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Mobile In-Situ Water Extractor (MISWE) for Mars, Moon, and Asteroids In Situ Resource Utilization

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In-Situ Resource Utilization (ISRU) facilitates planetary exploration by drawing needed resources, such as water, from the local environment. This work presents a 3-step in-situ water recovery approach: 1) mining the soil using deep fluted auger, 2) extracting the water from soil within the flutes, and 3) discarding the soil before transporting the water to a main storage facility. Drilling in icy soil and ice has already been demonstrated in vacuum chambers by the authors. This paper focuses on the second critical step: water extraction from the icy soil or ice within the deep flutes. This paper reports on tests demonstrating efficient collection of water from ice-bearing soil under Mars conditions. The water recovery Mobile In Situ Water Extractor (MISWE) breadboard collected as much as 92% of the water initially present in the soil, and required as little as 0.9 Whr/g of energy (80% efficient compared to theoretical). The extraction process took approximately 40 min.

I. Introduction

In-Situ Resource Utilization (ISRU) facilitates planetary exploration by drawing needed resources, such as water, from the local environment. ISRU became an overnight hot topic after Planetary Resources[7], a billionaire-backed company, announced it aims to mine asteroids for water and precious metals. Shackleton Energy Corp[8] is another company that is similarly interested in exploiting lunar water for commercial purposes. Extracting water on Asteroids, the Moon or Mars is an order of magnitude easier than processing minerals. To extract precious metals a new technology has to be developed that works in zero-g (or reduced gravity – Moon, Mars), and uses no or very little chemicals and water. Terrestrial methods of mineral extraction require a lot of water, various chemicals, and gravity, and hence cannot be adapted to space very easily. Extracting of water, is however feasible.

Transporting water from the Moon or Near Earth Objects (NEOs) could be very profitable given that launching water to space costs ~$20,000/liter. The major markets for water could be human consumption (e.g. International Space Station, Space Hotels), or refueling of spacecraft and satellites. The latter is of particular interest, since satellites reach their end of life as they run out of fuel required for station keeping. Refueling satellites in space means their life could be greatly extended, and in turn service companies could achieve greater profits from existing assets. NASA and industry have already been developing in space refueling technology, the first step in enabling refueling of satellites in space.

Many approaches to extracting water from frozen soil follow ‘terrestrial’ mining approach; they consist of mining rock-hard ice-bearing soil, transporting it to a crusher and reactor, and then extracting and storing of water. Material transfer and processing methods depend on the type and size of the feedstock. In commercial applications, the feedstock is crushed and in some cases pulverized in order to work with the material processing and extraction systems. Crushing of ice or icy-soils at Mars pressures or in vacuum (Moon, Asteroids) is a difficult problem. Crushing involves applying a pressure, and ice under pressure changes crystal structure and could melt or sublime. Using a pick to crush ice or icy soils works well only to a point. One cannot create icy-powder using this method.

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So what sort of feedstock will the transfer and processing system see? Most likely these will be chunks of ice and icy-soil. Even drier soil creates clods such as those shown in **Figure 1** on Mars. If a transfer system uses a pneumatic system, the diameter of all the hoses must be sized accordingly (Zacny et al., 2008). Large diameter hose means more gas is required, and the gas pressures and flow rates have to be higher. If the system uses an auger system, the flute depth and pitch has to be large, otherwise the system may jam.

In addition, there are also some critical issues with mining and transportation of icy regolith. First, conventional excavators will not be able to penetrate soil having any substantial ice fraction (icy-soils are harder than concrete). A potential method may be a percussive pick and a shovel approach as used in construction, but that is very difficult to automate. Second, as was found during the Mars Phoenix mission, any exposed ice would sublime, leaving behind dry soil (**Figure 2**). Thus, even if the excavator manages to acquire some chunks of icy-soil, some ice would sublime away by the time it gets to the processing plant.

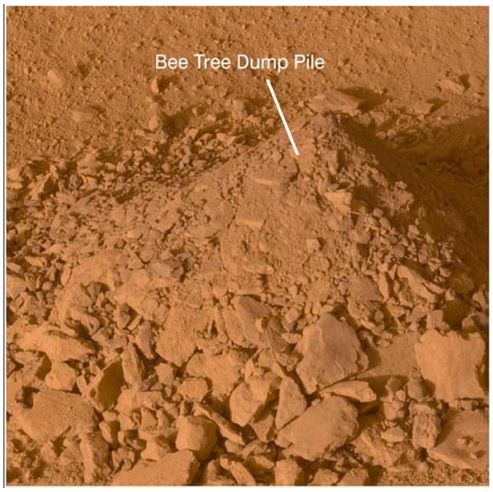


Figure 1. View of Bee Tree dump pile at the *Phoenix* site made from La Mancha excavations. Note the cloddy nature of the materials. (Arvidson et al., 2009)

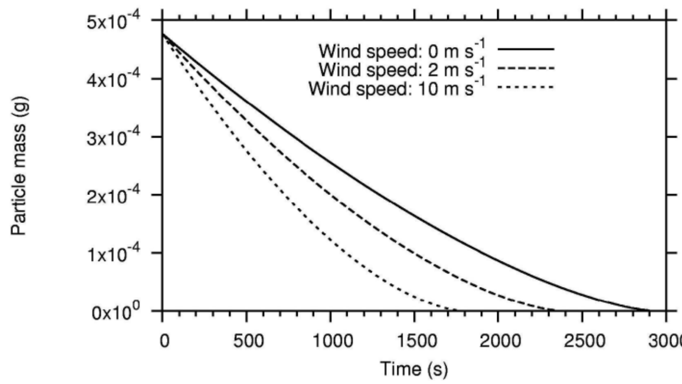


Figure 2. Particle mass variation with time for a single, spherical ice particle; p = 600 Pa CO2, T = 253K, RHi = 0.25, no radiation absorption, initial radius, r0 = 0.5 mm. (Taylor et al., 2006)

The solution to these problems is an integrated mobile mining and water extraction system that uses an auger based excavation approach (used every day in Arctic and Antarctic) and an integrated water-ice extraction plant – hence, if the water-ice does sublime, it will sublime straight into the extraction system. The proposed system, an auger with a reactor, eliminates the weak link – the transfer system. The system has 3 steps: 1) mining the soil using deep fluted auger, 2) extracting the water from soil within the flutes, and 3) discarding the soil (steps 1-3 done in-situ) before transporting the water to a main storage facility. Hence only the water is transported back, while dry soil is left behind. Assuming water content of 10% by mass in the soil, there is therefore an order of magnitude difference in the mass and bulk of material to be transported.

This approach offers significant advantages over conventional approaches. It takes advantage of a proven and tested excavation method using a deep fluted auger and recovers water in situ. There are no alternative excavation methods for concrete-hard soil but drill and blast; a very complex and yet to be proven method in planetary setting (which also requires drilling as its first step, in a multi-step process).

Things to consider:

- In our previous studies we found that excavation forces with a 4.5 cm wide scoop in soils with water content as low as 5 wt% and only -20°C are in excess of 3500 Newton. This requires a 2 ton or larger excavator. At higher water content, the scoop type excavator just doesn't work, even if percussion is triggered. (On Earth massive excavators are used for soft soils and overburden but not rocks, permafrost, or even soft coal).
- In 2007, Honeybee Robotics built the Icy Soil Acquisition Device (ISAD) for the Mars Phoenix mission (Bonitz et al., 2008). The ISAD consisted of a scoop with a small rasp bit. The rasp bit was added because as it was found during early tests, the scoop was unable to penetrate icy-soils or ice. The rasp bit successfully acquired ice shavings and icy-soil directly into the scoop.

• We have already demonstrated drilling in ice and ice cemented ground at rates of >1 kg/hr and energy of 1 kg per 100 Whr (Paulsen et al., 2011; Zacny et al., 2011). Higher penetration rates are possible with more powerful actuators (e.g. 6 inch diameter auger powered by 1.3 kW motor can penetrate Arctic permafrost at the rate of ~10 cm/min).

II. Sources of Water in the Solar System

A. Water on Mars

Most of the exploration of Mars that has taken place to date has either involved viewing the surface from orbit, or *in situ* examination of the surface. The *Viking 1 and 2* mission had a scoop to acquire subsurface material, as did the *Phoenix* mission, but neither mission explored the subsurface to any significant degree. The Mars *Phoenix* mission confirmed the ice in the northern Polar Regions is covered by a few inches of soil. In fact the *Phoenix* thrusters uncovered the ice layers during landing (**Figure 3**).

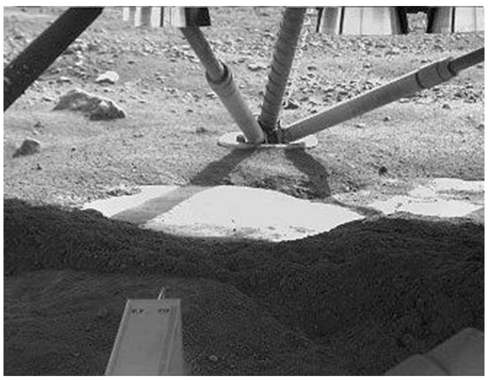


Figure 3. *Phoenix* thrusters removed top soil to expose ice on Mars. Photo: NASA

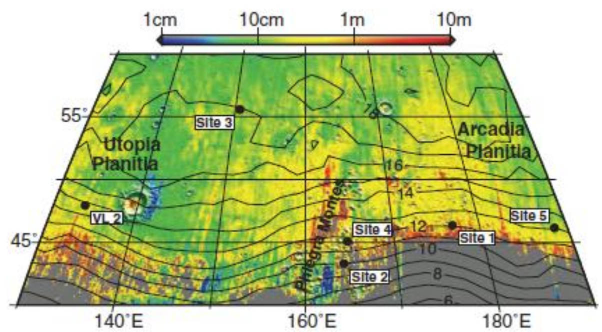


Figure 4. *Viking 2* (VL 2) and locations of crater-excavated near-surface ice (1-5) are labeled and expected ice depths shown (Byrne et al., 2009).

According to the Byrne et al., (2009) analysis, *Viking 2* dug down 15 cm and at this location ice is expected at a depth of ~24 cm (**Figure 4**). Hence, *Viking 2* could have discovered ice if it has dug just 10 cm deeper.

Studies of the morphology of craters also suggest the existence of widespread subsurface ice deposits (rapp, 2008). The neutron spectrometer aboard *Mars Odyssey* also found evidence of widespread near-surface (top~1 m) H_2O on Mars as shown in **Figure 5**. What is particularly intriguing is Region “A” that has an average of about 8 to 10% H_2O content in the top ~ 1 m, in an extensive equatorial zone. Since the pixels for these observations were 5°×5°, there is a great deal of H_2O in the equatorial area. However, it is not known how this H_2O is distributed horizontally and vertically.

