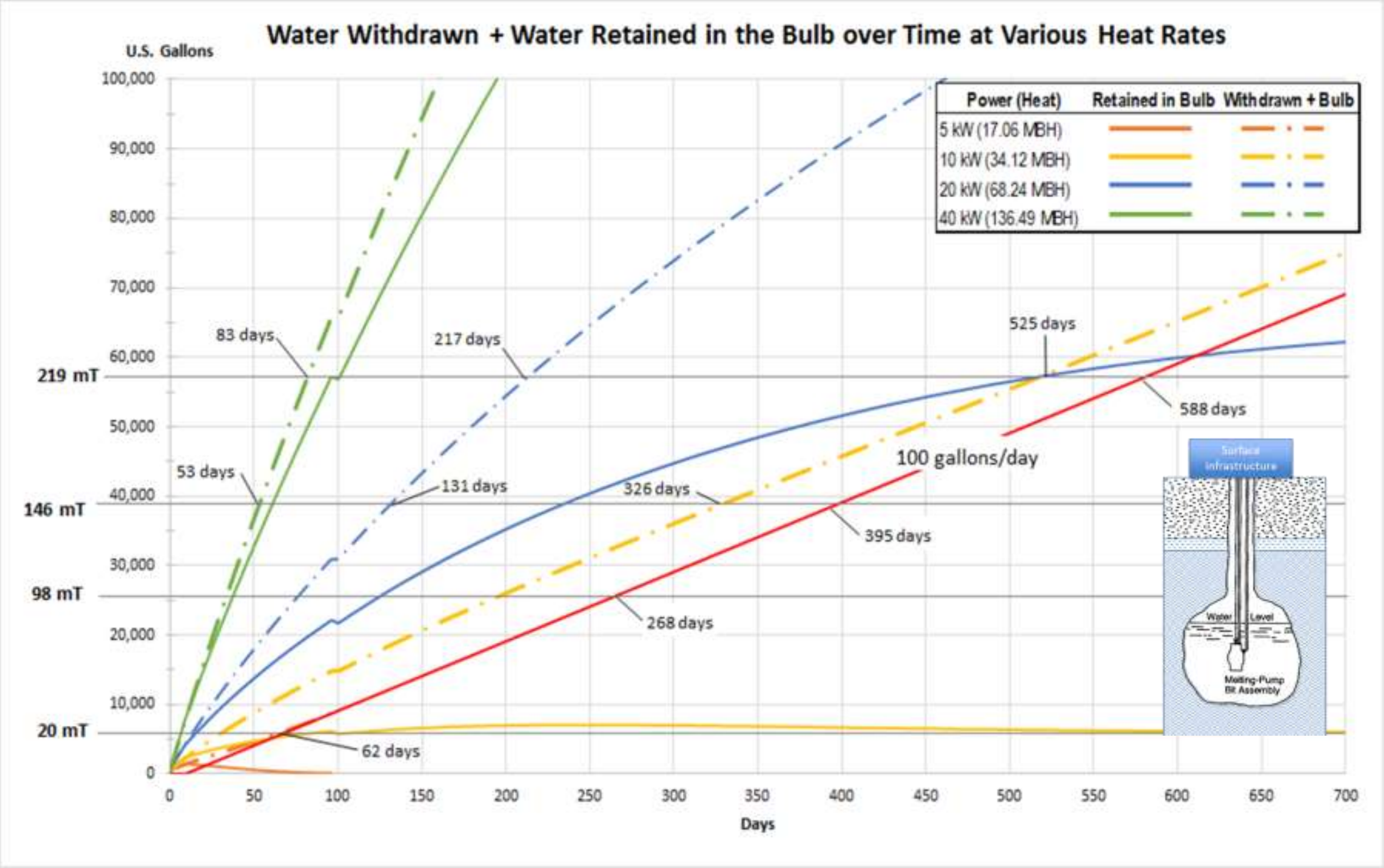
Energy Required to withdraw water from a Rodwell

- **Energy required for several reasons in order to “mine” water ice**
  - Change ice to liquid water (adding sensible heat and latent heat; see graph at right)
  - Once melted, keep water liquid until desired quantity is pumped out (i.e., feed heat lost to surrounding ice and atmosphere in cavity)
  - Pump liquid to the surface from a liquid water pool that is gradually sinking as water is withdrawn (recall Old South Pole Station Rodwell example)
- **CRREL simulation combines the effects of the first two; pump energy must be determined separately**



