Extra-Terrestrial Water Extraction

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ABSTRACT

Human spaceflight, from the outset, has relied entirely on the use of terrestrial resources. Everything we as a species have accomplished has been with the aid of materials processed from our own planet. To date, all orbital missions and the few lunar expeditions have been limited enough in crew size and duration so as to obviate the development of alternative sources of supplies. With the nation's new space vision taking form, however, making use of extra-terrestrial resources will soon become imperative to reducing mission costs and complexity. Sustained human exploration of the solar system will require the ability to develop off-Earth resources. In situ resource utilization is of utmost importance to the fulfillment of this nation's new space vision. Particularly, water is the most essential resource for human existence and one of the most costly in terms of getting it to space; in addition, water can be processed to produce rocket fuel. By lowering mission costs, developing an off-Earth water source will dramatically increase the feasibility of robust long-duration and deep-space manned missions. Though plentiful on Earth, water was once thought to be sparse throughout most of the rest of the solar system; however, evidence shows it is existent on the Moon, on Mars, in comets, in asteroids, and elsewhere. In most cases, the water is not available in large pure ores but is commingled with the material in which it is found. Extra-Terrestrial Water Extraction is a simple process that employs basic scientific principles to remove water from an in situ ore. A sublimation or vaporization process (depending on the alien environment) removes the water from its ore, and a condensation process returns the water to liquid form for human consumption. The University of Texas at Austin Extra-Terrestrial Water Extraction (UT-ETWE) team has explored the benefits and feasibility of off-Earth water extraction. The following paper is a report of Team UT-ETWE's findings.

INTRODUCTION

The University of Texas at Austin Extra-Terrestrial Water Extraction (UT-ETWE) team started out as the Mars Drilling and Mining Company (MDMC) at the beginning of the Fall 2005 semester. Originally incorporated for *Space and Mission Design*, one of the Aerospace Department's senior design classes, the team's goal was to design a discovery class water mining mission to the northern hemisphere of Mars that would mine 50 gallons of water from the Martian regolith. Seeking to capitalize on the mood produced by Mars Odyssey's recent detection of what would appear to be Martian water, the successful Mars Exploration Rover landings that have sparked the imagination of a new generation, and the renewed political interest in space exploration, MDMC wanted to design a technology that would help facilitate the next step forward in human exploration of our solar system.

By the end of the semester, MDMC had developed a high-level system design for

Mission ESCAPE (Extract, Sublimate, Condense, Analyze, Purify, Evaluate), a mission that would launch in the 2014 time frame. A rendering of the ESCAPE rover can be seen in *Figure 1*. However, this design was no more than a vessel, window dressing, for the nuts and bolts of the design effort: extraterrestrial water extraction.

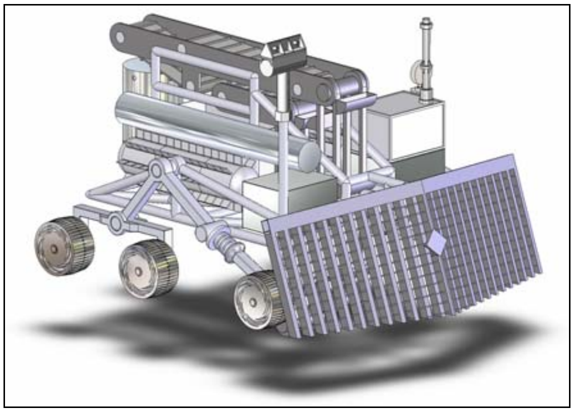

Figure 1. The MDMC Mission ESCAPE rover.

With *Space and Mission Design* over and the RASC-AL design forum on the horizon, the team decided to focus solely on water extraction. MDMC became UT-ETWE as the team's technological scope narrowed to only processing previously mined water ore and its scope of application widened to encompass other extraterrestrial sources of water. To emphasize, UT-ETWE's focus for the 2005 RASC-AL Forum has been only to explore the process of water extraction from a previously mined water ore. Extracting the ore is not currently in the team's purview.

In its submission to the RASC-AL project selection committee, UT-ETWE promised to provide results and conclusions from water extraction tests and a study of the benefits ETWE can provide to human space exploration efforts. This paper details the progress the team has made to date in trying to fulfill its project goals.

IN SITU RESOURCE UTILIZATION

To date, human spaceflight has relied entirely on the use of terrestrial resources. Everything we as a species have accomplished has been with the aid of materials processed from our own planet. Prior human spaceflight missions have been limited enough in crew size and duration to render unnecessary the development of alternative sources of supplies. The scope of the nation's new space vision, however, is such that making use of extra-terrestrial resources is imperative to reducing mission costs and complexity. Sustained human exploration of the solar system will require the ability to develop off-Earth resources. In situ resource utilization (ISRU), that is, the use of resources local to an exploration effort, is of utmost importance to the fulfillment of this nation's vision for space exploration.

NASA's Capability Roadmap Workshop for ISRU [1] suggests that the benefits of ISRU are, among others things, that it reduces cost, reduces mass, reduces risk, and enables flexible and sustainable planetary surface exploration. ISRU does many things, but only one of them is of real importance, as all other benefits are directly descendent from, and subsequent to the first. Developing ISRU capabilities reduces mission mass. Lower mass missions reduce cost, complexity, and risk, and thereby enable flexible and sustainable missions to be carried out. All other benefits can be similarly traced back to mission mass reduction.