While near-surface H_2O is more prevalent at higher latitudes (e.g. *Phoenix* 68°N), it seems likely that it would be more desirable to establish a human outpost in a more benign equatorial region (e.g. *Viking 2* at 48°N). For example, the area that the *Phoenix* has landed in is covered in a 30 cm-deep layer of frozen carbon dioxide[9] during winter (it is believed that the weight of the CO_2 ice caused one of the panels to snap – hence now only one can be seen from orbit). In general, going further north means that there will be more CO_2 ice accumulation in the winter season because of lower temperatures reaching the frost point of CO_2 at 148 K (-125 °C) (Aharonson et al., 2003; Leighton and Murray, 1996; Wall, 1981). This also means that during this time, it is unlikely the excavator would be able to work. On the other hand, at the *Viking* Lander 2 site, a thin layer of water frost/snow covers the ground each winter (note that the white snow is not CO_2 but water. The lowest predawn temperature during the *Viking* mission was -120 °C, above the frost point of carbon dioxide (Kieffer, 1976; Forget, 1998). Note that this deposited water-ice could also be mined. If the missions, however, requires larger quantities of CO_2, going further north where winter temperatures fall below the CO_2 frost temperatures of -125 °C would be an option.

Moving further south (at the VL2 rather than *Phoenix* site) means that one has to dig through 24 cm of dry soil to get to ice-cemented ground while at the *Phoenix* site, the ice (mostly dirty-ice) is near the surface. Hence, the MISWE approach uses a 50 cm auger that collects the bottom 26 cm of icy-soil and has to operationally discard the top 24 cm of dry soil.

[9] http://www.jpl.nasa.gov/news/*Phoenix*/images.php?fileID=12901

Note that it is assumed that MISWE will be nuclear powered. This is to enable year-round operation. Solar powered spacecraft have a finite life span (e.g. *Phoenix*) or have to stop their operation and try to survive winter (MERs). The nuclear powered *Viking 2* lasted from September 3, 1976 until April 11, 1980. With more efficient ASRGs (*Viking* used very inefficient RTGs) the surface Mars mission could last 14 years (ASRG design life).

Note also that the majority of Martian surface is covered by rocks of various sizes (**Figure 6**). Hence a conventional excavator would have to either excavate these rocks (hence a regolith handling and processing system would have to deal with them) or move them aside. The auger based excavation system can selectively go to rock-free spots.

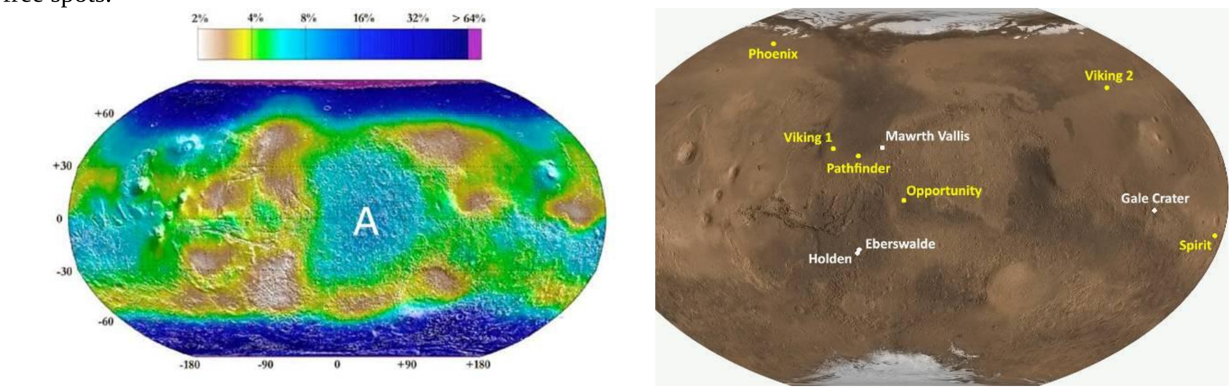


Figure 5. Measured H_2O content in top ~ 1 m of Mars in 5×5 pixels (Rapp, 2008) and locations of the past and future (MSL rover will land in Gale crater) missions. Photos courtesy NASA.

The following empirical model has been shown to accurately estimate Mars and terrestrial cumulative number of surface rocks per m^2 as a function of rock diameter, *D*,

$$n(D) = L e^{-s D}$$

where *L* is the total number of rocks of all sizes per square meter at a particular site and *s* is an empirical parameter for characterizing the rock distribution profile (Golombek and Rapp 1997). **Figure 7** assumes the vertical distribution follows a similar law, and shows the probability of encountering a rock greater than 1 cm (i.e. a rock size that can be easily handled by the auger) vs. drill diameter and penetration depth at the VL2 terrain. For a 5 cm diameter drill, drilling 0.5 m deep, the probability is 0.3. Extrapolating this to a 10 cm diameter drill, the probability would be 0.4.

Figure 6. Water Snow on *Viking 2* landing site in May, 1979 (Photo ID 21I093)[10]. *Viking* scoop dug 15 cm while it is expected the ice-cemented ground is at 24 cm depth. (Courtesy NASA)

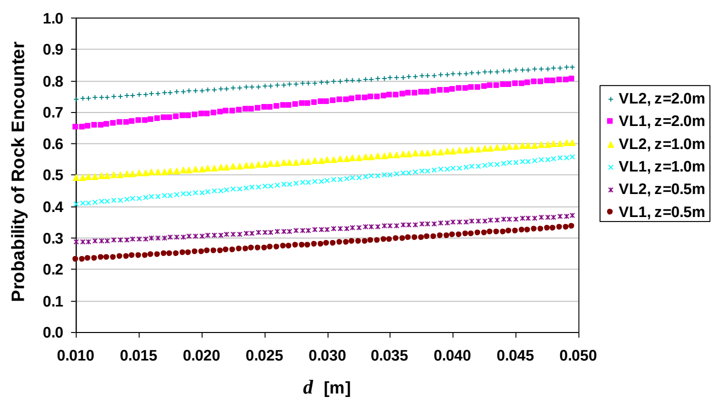


Figure 7. Probability of encountering a rock greater than a diameter of 1cm vs. drill diameter and penetration depth in the assumed volumetric rock distributions of VL1 and VL2 terrains (Courtesy G. Mungas, Firestar Engineering).

[10] http://mars.spherix.com/spie2/spie98.htm

B. Water on the Moon

On 22 August 1976, 170 grams of lunar samples were returned to Earth by the Soviet Luna 24 mission. A Soviet team analyzed the sample and found unambiguous signs of water in the rock--they reported that water made up 0.1 per cent of the sample's mass[11]. In 1978, they published the result in the Russian journal Geokhimiia. This journal also has an in English language version but it was not widely read in the West.

The 1990s saw three orbiter missions, of which Lunar Prospector, was the most significant. The low polar orbit allowed mapping of possible polar ice deposits. The Neutron Spectrometer data revealed large, potentially water ice deposits in the polar craters, estimated to be in the range of 3 billion metric tons at each pole (Feldman, et al., 1998).

Discovery of potential water-ice renewed interest in lunar exploration with eight missions launched between 2003 and 2010. These include the European Space Agency (ESA) SMART-1 in 2003, Japan Aerospace Exploration Agency (JAXA) SELENE in 2007, Chinese National Space Administration (CNSA) Change 1 in 2007, Indian Space Research Organization (ISRO) Chandrayaan-1 orbiter and the Moon Impact Probe (MIP) in 2008, NASAs Lunar Reconnaissance Orbiter (LRO) and Lunar Crater Observation and Sensing Satellite (LCROSS) in 2009, and finally CNSA Change 2 in 2010.

The 2009 LCROSS mission provided for the first time direct evidence of ground ice in the lunar regolith. Based on the mission data, the concentration of water ice in the regolith was estimated to be ~5.6% by mass (Colaprete et al., 2010). This water reservoir could be an enabling resource, not only to support human presence on the Moon, but also to support human exploration of other Solar System bodies, since it could also be mined and converted into hydrogen and oxygen (i.e. rocket fuel and oxidizer, respectively) to fuel the rocket for the journey home or on to other planetary destinations.

Lunar Exploration Neutron Detector (LEND) onboard NASA LRO identified hydrogen-rich areas (believed to be signatures of water-ice) within the top meter of the lunar regolith (Mitrofanov et al., 2011). Hence one meter class drill would be sufficient for Lunar water ISRU.

C. Water on Near Earth Objects (NEOs)

While comets, which have characteristic tails and generally orbit farther out in the solar system, are known to have water, asteroids in that region were thought to be too close to the sun to contain water on the surface. The largest asteroid in the solar system, Ceres, is thought to harbor a vast amount of frozen water, but scientists suspect all of it is buried beneath a rocky, dusty surface. More recent studies describe concrete proof of water ice on the surface of 24 Themis by measuring the specific characteristics of sunlight bouncing off the surface of the asteroid. They saw the tell-tale signatures of H2O coating most of the surface of the 123-mile (198-km) wide rock (Campins et al., 2010; Rivkin and Emery, 2010).

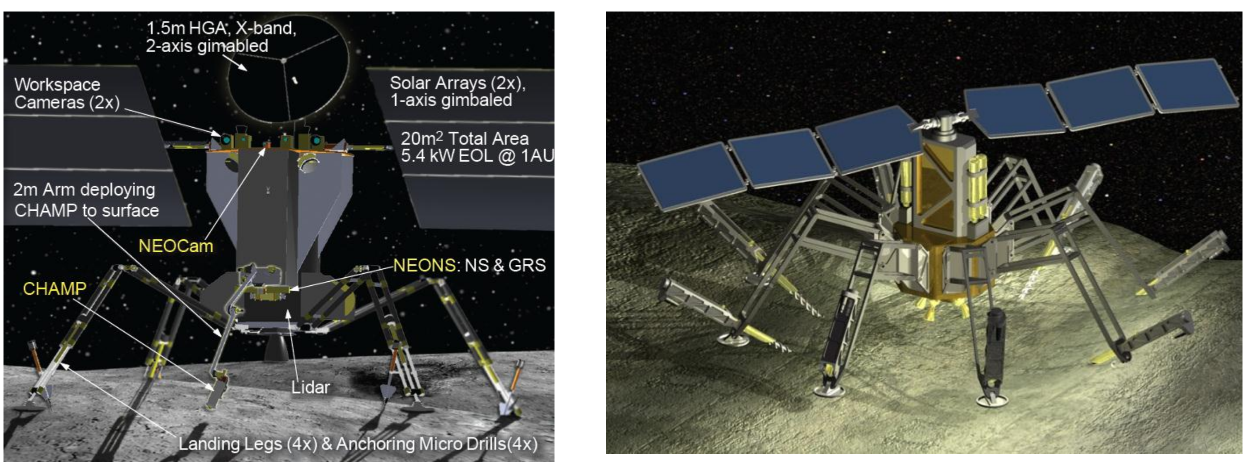


Figure 8. Left: Honeybee Robotics developed anchoring system for the Amore mission (Jones, et al., 2011)). The four anchors at oblique angle to the surface are driven into the surface to brace or grip the spacecraft to the surface. Right: A concept of the Asteroid water extraction system with water reactors attached to each leg of the lander based on the Amore Anchoring System. Hence, augers form a dual system: anchor and water extraction.