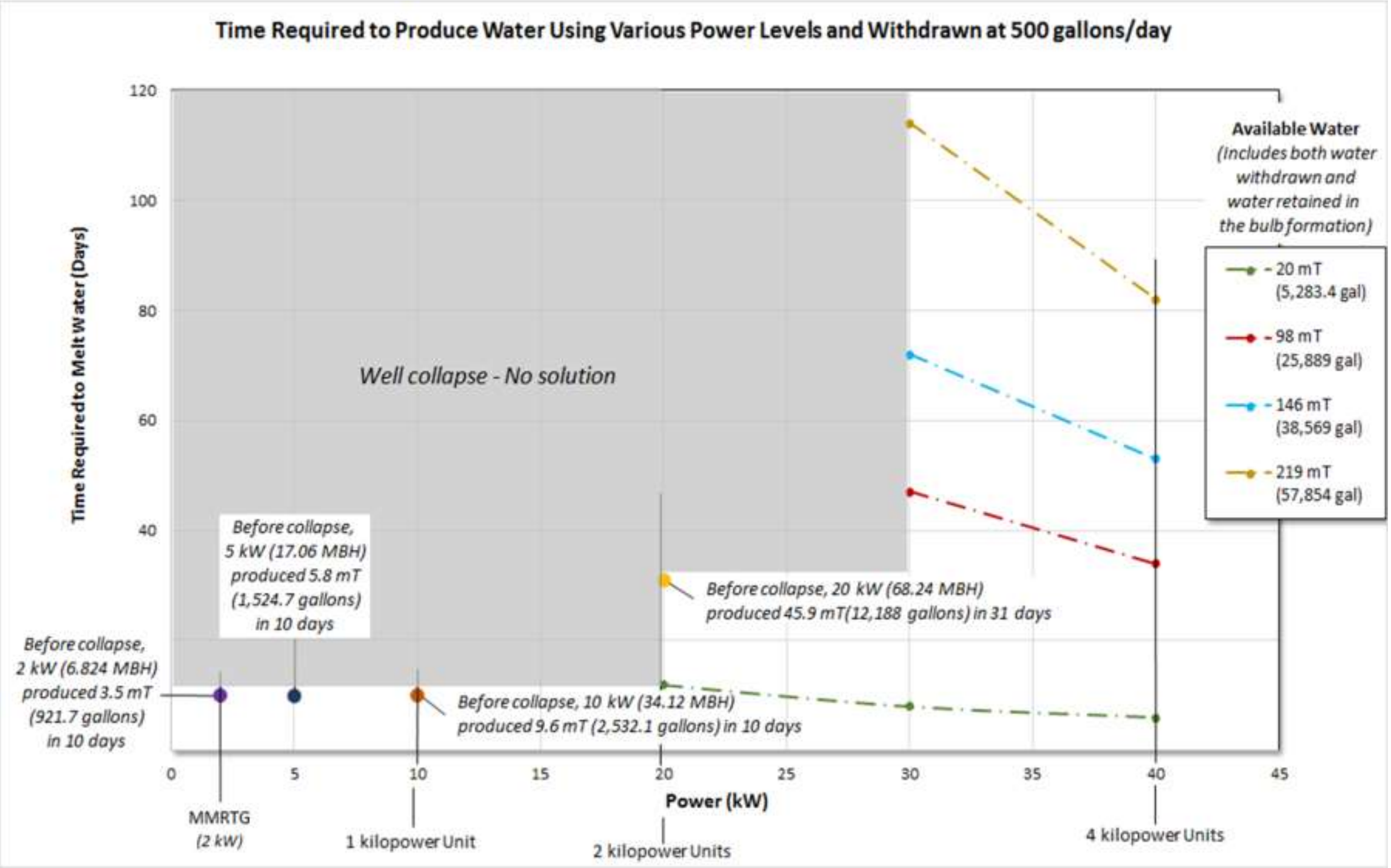
Calculated Energy Required to raise temperature and for solid to liquid phase change

Predicted Actual Time Needed to Withdraw Water for Cases 1-3 at a 100 gal/day Rate



