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Moon Water

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Abstract

Water was discovered on the Moon in October 2009 by the Chandrayaan-1 mission. That finding was verified by more advanced experiments in an attempt to ascertain the quantity and quality of the Moon's water. The conditions on the Moon such as no atmosphere and low temperatures, made the water in the form of ice. The origins of this water were determined to be meteorites and winds. The location of the water was determined to be affected by the diurnal cycle and cold traps in craters. The goals of this report were to estimate the amount of water ice present on the Moon, the location and to detail methods to obtain this water for human use. Research which analyzed and verified initial National Aeronautics and Space Administration (NASA) findings provided insight into the conditions conducive to the formation and maintenance of water ice. It was calculated that approximately 3.76×10^{12} grams of water ice is present within the cold traps of the permanently shadowed regions at the lunar poles. The quality of the water requires more experiments to be conducted through advancement of ovens and mass spectrometers. When the technological capabilities of satellites and rovers were analyzed it showed that the water will be useable by humans in the near future, with a lunar base being the best application for advancing space exploration.

Authorship Page

For clarification about the collaboration between the authors of this report, credit has been given to the primary author of each section listed below.

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Literature Review

The idea that there was water in some form on the Moon was not new when the Chandryaan-1 mission was sent. As early as 1962, it was speculated that water on the Moon existed [1]. At that time, even though there was no scientific evidence or proper technology to prove it, the belief was supported by theories that it would take billions of years for the possible ice in the permanently shadowed craters of the Moon to evaporate [2].

This idea of Moon water further motivated the discovery of probable ice on Mercury's North Pole in the early 1990's. The surface of Mercury was believed to be comparable to the surface of the Moon. Mercury was confirmed by the Arecibo Monostatic Radar as a region that gives a high radar reflection and was interpreted to be due to ice. Radar echoes taken from a satellite which observed one of Jupiter's largest Moons, Galilean, were compared to the radar echoes obtained from Mercury's poles. Due to the similar characteristics, it was interpreted that Mercury also had water ice present as Galilean was known to.

The 'Shackleton Crater', is an impact crater located in the South Pole of the Moon; it was believed to possibly have ice on its lower wall. This indication was made using the data of the Circular Polarization Ratios (CPR), which were taken by the Arecibo Monostatic Radar in 1992. CPR is the ratio of power, which is received in the same sense transmitted to the opposite sense. On a mirror like reflection the ratio would be zero; on a normal surface the CPR value would be less than a unit. Therefore, the CPR values obtained from a surface containing ice water would be greater than 1.

The Clementine space mission's analysis showed that approximately 10 km^2 of ice may be located at the Shackleton Crater [3]. It also showed that some of the areas in this crater might be under permanent sunlight for approximately 200 days, which would make it a possible location for human habitation. The frequency of sunlight meant that the detected ice would have to be in the lower walls deep within the crater. Yet, the new data of higher resolution obtained by the scientists [3], showed no difference in the CPR values obtained as the measurements go down the inner slope of the crater. The previously mentioned high CPR values, (values that are greater than 1), at the sunlit regions of the crater walls which were found in Shackleton, contradicted the initial understanding that a high CPR value would imply the presence of water ice.

The analysis of Clementine's bi-static radar observations was the first report which concluded the possibility of water ice at the lunar South Pole. This mission was sent in1994 and the mission's main purpose was to flight-qualify advanced light weight technologies that were developed by the Ballistic Missile Defense Organization. The Clementine mission was broken down into three phases: pre mapping, systematic mapping and post mapping. One of the goals was to obtain images of the polar region. The first set of complete images of the Moon's South Pole was obtained and showed approximately 15,500 km^2 of this region to have no sunlight. This fully shadowed area was suspected to have permanent ice deposits. The bistatic radar experiment showed the possibility of water ice at the South Pole [4].

However, Clementine's data consisted of low resolution radar images, and did not have sufficient coverage of the South Pole to obtain a better analysis of the relationships between the radar scattering properties, cold traps in permanently shadowed areas, and local terrain features. Also, CPR values obtained from a few small areas in the Sinus Iridum, a plain of basaltic lava on the Moon, showed similar CPR values as those from the Shackleton Crater. Because the Sinus Iridum is an area under sunlight, there is minimal chance that water ice is present in this crater. When compared to another crater, Schomberger G, it was seen that the obtained CPR values were similar to those from the Shackleton. Schomberger has sunlight during the lunar diurnal cycle, which was known not to be conducive to the retention of water ice. After experiments were conducted with a higher resolution compared to previous measurements, it was understood that a CPR value greater than 1 does not indicate that water ice is present beyond a reasonable doubt. A value greater than 1 could be from the rocks and other material that have scattered across the surface [5] [6]. The rocks and additional materials possibly contain proximal ejecta or have travelled down the slopes of craters.

New data was needed in order to answer the question of whether lunar water ice existed. Though a device that was able to reach a depth of 0.1 – 1 m into the lunar ice would have been ideal, none existed which could meet the power and mass requirements of the Chandrayaan-1 spacecraft. Use of advanced and lightweight Radio Frequency (RF) technology, NASA created a device that fit into the needed specifications. The Mini-Synthetic Aperture Radar (SAR) was designed to map the Moon's lunar poles. It gathered the scattering properties of the land in the permanently shadowed Polar Regions.

The debate on the presence of lunar water ice was due to insufficient evidence obtained from the CPR values of previous experiments. The Mini-SAR used hybrid polarization architecture to determine Stokes Parameters for the reflected signal. The architecture has the Mini-SAR's antenna transmits right circular polarization, but receives horizontal and vertical polarization components. These components were then used for reconstruction as Stokes Parameters. This parameter gave a description of the polarization state of an electromagnetic wave [7]. This helped distinguish volume scattering due to the presence of water ice from other surface features. Although there were speculations about the CPR value and the presence of ice, when searches on the lunar poles for water were conducted, locations that consisted of a high circular polarization were chosen. These areas are consistent with volume scattering from water ice which is buried at shallow depths. Other sensing data such as neutron spectroscopy will be used to provide a better understanding of the data and measurements that were obtained from the Mini-SAR. It was sent in October 2008 on India's Chandrayaan-1 spacecraft to the Moon [8].

Though other missions have suggested the possibility of water on the Moon so it was debatably a fact, it was the Chandrayaan-1 mission which proved the theory beyond a reasonable doubt. The mission was compromised by the failure of the satellite, which limited the continued findings by the "Moon Mineralogy Mapper" (M^3) group of Chandryaan-1. When it checked whether the Moon's surface could absorb wavelengths of 2.8 – 3.0 micrometers, the M^3 was limiting its measurement range to that of hydroxyls and water bearing materials [9]. Previously, measurements were taken for hydrogen; Chandrayaan-1 was the first mission to search specifically for water. Before the failure of the Indian satellite, readings from the M^3 showed that the lunar poles were positive for water absorption.

While the findings of Chandrayaan-1 were accepted, NASA was called on to further verify their findings. The first craft that attempted to verify the findings was the "Deep Impact" mission. The craft was designed to collect data from a passing meteor and was scheduled to do calibration for its instrumentations with the Moon. The sensitivity of the devices used in Deep Impact gave a much better quantitative analysis of the Moon and its available water. While the calibration of the device created some additional uncertainties, the Deep Impact satellite was able to view the entirety of the Moon over a year, which provided enough data for sufficient analysis. Not only was the Deep Impact satellite able to verify the findings of Chandrayaan-1, but it was also able to deduce a relationship between the water's location and temperature. This relationship was later used to help analyze what condition the water might be in on the Moon, which was named the diurnal cycle [10].

The other major mission that verified Chandrayaan-1's findings was the Lunar Crater Observation and Sensing Satellite (LCROSS) mission. LCROSS was designed to provide direct evidence of water ice in permanently shadowed craters. While the previous two missions were only able to scan the surface of the Moon, LCROSS was able to get some readings on the regolith composition underneath the top layer. It did so when a spent fuel rocket was crashed into the surface of the Moon in order to kick up the regolith below surface. The Lunar Reconnaissance Orbiter (LRO) which was the satellite in the LCROSS mission scanned the Moon from space similar to the previous missions. The important advancement from the LCROSS mission was that the LRO was able to quantify deeper layers of the Moon which had not been previously investigated for water ice. Unlike the other two missions, LCROSS visited the South Pole instead of the North Pole which was where Chandrayaan-1 found its ice water. The North and South Poles of the Moon have the same extremely cold environment, so the findings of one justified a possibility for similar results in the other. The LCROSS instruments had four instruments on board with the purpose of investigating water on the Moon. These instruments complemented each other in their investigation methods and the ranges over which they could be applied. The two most important devices were the near infrared spectrometer (NIR) and ultraviolet/visible spectrometers (UV/Vis) [11].

The instruments used in each mission all involved Radio Frequency (RF) spectrum analysis and thermal imaging. The RF measurements were more complete in the LCROSS experiment because multiple types of wavelengths were measured. It was the sophistication of the devices and the way in which they used the RF and thermal processes which eliminate the doubt from previous experiments' positive results for water. Because the ranges and processes the devices used overlapped, the findings were more valid. The crash of the spent fuel rocket created enough heat to cause the water to sublimate. The subliming effects of the crash were expected and used to create a new method for measurements. Since the LCROSS results were positive for the adsorption range of water in that state, the previous missions' findings for water in the form of ice were confirmed. The depth of water ice in regolith was hinted at during the LCROSS mission when the time for particles to settle was analyzed. The length of time for the settling to complete gives reason to believe that the water was distributed some depth into the regolith, most likely of several meters [12].

Before the most useful application of the water on the Moon could be determined, the quality of water available must be established. Logically, it can be assumed the water will contain the ions present in the lunar regolith composition. Prior studies from instruments on the Apollo and Lunar Prospector missions revealed the presence of mobile volatiles on or around the Moon, which progressed the understanding of the distribution of elements and the type of rocks on the lunar surface [13]. The Apollo missions brought back samples that became the basis of the lunar surface chemistry. The samples were shown in the Lunar Sourcebook: A User's Guide to the Moon [14]. In 1994, the Lunar Prospector spacecraft mapped the Moon's chemistry has been mapped since 1994 when the Lunar Prospector spacecraft orbited it [15]. When the density of the impact craters in the Maria, the regions which appear darker on the Moon, were measured and compared to the sites sampled by Apollo, the stratigraphy of the Maria was mapped in order to determine the composition.

The water ice trapped in the shadowed regions of the poles was discovered by the Clementine and Lunar Prospector missions [16][17]. Composition details of the polar deposits resulted from missions which used orbital radar imaging to determine the chemical composition of the deposits. The regolith composition was measured during the LCROSS mission from the resulting ejecta of the Centaur rocket crash with a series of instruments. The UV/VIS Spectrometer (VSP) captured emissions from the impact flash and ejecta. A large number of emission lines emerged within the first 0.8 seconds after impact. Many mission lines have not yet been identified, but possible species include CN, NH, NH_2, CO_2^+, and CS. From 1.1 to 3.1 seconds after impact, emission lines emerged indicating species, such as Na, Ag, H_2S, and H_20^+ [18]. The results showed a volatile rich regolith. Since the impact released a variety of volatiles other than water, these are possible sources of contamination.

With water found on the Moon, there are major questions about its origin. The main hypothesis involved solar winds and impacting meteors on the Moon. Without an atmosphere, these two processes affect the Moon much more than they do on Earth. Solar winds carry volatiles to the Moon, and meteors will deposit all the elements when crashing into the regolith. In addition to the lack of atmosphere, there are other reasons why these are the prominently believed sources of the water [13]. The state of the water along with its high mobility from temperature, and its location on the surface of the Moon play a key role as well. The solar wind and meteors bring volatiles to the Moon, but it is the temperature of the Moon which keeps them in the regolith. The craters at the North and South Poles trap volatiles inside of them because their temperature range is a mere few hundred Kelvin.

Because solar winds and meteor crashes will always occur on the Moon, the source of water is not finite. It was possible to investigate how frequently solar winds affect the Moon and deposit volatiles, and relation of these parameter with others aspects of the Moon created a clearer picture of the water source limitations. The rate at which water comes to the Moon through solar winds versus how much is currently there versus how much water a lunar outpost would require was investigated. The purpose was to find out if the amount of water already on the Moon at the rate which is arriving, is significantly lower than that required to sustain human life or if human inhabitation of the Moon was possible. The Moon's water is in the form of ice dust. This meant it was integrated with the rest of the Moon's chemicals. Also, the water is very dependent on the temperature in the region and is very easy to disperse. Any impact, as seen with the LCROSS mission, causes a majority of water to sublime and sends it like ballistic to other locations on the Moon [12]. Because of this, any meteorite impact or landing on the Moon has the potential to redistribute the water ice. The craters in the North and South Pole store dispersed water ice, but collection of the water would be difficult due to its form.

There was a need to detail the location of the water ice more to a more specific area than the general Polar Regions. It is in the permanently shadowed regions (PSRs) within the poles that retain water. The poles spend half of the time in darkness, but even when there is light available the craters are still minimally affected. With little temperature fluctuation, the ice does not typically leave these regions easily, so they are effectively trapped. To prepare for a crash into the Moon, the LCROSS mission had analyzed various craters in the South Pole and selected the one which was most likely to contain the most amount of water [12]. Pre-selection of a site provides a greater likelihood of water had the potential to skew data concerned with the average amount of water in a crater. Consideration of the Deep Impact results helped to compensate for this possible issue. The diurnal water cycle on the Moon, observed by Deep Impact, showed that an increased amount of water in one area is caused by the ice of another region's movement due to temperature [10].

The continued advancement of the devices used to investigate the lunar water has eliminated any doubt of its existence. With this known, it is possible to speculate about the potential uses of the water and what is required to harvest it.

Methodology

The goal of this project was to gain an understanding of what recent findings about water on the Moon meant for the future of humanity in space and to make recommendations that would maximize the findings' effects as well as to make an estimation on the quantity of water that is available. This required an in-depth assessment of key characteristics that must be satisfied in order for this water to be of use to humans. The assessment provided insight into the extent that current research supports the water findings, the processes which enable the use of these findings, the geography of the craters, events that bring water on the Moon, and the likelihood of engineering advancements created to fully take advantage of the Moon's newest known resource. To achieve this, the in-depth analysis included the following areas:

- Identifying the measurement methods, sensitivity, experiment duration, and device biases of the instruments used in the missions for Moon water discovery
- Estimating the amount of water, including the frequency of water addition
- Water quality analysis through inspection of chemicals and ice characteristics
- Identifying the main characteristics of a preferred site for water harvesting. These categories included data concerned with terrain type, latitude of the location, the likelihood of having a significant amount of water, etc.
- Looking into any advancements made/required to take advantage of Moon water
- Water filtration methods
- Assessing the possibility of a lunar base with respect to the water discovered on the Moon

Instrument Comparison

The literature review provided knowledge concerning the most important techniques for the verification of water on the Moon. Various characteristics of the instrumentation used were investigated through literature review. The measurement methods, device sensitivity and experiment duration affect how reliable the collected data was. By comparing the instrument findings, similarities in the results which the instruments obtained were found. Important areas focused on were the ranges of the instrumentation used, impacts created on the Moon and sensor overlapping. Quantifying these results provided a higher data reliability with respect to each successive mission.

Estimating the Amount of Water on the Moon

Before looking into the possible applications of the Moon water, the quantity should be known. Several NASA documentations were looked into but only estimates of the amount of water were stated. Since there were no published calculations found to verify these estimates, the team looked into various articles to make an estimate based on interpretation of available information and data in the literature. By using this value, the team was able to apply this information into the possible Moon water applications.

With the findings of water on the Moon, scientists have stated that the roots for the presence of this water are from comets, solar wind and other sources. In order to suggest the long term availability of this water, the frequency of the events that add water to the Moon should be known. Several research articles were investigated which provided insight to the different equations and calculations that had been previously conducted. With that information, the calculations were redone using the engineering calculation software MathCAD in order to analyze whether similar results can be obtained. These results provided a view for the behavior of this water ice based on effects such as comets and sublimation. This data was then used in comparison with any recent data that states how much water the scientists expect to be on the Moon.

To advance and verify the statistics developed, an exploration of Moon features was completed with Google Earth Pro. This program allows the user to look over the Moon and search for craters and other features of interest. The ability to use a latitude and longitude grid, land marker locaters, area calculation, elevation determination, and distance calculation allows a very in depth analysis of the Moon. No other source found provides a civilian the ability to investigate the Moon’s feature in such a firsthand manner. The ability to see shadows in a crater while aware of its latitude along with the elevation of the shadow compared to the surrounding terrain gives good insight into potential PSRs. These capabilities combined allow a verification of theories concerning PSR location and amount. The criteria for a crater to be considered to have a good permanently shadowed region were for the elevation of the shadow to be lower than

800 km. Based on previously reviewed literature, areas which had shadows, a low elevation, and were near walls which had a much higher elevation for them to protect the area even better from light and other elements were considered to be the most likely to have the potential to truly be permanently shadowed. The results are broken into the North and South Pole and latitude to allow the highest degree of comparison between potential water harvesting sites and water estimates. The Google Earth Pro area calculating feature took into account the elevation of the included area and therefore the values it produced are highly accurate.

Water State Analysis

In order to determine the proper methods for lunar water collection, filtration, and possible applications, the water condition must be analyzed. This included whether the water contains other chemicals from the regolith, the effect of temperature on contaminant binding, and the state of the water.

The first step to determining the water quality was to compare literature from the missions that led to water discovery. The instruments that were used in the missions, which resulted in data that indicated the presence of volatiles on the Moon, were focused on. The article, The Lunar Crater Observation and Sensing Satellite (LCROSS) Cratering Experiment [12], was concentrated on because its mission method resulted in the most detailed information for regolith composition. Another approach to gather information about general Moon composition was to investigate the compositions of synthetic lunar soil used in various scientific experiments and competitions.

Due to the extreme temperatures on the Moon, especially at sites where the lunar water is commonly found, general research was completed concerning chemical bonding at the expected temperatures. The Moon water cycle, which is temperature dependent, was analyzed for information relating to the state of the water. The Deep Impact satellite was able to deduce a relationship between the water’s location and temperature; therefore, literature on this satellite was focused on in order to determine the potential water conditions. Experts familiar with the lunar water cycle were contacted to clarify information and make suggestions for the effect of neighboring chemicals on the ice water.

Site Selection for Water Harvesting

To discuss site selection for water harvesting, standards which identified the optimal locations of the water were created. The data of the previously mentioned missions was used for the basis of this selection. Literature review was used to recognize trends in areas associated with higher levels of lunar water. Terrains found to be typical of high levels of water ice are further researched to find qualities which may make water harvesting easier than other locations. Obtaining information describing the types of terrains in conjunction with their latitude has proved difficult; therefore, educated assumptions were made when applicable. Topographic maps created which detailed the lunar Arctic regions were analyzed. Because some terrains are more or less likely to maintain a consistent level of ice water throughout the day, as seen from previous literature reviews, information about the effect of the lunar water cycle on the specific terrain was considered. For easy comparison between likely sites, a chart was compiled with these parameters in order for the optimum sites to be selected.

Advancements for Water Collection from Regolith

Separation of the water ice from the regolith is required for human use. Literature review was completed to find the current methods for lunar sample collection. Another important investigated was scientific research and experimentation for advancements in regolith collection. Since information specifically for the Moon is scarce, Mars was used as an analogue due to their similar terrains along with the fact that Mars had recently confirmed to have ice water [19]. The level of difficulty in finding information pertaining to regolith collection and potential advancements reflects the scientific community's interest in making regolith collection a reality. Ease in finding relative information was interpreted as a high amount of interest while great difficulty will show little scientific interest and a feeling of low importance. Competitions that deal with lunar rovers, regolith navigation capabilities, regolith collection, and ice water finding capabilities were used to measure interest in regolith collection along with gaining an understanding on how realistic the required advancements are.

Water Filtration

Once the information on the quality of water was gathered, different filtration techniques were compared to see which method would be paramount for filtering water from the Moon. Conditions of the Moon would have been taken into consideration when a method was picked. Any alterations that are required for current filtration methods due to the state of the water or to the chemicals that are present would have been significant factors in the analysis. Unfortunately, extremely limited information was found for water filtration from the regolith. However, experiments conducted by use of microwave systems under controlled conditions were looked into as an option for possible water extraction from regolith. Once the water is extracted, it can be closely analyzed to determine what filtration method would give optimum results.

Water Maintenance for Human Use

Making a determination concerning whether the Moon water can be used for a lunar base in an efficient manner required a comprehensive understanding of the frequency of events which add water to the Moon, current Moon water estimates, estimates of useable water, and the amount of water required for a lunar base crew of a given size. Each of those areas has slightly different methodologies for a proper discussion and analysis.

Once the quantity was roughly known (as the actual amount will contain a certain percentage of errors), the team looked into whether the amount of water is sufficient enough to implement a lunar base. The factors such as: reuse/recycling of water and how much water is needed for a crew member will be taken into consideration to check the practicality of the team's suggestion for a lunar base. Different data was compared and a final result was stated based on the analysis.