Near-Earth asteroids spend at least part of the orbit between 0.983 and 1.3 Astronomical Units from the Sun. Although we know of nearly 9,000 near-Earth asteroids, scientists believe the number may actually exceed one

[11] http://arxiv.org/abs/1205.5597v1

million. The near-Earth asteroids vary widely in composition. Each asteroid contains water, metals, and carbonaceous materials in various amounts. According to Planetary Resources a single water-rich 500-meter-wide asteroid contains 80 times more water than the largest supertanker could carry and could provide. If the water were converted to rocket propellant, it would provide more than 200 times the rocket fuel required to launch all the rockets ever launched in human history. The MISWE concept could also be adapted to Asteroid mining as shown in **Figure 8.**

III. Excavation of Icy Soil and Ice

This section presents various methods of penetrating icy soil and ice (drilling using augers and digging using scoops) and includes figures of merit such as energy/kg etc. The examples demonstrate the impossibility of excavating icy-soils using conventional digging systems and demonstrate that the low energy auger approach is most feasible based on the tests in vacuum chambers, in the Arctic, and in the Antarctic.

A. The strength of icy soil and ice

Table 1 and **Figure 9** list properties of icy-soil and ice as a function of ice saturation (for soil) and temperature (for ice). It can be seen that the strength, measured as Unconfined Compressive Strength or UCS (MPa), for icy-soil and ice at low temperature is similar to the strength of basalt (or 2-3 x the strength of concrete). A conventional back-hoe excavator therefore will not be able to dig into ice or icy-soil. This formation could either be drilled or blasted (blasting, however, needs drilling holes first for installing explosives).

Table 1. Strength of JSC-1a with various ice content at LN2 (77K) temperature[12].

Wt% water	Relative Density, Dr %	UCS, MPa
0-0.3	74-79	1-3.4 (soft)
0.6-1.5	70-85	6-14 (weak concrete)
8-9	84-98	31-43 (strong concrete)
10-11	84-92	70-71 (strong sandstone)
11.7-11.9 (sat)	91-94	57-95 (basalt)

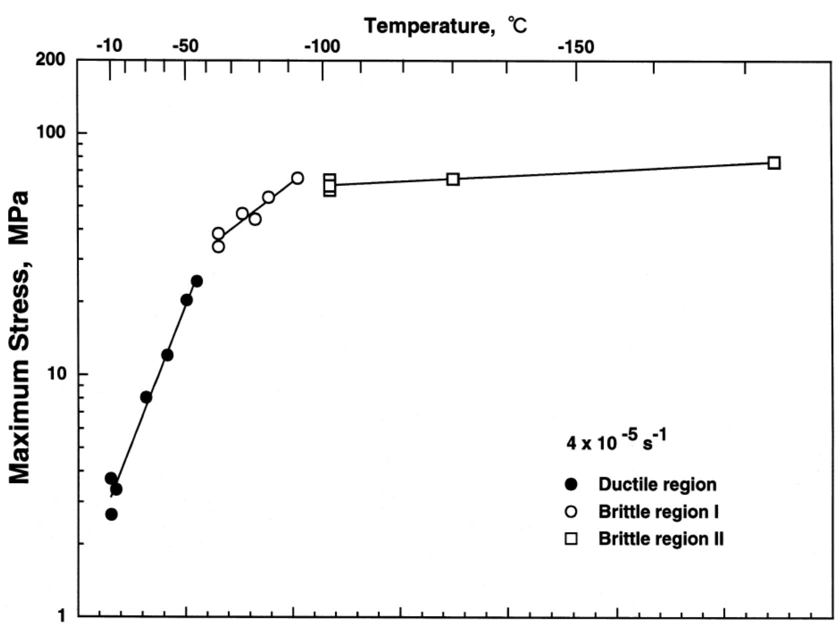


Figure 9. Strength of ice as a function of temperature (Arakawa and Maeno, 1997).

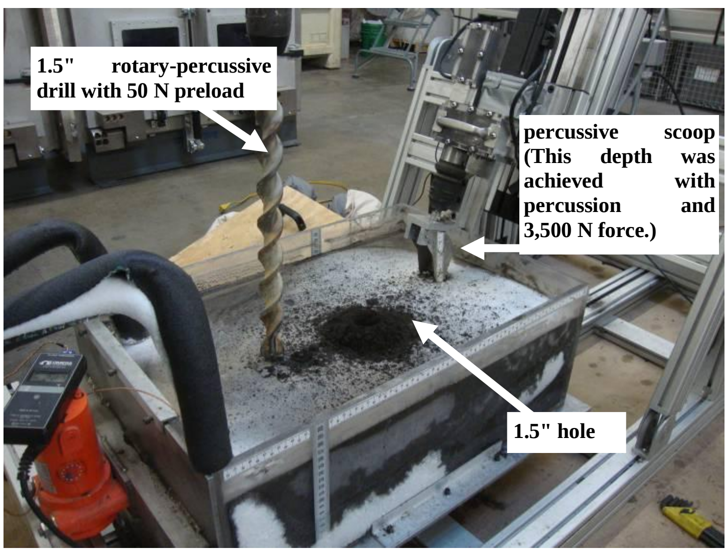
[12] Data compiled by Bob Gustafson of Orbital Technologies Corporation.

B. Excavation tests using static and percussive diggers and auger drills

We performed a number of digging and drilling tests in JSC-1a soil simulant with various water concentrations and frozen to –20°C. The digging system used a Surveyor replica scoop with a blade 45 mm wide. At water concentration of ~5 wt%, the scoop managed to penetrate ~1 cm into a soil with 3500 N force. Using a 150 W percussive system to drive the scoop into the regolith percussively, the maximum penetration depth was 5 cm at 3500 N force. In order to generate 3500 N forces on Mars, the Martian excavator has to weigh approximately 2100 kg on Earth. This is more than twice the mass of the 2011 Mars Science Laboratory Curiosity rover currently on Mars. Lunar excavation system would have to be 3x more massive (weigh over 6 tons).

The actual temperature at Mars, Moon, or NEOs is much lower than the temperature we performed the tests at (-20 °C); hence, the icy soil will be much stronger (Zacny and Cooper, 2006). Furthermore, if the water concentration is higher than 5 wt%, the soil will also be harder and the excavator will not be able to dig into it at all. Tests conducted with fully saturated JSC-1a at only –20 °C have shown that even the percussively actuated scoop was unable to dig into it (**Figure 10**). These experiments have effectively demonstrated that excavating ice-bound regolith, using conventional quasistatic or percussive digging systems, will be impossible.

However, the experiments also showed that rotary-percussive *drilling* into the fully saturated frozen regolith will be effective (**Figure 10**). A rotary-percussive drill was able to penetrate to a maximum depth in seconds, with a vertical force of <50 N. Tests conducted in 120 MPa basalt rocks (that strength is equivalent to a fully saturated soil at -100 °C or lower) with a percussive drill demonstrated effective and efficient penetration (Paulsen et al., 2011).



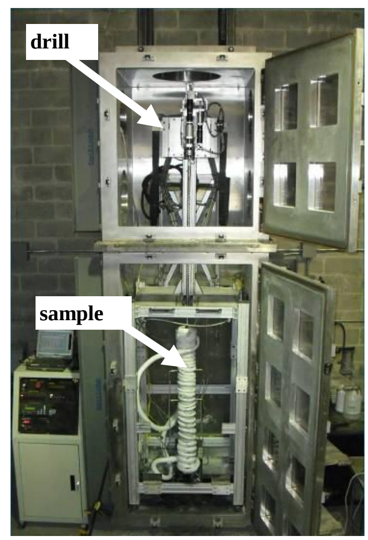


Figure 10. Left: Tests conducted with a 1) Surveyor replica scoop and a 2) rotary-percussive drill in JSC-1a soil simulant with various water concentrations and at –20 °C. Right: 3.5 m vacuum chamber with rotary-percussive drill and a sampling system was used for testing drilling approach under Mars conditions in ice, ice-cemented ground and rocks.

C. Arctic tests using large diameter auger

A number of excavation tests were performed on Devon Island in the Canadian High Arctic in 2006. Initially a pick and shovel was used to remove the active layer and reach the ice cemented ground at -10 °C (**Figure 11**). Removing of the active, soft layer was easy but the progress stopped at the ice-cemented ground. With each pick blow only a few millimeter deep cuts were made. The excavation with the pick was abandoned because of lack of progress. The strength of icy-soil is equivalent to the strength of medium strength rocks, and it increases with a decrease in temperature (Ma and Chang, 2002; Li et al., 2001) We next used a deep fluted ice auger (6 inch or 15 cm diameter) driven by 1300 Watt gas engine at 190 rpm (**Figure 12**). We drilled multiple holes in icy-grounds at a rate of 10 cm/min to a depth of ~50 cm. We noted that the material would always remain on the auger deep flutes and the easiest way to empty the auger would be to spin it at high velocity in the air. Cuttings were not sticking to the auger flutes because they were still cold. In addition, though the cutters were made of steel and designed for ice (not icy soil) there was relatively little wear observed. The auger excavated 8500 cc or 12 kg (at 1.5 g/cc) of material per 50 cm hole in 5 minutes. It consumed 110 Whr. Hence with this approach it is possible to acquire large quantities of material at low energy. To reduce the required power, a smaller diameter auger could be used instead.

Figure 11. Left: Once the icy-soil was reached the progress was virtually zero, even with a pick; Right: The pick penetrated only a few mm/ blow (arrows).

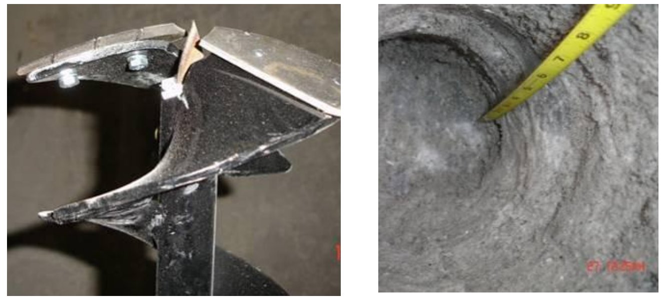


Figure 12. A 15 cm (6 in) ice auger worked well in icy soil. The auger drilled a 50 cm deep hole in ~4 minutes.

D. Antarctic Tests with IceBreaker Drill

The IceBreaker drill was used in a Mars analog site of Dry Valleys of Antarctica to acquire samples from up to 1 m depth in ice-cemented ground and to 2.5 m depth in ice (Paulsen et al., 2006; Zacny et al., 2012). The air temperature in Dry Valleys is always below freezing and in turn liquid water cannot form (hence the name). This also means that ice cemented ground is formed by vapor deposition – just as we believe it was formed on Mars or possibly the Moon. In addition, the ice-cemented ground is covered by a layer of dry soil – just like at the *Viking 2* landing site on Mars.