If reducing mass is the ultimate benefit brought about by ISRU, targeting the largest mass culprits in space exploration for ISRU replacement is perhaps the best way to go about developing plans for future human

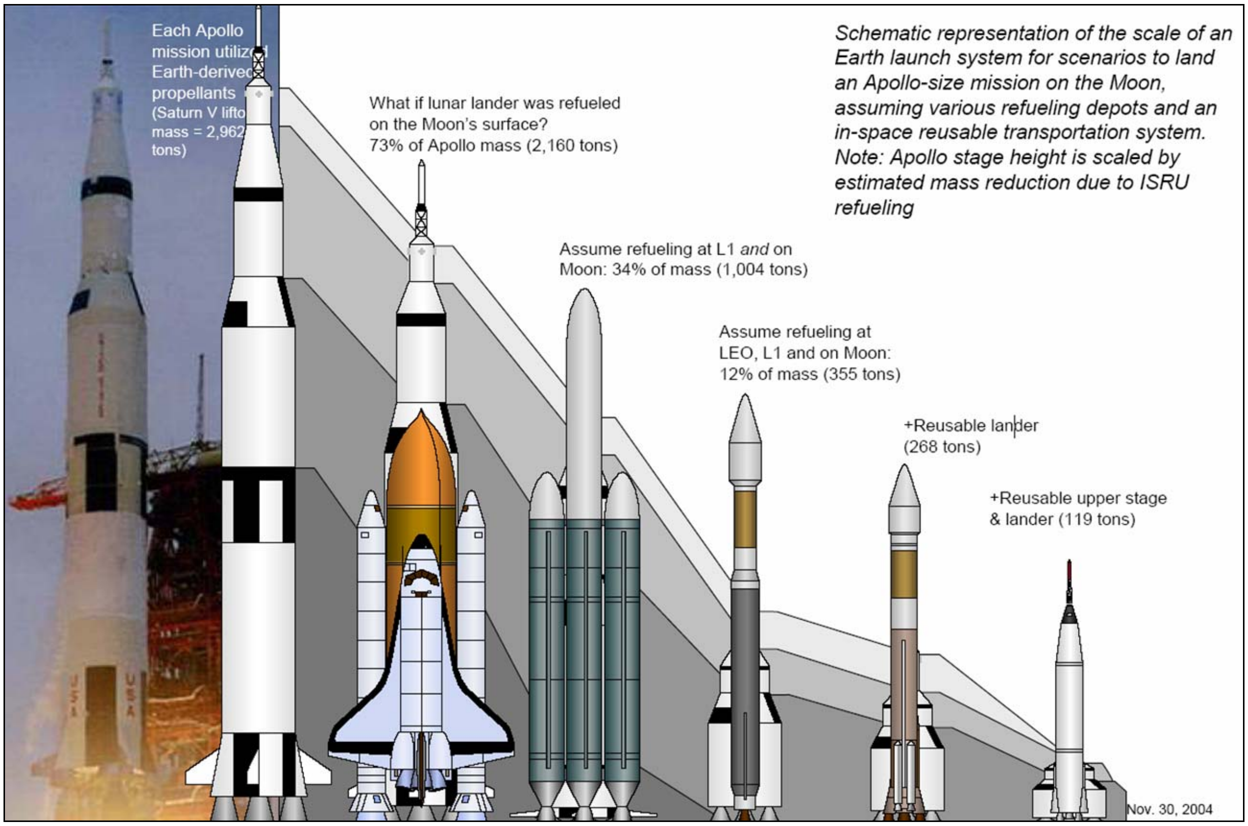

Figure 2. CSM Study: Propellant from the Moon will revolutionize our current space transportation approach. [1]

spaceflight missions. Hands down, fuel accounts for the largest fraction of mission mass out of all other mission consumables. The shuttle weighs roughly 4.4 million pounds at launch, 3.78 million pounds of which is fuel (86% of the weight). Water arguably accounts for the second largest fraction of consumable mass on space missions.

If missions did not have to cart all of their consumables around from start to finish, they would be significantly lighter. With ISRU, mission launch requirements for fuel and water could be significantly reduced. Extraterrestrial water sources could provide water for human consumption and hydrogen and oxygen for use as rocket fuel. Evidence has shown that water exists in a number of places in the solar system other than just on Earth. The Moon, Mars, and the asteroid belt between Mars and Jupiter, to name a few, are all places known to harbor water ore. Mining this ore would significantly reduce the cost of future missions, making them more likely to be completed.

REDUCING THE COST OF LAUNCH

Figure 2 illustrates the magnitude of mission mass reduction possible if initial launch mass requirements were not so high. By analyzing the Apollo missions, the NASA graphic supposes varying degrees of ISRU production capabilities. Refueling at the moon reduces launch mass by 27%. A stopover and refuel at an L1 station in addition to the refuel on the Moon would reduce launch mass by 66%. With stops at LEO and L1 for refueling, in addition to refueling on the Moon surface, launch mass

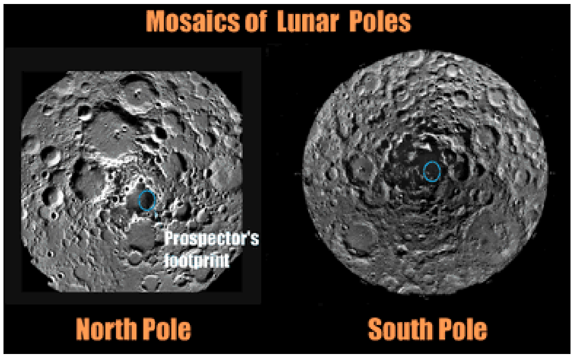

Figure 3: Water found on Moon by Lunar Prospector [2]

is reduced by a staggering 88%. Clearly, such refueling pit stops require a significant investment in space infrastructure, but amortized over the life of an extensive and sustained space exploration effort, the cost reduction would be significant.