An obvious factor to lunar base maintainability is the amount of water on the Moon and the amount that can be used. The quantity of water which can be used is highly dependent on the results obtained from other sections of this report. The Moon terrain, advancement in water collection from regolith, and filtration capabilities are the largest effects on the human use of Moon water. Based on separate literature reviews and the results of the previously mentioned sections, an estimate was made about the amount of usable water.

Use of reports detailing NASA workshops focused on lunar base requirements and more recent works concerning this topic were used to understand the amount of water required per person in space, agriculture, experimentation, and life support machines of a lunar base. The NASA workshop reports, NASA shuttle water recycling information, International Space Station (ISS) water recycling information, and relevant but general biosphere information was used to create an expected range of water losses for the water recycling process.

Results and Discussion

Interactions on the Moon Which Cause Water Ice

Understanding the features of the Moon, especially its interactions with water bearing elements in space and the lunar geography which caused the collection of water ice, was required to know how to calculate the amount of water ice. The first concern was what initially created the water on the Moon. The four types of sources that may have contributed to the Moon water are: solar wind effects, comet impacts, meteoroids that contain water, and degassing of the interior. The latter is stated to be the least certain of all four; therefore the three main factors are taken into consideration for calculating the potential amount of water ice that may be available [20]. The second concern was to examine what about the Moon retained the water ice. Knowledge of these two components provided the basis for all subsequent aspects of lunar water ice, including the amount, location, justification for initial investigations, parameters for further investigations, and uses of the water ice.

Solar winds are electrically charged particles that are emitted by the sun into space. Since there is a magnetic field that protects the surface from solar winds, they do not reach Earth. Research showed that it was unlikely that the water on the Moon was significantly from solar wind particles, since they do not contain or carry water ions. Data from the Lunar Prospector Neutron Spectrometer showed traces of hydrogen in the North and South Pole of the Moon. Hydrogen may react with oxygen on the Moon and in the regolith to form hydroxides or interact with other hydrogen atoms to form hydrogen gas. The form of the hydrogen molecules cannot be detected from this data. A simulation of the motion of particles in space was created in order to calculate the amount and the composition of hydrogen that reaches the cold traps on the Moon via solar winds [21]. The time it took for this hydrogen to be supplied by solar winds was 7 million years. For the particles to make it into cold traps, the required time is 100 million years. The key points and results of this experiment were considered for the analysis of the effects of solar winds on the Moon in the subsequent sections. The simulation, which detailed the interaction of solar wind particles and cold traps, was made from several assumptions. One was that the regolith is in an equilibrium state. The model started with an incident proton that comes in contact with the lunar surface. The solar wind proton was neutralized upon contact and was followed by backscattering. The amounts of incident protons that remained were implemented into the regolith [21]. The total delivery rate of hydrogen to the lunar poles is summarized in the Table 1 below.

Table 1: Delivery Rate of Hydrogen from Solar Wind Summary [21]

H/H^+	2.3%
H_2/H^+	21.7%
OH/H^+	66.7%
H_2O/H^+	6.8%

Table 1 showed that the largest delivery rate is for hydroxide from hydrogen ions. Based on how the results in Table 1 were obtained, the values were considered to be valid. However, in more recent laboratory experiments it was concluded that there was no evidence which showed a possibility for the solar winds to combine its hydrogen with the oxygen within the regolith; therefore, no considerable amounts of hydroxide or water ions [22]. Although solar wind has not greatly contributed to the amount of water ice accumulated, it still plays a role in distributing the compounds over the lunar surface. When these compounds get trapped in cold traps, they will be preserved [23].

Though it was shown by the lunar water cycle that all parts of the Moon had water ice at some point in the day [10], higher concentrations of water ice are found in the permanently shadowed regions of craters in the North and South Pole. These regions act as cold traps due to their low temperatures, with highs averaging only up to 100 K due to protection from sunlight. Radar readings initially taken by the Clementine mission and recently by Chandryaan-1 showed that these regions produced signatures conducive to water ice [24]. When the features of the Moon's geography were investigated it was possible to make a more accurate estimate for the amount of water on the Moon. Assumptions were made and the increased details associated with the geography were factored into calculations; this led to more realistic results.

When the events on the Moon were simulated and results of other researchers were verified, most calculations for water ice focused on latitudes of 60 degrees north and/or south and continued to 90 degrees. A preliminary list of craters between 70 degrees and 90 degrees, with their basic features, was created from a NASA list of all named lunar craters [25]. This can be seen in Table 2 below.

Table 2: Craters above 70 Degrees Latitude in the Arctic Regions [25]

Name of Crater	Latitude	Diameter (km)
Anaxagoras	73.4N	50
Amundsen	84.3S	101
Anaximenes	72.5N	80
Antoniadi	69.7S	143
Barrow	71.3N	92
Boltzmann	74.9S	76
Boussingault	70.2S	142
Brashear	73.8S	55
Brianchon	75.0N	134
Byrd	85.3N	93
Cabeus	84.9S	98
Carpenter	69.4N	59
Casatus	72.8S	108
Challis	79.5N	55
Cusanus	72.0N	63
De-Forest	77.3S	57
De-Sitter	80.1N	64
Demonax	77.9S	128
Desargues	70.2N	85
Doerfel	69.1S	68
Drygalski	79.3S	149
Euctemon	76.4N	62
Faustini	87.3S	39
Froelich	80.3N	58
Ganswindt	79.6S	74
Gioja	83.3N	41
Goldschmidt	73.2N	113
Hale	74.2S	83
Hedervari	81.8S	69
Hermite	86.0N	104
Heymans	75.3N	50
Hippocrates	70.7N	60
Idel'son	81.5S	60
Klaproth	69.8S	119
Le-Gentil	74.6S	128
Lindblad	70.4N	66
Main	80.8N	46
Malapert	84.9S	69
Merrill	75.2N	57
Meton	73.6N	130
Mezentsev	72.1N	89
		(continued)

Name of Crater	Latitude	Diameter (km)
Milankovivc	77.2N	101
Moretus	70.6S	111
Mouchez	78.3N	81
Nansen	80.9N	104
Neumayer	71.1S	76
Newton	76.7S	78
Niepce	72.7N	57
Nobile	85.2S	73
Numerov	70.7S	113
Pascal	74.6N	115
Peary	88.6N	73
Petermann	74.2N	73
Philolaus	72.1N	70
Plaskett	82.1N	109
Poinsot	79.5N	68
Poncelet	75.8N	69
Ricco	75.6N	65
Rittenhouse	74.5S	26
Roberts	71.1N	89
Rozhdestvenskiy	85.2N	177
Schomberger	76.7S	85
Schrodinger	75.0S	312
Schwarzschild	70.1N	212
Scoresby	77.7N	55
Scott	82.1S	103
Seares	73.5N	110
Shackleton	89.9S	19
Shi Shen	76.0N	43
Short	74.6S	70
Simpelius	73.0S	70
Sylvester	82.7N	58
Thiessen	75.4N	66
Wexler	69.1S	51
Wiechert	84.5S	41
Wilson	69.2S	69
Zeeman	75.2S	190

Table 2 showed there was a total crater area of 26,296 m^2 in the North Pole and 312,689 m^2 in the South Pole. Investigation of additional features of the craters in the table, such as the shadows in their interior and topology were included into calculations because of direct relationship to the amount and location of water ice, as seen in the "Water Ice Implantation Calculation" Section.

One of the most important findings showed that there was no crater between 80 degrees and 85 degrees south that did not have some area with significant features for a likely permanently shadowed region. This was found when Google Earth Pro was used to investigate the Moon [26]. With this fact known, it was deemed highly unlikely that an area which received less sunlight than the 85 degree south line would not have a greater number of PSRs than the areas below it. Unfortunately, the resolution of images for latitudes greater than 85 degrees south was too poor to make first hand comments.

Topography charts of the North and South Poles [27][28] were used to comment on the soil and elevation of craters. This information helped explain the instrument reliability based on performance and results. It also helped confirm theories about the North and South Pole having features conducive to water ice retention. A variety of soils and geologic features were found for the Arctic regions, but more importantly detailed information for within the craters was available as well. The mixed terrain and soil types of the poles were reasonable when the interactions of cold traps and the lunar water cycle were considered. Because of the water cycle, cold traps have a variety of soil types since materials from all over the Moon have the potential to come to rest in them. This theory was verified when the topography and geology of the poles were examined. The following tables detail the conditions of the crater regolith, separated by the South and North Pole. Table 3 and Table 4 were used in conjunction to understand the topography of the South Pole. Table 5 and Table 6 were used together to detail the topography of the North Pole.

Table 3: South Pole Topography Distribution [28]

Crater	Approximate Latitude	Color Code Noted
Cabeus	85	White - No photo coverage
Unnamed, most likely to be Shackleton and other adjacent craters	90 degree	light green – Ec
Malapart	85	pNbm
Amundsen	82	Very center - Nc; Inner region - Ip; outter Majority – Nc
Wiechert	85	Entire is Ec
Nobile		Center (majority) - Nc; Edge - pNc; closest to Amundsen – Nc
Hederavi		Majority - pNc; small part near Amundsen - Nc; semi secondary crater – Nc
Scott	81	Majority - pNc; small edge secondary crater - Ic2
Idelson	81	majority - Nbl, wall closest to pole - Nc
Ganswindt	79	majority - Nbl, walls furthest to pole - Nc
Nefed'ev	81	Majoirty - Nc; small - pNb; possibly Nbl
Kocher		all - Ic2
Ashbrook		mostly pNbr, some pNbm
Drygalski	80	most of floor - Ip; majority - pNc; cut by slice of - Esc; one secondary crater furthest from pole - Ioc; secondary crater on wall closest to pole - Ic2
Other	greater than 80	large area with no photo coverage; majority of area - pNbr; quarter of area - Nbl; 5 - 7 slivers - pNbm; some - Ip, Nbc, Ic2, some Nc
Le Gentil	75	Majority - Esc; a third – Nbl
Boltzmann		Totally - pNc; speck – Esc
Zeeman	75	center speck - Nc; off center speck - Nbc; most of center floor - Ntp; majority of walls - Nc; two craters high on walls furthest from pole - Ic2; secondary crater furthest from pole on side of wall - Ic1; sliver on wall closest to pole - Nbc
De Forest	78	Completely - Ic2
Numerov	71	4/5 - Ic2, wall (1/5) – Isc
Antoniadi	69.8	small center - Ic2; surrounding floor - Elm; outter rim and walls - Ic2
Schrodinger		floor pocket - Id; surrounding pocket still on floor - Ip; bottom of walls furthest from pole - Ntp; further up walls - Nbm; pockets on walls - Nbh, Ip; top of walls – Nb
Rittenhouse		exclusively – Ec
Hale	72	exclusively - Ic2
		(continued)

Crater	Approximate Latitude	Color Code Noted
Neumayer	71	center - Ntp; walls and edge - Nc
Demonax		floor - Ntp; wall close to amundsen small area - Ic2; from rocky center to walls - Nc
Boussingault	70	center floor - Ntp; surrounding walls - Nc, outer secondary crater - Ic2
Bouguslawsky		small floor - Ntp; wall pocket closest to Boussingault - Ec; walls and other - pNc
Schomberger	75	center/ majority - Ic2; outer medium area - Cc; surrounding – Isc
Simpelius		pnC
moretus	70	Ec
Short		majority/floor - Esc; closest to pole - pNc; furthest from pole – Ec
Newton		Nc
Casatus		Majority - Ioho; Near second crater and around - Ip; Wall closest to pole and Moretus - pNc
Klaproth		Majority - Ip; some - Ioho, Ioc, pNc
Doerfel		Ic2

Table 4: South Pole Topography Code Details [28]

Abbreviation	Topology Description
Ec	material of primary impact craters and their secondary craters, eratosthenian system, craterial material younger than most mare material - similar to unit Cc but less sharp and bright, queried where could be unit Ic2
pNbm	Basin material, prenectarian, basin massif material - large mountainous landforms commonly lying along arcs, gradiational with generally finer topography of unit pNbr - strongly uplifted parts of basin rims and inner rings
Nc	primary impact crater, nectarian system, crater material younger than nectaris basin but older than imbrium basin - few rim or interior textures visible expect in largest craters, queried where could be units pNc or Nbe
Ip	probable basin related materials, imbrian system, plains material - light colored, smooth, mostly flat surfaced deposits having superposition relations and crater densities indicating Imbrian age, so primary and secondary ejecta of Orientale and Imbrium basin and of craters
pNc	primary contact crater, prenectarian, crater material older than nectaris basin - rim relief normally the only feature visible except in largest craters, quiried where could be unit Nc
	(continued)

Abbreviation	Topology Description
Ic2	material of primary impact crater, imbrian system, upper imbrian crater material - younger than Orientale basin and part or all of unit Im1, older than parts of unit Im2, small craters lack fine textures, large craters have numerous small superposed craters, queried where could be units Ec, Ic1 or Ioc
Nbl	basin materials, nectarian system, basin material, lineated - lineated or otherwise textured material on basin flank, basin deposits corresponding to Hevelius formation of Orientale basin
pNb	basin material, pre-nectarian, basin material, undivided - rim, wall, and inner-ring materials, same as for corresponding features of Nectarian basins
pnbm	Basin material, prenectarian, basin massif material - large mountainous landforms commonly lying along arcs, gradiational with generally finer topography of unit
pNbr	strongly uplifted parts of basin rims and inner rings; basin materials, pre-nectarian, basin material, rugged - forms diverse rugged, mostly elevated terrain, intermediate between unit pNbm and generally less rugged, lower unit pNt, parts of South Pole-Aitken and Australe basins including main topographic rims, inner rings or other interior materials, and possible South pole-aitken ejecta near craters Clavius, Moretus, and Boussingault
Esc	secondary impact crater, eratosthenian system, secondary crater material;
Ioc	secondary impact crater/basin material, imbrian system, materials of orientale-basin satellitic craters - grouped in clusters and chains peripheral to Orientale basin and in some outlying areas, secondary impact craters of Orientale basin, quiried where could be primary craters;
Nbc	secondary impact crater, Nectarian System, material of Nectarian-basin satellitic craters - grouped clusters, chains, and groovelike chains mostly peripheral and approximately radial to Nectaris and other Nectarian basins, also includes more distant radially oriented groups, secondary impact craters of basin to which groups are radial or peripheral, origin of Humorum basin-radial groups at lat 56 degree to 64 degree S, long 0 to 30 E, and or quiried groups doubtful
Ntp	probable basin-related materials, nectarian system, terra-mantling and plains material - light colored, wavy, rolling, or planar surfaces more heavily cratered than unit Ip, primary and secondary ejecta of Nectarian basins and large craters equivalent to units Iohn, Ioho, and Ip, lacking their distinctive textures because of degradation by cratering or other aging processes
Ic1	primary impact crater, imbrian system, lower imbrian crater material - younger than imbrium basin but older than Orientale basin, morphologically subdued, commonly difficuly to distinguish from units Ic2 and Nc

The age of the soil is detailed as new (meaning the most recently formed), young (which was slightly older), and old. The terrains and soils of greatest interest were those which are “newer” than their surroundings and/or have plain like or basin qualities. Soils which were described as younger than adjacent soils inside of the craters were taken to represent cold traps even if the description from Table 4 does not describe it as an entirely “new” soil. Since cold traps continually gain new materials due to their extremely low temperatures, new and younger soil were of interest. “Ec” is of the greatest interest because it was described as “younger than most mare material.” From Table 3, craters with this quality were: the entire area directly at 90 degrees South, Wiechert, Rittenhouse, Bouguslawsky, Moretus, and Short. “Ip” indicated flat surfaced and mixed materials, features which craters Amundsen, Drygalski, Schrodinger, Casatus, and Klaproth all have. Another feature of interest was secondary craters which are areas of smaller impacts inside of larger craters. Craters with the indication for secondary craters in the South Pole include Drygalski, La Gentile, and Short. Other craters exist with secondary craters which were represented by the codes Ioc and Nbc. Equally detailed information about the North Pole was organized into Table 5 and Table 6.

Table 5: North Pole Topography Distribution [27]

Crater	Approximate Latitude	Color Code Location Details
Peary	88N	Ip -center; pNc - entire rim
Byrd	85N	Ip - majority; pNc - rim close to pole
Nansen	85N	Ip - small center; pNc - majority; Ic1 - secondary crater region closest to pole
Hermite	87N	Ip - center/majority; pNc - entire rim
Roshdestvensky	85N	pNc - half of the rim closest to hermite; Int - half of center; Ic2 - half of center to rim closest to plaskett; Ec - rim furthest from pole
Florey	87N	Ec
Unnamed	84N	Ec-entire
Main	81N	Ip - center; Nc - rim
Sylvester	81N	Ip - center; Nc - rim
de Sitter	80N	cf - center; Nc - rim
Lovelace	82N	Ic2 – entire
Gioja	83N	Ip - center, Nc - rim entire
Froelich	80N	Nc – entire
Challis	79N	Ec - Half; Ip - half floor; Nc - side rim
Scoresby	79N	Ec – Entire
Meton	75N	Ip1 - floor; IpNcl – rim
Baillaud	75N	Ip2 - floor; IpNcl - rim
Petermann	73N	Ip1 - floor; Nc - rim
Cusanus	71N	Ip - floor; Nc - rim
Karpinsky	71N	Ic1 - majority from outside rim into the floor, Ip - exact center of floor/small
Ricco	75N	Ec - entire
Milankovic	77N	Nt - center, pNc - majority of rim, Ec - edge close to ricco
Heymans	75N	Ip - floor; Nc - rim
Merrill	75N	Ip - majority/floor, Nc - rim
Brianchon	75N	Ip1 - majority/floor, pNc - rim, Ic2 - small secondary
Poncelet	78N	Ip1 - floor, Nc - rim, Ic1 - secondary rim
Lindbald	70N	Ic1 - entire
Desargues	70N	Ip - half floor, Ip2 - half of floor, pNc - rim
Carpenter	70N	Cc - entire
Anaxagoras	72N	Cc - entire
Mouchez	78N	IpNcl - rim, Ip1- small floor

Table 6: North Pole Topography Code Details [27]

Color Code	Meaning
Ip	Undivided plains material, light, smooth, flat surface in low areas. Higher density of craters than mare
pNc	Materials of highly subdued craters, discontinuous, subdued rimcrests and rounded, curved or straight rim remnants
Ic1	Materials of moderately subdued craters, subdued topographic detail, fairly continuous rimcrest, terraced walls, radial rim facies and secondary craters on very large craters (Irfum, Compton), on other craters outer rim facies indistinct or smooth, small craters have shallow bowls with rubdued rims, irregular shadows
Int	Terra material (Imbrian and Nectarian), on high-resolution pictures, hummocky plain with some subdued hills (kilometers in size) mostly in low areas, On medium-resolution pictures light, fairly smooth and level plains, surface more undulating and contacts more diffuse than those of plain units, mixture of hilly material and plains material in areas too small to map separately.
Ic2	Material of moderately fresh craters, subdued but distinct topographic detail, fairly continues rimcrest, on high-resolution pictures and around large craters (plato, Plaskett) terraced radially ribbed rim facies and secondary craters, on medium-resolution pictures, outer rim facies indistinct or smooth, small craters have deep bowls, rim more subdued than those in unit Ec
Ec	Material of fresh craters, fairly sharp topographic detail, sharp continuous rimcrest, on high-resolution pictures, deep, somewhat subdued interior, terraced walls, raidially ribbed rim materials, and secondary crater clusters and chains, small craters have deep bowls
Nc	Material of subdued craters, continuous to interrupted subdued rimcrest. Only large craters show terrace remnants, outer rim facies only on d'alembert. Small craters have smooth walls, mostly flat floors.
cf	fractured crater floor, occurs in craters of Nectarian, Imbrian, and Copernican age
IpNcl	Material of lineatred craters, (Imbrian, Nectarian, and pre-Nectarian), linear subparallel arrays of troughs and ridges radial to Imbrium basin, on crater rims
Ip1	Older plains material, light, fairly smooth, flat to locally undulatory surface. Crater density like that on Fra Mauro Formation. Contacts locally diffuse
Ip2	Younger plains material, light, smooth, flat surface. Lower sensity of craters than Ip1. contacts mostly sharp
Int	Terra material (Imbrian and Nectarian), on high-resolution pictures, hummocky plain with some subdued hills (kilometers in size) mostly in low areas, On medium-resolution pictures light, fairly smooth and level plains, surface more undulating and contacts more diffuse than those of plain units, mixture of hilly material and plains material in areas too small to map separately
	(continued)

Color Code	Meaning
Nt	Terra material, irregular hills and depressions, a few km to tens of km in size, on medium resolution pictures, somewhat subdued highlands. on high and low areas.
Cc	Material of rayed craters, sharp topographic detail in all photographic scales, sharp continuous rimcrest. On high resolution pictures, deep rugged interior, terraced walls, radially ribbed rim materials, and secondary crater clusers and chains. rays visible on near side images. Small craters are sharp rimmed with deep bowls.

Some craters with very unique topographic features from Table 5 were Peary, Bryd, Nansen, Hermite, Florey, Main, Scoresby, and the unnamed crater to name a few. These craters commonly had floors of Ip, Ip1, Ip2, and Ec. Ip, Ip1, Ip2, and Ec represent, as seen in Table 6, plains with flat terrain and "young" regolith. Carpenter and Anaxagoras have very rough terrain, represented by Cc in Table 6. Roshdestvensky, Sylvester, De Sitter, Lovelace, Gioja, Froelich, Baillaud, Karpinsky, Carpenter, and Anaxagoras have similar terrains, but are at lower elevations. This causes lower temperatures due to increased protection from the sun: therefore these craters have a higher likelihood for trapping water ice.