During the testing, the 1 inch drill demonstrated drilling at the 1-1-100-100 level; that is it penetrated 1 meter in approximately 1 hour with roughly 100 Watts power and less than 100 Newton Weight on Bit (**Figure 13**). This corresponds to a total drilling energy of approximately 100 Whr. At the same time, the drill successfully acquired and deposited ~500 cc or ~1 kg of icy-soil into a container.

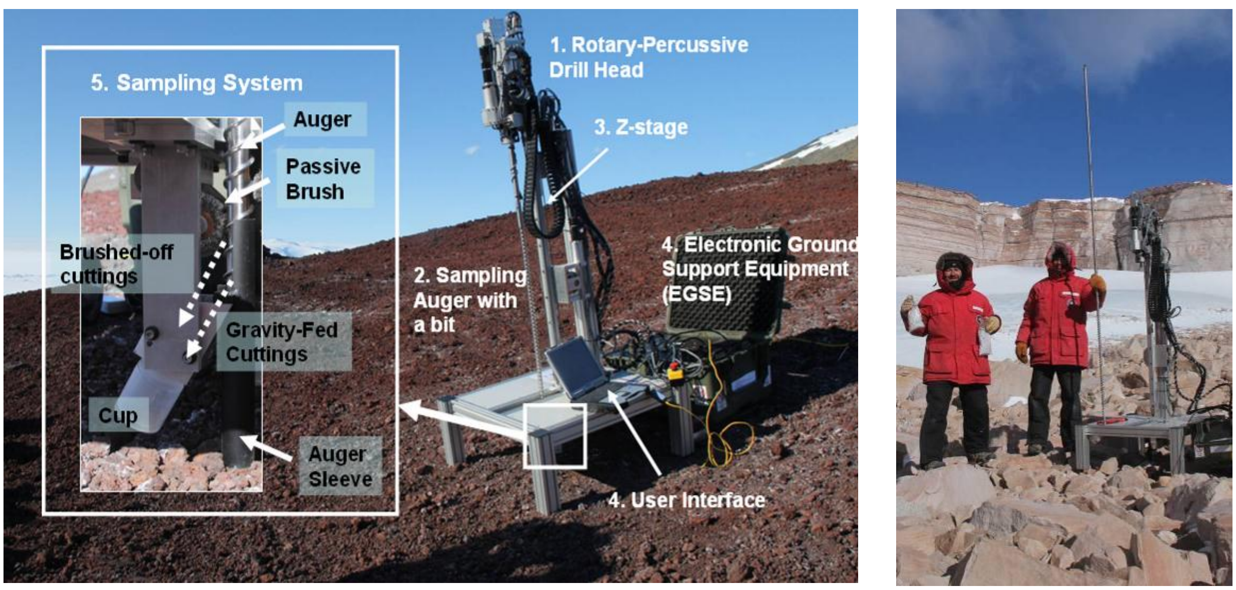


Figure 13. Left: Drill components; Right: Kris Zacny (PI) holds two full sample bags while Gale Paulsen holds 2.5 m drill string.

IV. Mobile In-Situ Water Extractor (MISWE)

The proposed water extraction system, called the Mobile In-Situ Water Extractor (MISWE), consists of the Icy-Soil Acquisition and Delivery System (ISADS), and the Volatiles Extraction and Capture System (VECS) as shown in **Figure 14**. The ISADS is a deep fluted auger that drills into the ice or icy-soils and retains material on its flutes. Upon material acquisition, the ISADS is retracted into VECS and sealed. The VECS consists of a cylindrical heat exchanger and volatiles transfer system (a reactor). The material on the deep flutes is initially heated, for example via conduction. However once some water sublimes and pressure inside the reactor increases, the further heat transfer could be accomplished via very efficient convection. Vapor is bled into a water collection canister by a one way valve where it condenses. The heat from the canister can be transferred back to the reactor. After water extraction the ISADS is lowered towards the ground and spun at high speed to eject the dry soil via centrifugal action. At the same time, the collected water is pumped from the canister into a storage container within the rover's Warm Electronics Box. The MISWE rover then moves to the next location and the operation is repeated. Once the water tanks on the MISWE rover are full, the rover drives back to the base while leaving dry soil and "Swiss cheese" holes pattern in the ground.

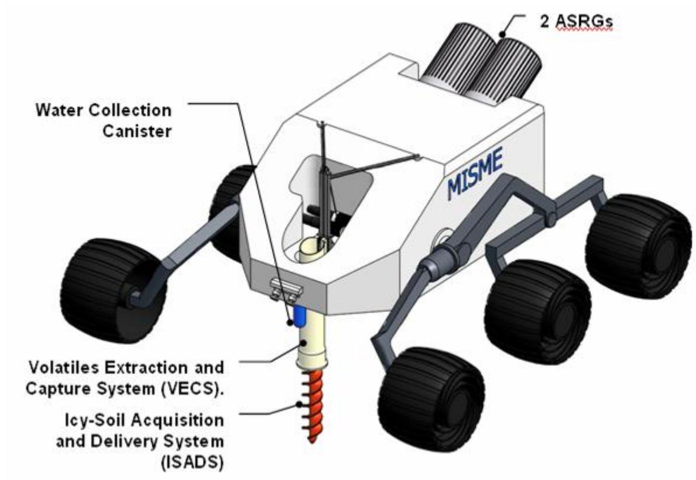


Figure 14. A concept of a Mobile In-Situ Water Extractor (MISWE).

Since the regolith is not actually transferred, there is no need for a transfer system and associated dust tolerant valves. Also, if a rover is powered using Radioisotope Thermal Generators (RTG) or more efficient the Advanced Stirling Radioisotope Generator (ASRG), the heat generated by the unit can be transferred to the reactor. For example, the RTG on the 2011 MSL rover generates ~120 Watts electrical power and > 1 kW heat, which is used to keep the Warm Electronics Box (WEB) warm.

There is an added advantage of using an auger. The top soil on Mars (and maybe Moon) is covered by dry soil. The auger proposed approach, preferentially excludes the top soil while keeping the bottom soil (more likely filled with ice) on its flutes. The volume of soil on the flutes is smaller than volume of excavated soil from the hole for 2 reasons: fluff factor (soil becomes fluffier as it is drilled) and volume of metal auger itself fills part of the hole. Note that drilling telemetry will indicate at which point the auger enters icy-soil.

A. Sequence of Operations

MISWE is designed to be deployable from a mid-size, 2.5m long rover. The ISADS auger, in its base configuration is 10 cm diameter and drills up to 50 cm deep. The volume of sample per single operation is approximately 3500 cc and the mass is ~5 kg at 1.5 g/cc material density (mixture of ice and soil). The sequence of operations is shown in **Figure 15** and is as follows:

1. The MISWE lowers and preloads the VECS sleeve onto the rock-free surface.
2. ISADS auger starts drilling and acquires icy-soil
3. Upon reaching the target depth (in this case it is 50 cm), ISADS auger retracts from the hole back into the VECS sleeve
4. MISWE moves into a new location and preloads the VECS sleeve against a fresh surface creating a seal
5. ISADS starts heating up the icy-soil. Water sublimes and creates pressure within the VECS. Higher pressure speeds up the heating process of the soil because of gas convection heat transfer. At the same time, water-vapor is bled into a canister via one way valve and condenses into a collection canister, forming liquid.
6. Liquid water is pumped into a storage tank within the Warm Electronics Box.
7. The VECS moves up exposing the ISADS auger. The auger is spun ejecting dry soil.
8. The ISADS auger moves into the stowed position and the rover moves onto the next location.

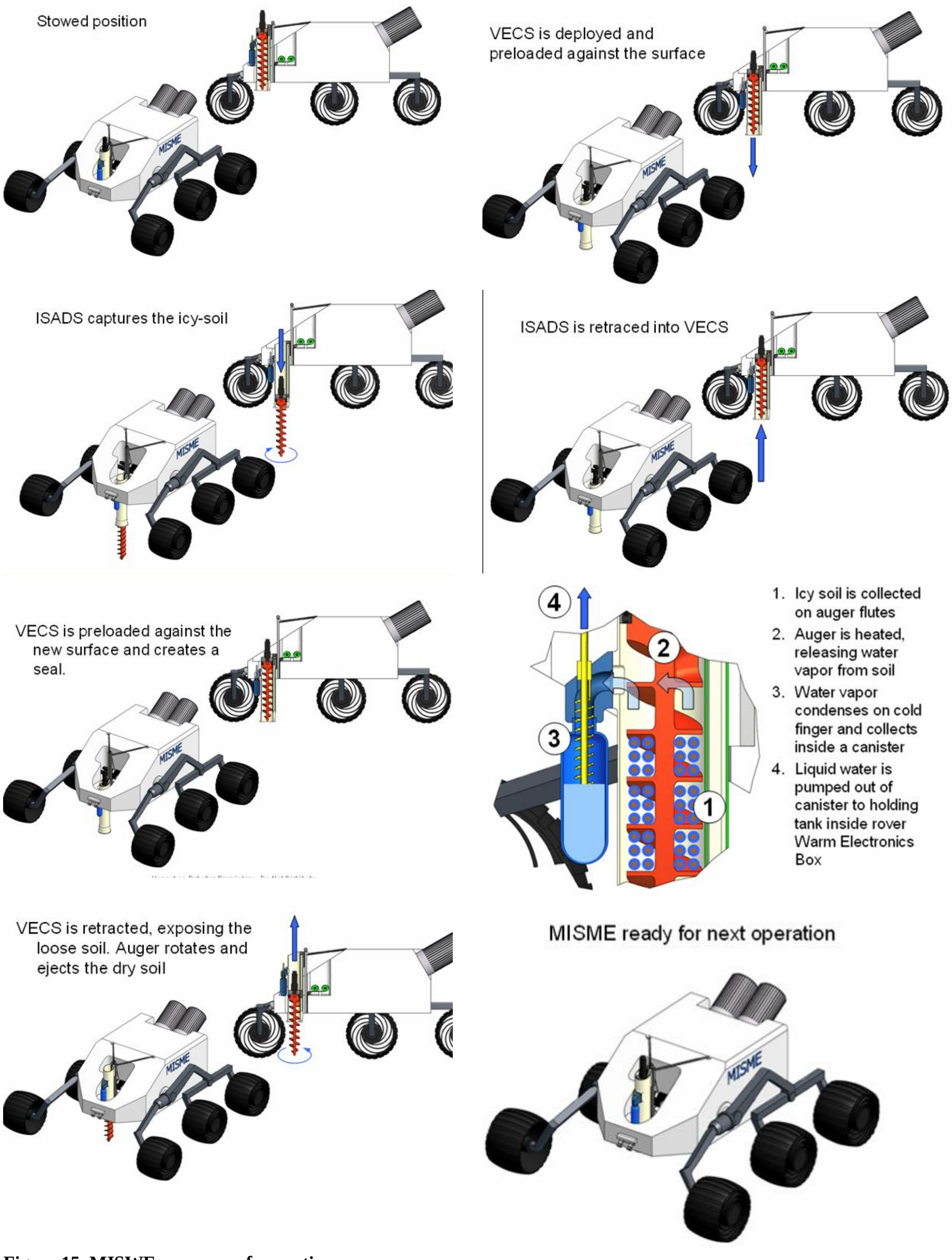


Figure 15. MISWE sequence of operations.