WHERE TO FIND WATER & HOW TO GET THERE

Evidence of water has been found in a number of places throughout the solar system. Clementine and Lunar Prospector have shown that water exists at the North and South Poles of the Moon (*Figure 3*). Mars Odyssey pointed to significant water deposits on Mars (*Figure 4*). Galileo provided rather definitive proof of the presence of water on Europa. Spectral analysis of the tails of comets gives a strong indication that comets contain water. Scientists theorize that asteroids may also be a source of water.

Water is all over the solar system; as a civilization we can take advantage of the benefits it provides to human space travel.

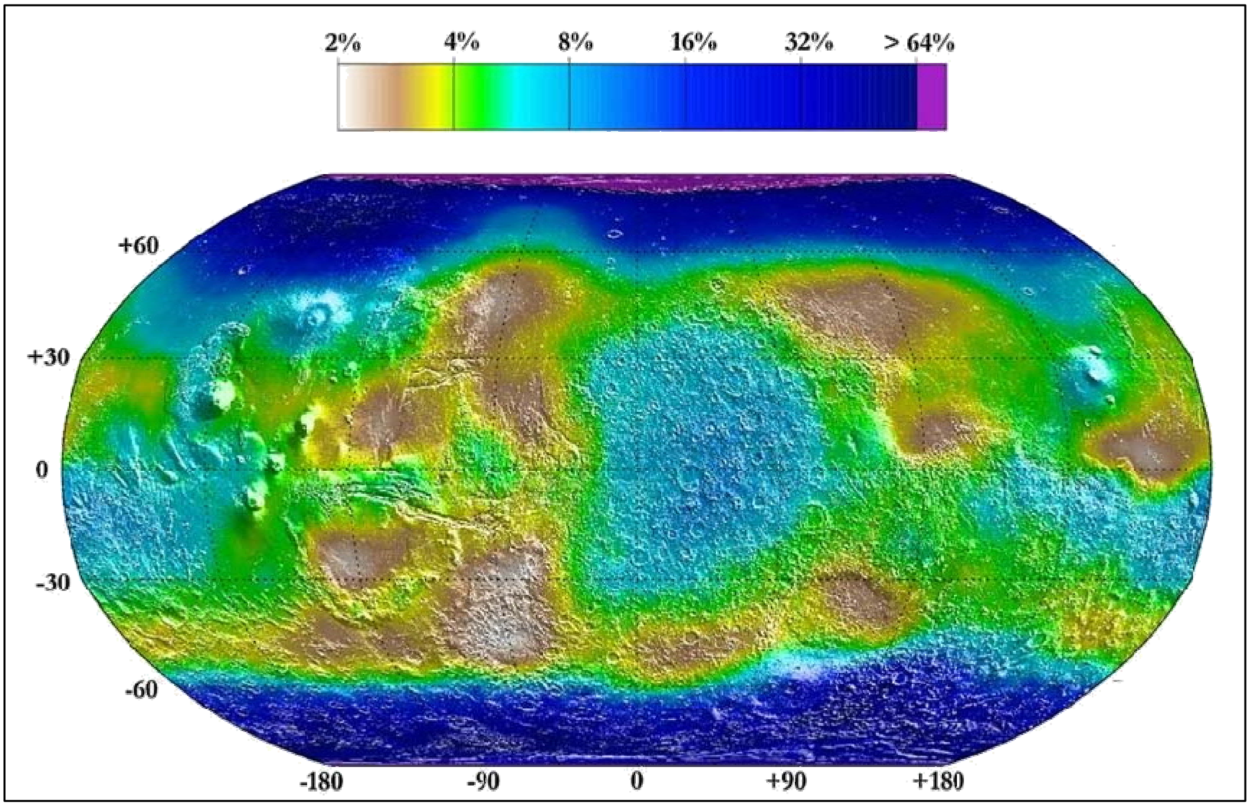

Figure 4: Mars Odyssey - Neutron Spectrometer. Lower-limit of water mass fraction on Mars [3]

As is shown in Figure 2, going places in space becomes significantly easier to do when the mass required to get there is reduced. A common measure of space travel capability is called the *delta V*. Delta V is the change in velocity required to movefrom one orbit to another. When traveling in space, going from one place to the next usually requires switching orbits multiple times. Low delta V requirements generally result in low mass requirements for a mission.

One delta V example is a mission to the Asteroid Belt from low Earth orbit (LEO). Without flybys, such a mission, if flown straight from LEO on the most conservative trajectory, would cost roughly 23.5 km/s in total delta V. For one space ship to manage that entire mission would require quite a bit of fuel to go along for the ride. If, however, the mission were launched from an orbit about our next-door neighbor, the Moon, mass requirements would be significantly reduced. With stopovers for refueling at Mars orbit on the way there and on the way back and with a refueling on arrival at the Asteroid Belt, the largest delta V required for any one leg of the journey would be roughly 6.75 km/s. As a comparison, the delta V required to launch from the Earth's surface to low Earth orbit is roughly 7.7 km/s. Taking advantage of fuel derived from water throughout the solar system is clearly beneficial to sustained exploration.