Detailed Estimate for the Amount of Water Ice

Effective Area for Water Ice Retention

The first step which was required to create a water estimate that took lunar geography into account was by researching the findings of the Clementine, Lunar Prospector, LCROSS, and Chandrayaan-1 missions. This allowed new, original statistics to be created. A greater amount of detailed information was found on the Clementine mission, the oldest of those four, which also had the least advanced instruments. Clementine's results were the basis for the other three missions' investment of time and money for superior instruments. It was required to know the likelihood that a given region in the North and South Pole would consist of a permanently shadowed region.

Earth-based radar and advanced modeling techniques examined Moon conditions for areas likely to be permanently shadowed and then compared it to the results of the Clementine mission preliminary estimates concerning the PSRs on the Moon. For an area of 84,375 km^2 at the North Pole 2,650 km^2 of it would be a permanently shadowed region; in the South Pole it was found that for an area of 92625 km^2, 5100 km^2 of it would be permanently shadowed [29]. Simple statistics were used to show that 3.1% of the area investigated in the North Pole and 5.5% of the area in the South Pole were permanently shadowed. Because the estimates for permanent shadows used computer modeling of the Moon's interaction with the sun and Clementine data, it is more reliable than Clementine data alone. While Clementine results were debated, the Earth-based radar technique was used and refined for decades to make topographic maps of celestial bodies, which made it extremely reliable.

While the final amount of PSRs investigated had sufficient details to form statistics, no information was available concerning what was originally believed to be PSRs before the investigation was completed. Had that information been available, more accurate statistics would have been incorporated for further area investigations. The information used to create the PSR statistics did not detail whether or not the original data considered contained craters exclusively. Only craters have shown evidence of being permanently shadowed, so the inclusion of non-cratered terrain will skew the statistics to lower values. The percentages calculated, 3.1% of the area in the North Pole and 5.5% of the area in the South Pole were used to examine the areas of craters likely to be PSRs. By examining only craters, it must be noted that there is a higher likelihood of a region being permanently shadowed than what the previous calculations represented.

With the area of the shadowed regions calculated above, it was important to find the area within those regions that will produce statistically significant data for water ice. This meant fine tuning the estimate for the area of cold traps, which was done with the LCROSS data. When deciding a location to crash the spent fuel cell of the LCROSS mission, NASA investigated permanently shadowed areas and used neutron detection to locate areas most likely for water ice. Out of nine possible crater regions only two were found to have statistically significantly data for water ice [30]. The available characteristics of the nine regions of craters measured with the neutron detector were further investigated. From this it was possible to create statistics concerned with the percent chance for a permanently shadowed area to generate reliable water ice measurements. The total area of the nine craters investigated was 4,556 km^2 while the two reliable craters only had an area of 1,291 km^2. This showed that 34.8% of a given area would be likely to produce trust worthy results for cold traps based on neutron spectrometer measurements. Because LCROSS was the most advanced mission sent to investigate the possibility of water ice, the data was extremely reliable. The combination of the calculated permanently shadowed areas in the lunar poles with the percent for areas with reliable water ice measurements produced the following results: 750 km^2 in the North Pole and 1,443km^2 in the South Pole have water ice approximately.

The values of 750 km^2 and 1,443 km^2 were created without extensive detail concerned with the amount of craters with shadowed areas, but instead began with a general area's likelihood for permanent shadows. The first assumption made for the new estimate of water ice was that focusing on craters at latitudes higher than 70 degrees will provide clearer insight to the area with the highest concentration of water ice. Through the use of an area calculator in Google Pro, it was found that for an area of 117,295 km^2 in the South Pole originally thought to be shadowed craters, only 12,385.4 km^2 would actually be. This resulted in 10.56% of the area being permanently shadowed from those craters which were originally believed to be shadowed. When the craters above 70 degrees south which were incorporated into calculations, it resulted in an increase of the total area to 237,437 km^2 and a decrease in the percentage of PSRs to 5.22%. The statistics calculated which were concerned with the area of PSRs within a specified region of the North and South Pole, had concluded that 5.5% of an area in the South Pole would be permanently shadowed. Because the values produced from two different methods of observation were so close together, the results are verified as accurate. This value verifies earlier theories about regions that retained water ice based on Clementine mission data though it used a more limited area. Table 7, below, highlights the craters of the South Pole and their statistics created by compiling the Google Earth Pro data.

Table 7: South Pole Craters with Significant Shaded Regions and Area Statistics

Craters with Well Defined Shadows	Latitude	Shaded Area (km)	Total Area (km^2)
Antoniadi	69.7S	58	14654
Casatus	72.8S	123.4	8150
Boltzman	74.9S	337	3524
Hale	74.2S	344	5161
De Forest	77.3S	779	2504
Demonax	77.9S	202	12093
Drygalski	79.3S	977	23094
Ganswindt	79.6S	896	4823
Newton	76.7S	249	5667
Idel'son	81.5S	578	2350
Hedervari	81.8S	323	4197
Scott	84.5S	1760	16215
Wiechert		515	1706
Nefedev	81.1S	671	2782
Kocher	84.6S	239	460
Amundsen	84.3S	4334	9915
Total		12385.4	117295
%PSR		10.60	
70-75 Total		862.4	31489
%PSR		2.74	
75-80		3103	48181
%PSR		6.44	
80-85		8420	37625
%PSR		22.38	

Table 7 made it obvious that in-between the latitudes of 80 – 85 degrees there is a drastic increase in the percent of shadowed regions. From previous calculations it was found that 34.8% of PSRs believed to be cold traps will have statistically significant data to be confirmed as cold traps. Of the 12,385.4 km^2 shadowed area calculated in Google Earth Pro imagery, 4,303.93 km^2 is likely to be an effective cold trap in the South Pole. 4,303.93 km^2 is almost three times the area found when an estimate for effective cold traps was made without the consideration of craters above the 70 degree latitude. The same procedure was used to analyze the geography of the lunar North Pole. The results can be seen in Table 8 below.

Table 8: North Pole Craters and Significant Shadowed Regions Observed with Google Earth Pro

Craters	Latitude	Shadowed Area (km)	Total Area (km^2)
Brianchon	75.0N	36.7	15978
Baillaud	74.6N	79.3	6623
Anaxagoras	73.4N	132	2128
Carpenter	69.4N	8.36	2815
Philolaus	72.1N	57.1	3954
Karpinskiy	73.3N	160	6900
Euctemon	76.4N	168	3161
Merrill	75.2N	49.7	2753
Shi Shen	76.0N	132	1808
Froelich	80.3N	365.9	2274
De Sitter	80.1N	712	3268
Gioja	83.3N	280	1444
Main	80.8N	87.4	1981
LoveLace	82.3N	580	2537
Sylvester	82.7N	559	2785
Rozhedestvenskiy	85.2N	525.9	22220
Total*		3933.36	82629
%PSR		4.76	
70-75 Totals		473.46	38398
%PSR		1.23	
75-80		349.7	7722
%PSR		4.53	
80-85		2584.3	14289
%PSR		18.09	
85-90*		525.9	22220
%PSR		2.37	

As expected, the amount of permanently shadowed areas in the North Pole was less than the South Pole. The total shadowed area of the South Pole calculated at 12,385 km^2 meant that the North Pole has approximately 32% of the shadowed area of the South Pole. This does not reflect how effective those shadowed areas are at trapping water ice, though the assumptions used to choose the areas of interest increased the likelihood of effectiveness. The values calculated for both poles, which used Google Earth Pro, are within the limits of possible shadowed regions seen from Clementine data and Earth-based radar estimates. The results from the North Pole above 85 degrees include areas which had extremely poor resolution and resulted in a very poor approximation compared to what is already known for those latitudes. Above 85 degrees, for both the North and South Pole, should be the best areas for cold traps given the very limited sunlight. The calculations of Table 7 showed a drastic increase in percentage (4.53% to 18.09%) from the 75 to 80 degree range to the 80 to 85 degree range. This was a much more consistent and expected pattern than the drop to 2.37% shadowed area for latitudes greater than 85 degrees, but this was to be expected when only one crater not completely above 85 degrees is concerned and not the more important craters located right by the pole. The same trend, a drastic percentage increase for shadowed areas, was seen for the data available in the South Pole. If this trend continued for the areas above 85 degrees latitude, the potential for areas of high interest for water ice would significantly increase. The topology, detailed in Table 3, Table 4, Table 5, and Table 6, showed additional features which are conducive to water ice retention as the latitude increased as well.

Water Ice Implantation Calculations

With an area chosen to be a reliable source of water ice, the amount of water ice in the regolith needs to be known. Although the final amount of water has not yet been officially stated, there were several estimations that were made. There are many theories as to how the Moon water originated; the theory that water ice exists in the permanently shadowed lunar regions of the Moon stated in 1962 [1].

In September of 2008, ice was believed to be over an area of 1850 km^2 at each Pole [31]. The estimate for the amount of ice on the Moon was 6.6 billion tons. This data was based on a model and significant uncertainties with respect to the actual value for water on the Moon may have been considered. In March of 1998, scientists from the Apollo mission estimated the Moon to have 300 million metric tons of ice at the lunar poles. Dr. Alan Binder from the Lunar Research Institute, Gilroy, CA had stated that "We based those earlier, conscientiously conservative estimates on graphs of neutron spectrometer data, which showed distinctive dips over the lunar Polar Regions. This indicated significant hydrogen enrichment, a telltale signature of the presence of water ice [32]." However, this data did not provide information on the structure of the water ice. From the analysis that was obtained through the models, the presence of hydrogen at the Moon's poles was observed. It was believed that this data indicated the presence of water ice [32].

The LCROSS mission sent out on October 9, 2009, discovered water ice in the lunar South Pole approximately two months after launch. The LCROSS mission's team approximated 220 pounds of water, which is equivalent to a 24 gallon buckets. This amount of water was observed in a crater with a diameter of 20 meters [33]. This information was incorporated into calculations and an original estimate as to how much water is present in the entire lunar crater. For calculations, the following assumptions were made:

- 100% Moon water was from comets
- The composition of elements in the comet is the same as Halley's comet [34]
- The impact vapor composition of the Moon's atmosphere contains matter only from the comets [34]
- For the calculations, it was assumed that all of the comet matter is vaporized during the impact [34]
- The water ice that was trapped in shadowed areas at the time of landing, will remain permanently shadowed regardless of the Moon's cycle; and
- The radius of the vapor cloud formed is the same as the radius of the crater that is being formed. This is based on the assumption that the vapor cloud formed will come in contact with the cold temperature and condense quickly to fall into the cold traps.

Results from the Lunar Prospector Mission provided the following initial data on the area of the cold traps that occupy water ice (S_c) and the volume fraction of ice in a 0.5 m layer of soil near the surface (δ_{ice}), as well as the mass of the water ice in the lunar Polar Regions (m_i) [20]. The equations and relationships represented are based on the information provided in a previously conducted calculation. The variables used for input into Mathcad are shown below [34].

S_c- Area of ice occupied cold traps

δ_{ice}- Volume fraction of water ice within a 0.5m layer of soil near the surface

d_i- Comet size

v_i- Comet velocity

v_{max}- Velocity of the outer cloud edge

v_{esc}- Escape Velocity for the Moon

g_m- Gravitational field on the Moon

ρ_i- Comet density

ρ_t- Density of regolith

m_i- Comet mass

m_{ej}- Mass of the material ejected on impact

m_{ice}- Mass of water in lunar polar regions

m_{esc}- Mass of the matter that escape from the Moon

m_r- Mass of vapor remaining in the gravitational field

The following values were assigned to the variables shown above. Most values were derived as an average value from a given range.

$S_c = 4 \times 10^{14}$ cm^2	$m_{ice} = 5.05 \times 10^{14}$ g	$\rho_t = 1.8$ gcm^{-3}
$v_{esc} = 2.4$ kms-1	$m_i = 4 \times 10^{15}$ g	$\rho_i = 1$ gcm^{-3}
$v_i = 23$ kms^{-1}	d_i =km	g_m =cms^{-2}

For calculating the mass of the material ejected, equation (1) was used [34]:

$$\frac{m_{ej}}{m_i} = 0.2 \cdot \left[\frac{v_i^{\,2}}{g_m} \left(\frac{\rho_t}{m_i} \right)^{\frac{1}{3}} \right]^{0.46} \qquad (1)$$

The amount of mater escaping the Moon was found through the relationship shown in (2) [34]:

$$\frac{m_{esc}}{m_i} = 0.1 \cdot \left(\frac{\rho_i}{\rho_t}\right)^{0.2} \cdot \left(\frac{v}{v_{esc}}\right)^{1.2} \qquad (2)$$

$$m_{ej} = 2.4 \times 10^{17} \cdot g$$

v is the velocity distribution about the radius. v can also be expressed in terms of v_{max} and other parameters as shown below [34]:

v- Velocity distribution about the radius

r- Radius in the impact vapor cloud

R_{max}- Radius growth rate with time

t- Time taken for the cloud to reach this radius

The relationship between the velocity and the radius is shown in equation (3) [34]:

$$v = \frac{v_{max} \cdot r}{R_{max}} \qquad (3)$$

Then the following relationship was used in equation (3) to obtain equation (4). This represents another format for expressing the relationship of the velocity distribution about the radius [34]:

$$v = \frac{r}{t}$$

$$R_{max} = v_{max} \cdot t \qquad (4)$$

The next step was to estimate a value for the radius of the impact cloud. Data on impact craters which were considered are listed in Table 9.

Table 9: Name and Size of Several Polar Craters [35]

Crater	Radius (km)
Unnamed (South Pole)	20.34
Shoemaker	19.34
Cabeaus	16.93
Faustini	14.93
De Gerlache	9.77
Shackleton	7.98
Unnamed (North Pole)	20.0

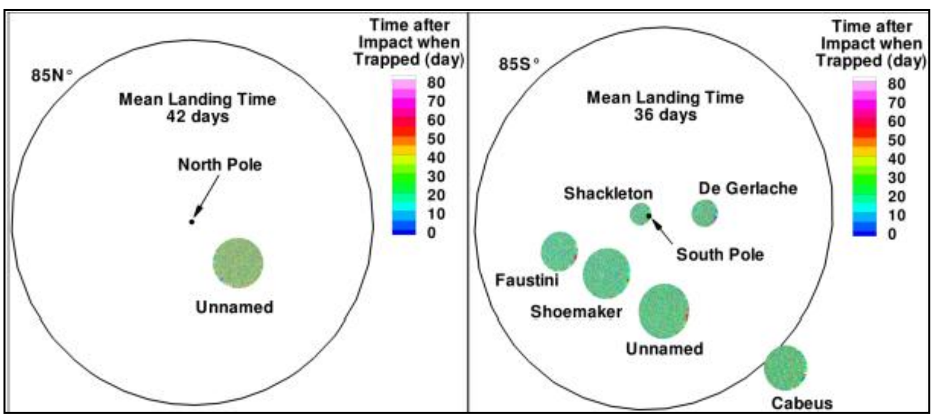

Figure 1: The Location of the Craters in Table 9 [35]

The average value of these craters was calculated to be 15.61km. This value was used in equation (2) to calculate for v. The relationship between the ejected masses is shown below [34]:

$$m_{esc} = 4.397 \times 10^{15}\,\mathrm{g}$$

$$\frac{m_{esc}}{m_i} = 1.099$$

The value for t in equation (4), 0.8s, was selected so that the ratio m_{esc}/m_i would be close to 1 since previous calculations [34] had found that velocities exceeding the escape velocity had a ratio that was close to 1.01.

The mass of the vapor from the comet that remains in the Moon's gravitational field, that is, the vapor that has a velocity smaller than the escape velocity, was explained and calculated below. For the cloud that forms during the impact, the velocity at the outer edge, v_{max} can be estimated by the range $v_i/2$-$v_i/3$. As the impactor velocity increases, it tends to depend on the comet velocity [34]. The relationships for the maximum values of the velocities at the outer cloud edge and the mass of vapor remaining in the gravitational field are shown by equations (5) and (6).

$$v_{max} := \left(\frac{5 \cdot v_i}{12}\right) = 9.583 \times 10^3 \frac{m}{s} \tag{5}$$

$$m_r := m_i \cdot \left(\frac{v_{esc}}{v_{max}}\right)^3 = 6.283 \times 10^{13} \cdot g \tag{6}$$

As the velocity of the impactor increased, the fractions of volatiles in the impact vapor decreased. An assumption was made that matter from the comets and the target areas are well mix in the impact vapor created. The comet impact creates a temporary atmosphere on the Moon. It consists of both materials from the comet and the regolith. For the assumed impact velocity, the atmosphere contained approximately the same amount of matter from the comet and the regolith. Since regolith does not contain many volatiles, previously conducted thermodynamic calculations showed that the composition of the impact vapor is not different from the cometary matter. This statement held true when $m_i/m_v > 0.03$, which accounted for all of the Moon-comet impact velocities, where m_v is the mass of the vapor. The elemental composition of Halley's Comet was considered for calculations. H_2O will account for approximately 20% of the atmosphere produced where other compounds produced are: H_2: 40%, CO: 30%, CO_2: 5%, N_2: 3%, S_2: 3% [34].

It was also important to know which components condensed within the cold traps of the Moon. In order to calculate this, the surface temperature of the cold traps ($T_{.c}$) and the partial pressure of the compounds stated above were investigated. Equation (7) was used to find T_c [34].

T_C- Surface temperature of the cold traps

T_{eq}- surface temperature on the day side

D_C- Diameter

d_C- Trap depth

θ- Trap latitude

α- Declination of the Sun

a_M-the ratio of reflected to incident light of the lunar surface

$$\left(\frac{T_c}{T_{eq}}\right)^4 \cdot \alpha_M \cdot \cos(\theta + \alpha) \cdot \frac{d_c}{D_c} \qquad (7)$$

T_c was found to be within the range of 50-100 K. If these cold traps aren't effected by solar radiation, this temperature is determined by internal sources of heat and T_c=30 K. When a comet with a comet diameter of 2 km was considered, the mass of the atmosphere produced by the impact is 10^{14} g and pressure 10 to 8 bar. It was found that condensation of water can occur in cold traps based on these conditions. It has also been shown through calculations that the gases that do condense, all fall into the cold traps and that the temperature of these cold traps remains constant during the time period of condensation. The final calculations were that the impact of a comet would give approximately 10^8 Mg of H_2O with a surface density of 0.3 gcm^{-2} within the cold traps [34]. Table 10 provides a summary of the calculated values.

Table 10: Summary of the Calculated Data

Calculated Parameter	Value
Mass of material ejected on impact (m_{ej})	2.4×10^{17}g
Mass of the matter that escape from Moon (m_{esc})	4.397×10^{15}g
Mass of the vapor from the comet that remains in the Moon's gravitational field (m_r)	6.283×10^{13}g

The data provided by the Lunar Prospector Mission in March 1998 was used for an estimation of the amount of water. In equation (8), V_r is the volume of the regolith that remains under the Moon's gravitational field [34].

$$\rho_t = \frac{m_r}{V_r} \tag{8}$$

$$Vr := \frac{m_r}{\rho_t} = 3.49 \times 10^7 \, m^3$$

Based on the previous assumption that all of the vapor will condense and fall into the cold traps of the polar region, the volume of ice within this entire regolith volume was calculated. The volume fraction of water ice within a 0.5 m layer of soil near the surface is represented below [34].

$$\delta_{ice} := 1.25\%$$

$$Vr \cdot \delta_{ice} = 4.363 \times 10^5 \, m^3$$

This value comes to approximately 16 tons of water ice. Several other relationships for finding various data needed are shown in equations (9) and (10) [34]:

$$d_c = \left(C \cdot d_i\right)^{0.8} \cdot v_i^{0.44} \tag{9}$$

$$\rho_{ice} = \frac{m_{ice}}{V_r \cdot \delta_{ice}} \tag{10}$$

$$\rho_{ice} := 0.3 g \cdot cm^{-2}$$

$$\rho_{ice} = 3 \times 10^9 g \cdot km^{-2}$$

In equation (9), C is the proportionality constant. The estimated amount of ice in the craters mentioned in Table 11 was found by using the surface density value ρ_{ice}. These craters can be seen in Figure 1.

Table 11: Estimated Mass of Water in Selected Craters

Crater	Radius (km)	Area (km^2)	Estimated Mass of water (g)
Unnamed (South Pole)	20.34	1300	3.90×10^{12}
Shoemaker	19.34	1175	3.52×10^{12}
Cabeaus	16.93	900	2.7×10^{12}
Faustini	14.93	700	2.1×10^{12}
De Gerlache	9.77	300	8.99×10^{11}
Shackleton	7.98	200	5.99×10^{11}
Unnamed (North Pole)	20.0	1257	3.76×10^{12}

Based on the data gathered from the "Effective Area for Water Ice Retention" section of this report, it was found that an area of 4303 km^2 is likely to be an effective cold trap. It was assumed that the crater shape can be approximated as a circle and that the water present in a crater is from comets. From these assumptions, the following values were obtained:

$$m_{esc} = 1.239 \times 10^{16} \cdot g$$

$$\frac{m_{esc}}{m_i} = 3.098$$

$$m_r := m_i \cdot \left(\frac{v_{esc}}{v_{max.new}} \right)^3 = 5.583 \times 10^{11} \cdot g$$

The relationships for the maximum values of the velocities at the outer cloud edge and mass of vapor remaining in the gravitational field based on Google Earth Pro Observations. Based on the values of the shaded areas obtained, Table 12 was developed.