B. CECS Reactor Pressure-Temperature Diagram

Figure 16 shows a reaction within VECS plotted on the water Pressure-Temperature diagram. The reaction proceeds from point 1 through 2, 3, and ends at point 4. Point 1 refers to in-situ icy-soil. When the icy-soil is inside the VECS reactor, the temperature increases and water vapor is released. Once more water-vapor is released into the reactor the heat convection becomes a predominant heating method. During this time, temperature increases further and so does the pressure as more water vapor sublimes. At point 3, the one way valve (check valve) leading to the water canister is opened, and water vapor bleeds into the canister. Inside the canister (point 4) the pressure drops and water vapor condenses forming liquid water or ice. The heat liberated can be funneled back into the reactor if possible.

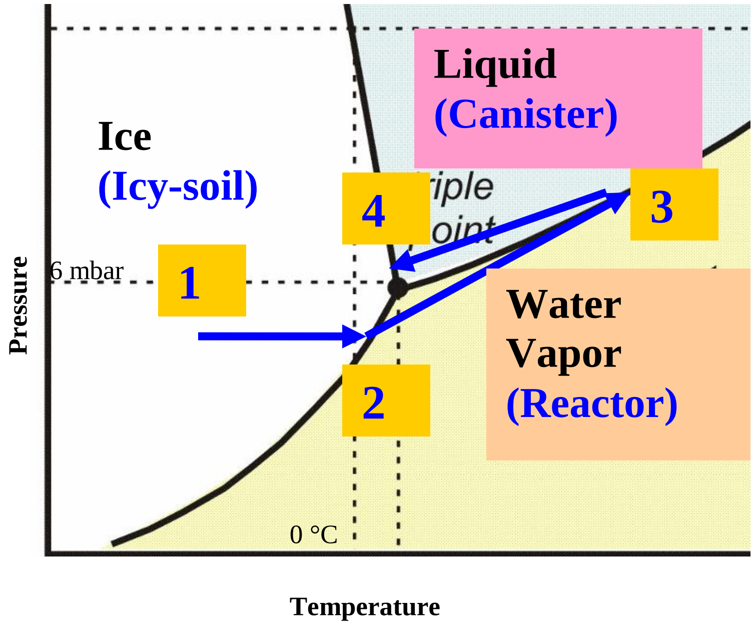


Figure 16. The MISWE reaction curve shown on the Pressure-Temperature water diagram.

Note that at the time of being discarded, the soil will be at high temperature and it will retain this temperature for some time. This is important because it means that the vapor remaining inside the VECS will not re-condense onto the soil grains and make them stick to the auger flutes.

C. Power Source for the MISWE

It is assumed that the MISWE rover will be powered by a nuclear device such as Advanced Stirling Radioisotope Generator (ASRG). Using solar panels at high latitudes will not be effective, especially in winter when the sun is low. In addition, solar panels would only be able to charge the batteries during the day, while during the night the batteries will be used to keep the spacecraft warm. At the Viking 2 site in winter water-ice forms frost, and this frost would cover the solar panels. Keeping solar panels warm to sublime this water-ice would just add to the energy expenditure. The Phoenix lander towards the end of its mission could generate enough power to keep itself warm. Once the energy in the batteries dropped below the critical value, the spacecraft froze. Recently the MER rover Spirit mission ended because the spacecraft froze (its solar panels could not be oriented towards the sun and in turn the battery could not be recharged).

The advantage of using ASRG is that this power source generates approximately 350 Watt of heat and 140 Watt of electrical power (system efficiency is >27%). The MISWE in its base design would use 2 ASRGs, in which case it would have 700 Watt of heat power and ~300 Watt of electrical power. This would deteriorate by 10% over the 14 year life period[13]. The heat could be transferred into the reactor as well as Warm Electronics Box (WEB) as it is done on the 2011 Mars Science Laboratory Rover. The electrical power could be used for housekeeping (communication, data processing), to power the ISADS auger, for mobility, and potentially for microwave heating.

D. Selection of Heating Method

We selected conductive heating as the most suitable approach to drying the icy soil. The alternative heating approach of chief interest was the use of a magnetron, i.e. microwaving the soil. Conductive heating is more attractive for three main reasons: it is simpler to implement, more flexible, and imposes fewer requirements on the surrounding hardware.

First, conductive heating can be implemented through a simple resistive heater, which can be either embedded within the auger or mounted to the auger surfaces. Several heaters can be used to provide distributed heating, bringing the entire mass of soil to target temperature with a minimum of wasted heat. Microwave heating, in comparison, requires waveform manipulation to avoid hot spots, or moving either the magnetron or the auger (this is

[13] http://www.ne.doe.gov/pdfFiles/factSheets/SpaceRadioisotopePowerSystemsASRG.pdf

why food is rotated within a microwave oven). This in turn would require additional actuators making system more complex. Heating of the regolith depends on absorption of the microwave energy.

Ethridge and Kaukler (2012) performed a simple experiment with microwave water extraction but due to complexity and cost of performing more controlled experiments, they developed several computer models instead. They noted that the extent of microwave absorption is dependent on several factors. The penetration depth is greatly affected by the microwave frequency. Long wavelengths (lower frequencies) penetrate deeper than short wavelength (higher frequencies). Knowledge of the dielectric properties is required to calculate the penetration depth and to model soil heating and water extraction.

Second, conductive heating is more flexible in its implementation, in that it can be delivered by means other than electrical power. A direct feed from the ASRG, concentrated solar radiation, or burning propellant are all conceivable alternatives to electrical power for delivering conducted heat to the VECS. Microwave system requires electrical power and in turn, by its nature will be less efficient. For example, 1.1 kilowatt input will generally create about 700 watts of microwave power (~65%). MISWE would require 1000 Watts of heating power for ~40 min; this translates to 1.5 kWh of electrical power and 1 kWhr of electrical energy. To generate that much electricity, 2 ASRGs need to charge the batteries for at least 4 hours. Hence, MISWE water extraction process would have to take a 4 hour break after every cycle, just to recharge its batteries.

Third, conductive heating imposes fewer requirements on the surrounding hardware. Using a magnetron would require that the rover and interfacing components be well grounded, or else they would build up a static charge. This could have serious consequences for the rover itself, as well as any other equipment that it interfaced with. In particular, at Mars conditions Paschen curve is at its minimum and hence any substantial charge built up will cause spark. In addition, charge build up on the rover body, solar panels etc., will attract dust and reduce solar power output and may cause accelerated wear to the moving components (joints etc.).

V. Alternative methods of water extraction

The energy to melt ice (latent heat of fusion) is 334 kJ/kg or 100 Wh/kg while the energy to vaporize water (latent heat of vaporization) is 2260 kJ/kg or 628 Wh/kg or 0.63 Wh/g (6x larger). Hence from the energy stand point, it would make more sense to just melt ice and recover liquid water rather than vaporize ice or water and then capture the vapors inside cold trap. Capturing water instead of vapor on Mars or the Moon would work because these two bodies have substantial gravity. However, this approach would not work on Asteroids, with near zero gravity. However, the main reasons for capturing vapor rather than liquid water are ease of transfer across larger distances and the fact that water from vapor is clean, while melted water will contain various chemicals that would no doubt corrode and slowly destroy the hardware. On the Moon LCROSS liberated large amounts of water, but it is not water you would want to drink without some processing. It is tainted with chemical and even isotopic poisons; it is more of a carbonated soup stocked with metals and organics[14]. On Mars, water will most probably include perchlorates, which is a highly oxidizing compound[15].

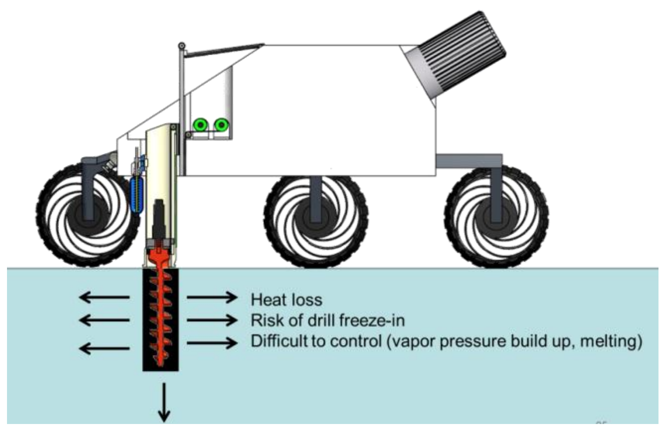


Figure 17. Alternative (but infeasible) method is to extract water from the borehole via hollow auger/drill system.

A. Water extraction in a hole

MISWE relies on bringing the soil into the reactor above the surface. However, another obvious way of water extraction is to 'pump' it directly from the borehole into a cold trap; sort of like oil (if the system would end up just melting the ice) or natural gas recovery (if the drill would sublime the ice).

There are, however, a few problems with these approaches:

[14] Water on The Moon, I. Historical Overview by Arlin Crotts (Columbia University) http://arxiv.org/abs/1205.5597

[15] http://www.newstrackindia.com/newsdetails/236233

1. *Melting only:*

A major fraction of the heat pumped into the formation will end up warming up the planet itself. Cold Regions Research and Engineering Laboratory developed several melt probes and performed detailed thermal analysis of such devices. It was concluded, that for the probe to be most efficient (i.e. penetrate the formation without losing too much heat laterally), it has to have high penetration rate (which requires lots of power) and low diameter (Aamot, 1967). Based on these findings, two probes were developed (**Table 2**). These highly efficient probes still loose over 50% of heat to the formation. Hence, for the water recovery system to be very efficient, it has to heat up the formation while drilling (drilling is required because ice could be mixed with icy-soil, and such formation would be impossible to penetrate with a melt probe). Note however, that the drilling system would have to be quite powerful to achieve 2.5 m/hr or 6 m/hr penetration rate. In practice, penetration rate would be on the order of 1 m/hr, in which case, more energy would be lost to the formation.