EXTRA-TERRESTRIAL WATER EXTRACTION

ETWE is designed to take advantage of predicted local atmospheric conditions in the form of a three-phase water sublimation, condensation, and separation scheme as outlined in *Figure 5*. Efficient water extraction favors an environment in which the ambient temperature and pressure are such that H_20 can transition from solid to

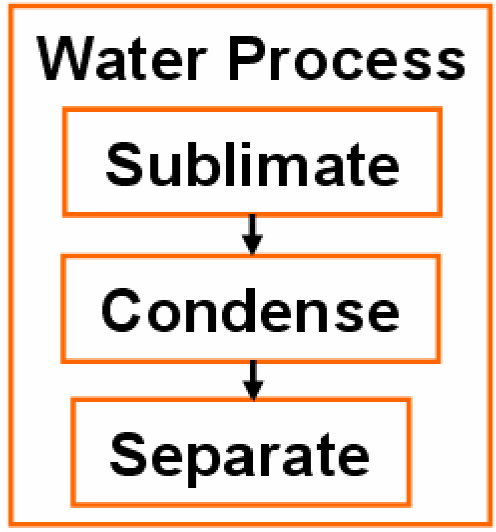

Figure 5. Water Process Basics

gaseous state with relatively little energy addition or subtraction (i.e. heat and pressure).

The sublimation process is illustrated by the H_20 phase diagram in *Figure 6*. A mined regolith sample is assumed to contain solid water molecules at the temperature and pressure conditions indicated by the red marker in the "solid water" region of *Figure 6*. Through heat addition and pressure reduction, water molecules will sublimate (the direct transition from solid state to

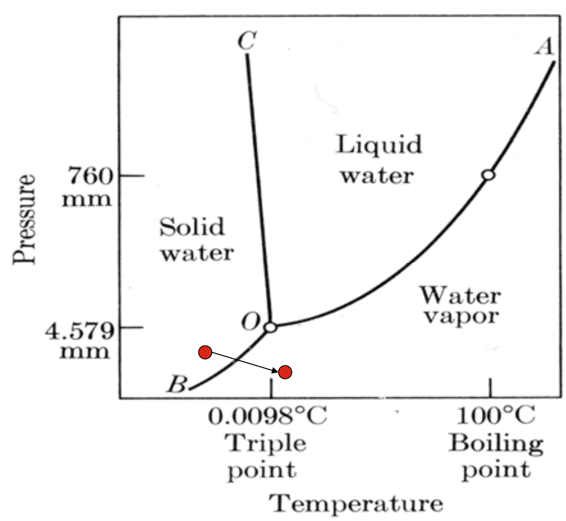

Figure 6. Water Process: Sublimation [4]

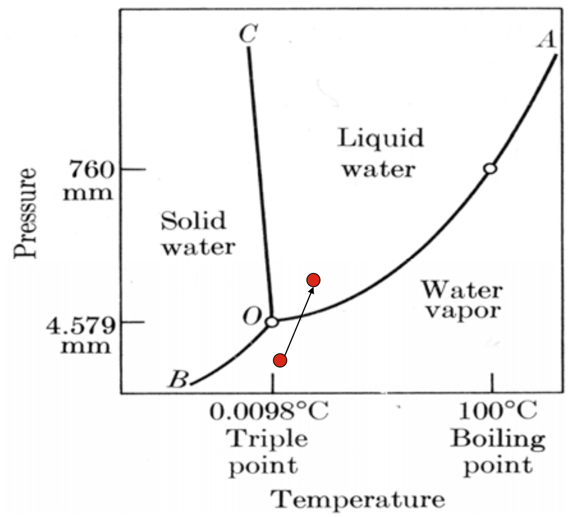

Figure 7. Water Process: Condensation [4]

gaseous state as seen in *Figure 6*) and begin to withdraw from the mined regolith. These gaseous water molecules can be drawn into a condensation chamber via a favorable pressure gradient between the condensation chamber and the sublimation chamber. At this point in the process, the water molecules have successfully been removed from the regolith sample.

Upon entry into the condensation chamber, the water molecules will be in the temperature and pressure region occupied by the red marker in the "water vapor" segment of *Figure 7*. Pressurization of the gaseous $H_2 0$ sample will cause the majority of the gaseous water molecules to condense into a

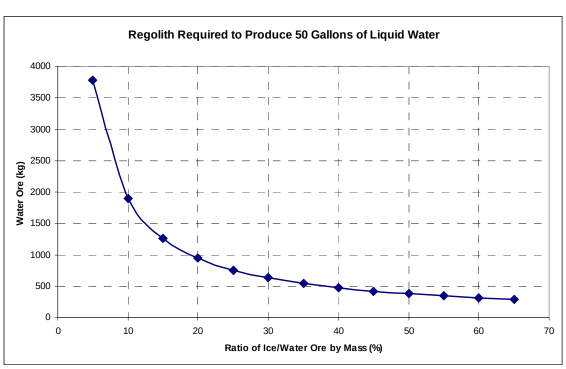

Figure 8: Regolith Requirements for 50 Gallons of Water

liquid state, as indicated by the arrow in *Figure 7*. Finally, other atmospheric gases drawn into the condensation chamber and the negligible amount of remaining water vapor are vented from the top of the chamber, leaving only the liquid water.

The amount of water ore required to produce a given amount of liquid water is dependant on the mass ratio of ice to ore for any particular sample. To give a brief illustration of this relationship, *Figure 8* displays the amount of water ore required to produce 50 gallons of water as a function of ice-to-water ore mass fraction.