Table 12: New Estimates for Moon Water Based on Shadow Region Observations

Crater with Well Defined Shadows	Total Area (km^2)	Estimated Amount of Water (g)
Antoniadi	58	1.74×10^{11}
Casatus	123.4	3.702×10^{11}
Boltzman	337	1.011×10^{12}
Hale	344	1.032×10^{12}
De Forest	779	2.337×10^{12}
Demonax	202	6.06×10^{11}
Drygalski	977	2.931×10^{12}
Ganswindt	896	2.688×10^{12}
Newton	249	7.47×10^{11}
Idel'son	578	1.734×10^{12}
Hedervari	323	9.69×10^{11}
Scott	1760	5.28×10^{12}
Wiechert	515	1.545×10^{12}
Nefedev	671	2.013×10^{12}
Kocher	239	7.17×10^{11}
Amundsen	4334	1.3002×10^{13}

From Table 12, the total amount of water was calculated to be 3.72 x 10^{13} g. This value incorporated the effects of solar winds, comets, and lunar geography, which made it highly accurate and reliable.

Sublimation of the water ice has the potential to decrease the amount of water on the Moon. Sublimation is the process where a substance goes from solid state into the gas phase without the liquid phase in between. It was estimated that the temperature at the permanently shadowed craters could be around 40 K [36]. Three equations for water sublimation only detailed a minimum temperature of 110 K. Extrapolation were used to estimate the sublimation rate at 40 K. The relationship shown in equation (11) was used for the analysis [37].

$S_{.0}$ -Sublimation rate for a planar surface of pure water ice

$P_{sat}(T)$- Saturation vapor pressure over a planar surface of pure water ice, which is a function of temperature in Kelvins

M_W- Molecular weight of water

R- Universal Gas Constant

T- Temperature (K)

$$S_0 = P_{sat.}(T) \cdot \left(\frac{M_w}{2 \cdot \pi \cdot R \cdot T} \right)^{\frac{1}{2}} \qquad (11)$$

There were three different equations derived for calculating the sublimation rate and each equation had their own temperature range for which it is valid. All of them are given as a function of temperature in Kelvins. Equation (12) represents the saturation vapor pressure over the temperature range of 193.15 K -273.15 K [38].

$$P_{sat.1}(T) = 6.1115 e^{\left[\frac{22.542 \cdot (T - 273.15)}{273.48 + (T - 273.15)} \right]} \qquad (12)$$

Equation (13) represents the saturation vapor pressure over the temperature range of 190.0 - 273.16 K [39].

$$P_{sat.2}(T) = 6.11657 \cdot e^{\left[-13.9281690 \cdot \left[1-\left(\frac{T}{273.16}\right)^{-1.5}\right]+34.7078238 \cdot \left[1-\left(\frac{T}{273.16}\right)^{-1.25}\right]\right]} \quad (13)$$

Equation (14) represents the saturation vapor pressure over the temperature range of 110.0 - 273.15 K [40].

$$P_{sat.3}(T) = 0.01 \cdot e^{\left(9.550426-\frac{5723.265}{T}+3.53068 \cdot \ln(T)-0.00728332 \cdot T\right)} \quad (14)$$

The temperature range of 110 -273.16 K was used and the graphs were plotted separately. This can be seen in Appendix A of the report. For temperatures below 100 K, the equation (14) is considered since the temperature goes down to 110 K compared to equations (12) and (13). This is a similar approach to the calculations conducted by Scientist E.L Andreas. However, the approach used for extrapolation may slightly differ. It was assumed that the ice layer used for calculation is pure ice [36]. The following graph is plotted by combining the three separate graphs; it is represented in Figure 2.

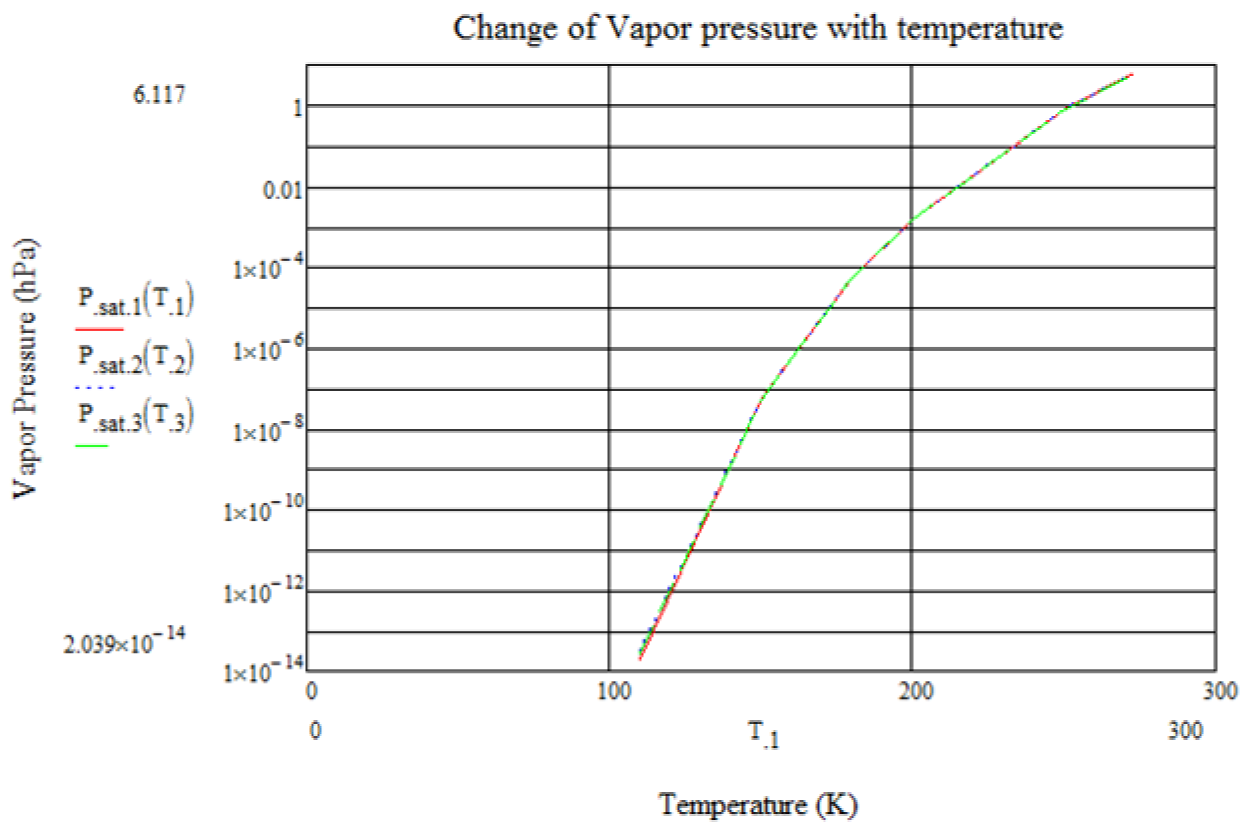

Figure 2: Graph of Vapor Pressure with the Temperature

An estimate for the sublimation rate at 40 K is found by continuing the shape of the curve until it reaches that temperature. This value is compared to the author's value and it is examined whether the ice will sublimate. Equation (15) shows the input for temperature T_3 used to obtain results for vapor pressure obtained using MathCAD.

$$T_3 := \begin{pmatrix} 40.00 \\ 80.00 \\ 100.00 \\ 170.00 \\ 230.00 \\ 273.16 \end{pmatrix} \qquad P_{sat}(T_3) := 0.01 \cdot e^{\left(9.550426 - \frac{5723.265}{T_3} + 3.53068 \cdot \ln(T_3) - 0.00728332 \cdot T_3\right)} \tag{15}$$

By substituting the values for temperature in Kelvins to the expression for vapor pressure, values for the sublimation rate can be obtained. This is shown in equation (16).

$$P_{sat}(T_3) = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 7.31 \times 10^{-6} \\ 0.089 \\ 6.117 \end{pmatrix} \qquad S_0 := \overrightarrow{\left[P_{sat}(T_3) \cdot \left(\frac{M_w}{2 \cdot \pi \cdot R \cdot T_3} \right)^{\frac{1}{2}} \right]} = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 1.041 \times 10^{-8} \\ 1.096 \times 10^{-4} \\ 6.872 \times 10^{-3} \end{pmatrix} \frac{K^{0.5} \cdot s}{m} \qquad (16)$$

The calculations were completed using MathCAD. The value zero is shown since the calculated value for sublimation rate turns out to be a very small number. The green lines indicated in Figure 3 represent the tracing for finding the sublimation rate at 40 K. The value obtained was read to be approximately 10^{-57} $\mu gcm^{-2}h^{-1}$.

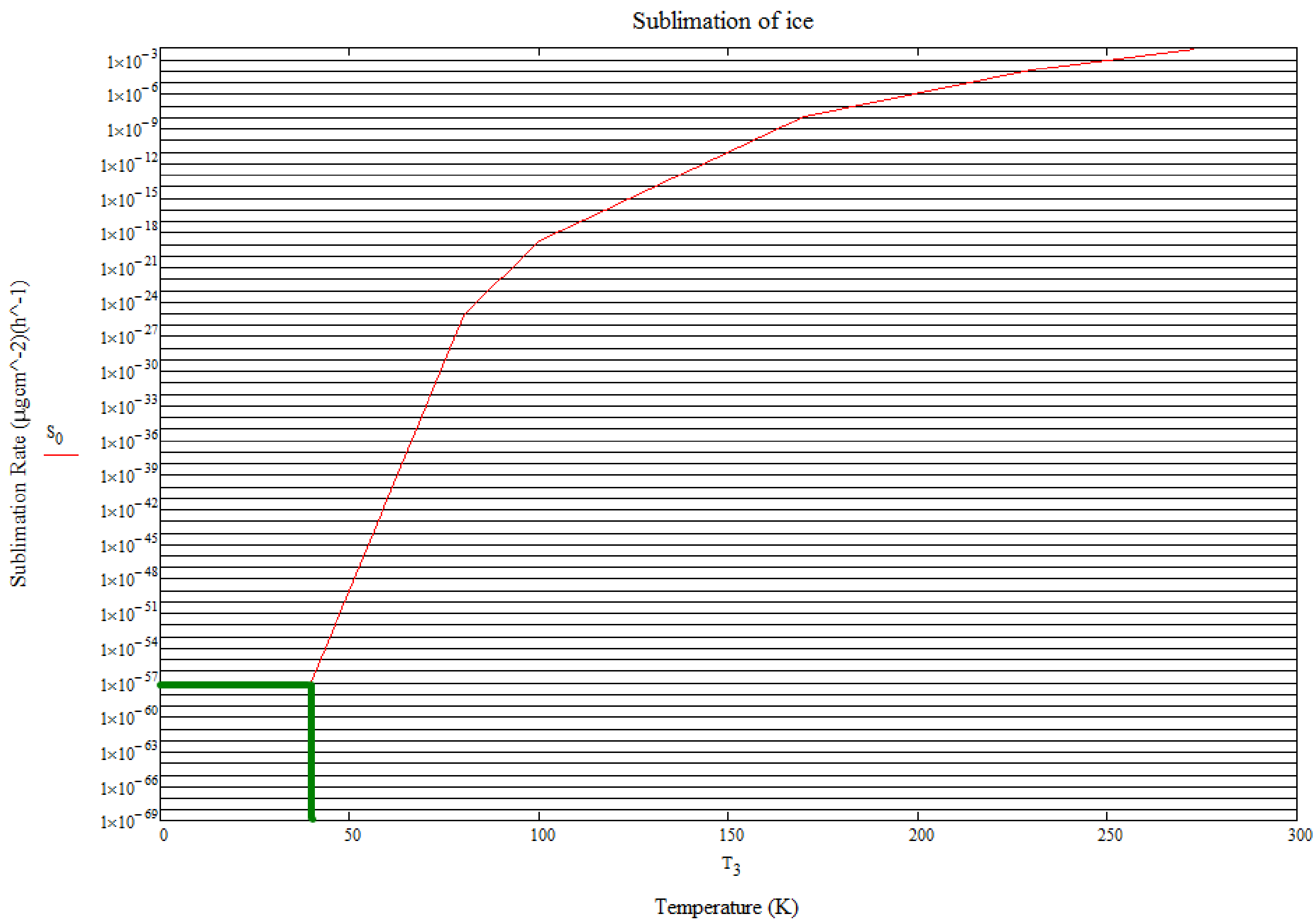

Figure 3: Graph for Temperature vs. Sublimation Rate Using MathCAD

If the shape of the graph is continued in a similar style based on its behavior for temperatures above 110 K, the curve is similar to the orange line showed in Figure 3. At this point, the sublimation rate corresponding to 40 K is around 10^{-47} $\mu gcm^{-2}h^{-1}$. The average value found through these two analyses is considered to be the sublimation rate at 40 K.

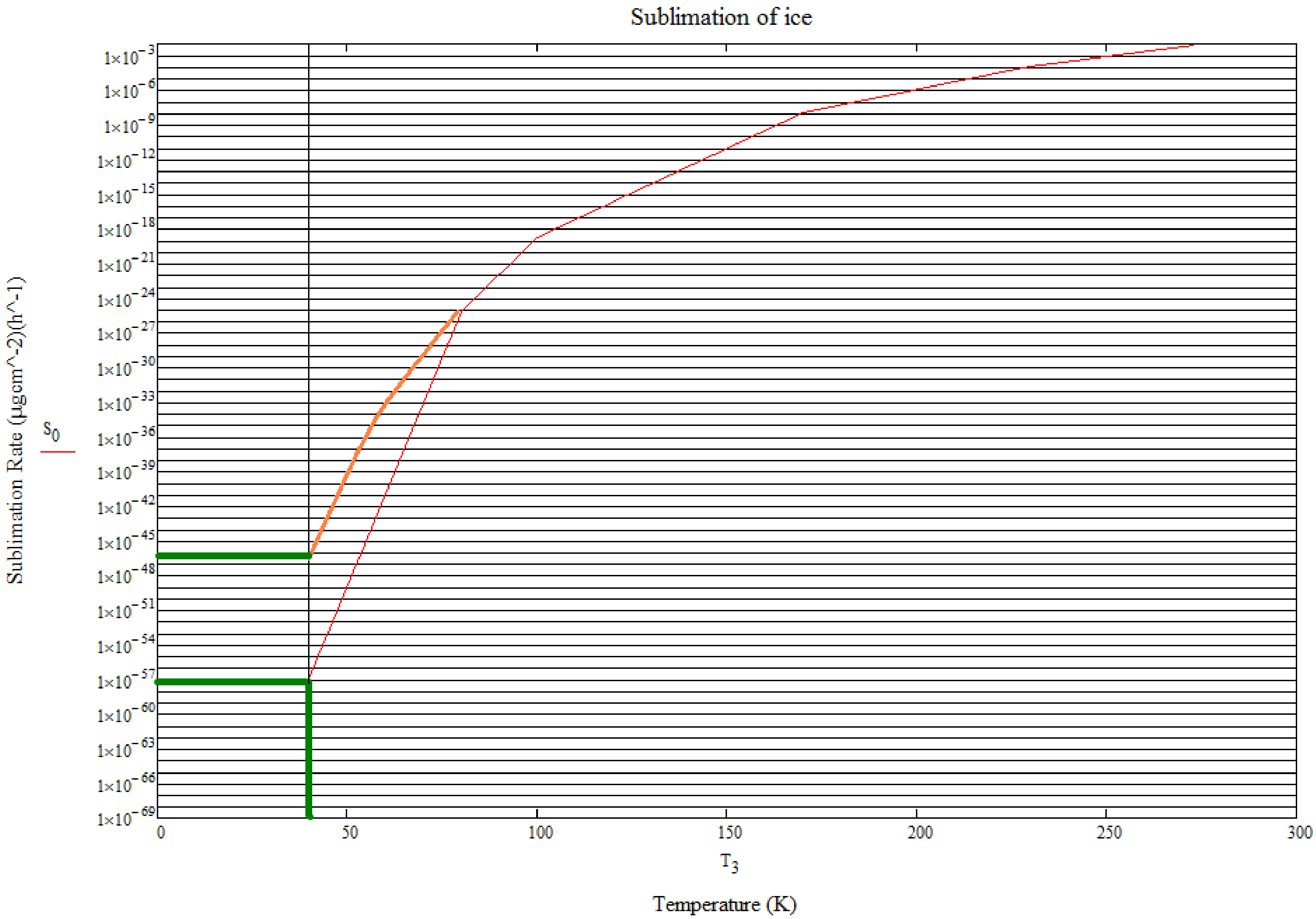

Figure 4: Modification of Figure 3 Using an Extension of the Curve Parameter

The values obtained with the MathCAD calculations were similar to the model's original calculations conducted by the scientists. The sublimation rate was very small; therefore, the sublimation rate was almost negligible with the conclusion that sublimation does not affect water ice in the regolith. This was an important factor when considering future robot missions as the water will not sublimate until the temperature reaches about 100 K. So when any design for Moon exploration equipment mechanism is being developed, it should be created so that the heat released will have no relationship to values that would create an inaccuracy for the data gathered on water ice in the regolith. These results were compared against other calculations that were conducted by scientists.

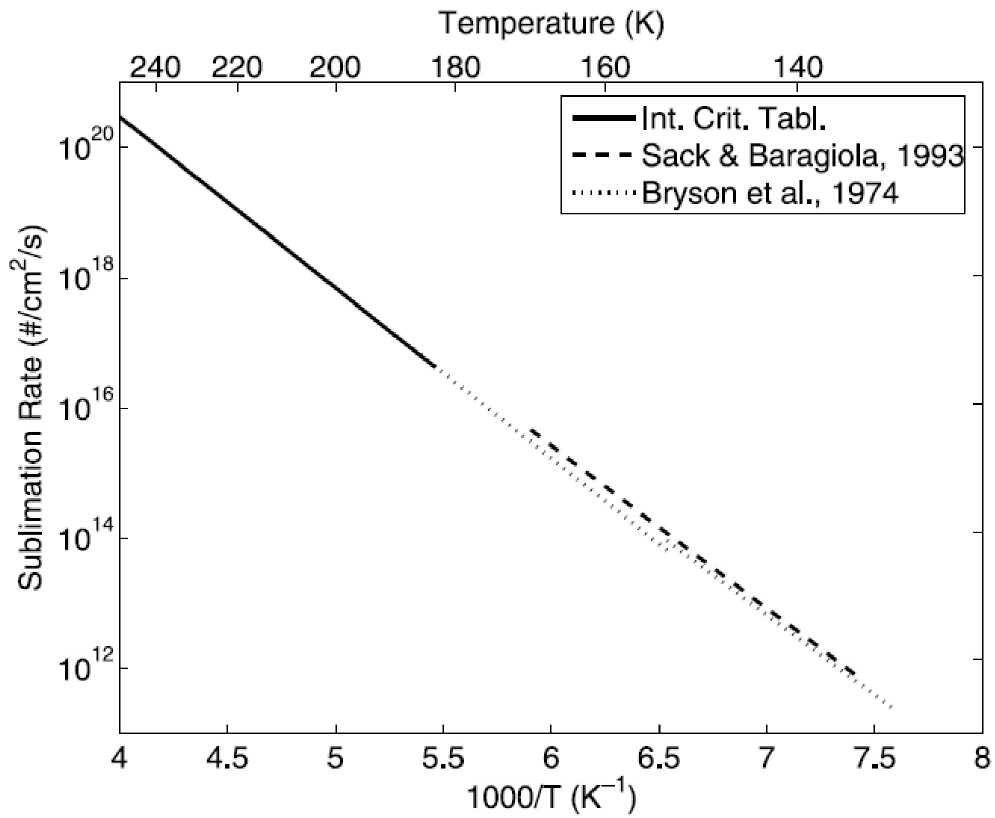

Figure 5: Graph for the Sublimation Rate [41]

To make the units similar for the ease of comparison, the graph obtained in Figure 3 was modified. The following unit conversion was applied to the sublimation rate (y axis) to make it constant with the units of Figure 5 [42] [43] [44]. It was renamed as $S._{0mod}$, it can be seen in equation (17). The temperature scale (x axis) was also modified as 1000/T.

$$S_{0.mod} := \frac{S_0 \cdot 18.01 \cdot 6.023 \cdot 10^{23} \cdot 10^{-6}}{3600} \qquad (17)$$