Table 2. Melt probes developed by the Cold Regions Research and Engineering Laboratory (Aamot, 1968)

Probe	**Diameter (cm)**	**Length (cm)**	**Penetration Rate in ice at -28C cm/hr**	**Power Watt**	**Energy to penetrate 1 probe length (250 cm) Whr**	**Energy to melt equivalent volume of ice Whr**	**Probe efficiency %**
1	12.7	250	600	15,000	6250	3024	48
2	10.92	250	250	5,000	5000	2269	45

2. *Melting and Vaporization:*

Treffer et al (2006) performed several laboratory experiments with simple melting probes under cryo-vacuum conditions and compared the results with tests in a terrestrial environment (Treffer et al., 2006). The experiments revealed that under vacuum conditions the downward motion of a heated probe in an ice sheet is characterized by intermittent periods of sublimation and melting of the surrounding ice, sometimes interrupted by periods where a part of the probe's outer surface is frozen to the surrounding ice. This leads to a temporary blocking of the probe's downward motion. During the periods of ice sublimation the penetration process is significantly more power consuming, due to the large difference between the latent heat of sublimation and the latent heat of melting for water ice. The average penetration rate for a 11.5 cm diameter probe with a 600 Watt heater was 10 cm/hr. this is very slow and based on the thermal model developed by Aamot at CRREL, the fraction of energy lost would be considerably higher than the 55% reported for very fast (250 cm/hr and 600 cm/hr) powerful (kWs) melting probes.

In addition, having a probe inside a borehole means that the probe will have to be instrumented with temperature sensors thorough its length to continually control its thermal state (with the goal of preventing freezing in the hole). The probe would also have to have enough power, to be able to melt itself out in case of freezing in. The power budget will have to include potential heat losses to the formation. If the thermal conductivity of the formation were to be significant, the required power would of course be much larger (imagine trying to heat up a rod inserted into a large block of copper – all the heat flowing down the rod would immediately flow into the highly conductive copper, while the rod would remain cold).

To prevent possible freezing in, the system would have to have couple of kW of power capability, and this is quite difficult to achieve even with several ASRGs running in parallel.

C. Drilling and Blasting

Another possible method of water extraction is using a more conventional drill and blast approach; that is to drill blast holes, lower explosives into them and then blast the entire area. This method is used every day in the mining environment and even underground. The primary author worked several years in South African coal, diamond and gold mines and is quite familiar with the practicalities of using such an approach. First, in low gravity environment, it may be possible for the blasted ice and icy-soil to reach large distances. And hence, all equipment needs to be protected from falling debris. Even if less powerful explosive is used to prevent material to become airborne, a dedicated backhoe is still required to lift the blasted material and transfer it into a loader. The loader then needs to deliver the material into a primary crusher to be sure than conglomerate can fit into the water extraction reactor and fall out at the bottom of the reactor after the reaction process. This is a very robotically intensive process and probably would be possible if millions of tons of material were required to be excavated per year. However, for smaller habitat settlements, this approach would of course be overkill.

VI. Experimental Setup

The experimental setup consisted of the reactor and cold trap, vacuum chamber, computer and data acquisition hardware (see **Figure 18**). The reactor/auger assembly was preloaded against a tray of air-dry JSC-1A and placed inside the vacuum chamber along with the cold trap for capturing water vapor. The reactor assembly consisted of utilizing a cartridge heater (0.25 inch diameter, 4 inch length, up to 300 Watts, 120 VAC 2.5A with built in temperature sensor) inside an auger (2 inch dia. x 4 inch length) packed with frozen JSC-1A (6% and 12% water saturation), which was housed in a clear acrylic tube (reactor) and preloaded onto a deep tray of air dry JSC-1A, creating a leaky seal. The water content of air dry JSC-1A was 0.3wt%. The cold trap was kept at subzero temperatures by utilizing a heat exchanger via a chiller, at -40 °C. Power to the cartridge heater was controlled with a Variac variable transformer. The data acquisition hardware recorded changes in temperature and pressure from the various thermocouples and pressure transducers installed within the system.

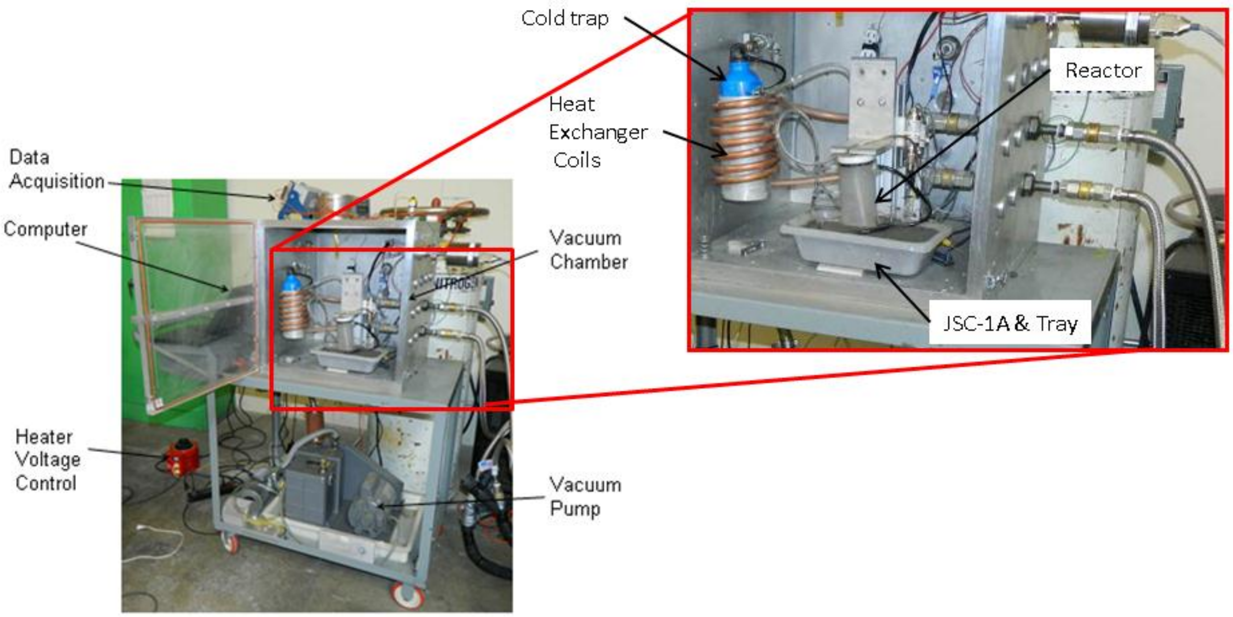


Figure 18. Experimental Setup. Reactor sealed against JSC-1A inside the vacuum chamber.

A 0.5 inch hose installed on the top of the reactor lid allowed vapor to flow into the 900 ml aluminum cold trap canister (see **Figure 19**). Clamps were used to seal the reactor housing with the auger inside, which was then preloaded against the tray of JSC-1A by lowering the preload bracket and compressing the preload spring.

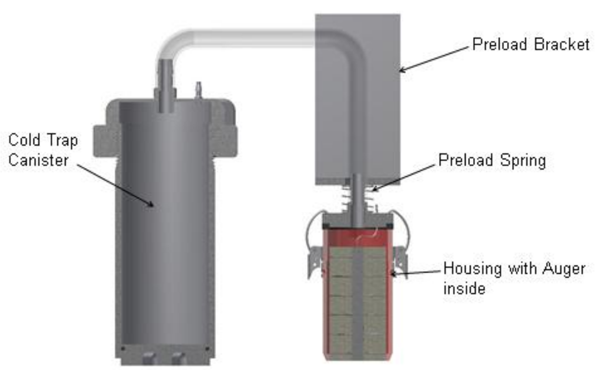


Figure 19. Section view of reactor assembly and cold trap canister & auger.

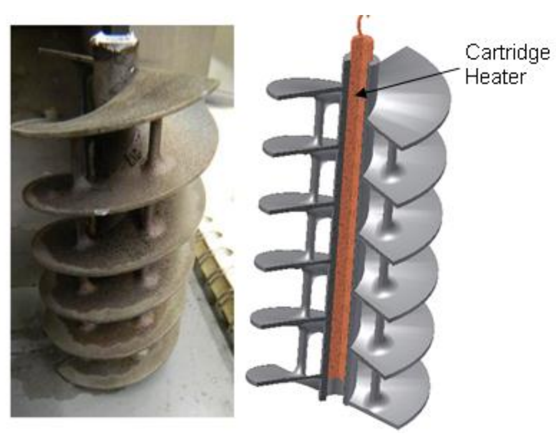


Figure 20 Auger with cartridge hole in the center. Pins run along the length of the auger for better heat distribution through frozen soil. Cartridge heater installation on the right.

A. Auger Assembly (ISADS)

The purpose of the auger is to drill and capture icy soil on its deep flutes. A partial Selective Laser Sintered (SLS) auger prototype was made, which measured 2 inch (5 cm) in diameter by 4 inch (10 cm) in length with 0.050 inch thick flutes. A 0.25 inch thru hole down the center allowed a cartridge heater to be installed for testing. For better heat distribution through the frozen soil, the auger was designed with pins 0.050 inch in diameter running along the length of the auger, in a circular pattern approximately 0.5 inch from the center (see Figure 20).

B. Reactor Assembly (V.E.C.S)

The purpose of the reactor is to seal the auger with its icy soil and assist with the transfer of water vapor to the cold trap (**Figure 21**). The reactor consisted of a clear acrylic tube with the auger assembly housed inside it. The reactor cap was sealed onto the housing with hook clamps on either side. A 3/8 inch NPT male fitting was installed on the cap, where a 0.5 inch hose allowed vapor to flow into the cold trap. To allow for vapor to freely flow to the top of the reactor, grooves were cut into the acrylic tube leading to the top vapor outlet. Thermocouples were installed inside the reactor housing to measure temperature changes (see **Figure 22**). The lower temperature thermocouple was installed on the inside wall, near the lower lip, measuring vapor temperature in the lower region. The upper temperature thermocouple was installed near the housing cap to measure vapor temperature as vapor gathered to flow to the cold trap. To measure pressure changes within the system, two 0.125 inch NPT fittings were installed on the reactor, which lead to pressure transducers nearby. Each transducer measured pressure changes at the thermocouple location.

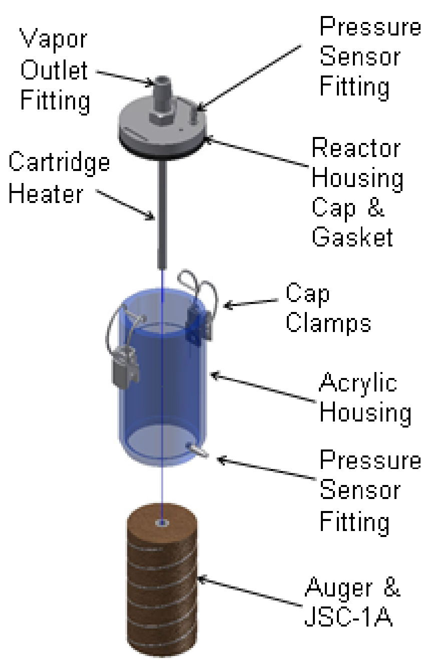


Figure 21. Exploded view of reactor assembly showing JSC-1A packed onto auger.