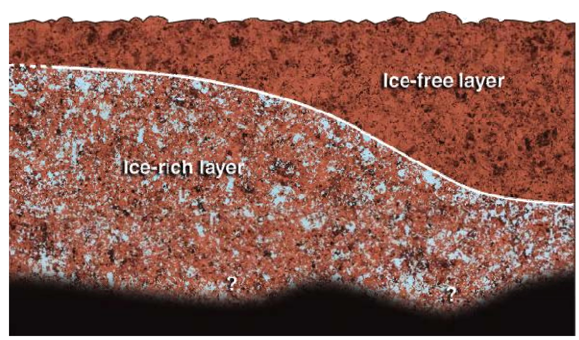

Figure 9: Hypothetical Martian Subsurface Regolith Structure [5]

TESTING FOR ETWE ON MARS

UT-ETWE, formerly MDMC, was initially focused solely on extraction of water from the Martian regolith. Data from Mars Odyssey's neutron spectrometer indicated high levels of hydrogen, presumably water, in the far northern and far southern latitudes of Mars, as is indicated in *Figure 4* by the blue swaths towards the top and bottom of the map. The neutron spectrometer was capable of detecting the presence of hydrogen at depths of up to three meters below the surface. Current theory is that an ice-rich layer of Mars regolith exists below, and is protected by, approximately a 10 cm desiccated regolith layer where no water exists at all [6]. *Figure 9* gives a basic idea of the Martian subsurface regolith structure.

Though UT-ETWE has widened its scope to include other sources of extraterrestrial water, it has continued forward with the development of a test procedure that calls for the processing of a simulated Martian ice/regolith water ore. The following is the test procedure that UT-ETWE has as its goal:

An outer vacuum chamber (*Figure 10*) will bring the test apparatus (*Figure 11*) down to `Martian atmospheric pressure. Inside the larger vacuum chamber, a smaller vacuum chamber containing a simulated Martian ice/regolith mixture (that has been cooled to at least -10ºC) will be positioned with a valve open to the outer chamber. Once the outer and inner chambers reach Martian atmospheric pressure, the inner chamber valve will close and a pneumatic multi-stroke piston will begin evacuating the remaining atmosphere. As the pressure is reduced and heat is added to the chamber, water vapor will sublimate out of the ice/regolith mixture. This water vapor and other gases present will pass through the multi-stroke pneumatic piston and collect in a vapor bag. After enough gas has filled the vapor bag, the external vacuum chamber will return to Earth-atmospheric conditions; this pressurization of the test apparatus replicates the condensation phase of the water process. As the vapor bag is returned to atmospheric conditions, water vapor will condense into liquid form. Separation of the water from whatever other gases may have entered the vapor bag can be accomplished by compressing the bag so as to reduce the volume over the water without expelling any liquid.

Figure 10. Vacuum Chamber

Figure 11. Extra-Terrestrial Water Extraction Test Apparatus

The test apparatus described in the preceding paragraph and shown in *Figure 11* consists primarily of the sublimation chamber, the piston assembly, and the vapor bag. *Figure 12* is an illustration of the basic process that the test procedure accomplishes. In *Part 1* of *Figure 12*, an ice/regolith composition is enclosed in the sublimation chamber with some amount atmosphere. The piston assembly begins its upstroke in *Part 2*. As the pressure is reduced in the sublimation chamber and the chamber is heated, water vapor begins to sublimate out of the ice/regolith mixture. Eventually, as shown in *Part 3*, the piston will have removed as much of the atmosphere and water vapor as it physically can. The piston then begins its compression stroke so that its contents are expelled into the vapor bag as indicated in *Part 4*. Once the piston has fully compressed and numerous cycles have been completed, most of the atmosphere and water vapor will have been evacuated into the vapor bag. In Part 5, the water in the vapor bag will condense to liquid when pressurized.

In order to develop a Mars regolith simulant, UT-ETWE assumed that Martian regolith is similar in nature to a medium clay and has a