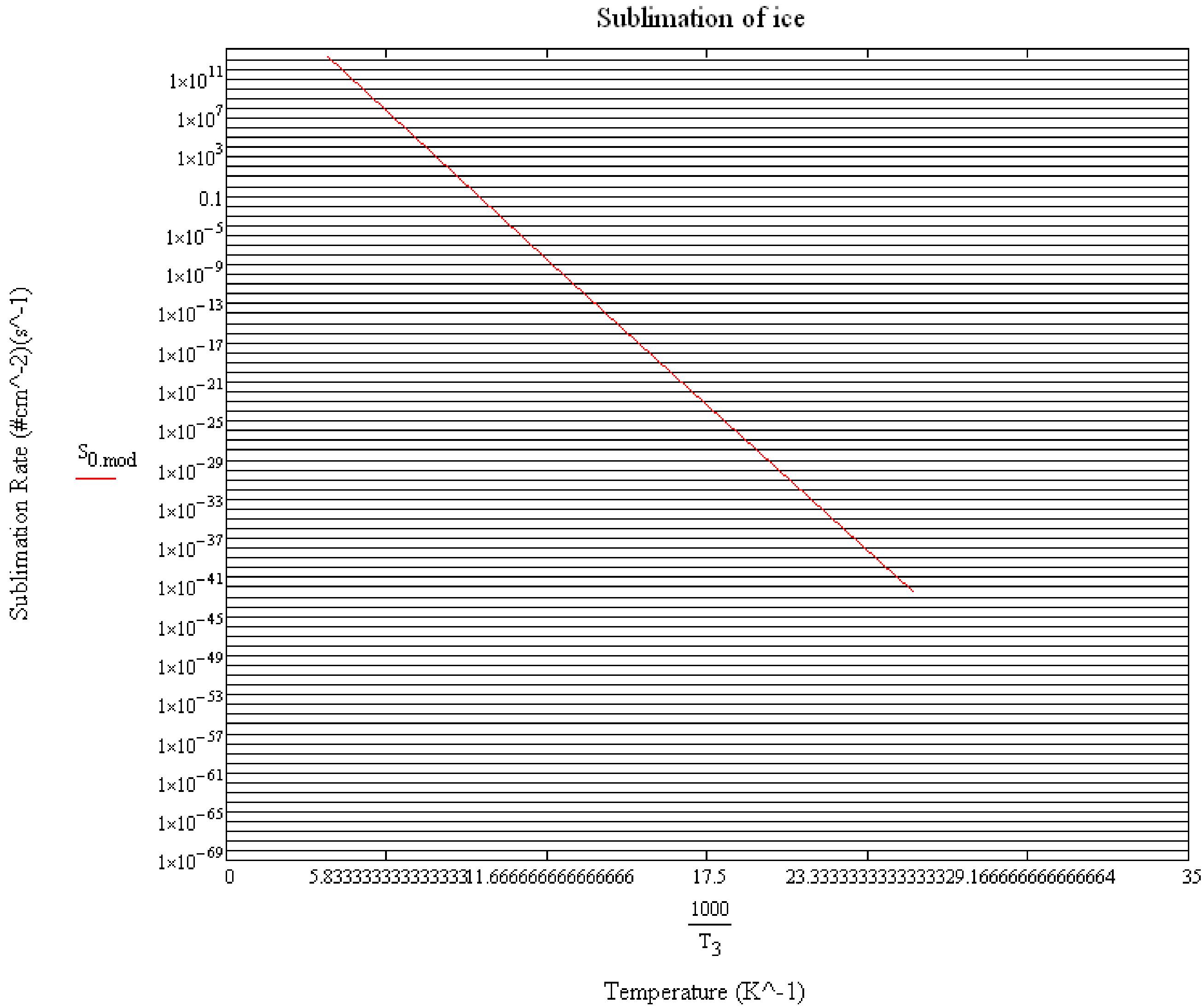

Figure 6: Graphical Results of the Modified Equation for the Sublimation Rate Using Equation (17)

The pattern for both graphs was the same; they are both linear with a negative constant gradient. Although the values are not the same, it was concluded that the sublimation rate calculations that were completed provide reasonable estimations. The difference for the values may be due to the range of the temperature that the equations were valid for. Some other results that were used for a basis comparison for new estimations are below:

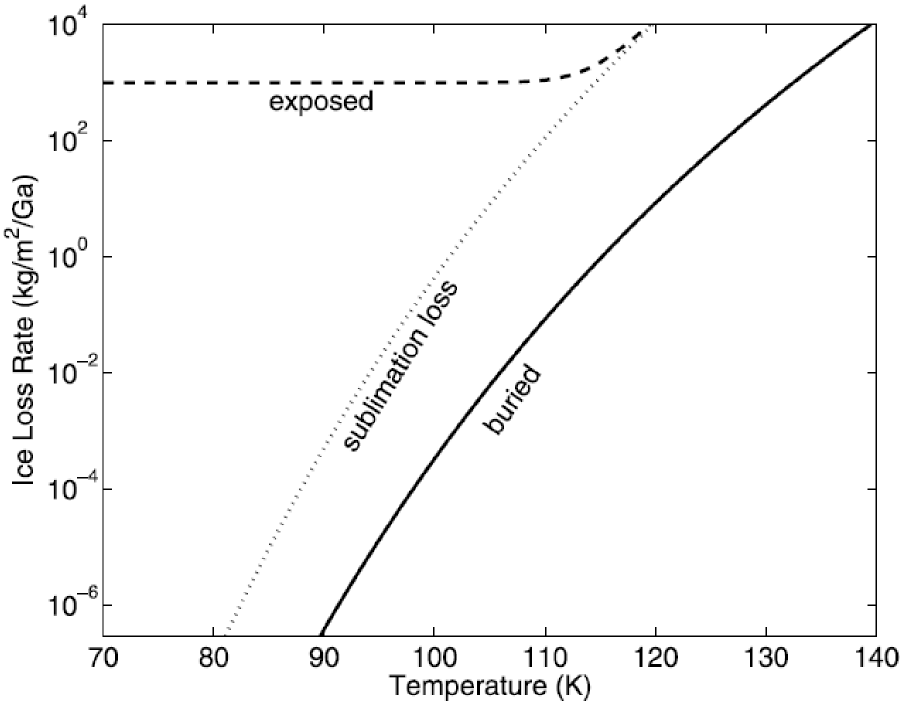

Figure 7: Solid Line- Loss Rate of Ice that Is Buried Under a 10 cm Think Layer of 75 Micrometer Grains [41]

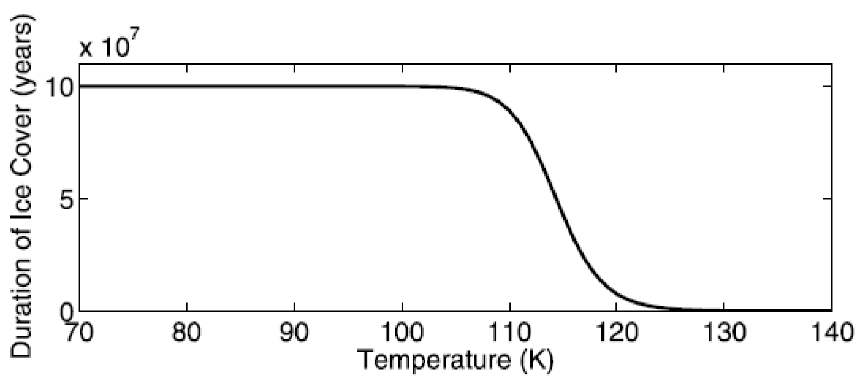

Figure 8: Accumulation of Ground Ice after 1 Billion Years for an Initial Ice Cover [41]

Figure 7 and Figure 8 show the behavior of ground ice over a large time period. It can be seen that the ice cover decreases with the increase of temperature but a small amount of the H_2O will remain within the regolith.

Water Quality

Before beginning the lunar water filtration process or the final decision for applications, the water quality must be known. This includes the effect of temperature on contaminant binding.

The process used to verify the water on the Moon uncovered buried volatiles in the regolith. The LCROSS mission used the Centaur upper stage from the LRO to strike the Cabeus Crater on the Moon. This extended the LRO observations several meters into the soil. The captured emissions from the LCROSS impact plume revealed possible species of chemicals such as CN, NH, NH_2, CO_2^+, CS, Na, Ag, H_2S, and H_2O^+ [18].These were possible sources of contamination in the water; therefore, the water condition must be analyzed further.

Although the focus has been primarily on the search for water ice, other volatiles expected to be trapped in the permanently shadowed regions (PSRs) were detailed. As the LRO satellite flew past the impact site, the Lyman Alpha Mapping Project (LAMP) imaging spectrograph detected far-ultraviolet (FUV) emissions associated with the LCROSS impact. A net spectrum of the plume and elemental concentrations was extracted from this data, detailed in Table 13 [11].

This gave an estimated weight percent of the elements in the soil neighboring the lunar water. The Moon's Polar Regions and PSRs have extreme cold temperatures which affect the chemicals of the regolith. Temperatures range from 35 to 100k in the PSRs compared to 200k in the surrounding Polar Regions [11]. Few species can sublimate at such low temperatures as seen in the previous section; therefore, these regions are potential cold traps for not just water ice but the other volatile species as well [45]. Mark Simon, a chemist from CASTion Corporation (Thermoenergy), believed that it was logical to assume that the water will contain elements that make up the composition of the soil. The assumption that the water will contain ions present in the lunar regolith composition proved to be true.

Table 13: Elemental Concentrations of LCROSS Impact Site [11]

Element	Least-squares fit column density (cm^{-2})	Soil mass abundance (%)
H	$<4.3 \times 10^{9}$	(See H_2)
B	$<3.2 \times 10^{11}$	<0.04
C	$<6.2 \times 10^{11}$	<0.09
N	$<3.9 \times 10^{13}$	<6.6
O	$<8.3 \times 10^{10}$	<0.02
Mg	1.3×10^{12} T 5.3×10^{9}	0.4
Al	$<2.8 \times 10^{10}$	<0.009
Si	$<6.0 \times 10^{10}$	<0.02
P	$<9.3 \times 10^{10}$	<0.04
S	$<1.5 \times 10^{11}$	<0.06
Cl	$<4.7 \times 10^{11}$	<0.2
Ca	3.3×10^{12} T 1.3×10^{10}	1.6
Sc	$<1.7 \times 10^{11}$	<0.09
V	$<4.0 \times 10^{12}$	<2.4
Mn	$<1.9 \times 10^{12}$	<1.3
Fe	$<7.6 \times 10^{11}$	<0.5
Co	$<1.5 \times 10^{12}$	<1.0
Zn	$<4.0 \times 10^{12}$	<3.1
As	$<2.0 \times 10^{10}$	<0.02
Au	$<6.8 \times 10^{11}$	<1.6
Hg	$5.0 \times 10^{11} \pm 2.9 \times 10^{8}$	1.2
H2	$5.8 \times 10^{13} \pm 1.0 \times 10^{11}$	1.4
CO	$1.7 \times 10^{13} \pm 1.5 \times 10^{11}$	5.7

Throughout the investigation the behavior of the Moon water was analyzed. Figure 9, gives an overall view of how the different minerals are spread out across the Moon. Specifically, the image details the side of the Moon which faces Earth. The blue color shows water and OH (hydroxyl) that were detected on the Moon. It was shown that the concentration of OH is higher near the lunar poles. The image depicted a representation of a highly diagnostic absorption of infrared light. Taken by the Chandrayaan-1 M^3, Figure 10 shows an image on the water rich minerals that surround a more recently formed crater. The blue color shown in the image on the right had side represents the ability of these minerals to absorb water. Because of this high concentration at the poles for water ice, filtration methods can focus on the composition of regolith in the Arctic regions exclusively.

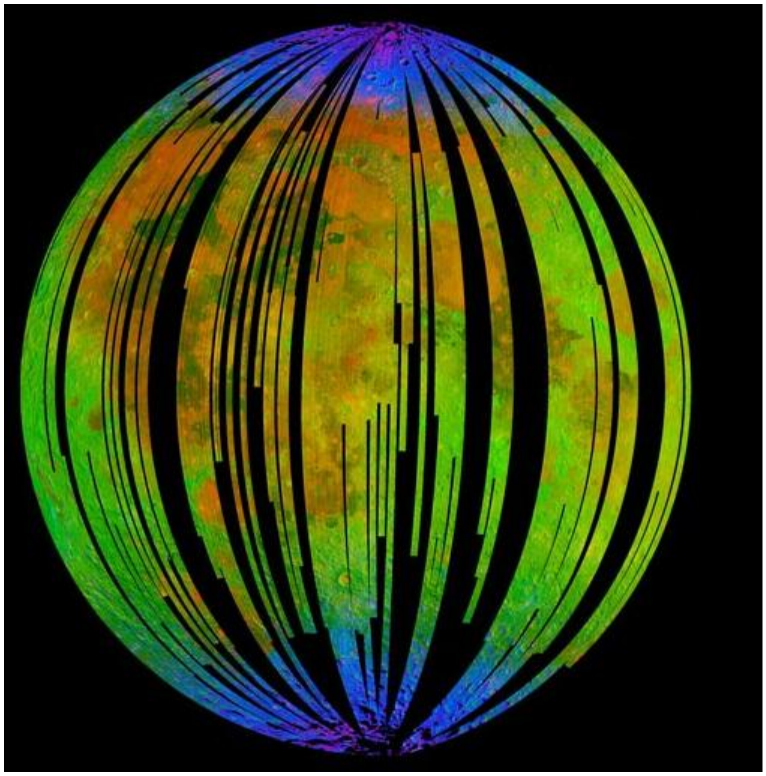

Figure 9: Different Materials on the Earth Side of the Moon, taken by the Chandrayaan-1 Mission [52]

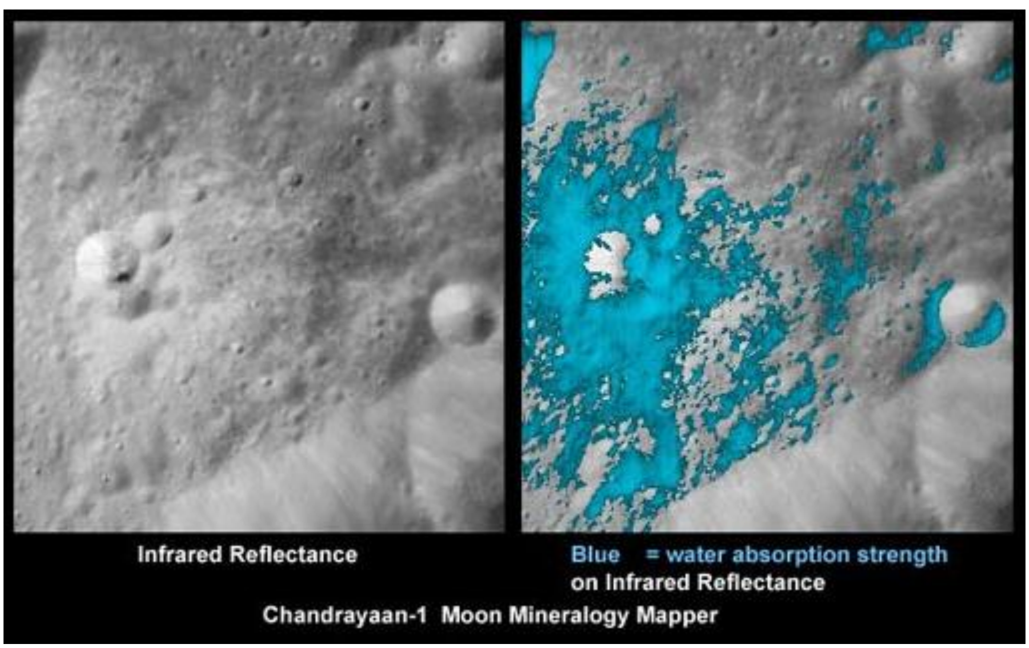

Figure 10: A Young Lunar Crater of the Moon [52]

Another topic focused on was the water abundance change with time of day, the lunar diurnal cycle, were found and briefly discussed in literature review and geography details. This was observed at the Moon's North Pole and was completed between the 2nd and 9th June, 2009. In Figure 11, the red color represents weak signals and the blue color represents strong signals observed by the Deep Impact Mission. The changes in the signals with respect to time are detailed in Figure 11. This cycle would suggest solar wind to be a possible method for rehydration from hydrogen ions that are in the solar wind. Figure 12 shows the behavior of water during the day. In the morning, the water and hydroxyl molecules are contained on the Moon, since the Moon is cold from minimal sunlight. However, later in the day as the Moon heats up, some of the molecules tend to move away from the Moon and thus are temporarily lost. Once again towards evening, the Moon cools down and the amount of molecules in the regolith is similar to that of the morning. Irrespective of which terrain is being considered, the surface of the Moon is hydrated during some time period of the day. As the diurnal cycle is understood and detailed more accurately, other volatiles which are also affected can be taken into consideration for future filtration methods. Figure 11 showed a 90 degree rotation with a seven day period. This knowledge concerning a time range can be used to optimize any possible filtration for water.

The stability of this Moon water was also a topic of interest. It was vital to know the characteristics of the Moon water to suggest methods for extracting and making use of it. Calculations on polar impact craters on the Moon and mercury were conducted [45]. Models very similar to actual craters were used and the effect of sunlight and infrared radiation as well as the thermophysical properties that regolith possessed was also considered. Thermal sublimation played an important role for the time period that the ice deposits will last as well as to help provide information as the polar surface temperatures were believed to behave as a cold trap. Previous thermal models were created and have concluded the stability of the water ice present; however, due to the simplicity of the models, radar observations of the actual Moon surface cannot be analyzed with them. The following are new calculations based on a more accurate model which are similar to the craters on Moon and Mercury. The conclusions were:

- "In unshaded polar surfaces, water ice deposits are not stable against sublimation throughout the age of the solar system on either body [46]"
- "Unshaded subsurface ice is stable within 2± latitude of the lunar poles [46]"

This information helped the team to determine the optimum period for utilizing the water ice. Since the ice deposits were not stable against sublimation and there was evidence for the behavior of the water with the time of day, the team was able to make a valid estimation that morning and/or evening time would be the most optimum for utilizing the Moon water. The strong water signature during this time is shown in Figure 11.

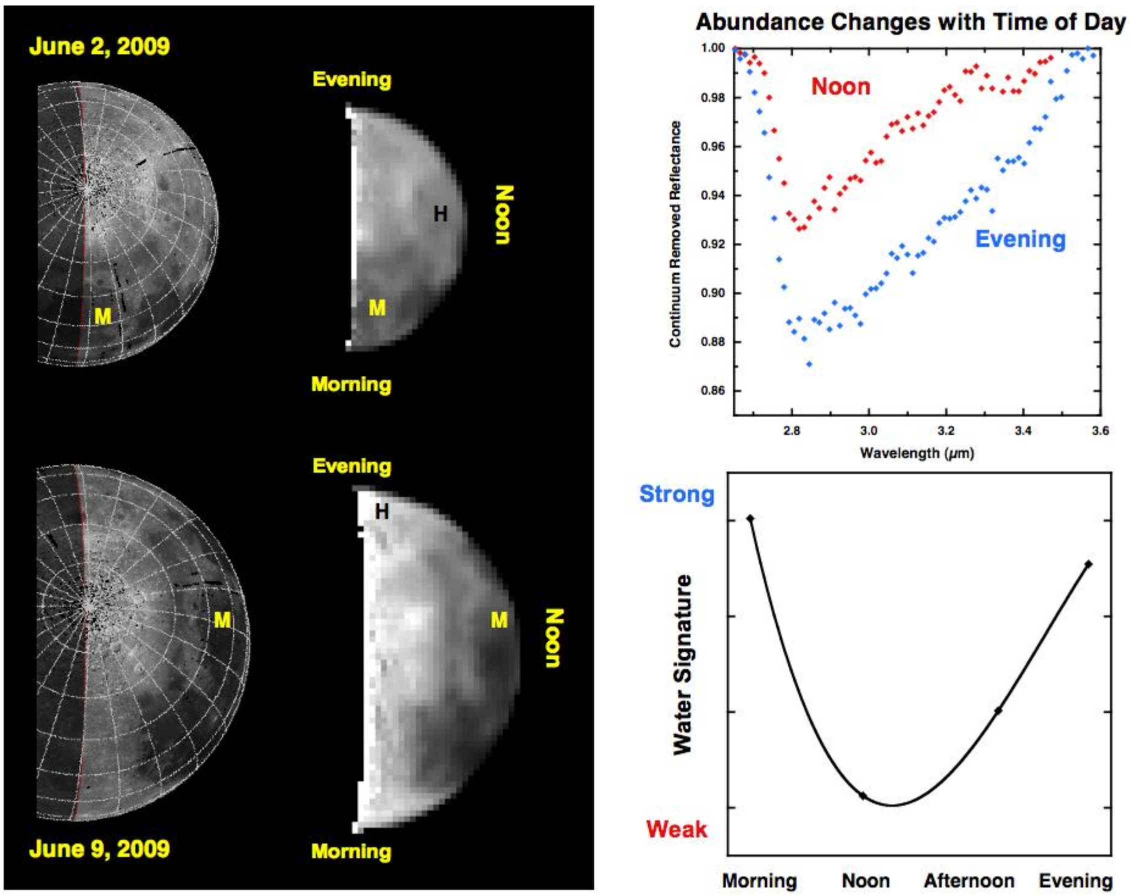

Figure 11: Water Abundance with Time of Day [52]

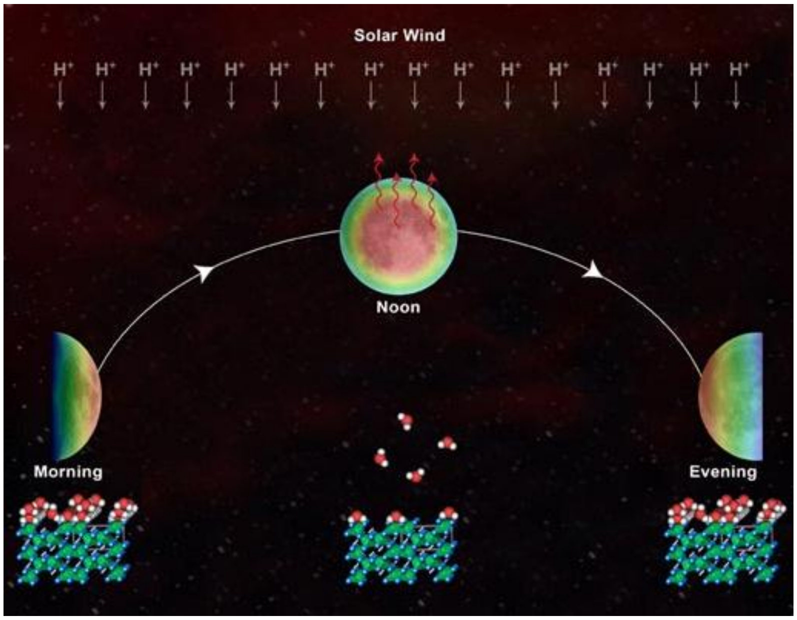

Figure 12: Day Time Water Cycle of the Moon [52]

After samples from the lunar poles are available, the quality of the water can be determined. Therefore, due to the insufficient information on the quality of lunar water, more experiments are required before filtration methods can be determined. Since the discovery of water ice on the moon, NASA scientists have been working on methods to extract the Moon water from the soil. One possibility is using the same concept that is used in a household microwave. A team at NASA created a simulant of the lunar soil and was able to "cook water out of the soil" [47]. For running this experiment, the following equipment was used:

- One-kilowatt microwave oven
- Simulant in a quartz container: where the container is a good light transmitter and is high temperature resistant
- Separate liquid nitrogen cooled container with a simulant: This was used to have the same effect as the ground under the top layer of the regolith

A turbo-molecular vacuum pump was used to create the same environment as that of the Moon. A line was attached from the pump to the flask that collects the water, which was frozen under the liquid nitrogen. Next, both these containers were placed in the microwave and heated for two minutes. One of the main advantages of using microwave energy was that it penetrates the soil by heating it from inside out. It was observed that within a temperature increase from -150C to -50C, the pressure of the water vapor gently increased.