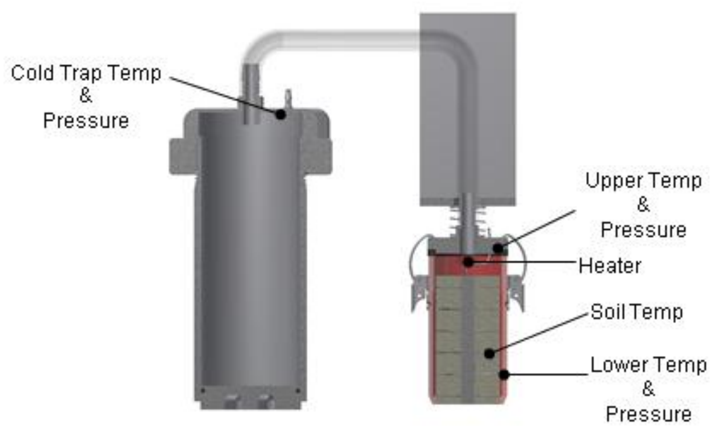


Figure 22. Thermocouple and pressure sensor locations. A thermocouple was inserted into the soil prior to freezing.

The reactor housing went through two phases of design changes (**Figure 23**). The second and the final iteration of the reactor proved successful with the few incorporated design changes and upgrades. The vapor outlet was moved to the top of the cap, and a larger 3/8" diameter fitting was used. This not only allowed better flow of vapor into the cold trap, but moving it to the top ensured no loose JSC-1A would get into the tubing. The upper pressure transducer fitting was also moved to the top of the cap for ease of installation and assembly. To remedy the cap sealing problem, two hook clamps were installed opposite side of each other and used to clamp the cap onto it. The new design greatly simplified and decreased set up time.

Figure 23. Final design of the VECS reactor has larger vapor outlet.

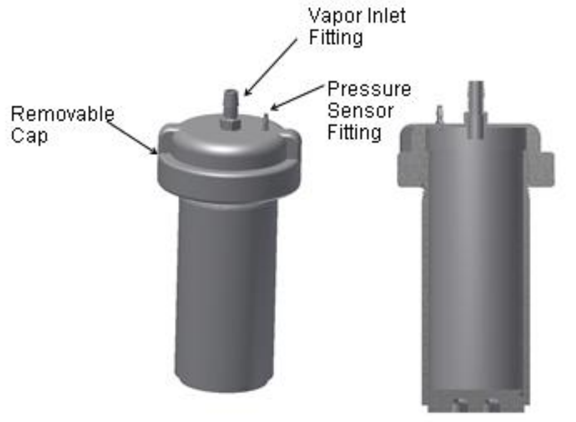


Figure 24. Cold trap canister with removable cap. Assembly consisted of a 3 inch diameter aluminum tube with a screw lid and open at the bottom.

C. Cold Trap Assembly

The cold trap had to meet a few conditions. It had to be cold enough to allow vapor to condense and large enough to prevent pressure buildup. A cold trap canister was constructed using a 3 inch inner diameter by 8 inch long aluminum tube that was threaded on one end (see **Figure 24**). An aluminum tube cap was used for the top to allow for easy removal and extraction of water. The cap itself was fitted with a 3/8 inch NPT fitting for the vapor inlet tube. A 0.125 inch NPT fitting was also installed for a pressure transducer to measure the pressure within the canister. To measure the vapor temperature inside the canister, a thermocouple was also installed, hanging within. The canister was wrapped with copper tubing with ethylene glycol being pumped through them from a chiller set at -25°C. The assembly was wrapped in foam to maximize insulation.

The cold trap design was refined through an iterative design process. Initially, the cold trap was placed in an ice bath during testing. Glass jars were used during the first two iterations of the cold trap. The reason a glass jar was used was to allow viewing of the condensed vapor. The initial design used a 75 ml jar fitted with 0.125 inch NPTs. The small volume and low surface area of the jar caused pressure build up and caused blowouts through the soil the reactor was preloaded against during testing (the vapor could not condense fast enough causing the blowouts). A larger (234 ml) jar was used for the second iteration of the cold trap design. Although noticeable improvements were seen in the amount of water extracted, the problem with pressure buildup and blowout still existed.

The larger jar remedied the surface area dilemma, allowing more area for water vapor to condense onto, but more could still did not get cold enough to speed up the condensation time. Significant increase in the amount of water extracted was seen with the current larger 900 ml design of the cold trap.

Prior to arriving at the final design for the cold trap canister, copper heat exchanger coils were installed inside the vacuum chamber. The water canister used as a cold trap had the smaller 0.125 inch NPT fittings installed. During testing sudden blowouts also occurred due to water freezing at the inlet of the canister. Thus the hose and inlet port have to be kept above 0°C. The larger volume and surface area of the current cold trap, coupled with the use of a chiller and insulated hose resulted in 92% water extracted.

D. Soil Preparation

In all tests, we used air dry JSC-1A feedstock. The air dry soil contained 0.3 wt% water. The soil was first mixed with water to achieve 12 wt% water saturation. To create the test sample, approximately 276 grams of JSC-1A was mixed with about 38 grams of water. About 200 grams of the saturated JSC-1A mixture was then packed onto the auger flutes (**Figure 25**). A thermocouple was inserted into the soil, for measuring soil temperature during the test, and placed in the freezer. Approximately 5% of the water was lost due to vaporization in the freezer.

After a successful test, the JSC-1A dumped off the auger was warm to the touch, and looked dry (**Figure 26**). To determine the amount of water still remaining in the soil, the sample was weighed after the test and logged. It was then baked in an oven at about 100°C for about an hour, at which point the sample was weight again. During one successful test, there were 0.6 grams of water still remaining in the sample; this corresponds to 0.3wt%.

Figure 25. Frozen JSC-1A packed onto auger prior to cartridge heater installation.

Figure 26. JSC-1A and auger after testing

VII. Testing

A total of 47 tests were completed with various stages of upgrades and modifications along the way. Each upgrade yielded improved results. Slight modifications in heating duration and heating power were tested. On average only one test could be done per day, due to time required for the 6 wt% or 12 wt% test sample to be prepared and frozen. All tests were timed and logged via data acquisition hardware, with a new data file created for each test.

A. Test Procedure

The test procedure typically started the day before, with the preparation of the soil sample. Specific amounts of air dry JSC-1A and water were mixed together to achieve 12% water saturation. The mixture was then packed onto the auger flutes and a thermocouple was inserted into the soil. The auger and soil combination was set inside a freezer at around -18°C for 24 hours. The remainder of the soil was weighed and the difference logged as the amount of mixture on the auger. The cold trap canister was rinsed and allowed to air dry overnight.

On the day of the test, the vacuum chamber was cleaned and the chamber door rubber seal cleaned and greased. The cold trap canister was placed inside the heat exchanger coils and the chiller turned on. The chiller was allowed to run for 20 minutes, to allow sufficient cooling of the cold trap canister.

The next step was to set up the computer and data acquisition. A new data file was created using the GUI, and all the channels of the data acquisition turned on ready to record. Actual recording of data would begin when the vacuum chamber was ready to be pumped down.

At this point the auger assembly was ready to be taken out of the freezer. The cartridge heater was installed into the center thru hole of the auger, and the entire assembly inserted into the reactor housing tube. The top cap, which the cartridge heater was attached to, was clamped shut onto the reactor housing using the hook clamps. The reactor assembly was then set on top of the tray of JSC-1A and the preload bracket lowered and locked, creating a seal between the reactor tube and the JSC-1A.

To start running the test, the vacuum chamber door was clamped shut, and the GUI was set to start recording data. The solenoid valve on the cold trap was flipped open to allow gasses to escape prior to testing. Next the vacuum pump was turned on and the chamber was pumped down to 7 torr (Mars Pressure), which usually took 5-10 minutes.

Once the pressure inside the chamber reached 7 torr, the cartridge heater voltage was set to 40 volts on the variable transformer. The heater was left on for 20-40 minutes, depending on the test. During that time, condensation was visible inside the acrylic reactor housing (see **Figure 27**), but gradually evaporated as the test progressed. During some instances, condensation could be seen inside the tubing as well.

Upon successful completion of the test, which was typically conducted for 40 minutes, the heater was turned off and the vacuum chamber pumped backup to atmosphere. The cold trap canister was extracted from the heat exchanger coils and its' contents weighed (**Figure 28**). The reactor was disassembled and the dry JSC-1A was

weighed, baked in an oven and weighed again to determine the amount of water that was still present in the soil after the test.

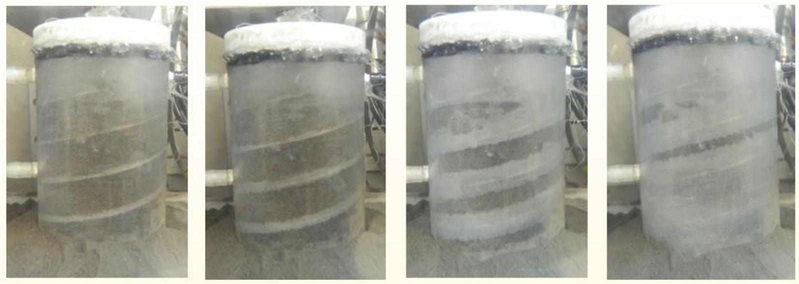


Figure 27. Condensation visible inside acrylic reactor housing, decreasing as test progresses.

Figure 28. Ice accumulation inside cold trap canister.

B. Test Results

The total energy that is required to raise the temperature of ice from -50 °C to 0 °C and then sublime it as shown in **Table 3** is 2694 kJ/kg. Since 1000 kJ = 280 Wh, the total theoretical energy is therefore 748 Whr/kg or 0.748 Wh/gram. This means that a 748 Watt heater is required for 1 hour to sublime 1 kg of ice initially at -50 °C. Subliming ice at 0 °C requires 726 Wh/kg, or not much less.

Table 3. Theoretical energy to sublime ice

Type of heat	Value	Cumulative Total per kg
specific heat of ice	2 kJ/kgK	100 kJ/kg [28 Whr]
latent heat of fusion	334 kJ/kg	434 kJ/kg [122 Whr]
latent heat of vaporization	2260 kJ/kg	2694 kJ/kg [754 Whr]

Test results gradually improved as the system was improved after each test (**Table 4**). Initial tests yielded minimal results, but careful observation and analysis helped make the necessary changes to increase the amount of water extracted. A total of 47 tests were conducted in Mars chamber of which test #42 yielded the best results at 18.7 grams extracted out of 20.5 grams. That is 92% water recovery using 17 Wh of energy (0.9 Wh/g). Since the required energy to sublime 1 gram of water is ~0.75 Wh/g, the system is therefore ~82% efficient (0.75 Wh / 0.9 Wh).