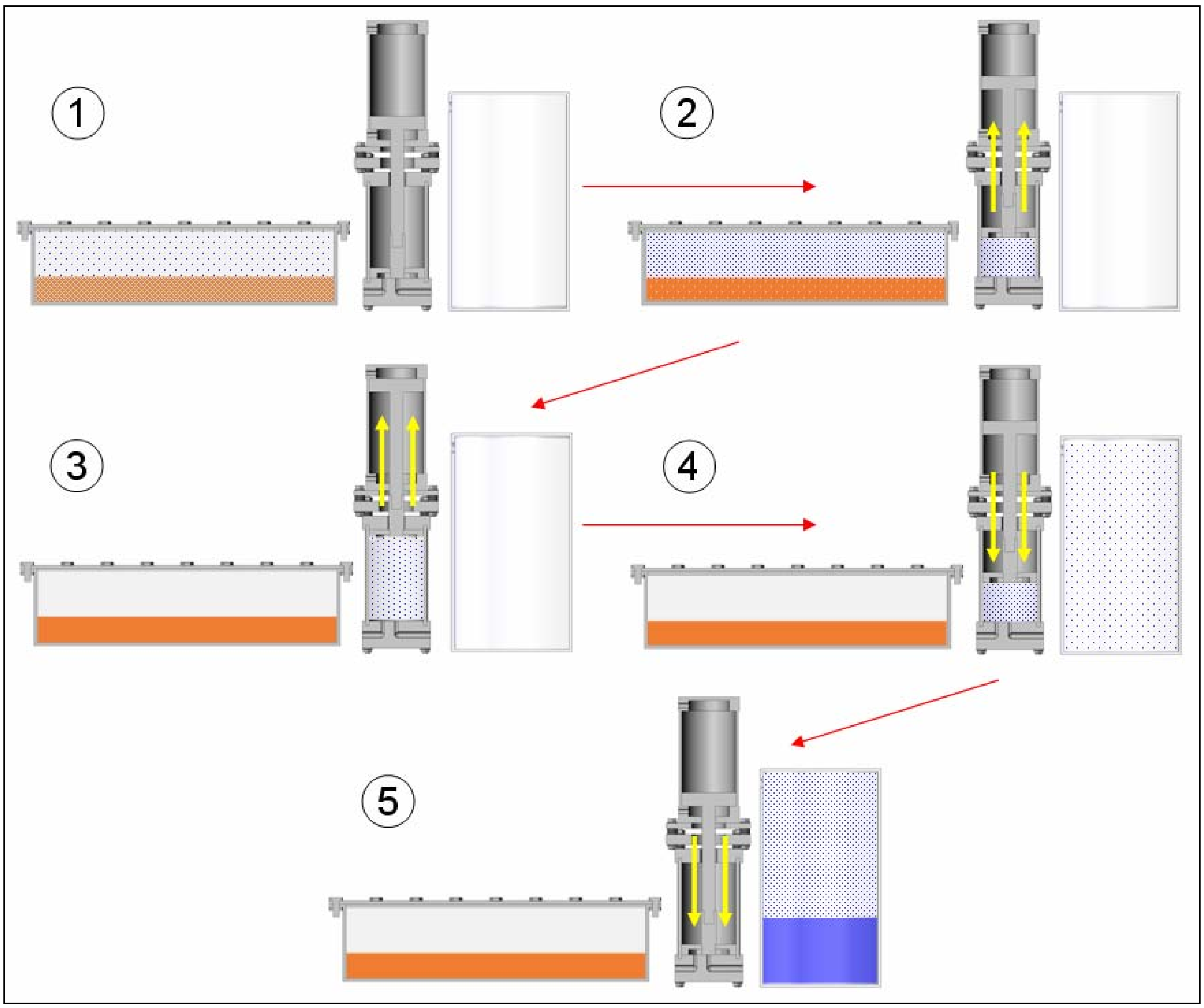

Figure 12. Extra-Terrestrial Water Extraction Flow Diagram

mid-range coefficient of cohesion (one of the defining characteristics of soils). Heavy clays are a result of recent water flows that, due to erosion, transported the clays from their original location. Though water flows may have been geologically recent, they were only recent enough to justify a medium clay approximation. Clay formation is related to gravitational force, which compresses the soil, and the microstructure attraction of clays to water. Mars's gravity is roughly 40% that of Earth's, so clays will be compressed to a lesser extent than they are on Earth. Without liquid water present, all clays become brittle. The reduced compression and brittle nature of the hypothesized clay are the basis for the assumption of a clay with a low coefficient of cohesion.

UT-ETWE decided to use a sandy clay for its simulant. Sandy-clays hold relatively tightly to liquid water but will sufficiently allow water ice to be sublimed out. A sample of sandy-clay with iron staining and some iron fragments was chosen and was baked in an oven to remove all liquid water.

Figure 13. Sublimation Chamber with Mars Regolith Simulant

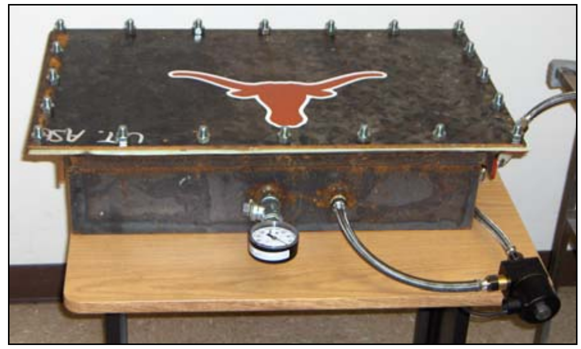

Figure 14. Sublimation Chamber

The regolith simulant can be seen in *Figure 13*. To achieve the proper ice mass fraction, the appropriate amount of crushed ice will be added to a known mass of regolith. Mixing the ice and simulant should be done carefully so as to not to cause the ice to melt.

ETWE TECHNOLOGY DEVELOPMENT

In order to realize UT-ETWE's testing goals, a number of items required fabrication, and quite a few more needed procurement. The sublimation chamber (*Figure 14*) and the piston housing and the compressed air hook-up components of the pneumatic piston assembly (*Figure 15*) were assembled by team members in the Aerospace Department's machine shop. Pressure gages, check valves, solenoid valves, flex lines, bushings, vapor bags, the pneumatic cylinder, and a number of other items all were purchased for the ETWE project.

UT-ETWE's test apparatus does not incorporate any groundbreaking technology; it is a simple application that relies on many off the shelf parts to accomplish its goal. From the one cubic meter steel sublimation chamber, a 12" flex hose connects to a solenoid valve that connects to 12" flex hose that connects to a check valve that connects to a 12" flex hose that connects to the inlet on the pneumatic piston assembly. The pneumatic cylinder that drives the piston