The observations showed the water ice followed a specific sublimation process. The water vapor was drawn to the surface via the vacuum and then it that was collected from the cold trap was once again condensed back into ice. When the regolith sample was weighed, it was calculated that 95% of the ice was extracted within 2 minutes. Of this ice, 99% was caught in the cold trap. “With our experimental metrics using a one-kilowatt microwave, we found that if we could extract two grams of water ice per minute, we could collect nearly a ton of water per year," said Dr. Edwin Ethridge of NASA [47]. Dr. Wiliam Kaukler, who was also a part of the project, stated “there needs to be a large volume of regolith to be heated up in order to extract the ice” [47]. He also mentioned that solar heating is not an option to power the oven since the ice is located within the shadowed craters of the Moon. The other reason for using microwaves is was the fact that it allows for deeper penetration into the soil. The high power and large amount of regolith needed by the oven limits its use. Once the water has been extracted its quality can be more easily determined.

Instruments Past, Present and Future

Previous Instruments

Theories about the possibility of Moon water have existed since the early 1960’s. Numerous space missions led to the confirmation of water on the Moon in October of 2009. Various missions and instruments were compared along with methods used for the verification of Moon water. This allowed for a recommendation as to which method would be ideal for further improvement for locating and gathering the water ice. The list below shows the missions that were analyzed:

- Apollo Mission, 1963-1972
- Arecibo Monostatic Radar, 1992
- Clementine Space Mission, 1994
- Lunar Prospector Space Mission, 1998
- Chandrayaan-1 Space Mission, 2008

First, the Apollo missions were considered. There were six Apollo Missions, Apollos 11, 12, 14-17, that landed on the Moon to collect information on various aspects such as soil mechanics, meteoroids, lunar imaging and solar winds to name a few. One of the conclusions that were made from the Apollo and Lunar Programs was the fact that the Moon, in comparison to Earth, lacks highly volatile elements [48]. The lunar samples collected by Apollo 11 from an area of the Moon known as the sea of tranquility were tested for elements of hydrogen, carbon, oxygen and silicon. One result suggested that a sample contained primarily H_2O. Other NASA laboratories did not produce the same results from the sample vapor. This lead to a belief that that the water's origin was from either a water vapor contamination, contamination from the rockets or vapor from the astronauts while on the mission [49]. This misinterpretation of the Moon's composition was due to the limited capabilities of technology available at that time. Table 14 is a summary of the most influential instruments used during Apollo missions that were considered in this report.

Table 14: Summary of the Apollo Missions [50]

Mission/Launch Date/Duration	Instrument/Experiment	Resolution
Apollo 11 1969 8 days, 3 hours, 18 minutes	• A 70 mm Hasselblad electric camera • Two 70mm lunar surface superwide-angle cameras • A Hasselblad El data camera • Two 35 mm Maurer data acquisition cameras • A surface close-up stereoscopic camera • A television camera: The photographs were taken at locations of interest as well as locations that the Apollo mission was planned to land. • Lunar Dust Detector: The mode of measurement was via power generation	--- --- --- --- --- --- Energy thresholds: 173 keV - 380 keV for electrons; 60 keV - 4.25 MeV for protons; sensors range 84 to 408 K
Apollo 12 1969 10 days, 4 hours, 36 minutes	• Same cameras as the Apollo 11 mission • Lunar Surface Magnetometer: The measurements were on magnetic fields • Solar Wind Spectrometer: For every 28.1 seconds, plasma measurements were made. The protons and electrons at the lunar surface were measured • Solar Wind Composition: Measured the type of ions and energies of solar wind on the lunar surface • Soil Mechanics: The lunar soil models were verified, variability in the lunar soil properties were determined, assisted with the geology of the Moon	±100, 200 or 400 gammas Flux rates of 2.5E6 to 2.5E11 particles cm^{-2} sec^{-1} --- ---
Apollo 14 1971 9 days	• Two 70 mm still cameras with multiple lenses • A 16 mm camera with four lenses • The Lunar Topographic camera • The landing module carried: • Two 70 mm cameras with 60 mm lenses • Lunar Dust Detector: The mode of measurement was via power generation from solar cells that vary due to the layering of the dust • Solar Wind Composition &Soil Mechanics, same as the Apollo 12 mission	--- --- --- --- Power output of each cell 0 - 150 mV; temperature sensors had range of 84 - 408 K ---
		(continued)

Mission/Launch Date/Duration	Instrument/Experiment	Resolution
Apollo 15, 1971 12 days, 7 hours, 12 minutes	• Similar instruments as before were used: Various cameras, Lunar Dust Detector, Lunar Surface Magnetometer, Soil Mechanics, Solar Wind Composition, Solar Wind Spectrometer • Lunar Rover Vehicle: This allowed for an extended range so that a broad variety of terrains could be looked into. The average speed of this vehicle was 10 km/hr	--- Longest traverse ~ 20 km
Apollo 16 1972 11 days, 1 hour, 51 minutes	• Similar instruments as before were used: Various cameras, Lunar Rover Vehicle, Lunar Surface Magnetometer, Soil Mechanics, Solar Wind Composition • Far UV cameras/Spectrograph	--- Far UV range (below 1600 angstrom), 20 degree field of view in imaging mode; 0.5 degree x 20 degree in spectrographic mode
Apollo 17 1972 12 days, 13 hours, 52 minutes	• Similar instruments as before were used: Various cameras, Lunar Rover Vehicle, Soil Mechanics • Lunar Surface Gravimeter: This instrument gathers accurate information of lunar gravity and its variation	--- 1 part in 10^{11}

Arecibo Monostatic Radar results which suggested ice on Mercury’s North Pole, was also used as a basis to suggest the possibility for Moon water. The radar was calculated with CPR’s. This is the ratio of the power in the transmitted sensor to the power in the received sensor [5]. The values obtained from the surfaces that possibly contained ice had a CPR value greater than 1. Such areas were believed to have water ice unless additional features indicated otherwise. The Arecibo Monostatic Radar observed the CPR values of the Shackleton Crater, a crater in the south pole of the Moon. Based on more recent images of the Shackleton Crater and other regions of the South Pole, it was unable to find evidence for water on the Moon [3]. The original experiment was analyzed with different radar for verification. Echoes were received from both senses of circular polarization using the National Science Foundation’s Robert C Byrd Green Bank Telescope, located in West Virginia. The results obtained from the data showed a high signal to noise ratio. Due to the weak calibration between these channels, there was a setback in calculating the CPR values making the results unreliable. This was improved for a test run later on and more accurate CPR values were obtained.

These images consisted of a higher resolution. No connection between the polarization properties and the degree of solar illumination was found as originally believed. High CPR values found in the Sinus Iridum suggested these values were due to a rough or blocky terrain [5]. Therefore, it was believed that the high CPR values alone are not sufficient to state the presence of water ice.

As for the location of the water ice, the literature review showed that the majority was believed to in the lunar poles. Initially in 1994, the Clementine space mission stated the presence of water ice at the Moon's South Pole. One of the goals of this mission was to gather images of the Polar Regions. This provided the first complete set of images with high resolution of the Moon's South Pole. The permanently shadowed areas of the Polar Regions were believed to be the specific location of the water ice. Once again, due to the lack of the required resolution of the images obtained, it was difficult for water ice to be confirmed. There was a need to develop a method to obtain higher resolution images to confirm whether water ice is present on the Moon [4]. Because the possible locations were permanently shadowed, there were additional difficulties for such images to be obtained. Some of the features of the instruments/techniques used in Clementine are [50]:

- Bistatic Radar Experiment: This radar takes a measurement containing a frequency of 2.273 GHz (13.19 cm wavelength). It transmits an unmodulated S-band right circular polarized signal through a 1.1 meter high-gain antenna
- High Resolution Camera: used to obtain images, the camera consisted of a resolution of 7-20 m.
- Long Wave Infrared Camera: takes images of the features in the dark side of the Moon
- Near Infrared Camera: analyses the Moon's surface

The literature showed the formation of water speculated to be the combination of hydrogen in the lunar poles which could combine with available oxygen. In 1998, the data gathered from the Lunar Prospector space mission indicated that there was a large amount of hydrogen in the Moon regolith at the South Pole [51]. Neutron data gathered by the Lunar

Prospector also confirmed the presence of water ice at the lunar poles [53]. Fewer features were observed in the neutrons, which created difficulties in providing a final conclusion.

It was clear that although there were signs of the presence of lunar ice, there was still no hard evidence that could scientifically prove it. CPR techniques alone did not provide definite results. This is why the Chandrayaan-1 mission was significant for the discovery of Moon water. The main goal of this mission, which took place in 2008, was to obtain topographic mapping of the lunar surface at high spatial resolution [54]. Due to the low resolution and insufficient viewing geometry available, the method of using CPR alone during previous missions proved to be ineffective for water ice to be confirmed. This is where the Mini-SAR device, which was sent on the Chandrayaan-1 mission, was different from the previous instruments. An architecture called 'Hybrid Polarization' allowed the use of Stokes Parameter and identified the presence of ice from other surface features such as surface roughness [8]. A more detailed description of this data method can be found in the literature review section of the report.

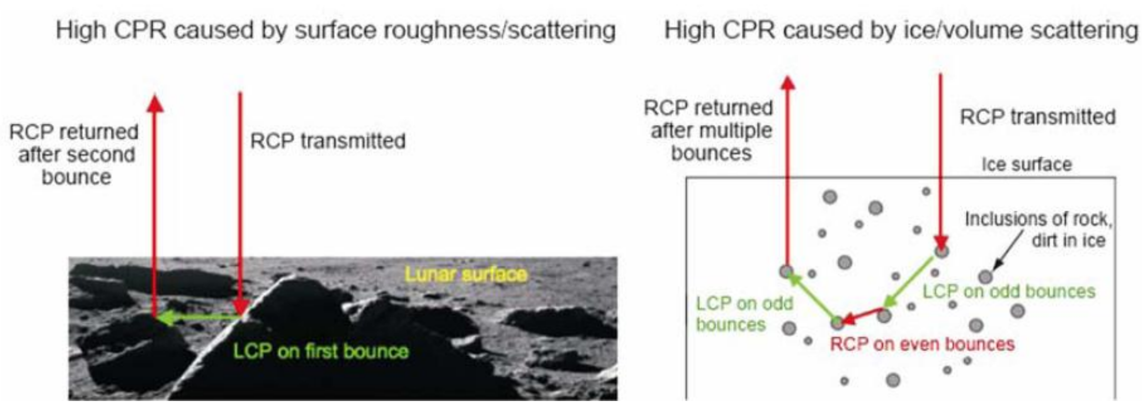

Figure 13: Surface Roughness and Volume Scattering's Effect on CPR Values [8]

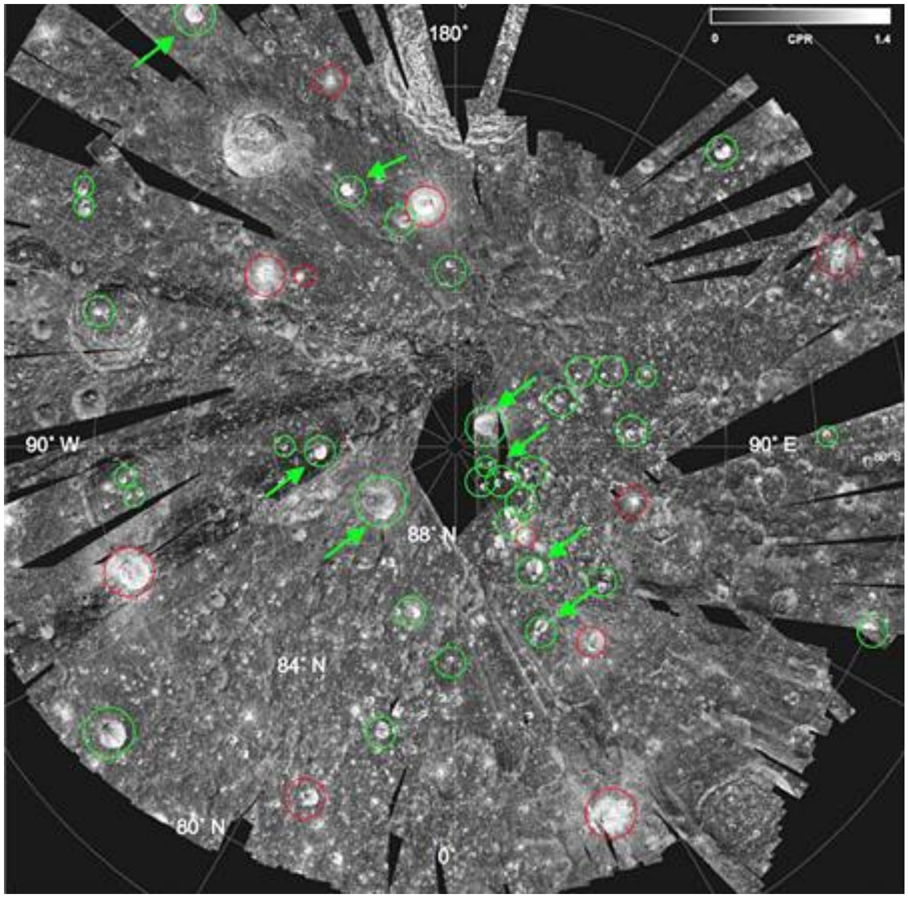

Figure 14: The Lunar North Pole with Mini-SAR Findings Highlighted [55]

Figure 14 was taken by the Mini-SAR device on Chandrayaan-1. It captured the Moon's North Pole details and showed CPR values that were obtained. The red circles indicate high CPR values at the inner and outer rims of the craters whereas the green circles consist of a high CPR at the inner rim but not at the outer rim. This image helped to understand areas that are permanently shadowed and that contain water ice. Due to the increased confidence in the Clementine method, its process is recommended for integration into future missions to investigate Moon water. When the regolith sample will be collected from the craters, other factors such as sublimation must be considered. The following is a quick overview of some specifications of the instruments used in Chandrayaan-1 Moon mission [50]:

- Chandrayaan-1 Imaging X-ray Spectrometer: uses 1-10 keV spectrum detecting X-rays at a resolution of 25 km. It determines the composition of the material at the lunar surface by identifying the elemental composition

- Hyper-Spectral Imager: consists of a resolution of 80 m and this instrument maps the mineralogy of the Moon's surface
- Lunar Laser Ranging Instrument: measures the topography of the surface from the polar orbit using a resolution of 10 m
- Mini-SAR: used for the detection of lunar water using a resolution of 100 m
- Moon Mineralogy Mapper (M3): this is an optical sensor that is used to identify and map mineral composition across the surface of the Moon. The resolution of the instrument is, 70 m/pixel high resolution, 140 m/pixel low resolution, 40 km field of view, 25% coverage high-res, 100% coverage low-res
- The Near-Infrared Spectrometer: also consisted of a resolution of 100 m was used to measure the surface mineralogy
- Terrain Mapping Camera: with the use of a 5 m resolution, the camera was used to generate maps of the lunar surface in high resolution

Table 15 summarizes the missions discussed and the conclusions on the technique and results of each mission. Each missions advanced gathering information on the geographical location of the Moon Water. Due to the conditions in permanently shadowed craters, robots are needed to obtain samples. Excavation methods could potentially supply heat the sample that is being collected, which would skew results. These, and other factors, were considered when advancements needed for water collection were analyzed.

Table 15: Comparison of the Instruments and Missions which Detailed the Moon Water

Instrument/Mission	Method of Analysis	Results and Conclusions
Apollo Space Missions	Soil Samples were gathered from the Moon and brought back to Earth for analysis	The water found in the regolith was said to be from other external sources. Result: No water on the Moon
Arecibo Monostatic Radar	Calculation of Circular Polarization Ratios. The mission was ground-based	The CPR value alone does not provide a 100% accuracy on the presence of Moon water
Clementine Space Mission	High resolution images. Bi-static radar observations	Water on the Moon was not confirmed.
Lunar Prospector Mission	Using the Neuron Spectrometer for taking measurements	A significant concentration of hydrogen was found in the Moon's South Pole regolith. Due to incomplete observations, water ice was not confirmed
Mini-SAR	Hybrid Polarization method was used for determining the Stokes Parameters for the reflected signal	Hybrid Polarization provided a more accurate method for testing of Moon water. Therefore, Moon water was confirmed

Advancements Required for Water Collection

Previous instruments have provided sufficient information to warrant the creation of more advanced equipment and robotics so that better measurements can be made by measuring samples in situ. First, the current capabilities of satellites which have investigated water ice at the poles were analyzed. This provided information on the baseline technologies necessary to determine possible sites for investigation. When combined with research completed on the short coming of the devices and the produced results, a guide for engineers to improve their design was created.

Once the earth based team has decided on the initial location, rovers equipped with devices that search for key features indicative to increased concentrated levels of ice water will be sent to the Moon. To make the most out of these water detecting instruments, the rovers will need to analyze the data and transmit it back to the earth team for verification. While the data is sent to the earth team, the rovers will need to be autonomous enough to decide if an area has enough factors that suggest a high probability of ice water. This will justify staying in or leaving the area. For maximum effectiveness, the rovers should also be able to collect and process the regolith to mission specifications.

NASA has created many successful rovers for Moon and Mars exploration. Recently, similar water that has been found on the Moon in the polar region has also been found on Mars' Polar Regions as well. The most relevant developments for water ice investigations on the Moon are the Mars rovers "Opportunity" and "Spirit." Launched in 2003 these two rovers are part of one mission to investigate water ice on Mars by analyzing the physical characteristics and chemical composition of craters [56].These missions were designed to understand how the water ice came to be on Mars along with the evolution of Mars in general. "Opportunity" and "Spirit" were not designed so humans can take advantage of a specific resource and therefore lack the instrumentation required to go beyond research and general analysis. Their instrumentation can be used as a guideline for rover guidance of crater terrain. A table of the most relevant instruments used in the Mars mission which are applicable to the water ice gathering missions to e proposed is seen below in Table 16

Table 16: Applicable instruments from the Mar's rover missions "Opportunity" and "Spirit" [56]

Instrument	Purpose	Applicability
Panoramic Camera (Pancam)	Determining the mineralogy, texture, and structure of the local terrain	With features of lunar craters conducive to water ice known the Pancam can help determine if the rover should investigate the area further.
Miniature Thermal Emission Spectrometer (Mini-TES)	For identifying promising rocks and soils for closer examination	Once satellites gather more information about the lunar soil this instrument will allow for measurements of highly likely water ice samples
Alpha Particle X-Ray Spectrometer (APXS)	For close-up analysis of the elemental composition of rocks and soil	To find water ice and if sent before humans its data can be used to better chose filtration methods for use
Magnets	For collecting magnetic dust particles	For lunar water ice collection and use magnets can be used to separate the water ice for other elements before other filtration processes. This will lighten the amount of material the rover has to carry.
		(continued)

Instrument	Purpose	Applicability
Microscopic Imager (MI)	For obtaining close-up, high-resolution images of rocks and soil	To decide if the soil and rocks are a size/style conducive to water ice and for finding more features relevant to water ice detection.
Rock Abrasion Tool (RAT)	For removing dusty and weathered rock surfaces and exposing fresh materials for examination by other instruments.	Modification to this instrument will allow investigation into water ice concentrations at varying depths of the moon. This is an area that has been delved into very little due to limitations of the radar used by satellites.