Note: assumes -80° C ice

Impact of Power Input for a 500 gal/day Withdrawal Rate



Before collapse, 2 kW (6.824 MBH) produced 3.5 mT (921.7 gallons) in 10 days

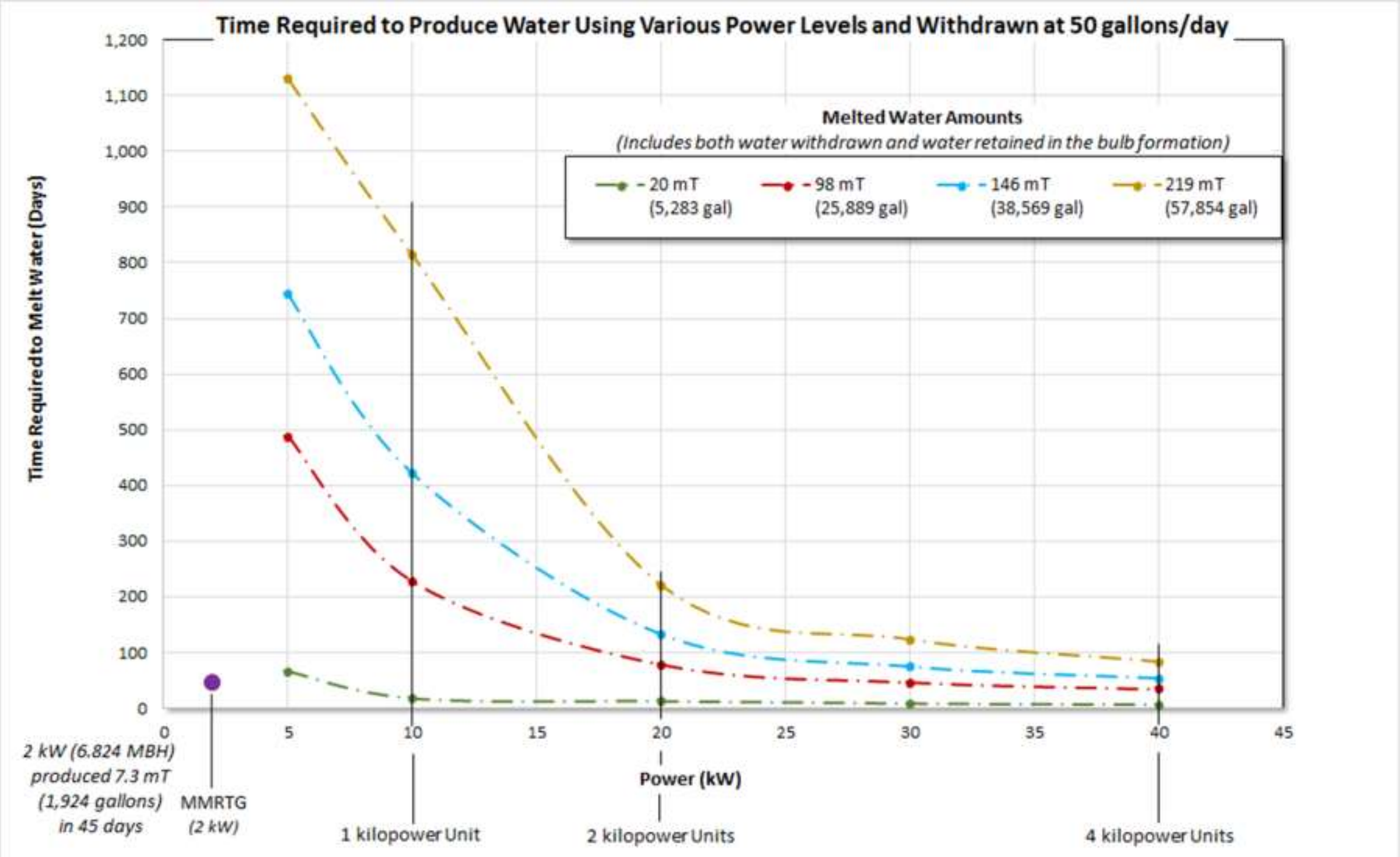
Before collapse, 5 kW (17.06 MBH) produced 5.8 mT (1,524.7 gallons) in 10 days