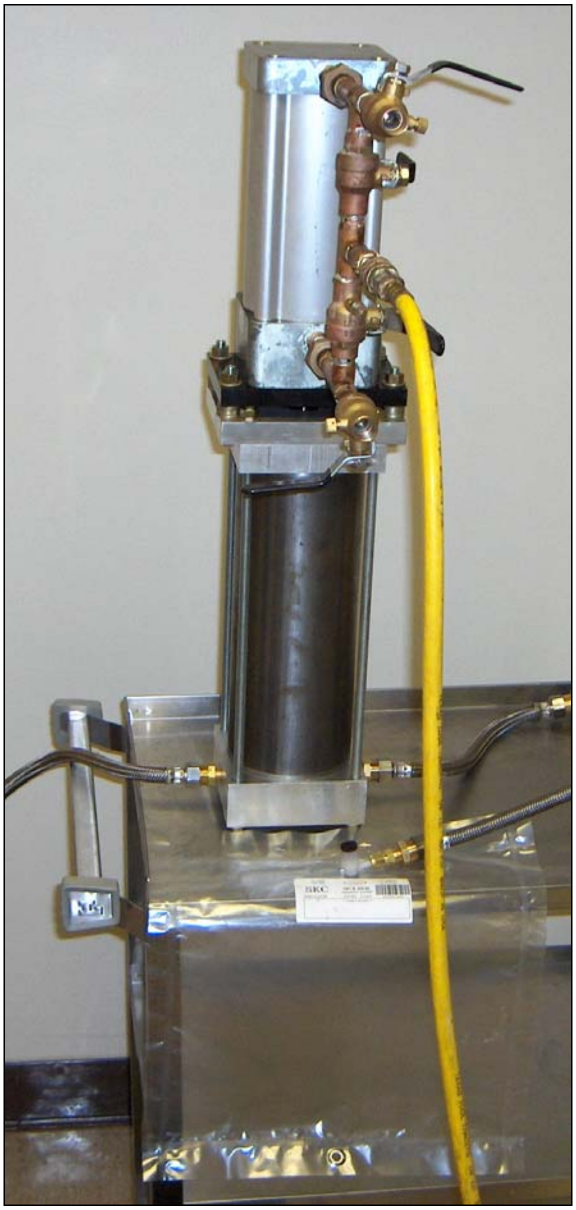

Figure 15. Pneumatic Piston Apparatus and Small Vapor Bag

assembly has a 4” bore and a 6” throw, and it is driven by a variable-pressure compressed air source. Currently the piston chamber is 4” in diameter and about 9” in length; plans call for reducing the chamber length to match the 6” throw of the cylinder. From the piston outlet, a 12” flex hose connects to a check valve that connects to a 12” flex hose that connects to a solenoid valve that connects to a 12” flex hose that connects to a 30 L vapor bag.

The two check valves serve to make sure that no matter what the piston is doing, the flow always moves from the sublimation chamber towards the vapor bag. Solenoid valves are in place so that during the testing process, when the outer vacuum chamber is being drawn down to Martian atmospheric pressure (approximately 6 millibars), the inside volumes of the test apparatus are also depressurized. These particular solenoid valves fail in the closed position (i.e. when powered off, they do not vent). During the draw down period of the test procedure, the solenoid valves are powered on/open. Once the test apparatus has been successfully depressurized, the solenoid valves are turned off/closed. Finally, the pressure gage on the sublimation chamber indicates gage pressure, and allows for a better understanding of the environment inside the sublimation chamber (multiple thermocouples are soon to be added to the inside of the chamber for accurate temperature readings).

ETWE TESTING PROGRESS

The UT-ETWE testing process has been at times successful and at other times disappointing. Having successfully assembled the sublimation chamber - pneumatic piston - vapor bag assembly, the team was thrilled when the pneumatic piston successfully moved air from an empty sublimation chamber to the vapor bag. Hopes were dashed, however, when the same type of leak issues that have plagued the operation of the outer vacuum chamber surfaced with the newly assembled test apparatus. Unless the test apparatus is airtight, the limited volume of the vapor bag will quickly fill with atmospheric gasses. Water vapor from inside the sublimation chamber barely has a chance to get into the vapor bag. Current remedies call for attaching a vacuum pump to pull down the sublimation chamber before starting the pneumatic piston. The leak concerns are relatively new, however, so this plan of action will not be completed until after this report has been submitted.

Problems with the vacuum chamber have been never ending. One of the two pumps the team has used is supposed to be capable of pulling a vacuum of 1 millitorr. Other than once drawing a vacuum of 8 torr (10.6 millibars; nearly Mars atmospheric pressure – 6 millibars), the pump has only been able to reduce pressure in the chamber to 100 torr (133 millibars). When the pump is piggy backed with a smaller pump (*Figure 16*), a pressure of 40 torr (53 millibars) has been achieved, which is still not enough. The team has stripped the vacuum chamber down, regreased it, inserted new O-rings, caulked chamber penetration points, and reworked part of the vacuum pump. Currently a pump repair kit is on order, so all the seals will soon be replaced, in case the pump is the main leak source. However, if this last attempt to solve the vacuum problem is not successful, the team will have to evaluate other options for testing. Other vacuum facilities exist on the UT Campus and in the Austin region; proper tests can and will be carried out.

Even if the vacuum chamber problems are not solved, once concerns with the test apparatus are sufficiently addressed, intermediate tests can be completed. Successful tests at room temperature and pressure with liquid water in the sublimation chamber and no Mars regolith simulant can at least show that the pneumatic piston is capable of moving water vapor from one location to the next. If the team is able to negotiate the use of another vacuum chamber, tests can continue with or without regolith simulant. Having successfully tested for water vapor transport, subsequent experiments can focus on only ice in the sublimation chamber at pressures below the triple point of water. To show that sublimation does indeed take place under the right conditions in the test apparatus, adding the regolith simulant will be the next and likely final step in proving the concept of extraterrestrial water extraction in feasible.

UT-ETWE has a significant amount of testing left to complete, but trouble shooting is most of what remains to be done. The testing apparatus is complete, so most of the team time can go into solving leak concerns.