One area of interest is the amount of energy put into the heating of the system. This was investigated by varying the amount of power put into the cartridge heater and the duration of the heating time. A few tests were performed, keeping the cartridge heater power at 34 watts and varying the heating duration. The highest yielding test out of the three, was the 40 minutes at 34 Watts, with 87% water recovery at a cost of 1.4 Wh per gram (energy efficiency of 55%).

Table 4. Selected results from 47 total tests. In these tests, initial soil saturation was 12wt% and the the Heater Power was 34 Watt.

Test ID	Water mass after freezing (g)	Water Extracted (g)	% Water Extracted	Heater/Dwell Duration (min)	W_{actual} (Whr)	Whr/g water	Energy Efficiency, %
35	20.21	16.06	79.46%	30	17	1.1	68
36	19.75	16.08	81.40%	30	17	1.1	68
38	20.12	17.50	86.96%	30	17	1.0	75
39	19.98	16.64	83.27%	40	23	1.4	55
40	22.00	19.86	90.24%	30/10	17	0.9	82
42	20.47	18.74	91.54%	30/10	17	0.9	82
45	20.88	16.10	77.11%	30/10	17	1.1	68
47	19.98	15.10	75.57%	25/10	14	0.9	82

Another approach for minimizing the amount of energy put into heating the system was to decrease the energy applied or the rate at which it was applied. The heater power was set to either 34 or 25 watts, and the duration was tested at varying amounts of time. In some cases, the system was allowed to "dwell" after the heater had been shut off. While these trials did not achieve especially high water recovery rates, they did return the lowest energy costs per gram of water recovered. Note that "dwell" tests have slightly inflated efficiency values. This is because during the dwell time some heat would flow via gaseous conduction – from the 7 torr and 25 °C atmosphere and radiation. This is probably around 10% of all thermal energy. Hence true efficiency values would be ~70%.

Figure 29 shows typical power, pressure, and temperature data for a test. In this particular case, the heater was on for 30 minutes and then the system was allowed to heat soak for another 10 minutes before the chamber was vented to atmosphere.

There are three thermocouples inside the reactor. These are labeled as "Upper Temp", "Lower Temp", and "Soil Temp". The insert in **Figure 29** shows their location. The cartridge heater has a built in thermocouple that is also recorded in the data file. Pressure transducers are connected to the reactor housing, near the upper and lower thermocouples. The "Upper Temp" thermocouple is installed through the top cap and measures the vapor inside. The "Lower Temp" thermocouple is mounted on the inside wall of the acrylic reactor housing and measures vapor temperature towards the bottom. To measure soil temperature during the test, a thermocouple ("Soil Temp") is embedded in the soil prior to freezing. To monitor conditions inside the cold trap canister, a thermocouple and pressure transducer is connected to the top of the cap. The heater temperature was taken to about 115°C max at around the 30 minute mark, at which point it was turned off and let to sit in vacuum for an additional 10 minutes. The soil temperature can be seen rapidly increasing in **Figure 29**, indicating that the soil inside reactor is dry. This is an important observation since the soil temperature can be used to monitor progression of the drying cycle and in turn help in optimizing the energy by switching off the heaters at the appropriate time (when T_{soil} starts climbing). It should also be noted that Cold Trap Pressure was slightly lower than Upper or Lower Pressure. This pressure gradient allowed water vapor to flow from the reactor to the Cold Trap. The reactor pressure was always just above the triple point of water helping with heat transfer via gases convection/conduction.

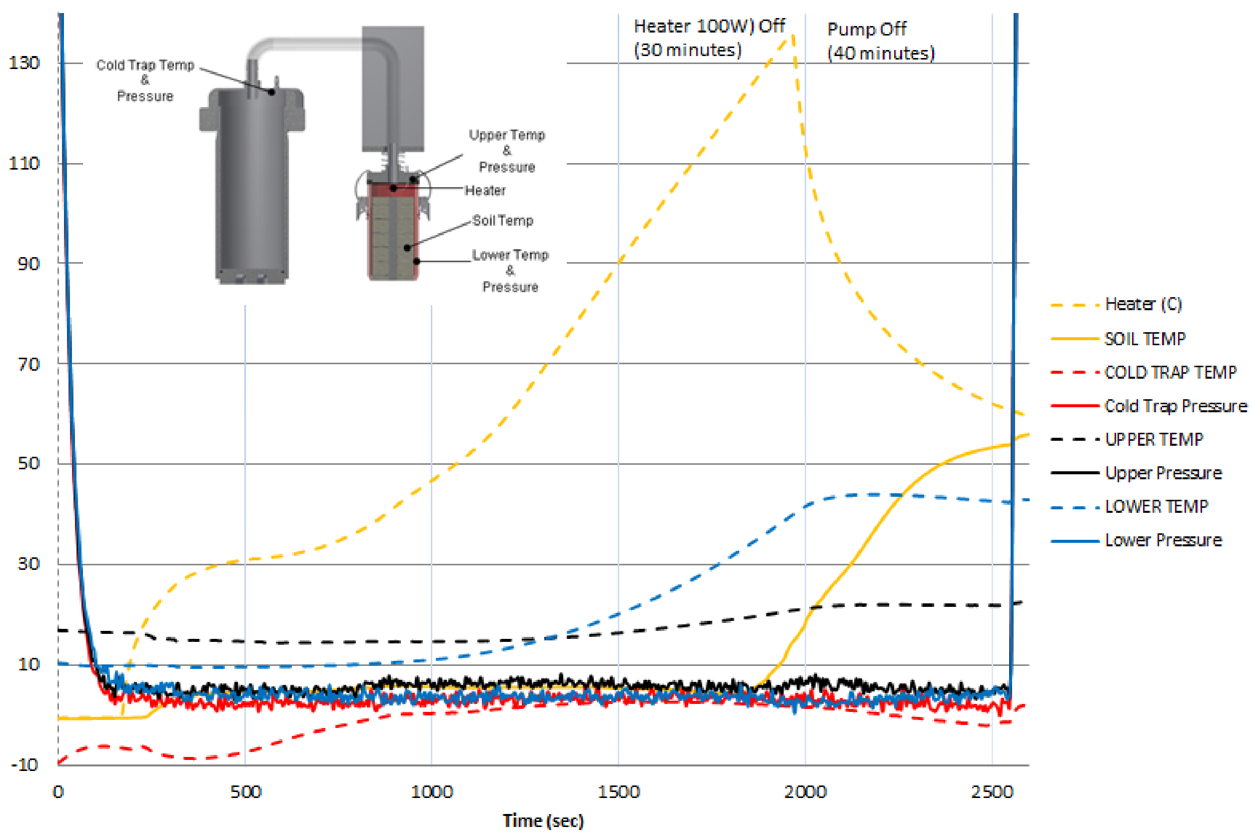


Figure 29. Thermocouple and pressure sensor plot from the highest yielding test, #42. The heater was turned off after 30 minutes while the test was allowed to run an additional 10 minutes before pumping the vacuum chamber back up.

C. Scaling to MISWE production size

A 2 inch (5 cm) diameter x 4 inch (10 cm) long auger, with fully saturated soil managed to recover ~19 grams of water in 40 minutes (Test #42 in **Table 4**). Hence, a 1 meter deep auger of the same diameter will be able to recover ~200 grams of water every 40 minutes and required 340 W of heat from ASRGs. Hence 2 ASRGs would be more than sufficient (each can contribute 350 Watt of heat).

Assuming drilling to 1 meter depth, roving to a new location, dispensing of dry soil after the process takes 20 minutes, 200 grams of water can be recovered every hour. Thus the total per day is 24 hrs x 200 g /hr = 4800 grams of water. If drilling and roving tasks take longer than 20 minutes, the production rate per day will naturally drop. However, in this case, a large diameter auger could be used (a 6 inch auger driven by 1.3 kW motor penetrated icy soil in the Arctic at a rate of 10 cm/min, i.e. using 220 Whr/m of electrical energy).

The above are just rough estimates and the actual production rate will be determined after performing full scale tests in vacuum chamber. However, these estimates point to the important conclusion, and that`s the water recovery rate with the MISWE system is feasible to be implemented in the actual ISRU mission.

VIII. Conclusions and Recommendations

The VECS system breadboard has been demonstrated to extract water from icy soil using feasible quantities of energy. Specifically, the VECS breadboard extracted 19 grams of water from icy soil (extraction efficiency of 92%) using as little as 34 Watts of power for 30 minutes. The required energy was 17 Wh or 0.9 Wh/gram of water (~80% energy efficiency).

We estimate the energy efficiency of the VECS system to be in excess of 70% but the actual efficiency may be influenced by manipulating the heating cycle. The power and duration of the applied heat and dwell time after the heating cycle has an effect on the resulting efficiency.

The energy efficiency of the VECS system may be influenced by manipulating the heating cycle. Conductive heating is the most suitable approach for delivering heat to the icy soil. In particular, it is more efficient than microwave system and it is easier to integrate. It also takes advantage of the thermal energy produced by ASRG (and otherwise radiated to space and lost).

A production rate of ~5 kg water/day is feasible using a 1 meter long and 5 cm in diameter auger. The total energy required would be ~340 Watt. Hence 2 ASRGs should be sufficient (each ASRG produces 140 Watt electrical + 350 Watt thermal).

The cold trap needs to be kept below freezing temperature of water and in turn away from direct exposure to sun. This is the case for the Moon, Asteroids and Mars. For example, one of the reasons why the soil stuck to the 2007 Mars Phoenix scoop was because the scoop was in direct sunlight. Keeping the scoop in the shadow of the lander helped alleviate the problem.

Soil temperature can be used to monitor the drying cycle. Once the temperature starts increasing, indicating that the soil is dry (i.e. heat is no longer absorbed by water sublimation process), the heating process can be terminated.

The pressure within the VECS reactor during the drying process was always higher than the pressure in the Cold Trap facilitating a flow of water vapor from the reactor to the Cold Trap. The absolute pressure in the reactor was at above the triple point of water facilitating heating cycle via gases conduction and convection.

Since soil can contain corrosive or toxic substances, extracting and then condensing water (instead of just extracting liquid water) ensures that end product is clean and in turn will be less likely to corrode the hardware, and can be consumed by humans.

Sealing the VECS reactor by pressing reactor/auger against the soil has been very successful. Since the flow resistance through the soil particles underneath the reactor was higher than the flow resistance to the Cold Trap, water vapor preferentially flowed into the Cold Trap.

The top soil on Mars is covered by dry soil. The auger approach, preferentially excludes the top soil while keeping the bottom soil (more likely filled with ice) on its flutes (volume of soil on the flutes is smaller than volume of excavated soil from the hole for 2 reasons: fluff factor (soil becomes fluffier as it is drilled) and volume of metal auger itself fills part of the hole). Note that drilling telemetry will indicate at which point the auger enters icy-soil.

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