Unlike the design of “Opportunity” and “Spirit,” many researchers have focused on what is needed to find water ice for the purpose of human use. Instruments were chosen for the ability to gather as much data as possible concerning water ice characteristics compared to the current Mars missions with multiple objectives. For the rovers to be the highest level of autonomous possible, combinations of several devices were found to be the most effective. Some examples of possible instruments are Ground Penetrating Radar (GPR), Light Detection and Ranging (Lidar), Stereo Vision, rakers, drills, and specialized ovens which are explained in more detail below.

Stereo Vision is the use of cameras placed on the rover so that the images viewed are slightly overlapping in order to better calculate the rover’s distance to an object. GPR scans underneath the surface of the ground for various patterns that occur when there is ice water. Lidar is used to allow the highest level of autonomy while travelling the lunar surface through light detection and ranging. It has already been used successfully in previous space missions. The methods it employs allow precise 3D topographic maps of its surroundings to be created [19]. This has a twofold benefit of being aware of the surface to decide a course to travel, as well as factoring the landscape into the potential for regolith with ice water.

To complete research investigating the best instruments to solidify the quantity and quality of the ice water, experiments are being conducted in locations on earth that are analogues to the Polar Regions of Mars and the Moon. Devon Island is an area of the Canadian High Arctic, which experts agree to be analogous of Mars and the Moon. Devon Island has polygonal terrain, which is the formation of the earth under the surface. It occurs due to subsurface ice wages and areas where sublimation occurred. When an imitation rover with the combination of GPR, Lidar, and stereo vision was sent to Devon Island it was able to produce data which accurately showed the area's polygonal terrain [19]. The ability of the instrument to accurately reproduce maps of not only terrain, but underground features which suggest a higher likely hood of water ice proves this combination of instruments will be effective in the investigations required in the lunar poles.

Another combination of instruments being researched for effective water ice calculations is X-ray diffraction (XRD) and X-ray fluorescence (XRF) as seen in the NASA's "CheMin" lander. Each instrument compensates for the range of analysis the other is unable to accurately measure. Because "CheMin" is able to analyze both chemicals and mineralogical compositions it can also scan for the compounds with the following elements: Na, Mg, Al, Si, Ca, Fe, F, CL, S. CheMin was sent to laboratories outside of NASA for verification of its accuracies and received a very positive review from each, not only for its measuring capabilities but for qualities required to survive lunar exploration [57]. With the approval from outside agencies, the results and accuracy of CheMin is very reliable. The verification also added to the pattern of effective lunar research created by having redundancies in the capabilities of the instruments in a device. Redundancies immediately available in a device provide highly trustworthy information. Redundancies in measurement capabilities will be a requirement of any advanced rover for future lunar missions. The capability to accurately measure other elements will provide researchers with better information for water devices will need to be created in order to best filter the water for human use.

The Surrey Satellite Technology Ltd. (SSTL), as an expansion on the water ice finding mission MoonLite, created a rover to take greater advantage of the resource called Moonraker. Its instrumentation, landing area, body design, and potential launch date are all completed to optimize not only the finding of water ice but to collect it [59]. Various methods for the procedure rakers should collect the regolith have been suggested. A few examples are front-end loaders, bucket wheel excavators, conveyor belts, and much more. The Apollo mission used a raker that filtered out particles above a certain diameter proving the devices functionally [60]. The basic technology for Moon rakers have been around for some time, now all that is left is optimizing the design for the location where water ice is found. The ability to collect the water ice provides better opportunities for humans to begin using the resource in the most effective manner as soon as they land on the Moon. Setting a Moonraker with a minimum percentage of water ice requirement and only allowing it to collect regolith, which meet that requirement combined with a storage facility for those samples will save astronauts time once they arrive on the Moon. The water ice will be immediately available in a known location for further testing and filtration with the advancement of regolith raking rovers.

Rakers are regolith collection tools which are most effective when specialized ovens are also available on the rover. The raking device will pull regolith into a container and then the ovens will heat the regolith in order to sublime the water particles. One proposed oven, called VAPoR, crushes the regolith to a fine powder, and while heating the regolith performs calculations for what other chemicals are in the sample. It is designed specifically for the lunar surface and invokes a combination of a vacuum pyrolysis mass spectrometer and evolved gas analyses (EGA). The specialized mass spectrometer releases the widest range of volatiles while the EGA provides the highest accuracies of measurements which can operate on the lunar surface. What is the most important feature of this oven is that was designed specifically for long term exploration missions on a lunar rover [61]. Unlike larger ovens which are utilized for large scale conversion of the ice into liquid water, when on a rover VAPoR's makes purpose is highly accurate measurements of the regolith only. Advanced ovens, such as VAPoR, allow greater flexibility in lunar water ice missions. A raker with water ice detection instrumentation can be paired with another rover with sample analysis capabilities. The increased instrumentation with specialized focus presents an opportunity to have more samples of greater reliability.

Drills modified for use on the Moon will be able to dig a few meters under the surface and will be able to take samples to better analyze the ground ice water amount. When reviewing data from the Lunar Prospector, it became obvious to rover designers that the capability to drill to depths of 40 cm as a minimum was needed. Since that time, robotic drilling missions have been undertaken at the lunar surface and have succeeded in surpassing the minimum requirement of 40 cm [58]. After the revised interest in the Moon began in the mid-1990s, numerous studies have been completed to increase the depth the drills will be able to reach. Among those, the University of Surrey (England) was able to create a drill which reached 1-2 meters in regolith simulated soil [62]. As far back as the Apollo missions rudimentary drills reached depths up to 3 meters to sample cores. These drills were not as able to produce reliable data as later models due to issues with heating [60]. When the lunar water cycle and the known effects of solar wind and meteorites of adding and dispersing volatiles are considered a drill is an obvious addition to a lunar rover searching for water ice. The top layers of regolith have inconsistent compositions because of their recent arrival to an area. Underneath those top layers, the regolith has settled over billions of years and the volatiles have been incorporated into it. Drilling will offer the greatest insight into an area's resources because they will be able to retrieve more consistent samples.

A major limitation of current planetary exploration is the power requirements needed to supply rovers that have all the capabilities required for effective exploration: locating, analyzing, and collecting. One power system currently being researched for future use on rovers used for water ice investigations is radioisotope thermoelectric generator (RTG). It is a power source with so much excess power, plans are underway to use the extra heat it produces to melt the water ice and its thermoelectric properties will be a means of electrolysis to the water ice [62]. This system, or a similar one, is much more suited to the poles of the Moon than the traditional solar panels. Due to the consistently low angle the sun's rays approach the article circle, it is likely that a rover at the pole might never see sunlight. Being able to use the power system to melt and electrolyze the water ice would save the placement of an additional instrument to do so. This would allow another instrument which locates water ice to provide additional redundancies thus creating more reliable samples. It should be noted that if the power system does create such excessive heat that a very thermally insulating material will need to be chosen for the body. This is to insure that the heat does not cause the water ice and other volatiles to sublime, destroying the ability to effectively collect and analyze any samples located.

Table 17: Summary of Instruments for the Advancement of Water Collection

Instrument	Purpose	Method	Validity	Comparable Device
Ground Penetrating Radar (GPR)	Analyzing subsurface features for water ice indication	Transmit a high energy electromagnetic pulse into the ground and measurement of reflection	Proven in field tests at Devon Island a Moon analogues site	No comparable device used in planetary exploration; widely used on Earth
Light Detection and Ranging (Lidar)	Allowing autonomous capabilities and creation of 3D topography maps	mm- to sm-scale accuracy of km range by measurement of light	Proven in field test at Devon Island a Moon analogues site	Used in various aerospace applications
Stereo Vision	Rover location and 3D modeling; complements Lidar capabilities	Duel cameras triangulate distance in an autonomous manner	Proven in field test at Devon Island a Moon analogous site	Similar instruments used on previous rovers
X-ray diffraction (XRD)	Chemical composition detection	Analysis of the spatial distribution of X-rays diffracted by atomic structures	Verified in combination with XRF in the "CheMin" NASA device	NASA claims were reproducible by outside laboratories
X-ray fluorescence (XRF)	Chemical composition detection	Energy-dispersive analysis of X-rays fluroresced	Verified in combination with XRF in the "CheMin" NASA device	NASA claims were reproducible by outside laboratories
Moonraker	Regolith Collection Device	Robotic arms and tills	Funded research with a near future launch date capabilities (2013)	Approach is common in lunar robotics competition and theory
Vapor Analysis by Pyrolysis of Regolith (VAPoR)	Regolith sublimation and chemical analysis	Use of a vacuum pyrolysis mass spectrometer and evolved gas analysis	Use of various planetary analog sites to determine known values proved effective	Mass spectrometers have been used on previous water ice finding missions and are a common chemical analysis tool.
				(continued)

Instrument	Purpose	Method	Validity	Comparable Device
Drills	Core drilling for subsurface samples	A controlled heat drill burrows below the top layer regolith	Development of improved method at several universities	Previous Soviet missions were able to drill useable samples
Radioisotope Thermoelectric Generator (RTG)	Power source for extended polar missions	Radioisotope Thermoelectric Generator	One of many new power sources developed for planetary exploration	Produced for the Mars Science Laboratory scheduled for launch in 2011

Water Harvest Site Selection

This report does not focus on the cost or politics involved with making it possible for people to take advantage of the Moon water. Examining only the technological requirements to facilitate life on the Moon, the first step is harvesting the regolith which contains ice particles. For this there needs to be a consensus concerning which areas of the Moon will be the most advantageous for further investigation. For ease of instrument placement and quick communication, the lunar equator on the near side is optimal. In situ data is known from the Apollo missions, but no evidence has shown an amount of water ice worth further investigation. Known features about lunar geography, such as excessive amounts of craters with cold trap due to the little sunlight, make it obvious a crater in the North or South Pole will be selected. If no further investigation was completed, the craters with the most positive results for water ice have been the Shoemaker, Cabeus, and Shackleton craters among others. Because that leaves too much inherent risk for failures or inconclusive findings, more information needs to be gathered before rovers can be sent.

To minimize cost and time, the first step for selecting a landing site for rovers is to have a team on earth analyzing the satellites. Because the initial investigations for water used electromagnetic radiation to find H_2O and OH, the search for a landing site will most likely continue this method. For better verification, more than one method of analysis should be utilized to know the lunar regolith composition. Renewed interest in landing on the Moon, mostly because of the findings of water ice and a belief that its existence on the Moon will help lunar base construction, has led to competitions in mission planning and prototype satellite and rover design.

An example of a new, more in situ, method of satellite was created by SSTL was funded by the UK Particle Physics and Astronomy Research Council (PPARC). It created the architecture and hardware for a new type of mini-satellite called Moon Lightweight Interior and Telecom Experiment (MoonLite). What is special about this satellite program was projectiles would be shot into the Moon regolith to transmit the information back to its orbiter. SSTL was able to decide features specific for investigation of volatiles in the cold traps, such as an antenna that is more robust due to water ice effects compared to other projectiles [59]. The technology for the projectiles already exists for military capabilities and the satellite itself does not require any especially original capabilities, making the use of similar mission architecture very plausible.

A very important piece of equipment which must be utilized for water harvesting site selection is terrain mapping cameras. While previous missions have had camera devices the resolutions have not been effective at eliminating doubt in the measurements of water ice. Measurements which advanced the belief of water ice have been questioned due to the features of lunar geography that can create false positives. Rough terrains can produce the similar results of water ice because of their effects on circular polarization and other radar measurement techniques from the paths the radar are forced to travel after coming into contact with them. Better cameras with higher resolutions than what is currently available will be able to confirm whether or not a crater actually has features which can damage the results to a statistically significant degree.

The “Effective Area for Water Ice Retention” section goes into great detail concerning the features of the craters of interest, which are the most likely on the Moon to contain water ice. It is obvious those craters would be highest on the list for water harvesting sites as they will be investigated in the greatest detail by satellites. An important detail to consider for rovers though, is the distances they will have to travel in order to investigate those craters. The amount of shaded areas and the distance that must be traversed to the next location of significance combined with the likelihood of water ice would be the greatest limiting factor in how many samples rovers will get to take. To make the most informed decision possible, images of the North and South Pole were taken using Google Earth Pro. They are seen below in Figure 15 and Figure 16.

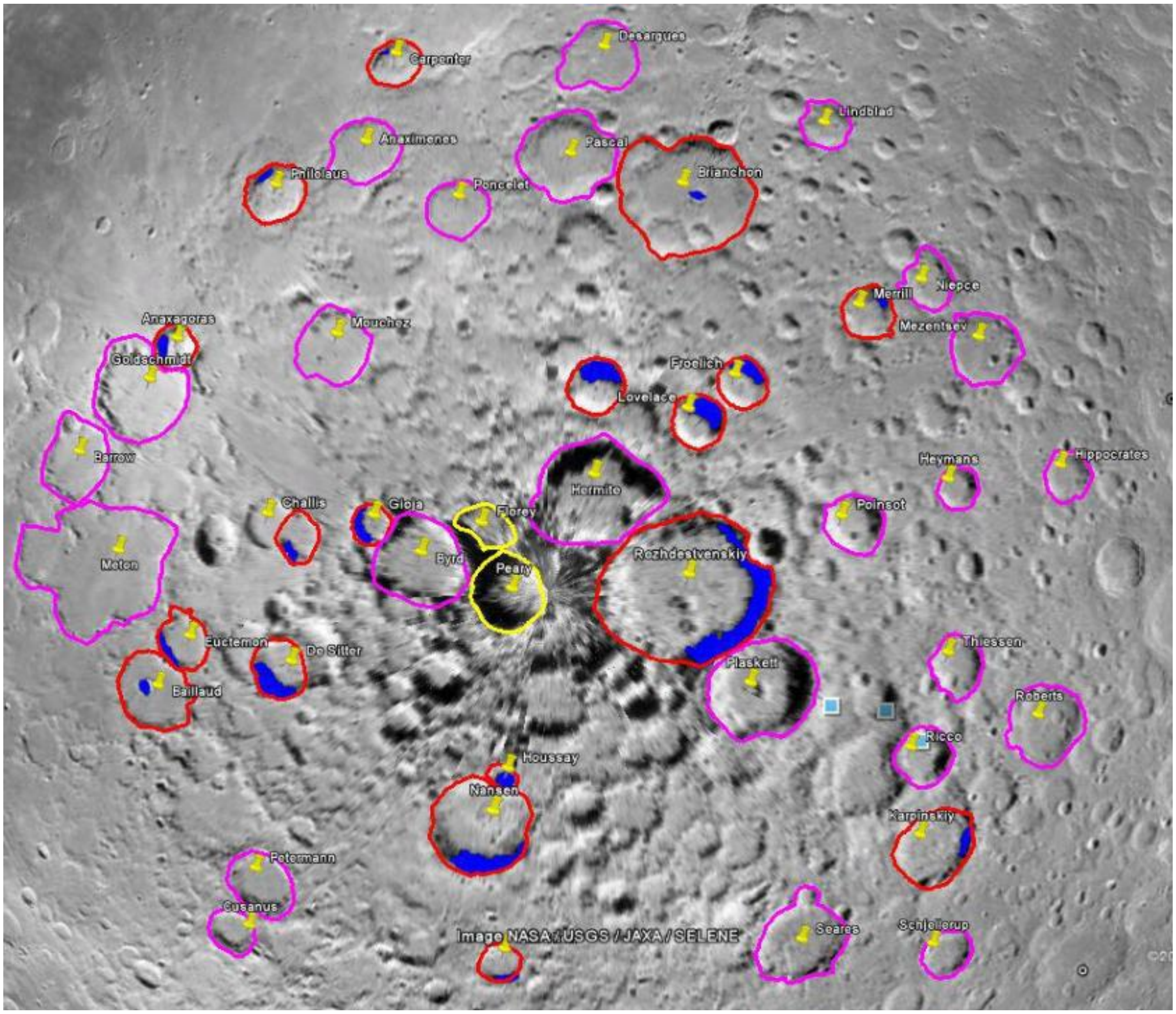

Figure 15: Craters and Shadowed Regions of the Lunar North Pole as Observed by Goggle Earth Pro

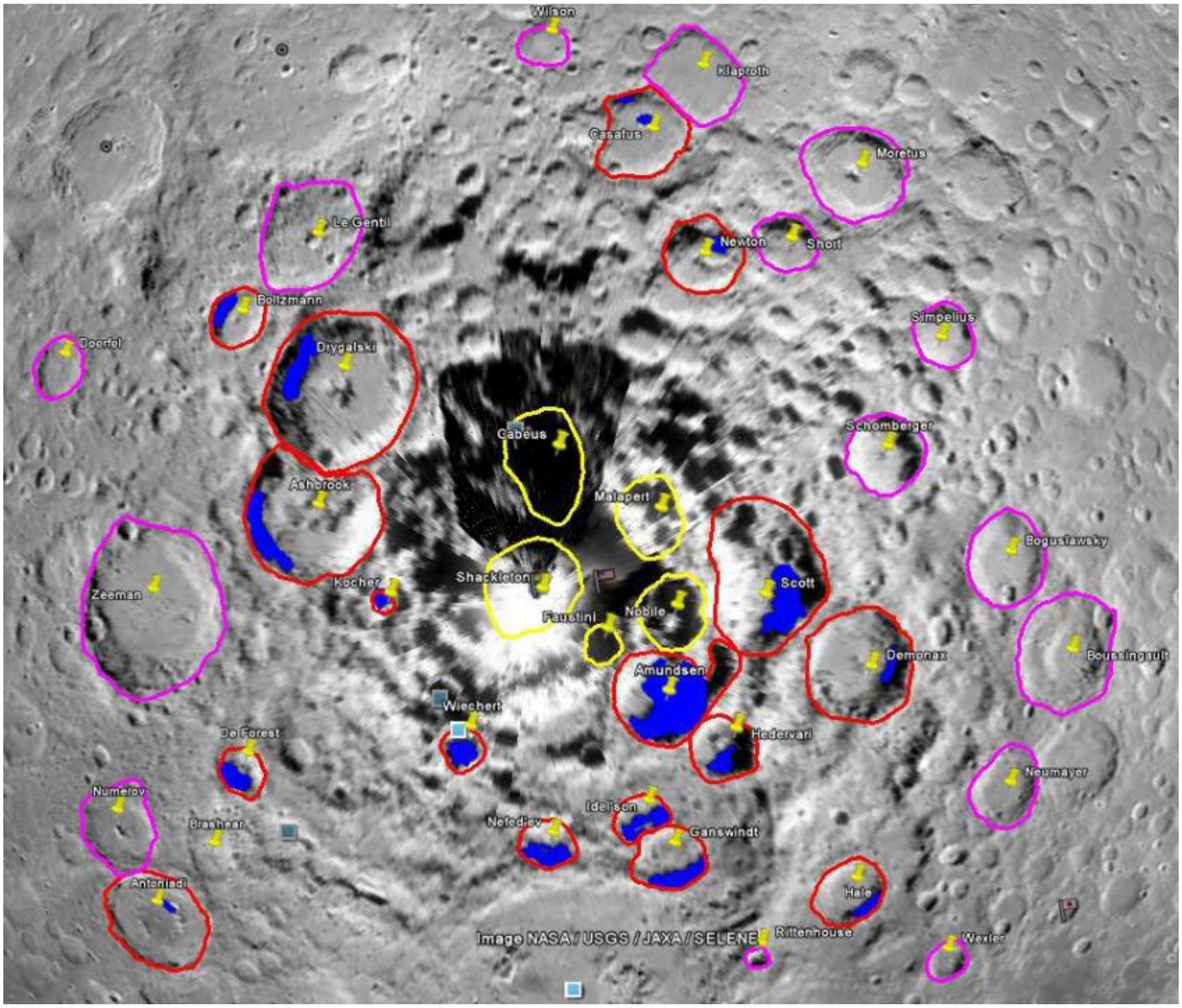

Figure 16: South Pole Craters and Shadowed Regions as Observed by Goggle Earth Pro

The blue regions of each photograph the craters shadow regions of the craters, which are below an elevation of 800 km or significantly lower than the surrounding terrain. The red are the outlines of the crater which shadowed regions. The purple outlines craters of the North Pole which had no shadowed regions. The yellow outlines are craters which are known to have shadowed regains, but whose resolution was too poor to be considered for any calculations. It is obvious the South Pole has much larger shadowed regions. The bottom right of Figure B also shows the craters of Scott, Amundsen, Hedervari, Idel'son, Ganswindt, Nefed'ev, and Wiechert are relatively close together. They are also in a trajectory that would make rover exploration more convenient. A rover will not be able to land inside of a crater because the heat from impact will cause the sublimation of volatiles as the LCROSS experiment showed; therefore, the trajectory is convenient for rover exploration. A rover would be able to land outside of Ganswindt, the least likely because of its latitude, and slowly work its way towards the pole where the most effective cold traps will be in an almost straight path. In the North Pole, the shadowed regions are much smaller than the South Pole and not group together at all. Distances of thousands of kilometers would have to be traversed between shadowed regions. The additional travel and time between shadowed regions allows a greater chance of damage to the rover before it can collect enough data. When considering the lunar geography, rover capabilities, and mission timelines the South Pole is the obvious place to focus for water collection.