Figure 16. Piggy-Backed Vacuum Pumps

ETWE PROJECTED COSTS AND TECHNICAL READINESS

NASA's Fiscal Year 2005 Budget, under Exploration Systems, calls for "$115 million in new funding for Technology Maturation to identify and develop the technologies and building blocks necessary in pursuit of the exploration vision, growing to $500 million by FY 2009," [7]. UT-ETWE believes that the extraterrestrial water extraction process can be validated and developed into flight ready hardware for very roughly $300,000 over the next three years. Of the approximately $1.5 billion that will be spent on Exploration Systems Technology Maturation from FY05 to FY09, this amounts to less than a drop in the bucket, not even one-tenth of one percent.

Under Space Science, the FY05 budget also sets aside "$691 million for Mars Exploration, 16 percent over FY04, and doubling by FY09 [to $1.268 billion] to support the exploration vision," [7]. NASA has scheduled four Mars Testbed missions for launch, one each, in the 2011, 2013-14, 2016, and 2018 launch windows. UT-ETWE, when it was MDMC, planned for its ESCAPE rover to fly in early 2014. The mission was to be a testbed mission for ETWE coupled with a secondary rover exploration expedition once the primary water extraction mission was completed. With creative budgeting for industry-style technology development instead of NASA-style technology development, the ESCAPE rover was priced at almost $50 million. The $50 million included the price of three prototypes and one deliverable which used two 300W RTGs, but did not account for the cost of launch of the 93" × 75" × 46", 1600 pound rover. Development and launch of the ESCAPE rover can easily fit into the NASA budgeting and planning scheme.

As ETWE does not only pertain to Mars exploration, also of importance is that NASA, under Space Science, has also budgeted "$70 million for Lunar Exploration, increasing to $420 million by FY09 to support annual missions with first by 2008," [7]. A mission similar to Mars ESCAPE could be planned for a trip to the Moon anytime from 2010 on, when the lunar testbed missions begin.

Currently, ETWE's technical readiness level (TRL) is firmly entrenched at the doorstep of TRL 3 (see *Figure 17*). Parts of the technology work according to design, but others still need to pass proof-of concept. Despite UT-ETWE's best efforts to move forward into TRL 4, the project is still stuck in TRL 3 limbo. Once some of the basic failings of the test apparatus have been solved, fully clearing TRL 3 should not be a problem. For UT-ETWE's testing process, passing TRL 4 will not be all that different from achieving TRL 3, as system integration of the test apparatus basically comes at the same time that proof of concept does.

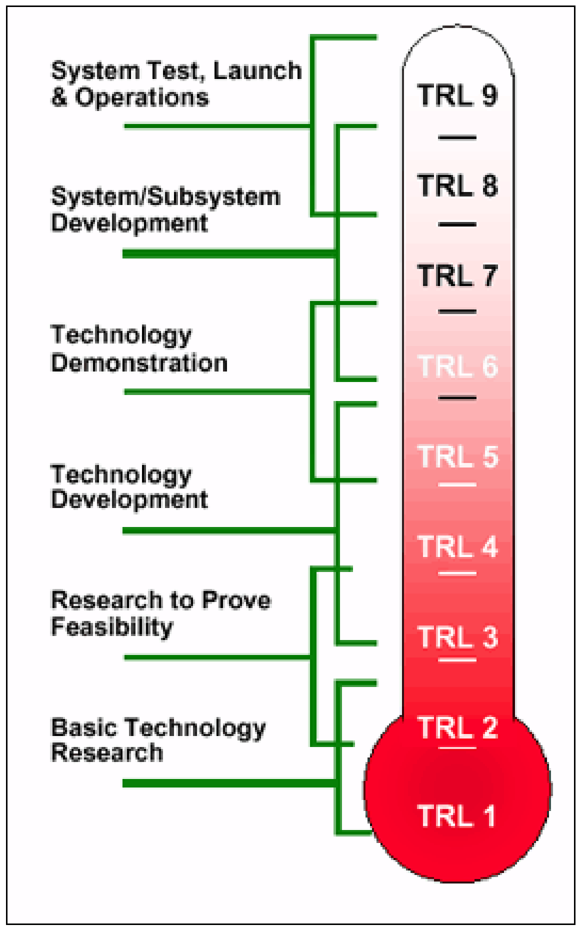

Figure 17. Technology Readiness Levels [8]

PROJECT OUTREACH

UT-ETWE has engaged in various public outreach efforts over the life of the ETWE project:

In March, the UT-ETWE team took part in the annual open-house held by the entire UT community. *Explore UT*, a weekend event, strives to bring the community to UT so that the students, staff, and faculty can show the general public all the school has to offer. Aerospace Engineering events are always a hit, particularly with kids, so the team had a good turnout to its ETWE demonstration. *Figure 18* and *Figure 19* are two pictures taken during *Explore UT*.

In April, the Aerospace Department at UT struck up a relationship with one of the local school districts, and the UT-ETWE team headed up the efforts to develop a permanent relationship. The Pflugerville Independent School District (ISD) has an aggressive design component to its elementary school art classes, so the presentation made to the fifth grade class of one of the thirteen elementary schools focused on the role art played in the UT-ETWE design process. Plans are in the works to follow up this outreach effort with trips to other elementary schools in the Pflugerville ISD.

Finally, the UT Public Affairs Department just recently conducted an interview with UT-ETWE team members for an article that is soon to be published on the school website. The article is to focus on other how Aerospace Department faculty use projects such as UT-ETWE to excite students about learning.

Figure 18. Jeff Jacob at Explore UT

Figure 19. Dave Weyburn at Explore UT

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