Before collapse, 10 kW (34.12 MBH) produced 9.6 mT (2,532.1 gallons) in 10 days

Before collapse, 20 kW (68.24 MBH) produced 45.9 mT(12,188 gallons) in 31 days

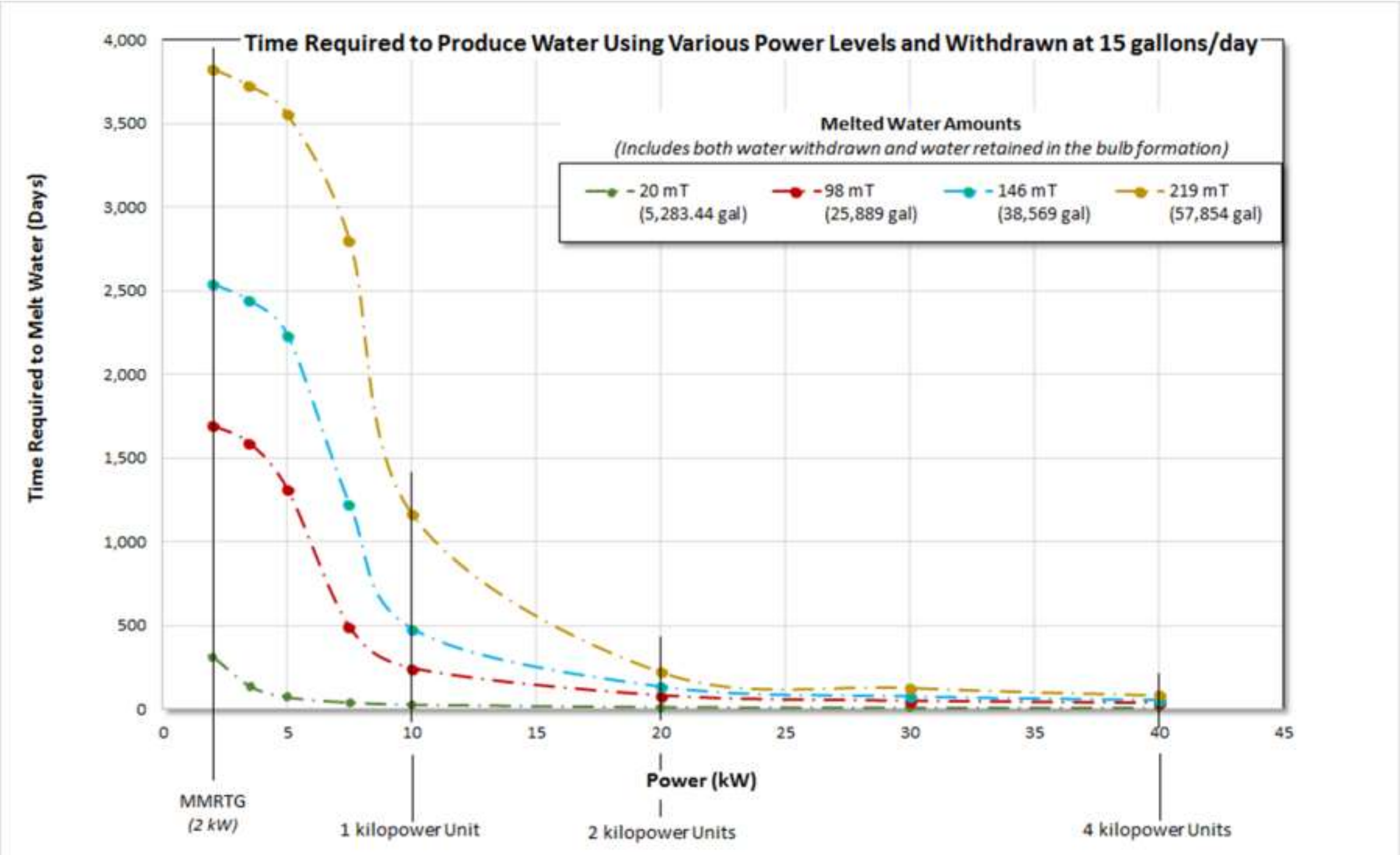
Note: assumes -80° C ice

Impact of Power Input for a 50 gal/day Withdrawal Rate



Note: assumes -80° C ice

Impact of Power Input for a 15 gal/day Withdrawal Rate



Note: assumes -80° C ice

Strategies for Water Withdrawal

- **For all cases, a cased hole must be drilled into the ice sheet**
  - Prevent debris layer from collapsing into access hole
  - Allow well to be pressurized (with atmospheric CO2?) to some TBD level to minimize sublimation
- **Option 1: Withdraw all water ever needed (e.g., for 5 crews, totaling ~100 mT) without stopping; store all water above ground until needed**
  - A trade study of power versus desired withdrawal rate/total time will be needed
  - Sufficient above ground storage will be required (recall diagram at beginning of this discussion)
    - Reuse descent stage propellant tankage?
    - Potential issues with long term storage: leaching from tank walls; UV degradation of tank material
  - Stored water is likely to be allowed to freeze and then re-melt as needed
    - Recall previous diagram (page xx) describing energy required to melt various quantities of ice
    - Consider storing water in multiple “small” containers to avoid re-melting too much ice at any one time
- **Option 2: Withdraw only enough water for immediate needs (e.g., for 1 crew, totaling ~20 mT); “store” water for future needs by leaving it below ground**
  - When sufficient water for immediate needs has been withdrawn, raise down hole equipment and allow the water pool to refreeze
  - TBD power and time will be required to restart the well; probably comparable to initial starting of well
  - Above ground water storage limited to that need for immediate use (or possibly less if the water is used to make propellant, consumed in another process, etc.)