There are physical characteristics of craters that make them more or less likely to have very effective cold traps and features for better measurement results. High backscatter and high CPR values suggest the presence of ice, but high incidence angles are generally not conducive to water ice. Ice reflects the radar used in the research missions in a certain manner, but overly rough or blocky terrain can create false positives. Smooth plain floors produce more accurate results along with craters not in the highland areas of the Moon [5]. CPR has been extensively used in attempted measurements of water ice, but because of the lunar geography its ability to produce accurate results is greatly diminished. Until CPR measurements can take into account the geography for the region surveyed, much of the data produced must be dismissed. This effect of the Moon on CPRs capabilities has the potential to lower the areas which can be considered cold traps. In order to receive statistically significant data, one must be able to confirm that the angle the radar is received back to the transmitter is not overly angled. Overly angled represents rocky terrain, which creates useless data. To fine tune locating those cold traps, which will give statistically significant data, required more knowledge concerning the topography of those regions.

The topography tables, located in the "Interactions on the Moon Which Cause Water Ice" section, were used to decide where to focus future investigations and to concentrate resources, such as satellites and rovers, when knowledge of measurement capabilities and Moon geography were combined. Craters with "young" soil are important because cold traps capture the materials which are transported around the Moon by the diurnal cycle, but were not enough criteria for justification for a harvesting site alone. A crater's shadows and topography were required to be taken into account together to be considered a good harvesting site for water ice. This is why Table 7 and Table 8 were also used when craters were analyzed for site selection as they detail highly effective PSRs. Craters with some combination of shadows, young soil, mixed soils, and plains are more likely to bring back statistically significant data which eliminates water ice positive results being unusable due to rocky terrain creating false positive from their effect on CPR measurements. The regolith inside of secondary craters has a high probability of being shaded due to double protection from the primary crater as well and the increased depth. Secondary craters might produce questionable data using modern water ice satellite detection methods. Until that technology is advanced, it is unlikely rovers can be sent out of the way to investigate secondary craters directly because the confidence of finding water ice will be low from preliminary CPR and neutron detection methods.

With Table 3, Table 4, and Table 7, it was possible to examine the topography of those craters found to have shaded areas in Google Earth Pro in order to evaluate the ones with the most effective cold traps. Amundsen has few rims and interior textures along basin and plains material making its shadowed regions likely of a style more conducive both to cold traps and statistically significant data with modern detecting methods Wiechert, being approximately 85 degrees South in latitude, has shown extremely "young" regolith; therefore it has extremely effective cold traps. Though more detail is not known about its ability to make reliable data through water ice detection, it has enough other positive features that it should be investigated anyway. The crater Scott only has well defined rims but otherwise very plain topography making cold traps a possibility at this location. Drygalski has many different types of features within it, with the common theme for each type being highly conducive to water ice retention and effective measurements; it is definitely a crater of high interest and importance for water ice collection. Boltzman only has one area with distinctively "young" regolith, but also has no distinctive physical features besides its rim; this has the potential to be a cold trap within Boltzman whose others features may not interfere with CPR measurements. Antoniadi has the youngest mare material available located directly at its shadowed area but its latitude, 69 degrees South makes it much less likely to be a cold trap despite its composition. Because Antoniadi has very fine textures any preliminary measurements concerning its water ice content can be trusted as accurate. Casatus is the last crater in the South Pole that could be viewed with Google Earth Pro; it showed shadows and has a promising topography for lunar water. Casatus has ejecta from secondary crater impacts, but has been bombarded to a degree that it has extensive plains with no distinctive features as well. The other craters with shadows listed in Table 7, either had terrain not conducive to good water ice detection or terrain which provided no addition support for their water ice trapping abilities. For this reason Amundsen, Wiechert, Scott, Drygalski, Boltzman, Antoniadi, Casatus are the craters to focus on in the South Pole for both satellite measurements and for the advancement of rovers.

Though the North Pole has yielded fewer areas with shadows, topography has the capability of making those shaded regions more effective cold traps than what has been examined in the South Pole. While the North Pole was shown to have significantly less shadowed regions than the South Pole, Table 5 and Table 6 show that though those regions are few they are likely to be very effective. Some craters were included in Table 5 when, although shadows were not visible through Google Earth Pro, their topographies were extremely conducive to cold traps and statistically significant measurement conditions using modern water ice detection methods. Those craters in the North Pole which listed Ip, Ip1, Ip2, and Ec would have uncorrupted data in CPR measurements from their plains and the young regolith indicated the effects of cold traps from the lunar water cycle are fairly numerous. In the South Pole, much less craters without shadows had topographies of interest than what was found in the North Pole. Depending on the capabilities and timeline of missions sent to make preliminary investigations of Moon water, those additional craters of the North Pole should be investigated after craters with shadows are completed.

Of higher interest in the North Pole are the craters, which had shadow regions at low elevations compared to their surroundings; these are Roshdestvensky, Sylvester, De Sitter, Lovelace, Gioja, Froelich, Baillaud, Karpinsky, Carpenter, and Anaxagoras. Due to the very rough terrain of Carpenter and Anaxagora and CPR and neutron detection methods, any positive measurements for water ice would be highly controversial from the potential false positive. Fortunately, the other shadowed craters have plains material within them, increasing the likelihood of reliable data once they are investigated; these plains are interrupted near the edges by the rims by less supportive terrain. The fact that every shadowed North Pole crater has plains material is an advantage over their southern counterparts. Many of these northern, shadowed, plains craters were above the 80 degree north latitude line, which creates a higher potential for limited sunlight entering the crater’s floor.

Water Maintenance for Human Use

Because of the limited quantity of water ice on the Moon and the difficulties that will be incurred when harvesting it, the most reasonable use of the water ice is as liquid water in a lunar base. This conclusion comes after the consideration of several factors: the frequency of events which increase the amount of water ice, the ability to collect the water ice, and the likelihood of devices able to take effective advantage of the water. Solar winds and meteorites are seen as the main contributors to water ice on the Moon, though the effect of meteorites significantly outweighs the effects of solar winds as seen in the water estimate section. These two methods do not increase the level of lunar water ice at a time; the current values were reached after several billion years. As seen in the previous section, cold traps in craters at the poles of the Moon are the most likely place for regolith with a high enough composition of water ice to be of interest. After the events which increase the levels of water ice occur, the water cycle must transport those volatiles to the traps for collection, taking a good deal of time.

Due to these very limiting factors, processes which significantly decrease the amount of water ice are not viable options on the Moon. After a literature review was completed, it was seen that the only two options under consideration was a lunar base and using the water ice for propellant of rockets. A lunar base requires the ability to reuse the resources it initially has for as long as possible. Its entire design concentrates on minimizing loses in a closed loop system. Rocket propellant is a single use item. Modern rockets are not able to directly use water to propel them; a large amount of water would be needed to make the components needed for flight. There are also no known methods to recapture exhausted fuel, so this is a finite use of the water ice which is sparsely available. While it is widely believed that the use of water for rocket propellant will be able to occur with higher efficiency at a faster rate, it is not conducive to long term exploration goals because of its damage to the water ice resources. Basically, rocket propellant from water ice would be a great sink which the sources of water ice will not be able to compensate for.

Lunar bases use water for a multitude of mandatory subsystems, along with the daily amount of water needed per occupant. After further research and exploration is completed, a better estimate of the amount of water ice on the Moon will be known. The advancement of rovers to collect the water ice and prepare it for humans will also play into the applications possible at a lunar base. Once the water ice has been collected, various methods exist to separate it from other volatiles both on rovers and later for further filtration. Guidelines have already been established concerning the needs of various sized crews for water for missions of specific durations. By comparing those guidelines to the current estimates of water ice, the feasibility of a particular lunar base can be established. Until these estimates have greater confidence, which with the advancements of research satellites and rovers, it will not be safe to send people to the Moon.

On lunar bases, to decrease expense created by dependency of Earth resource shipments, a water management system will follow a regenerative model. It is a life support system (LSS) which proper design will almost eliminate water loses. As it will be difficult to continuously collect water ice samples to sustain the lunar base on a daily basis, this life support system is critical to the maintenance of water on the Moon. For a human on earth nutritional requirement studies place the needs of a healthy human at approximately 2500 mL/day, a value which increases in space [63]. When considering the amount of water used by a human for daily living, the amount of water required for various crew sizes can be determined. Table 18 focuses on water requirements for crews to live in a lunar base; it does not include water used in experiments.

Table 18: Water Requirements for a Lunar Base [65]

Types of Mission	Need in Water (kg)
Crew of 4 for 30 days	3514.8
Crew of 4 for 60 days	7029.6
Crew of 8 for 90 days	21,088.8
Crew of 8 for 120 days	28,118.4
Crew of 16 for 180 days	84,335.2
Crew of 16 for 365 days	171,053.6

In a lunar base itself, there is a need to filter the water to varying degrees depending on its use and to recycle it to keep water loses at a minimum. A lunar base breaks down to being a biosphere, where it operates under the assumption that no new resources are capable of being introduced. This assumption will be especially true for the water maintenance systems, as water would be a cumbersome commodity requiring constant delivery otherwise given the usage by the crew and lunar base equipment. A water recovery system will filter the water to varying levels depending on use, as potable water for drinking will have a higher standard than hygiene water for cleaning. It would obviously require monitoring devices to ensure the water was within a certain safety factor for the application it was being sent to.

Humans and the atmosphere management subsystem provide contaminated water to the water recovery system directly. Humans input water to the recovery system through waste hygiene water from bathing, laundry, and waste. The atmosphere management system provides condensation trapped within its vents [63]. The technology for these requirements is already fairly well established. Earth based processes such as microfiltration, reverse osmosis, distillation, UV sterilization are applicable in space [66] but will need to compensate for the difference in the Moon's gravity. Water recovered from humans must receive the highest level of filtration and sterilization because it has the possibility of coming into contact with urine and feces. Currently, how the water was used determines what type of filtration system will be used to purify it and after it is purified the efficiency coefficient of that system determines where the water will be used afterwards. It is important to create redundancies in the water recovery system because any failure could leave Moon inhabitants very sick with limited medical options.

The long standing belief that water ice was available on the Moon lead researchers to create the foundation of knowledge for lunar bases long before the stations was feasible. While papers have been written on the topic before man reached the Moon, one of the first experimental mock lunar bases was created at the Johnson Space center in the mid 1990's. All possible parameters' effect on system performance was studied to maximize water recovery [64].These early investigations mocking space conditions on Earth paved the way for the first long duration base in space, the International Space Station (ISS).

The space shuttles along with the International Space Station have systems for the exact type of water recovery to support human life in space. The International Space Station is the closest existing model for the required machinery to recover water in a zero gravity environment [65]. The ISS is the most advanced example of water recovery available. Table 19 below, highlights the instruments used as the baseline for the ISS water recovery system.

Table 19: Mir Water Regeneration Systems for ISS Water Recovery System Requirements [65]

System	Purpose	Water Recovery Coefficient (%)	Saving of mass delivery (kg)
SRV-K	Water recovery from humidity condensate	100	16500
SPK-U	Urine feed and pretreatment	-	-
SRV-U	Water urine reclamation	80	6150
SRV-HG	Hygiene water processer	98	-

Currently the ISS water recovery system does not produce the same water recovery coefficient. This is due to the integration of the system which is not yet complete, and the incorporation of new features such as fecal water recovery. The water produced by the ISS water recovery system has been proven to surpass all quality requirements set for it without the additional features [67].

It is noted again that the interest of most researchers for a space base is with Mars. Because of the distance between Earth and Mars compared to the Earth and the Moon, any Mars base specifications will work on the Moon. It takes over a year and a half to reach Mars from earth using the lowest cost method when the two planets have the least distance between them while it only takes a few days to reach the Moon. Because of the increased difficulties to bring supplies to a Mars base, its systems will have additional robustness to them to compensate. Because of the analogues between Mars and the Moon, the available information concerning the needs of a Mars base can be used when considering a lunar base. Basically, the requirements for a successful base on Mars will be more than appropriate for a lunar base. A lunar base, which can have supplies brought to it much cheaper and in less time than a base on Mars, made to the specifications as a Mars base will have a very high safety factor in its design.

Conclusions

The lunar water ice can provide benefits for humanity and is a significant resource for future space exploration. Despite water ice being on the Moon for billions of years through the contribution of meteorites, the lunar water cycle and solar winds have spread it across the Moon. Cold traps in the permanently shadowed region of craters in the lunar North and South Poles have water ice in much large quantities than anywhere else on the Moon making them the only locations worth investigating. Currently available data shows the South Pole has a greater abundance of water ice than the North Pole. The geography of both Arctic regions also make it seem like a mission for water ice detection and collection by rovers for water ice will be better suited in the South Pole because of the proximity of its shadowed regions to one another. Before the water ice can be exploited for human use additional, and more reliable, information concerning the lunar water ice is required.

The advancements in aerospace technology used by NASA and other space organizations since the Apollo missions have made detection of lunar resources more accurate. When originally analyzed, Regolith collected from Apollo was not able to conclusively state whether water ice was available on the Moon at all. In less than 50 years, lunar water ice has become a fact and the only question remaining is the amount. The method used by the Chandryaan-1 mission was Circular Polarization, which has limitations concerning its reliability in areas with rough terrain because of potential false positives. As detection methods for water ice and other volatiles improve the exact locations, quantity and possibly even water quality can be measured from satellites to a greater reliability than currently available data can provide. Alternative detection methods along with detailed research into current methods' short comings make the needed advancements for improved water ice detection capable in the very near future.

Once remote sensing for water ice has detailed the quantities at various locations, sending rovers to the Moon for in situ investigations will be completely justified. Currently, there are many obstacles rovers would have to face before they can contribute significantly to making lunar water ice available for human use compared to scientific knowledge purposes. Once satellite detailing is complete, the locations for rover water ice investigations can be planned with realistic values concerning the amount of water ice in a specific area, the amount of distance needed to be traveled, baseline percentages of water ice content in regolith in detection equipment before power is used for processing equipment, among other important specifications. This will eliminate the wasted time spent in regions devoid of water ice which would occur if a rover was currently sent to the Moon for that purpose. The technological advancements needed for rovers to detect, collect, and process water ice from the lunar regolith have been underway for several years with intense support for the scientific community. A multitude of options exist for rovers, both in equipment capability and mission design, with the only limiting factor for the rovers being the additional measurements of lunar water ice needed before such an expensive mission can be justified. Technologically, humans are more than capable of producing rovers able to take significant advantage of the important lunar commodity.

There are several major ways that the lunar water ice will benefit humanity and space exploration. By creating the infrastructure to detect water ice and other Moon volatiles, from the measurement equipment to the satellites to the rovers, on the Moon better technology will be available for exploration to more distant celestial bodies. With the detection of water ice through satellites and the collection and preliminary processing with rovers, significant steps will be taken for a lunar base. Because of the amount of water required by crews for extended stays in space(as water is used for drinking, life support systems, and in experiments) is much greater than in any one location it is available on the Moon, rovers will have to do extensive excavations for water ice before humans would be able to take full advantage of it. Lunar bases provide an abundance of new opportunities to humanity in space; they provide the capability for longer duration missions than currently possible and the first truly in situ investigations into a celestial body besides Earth. Those investigations will provide an abundance of new details concerning space in general, but very importantly the additional resources which could be of use to mankind in space. Having the first space base on the Moon makes sense for a variety of reasons. The first advantage of a lunar base is the expense of set up. The Moon is the nearest celestial body to Earth, making any missions required cheaper than other locations in the solar system. Another important feature of a base on the Moon is its distance to Earth, any emergency situations for the crew or equipment can be quickly resolved.

An infrastructure, which exploited the lunar water ice before human inhabitation of the Moon, would greatly help the success of a lunar base mission. Because of the amount required, any use of a lunar resource will significantly cut down the cost for a lunar base. This is especially true for water, which has a large mass and volume and would take up valuable space for other necessities. Since water recycling techniques for use in space have been in place for shuttle missions, and more extensively for the ISS, once the water ice has been collected very little of it will go to waste. The high efficiency of life support system for treatment of waste water and its reuse currently in use in space will only increase by the time a lunar base is a possibility as all other space technologies have done. So though the amount of water ice on the Moon is small compared to that available on Earth, the technology available to insure its continued usability for the humans at a lunar base is already available. Though this report did not go into detail concerning the costs involved with any of the space missions or technologies involved, the ability to eliminate or even greatly reduce the cost of use for such a highly important commodity like water creates a higher likelihood of the eventual development of a lunar base.

While any deep space missions in the near future can only be done by satellites and other robotic apparatuses, a lunar base has the potential to jump start human exploration in a major way. Because of the lunar water ice, the current technology available for preliminary investigations, and the advancements to collection rovers available in the near future humanity in space has a multitude of advantages to be gained. The scientific community has made a great deal of advancements for the study and use of lunar water. Any human can understand the need and importance of water, so experiments involved with the lunar water ice have the potential for greater community interest since a concept of its relevance is easy to see. Since increase knowledge concerning lunar water ice is easy to justify, the depth of its potential impact to humanity in space is too great to imagine.

Appendix A

Equations and results for solving the sublimation rate of ice. The same temperature scale is used as the experiments used for a basis.

$$T_1 := \begin{pmatrix} 110.00 \\ 150.00 \\ 180.00 \\ 200.00 \\ 250.00 \\ 273.16 \end{pmatrix} \qquad P_{sat.1}(T_1) := 6.1115e^{\left[\frac{22.542\cdot(T_1-273.15)}{273.48+(T_1-273.15)}\right]} \tag{18}$$

Equation (18) represents the relationship used for calculating the vapor pressure vs. temperature which is shown in Figure 17. The temperature range is given in Kelvins.

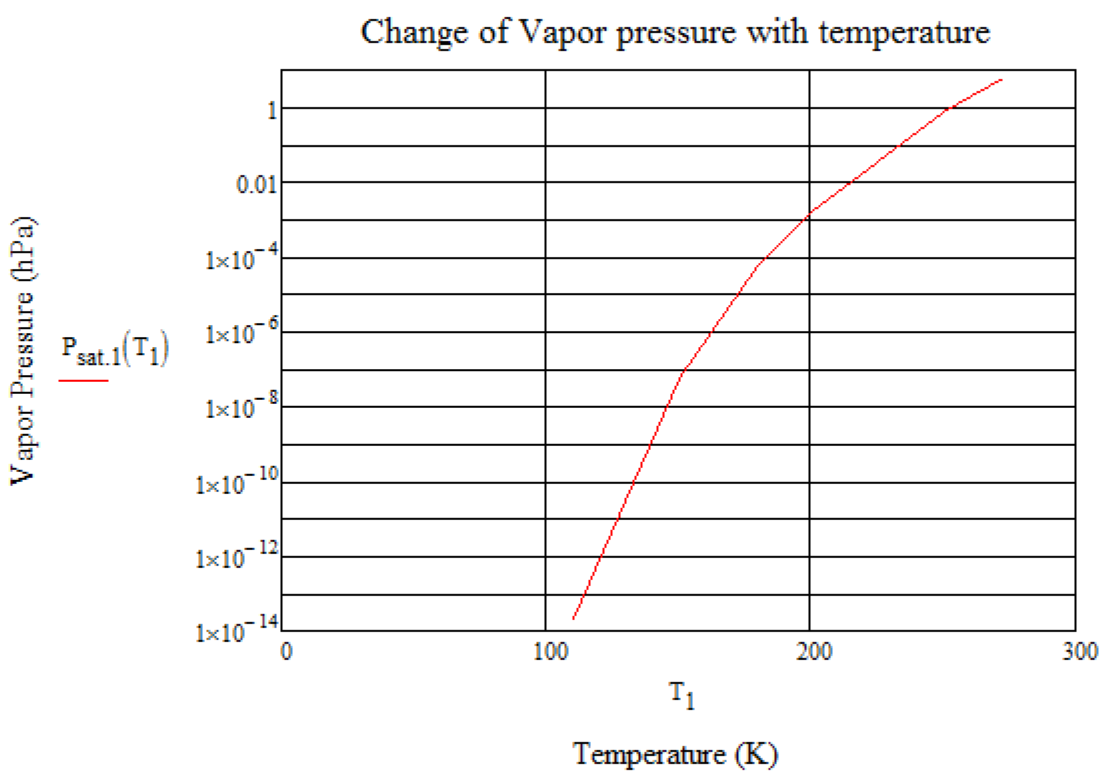

Figure 17: Vapor pressure distribution for equation (18)

$$P_{sat.2}(T_2) := 6.11657 \cdot e^{\left[-13.9281690 \cdot \left[1-\left(\frac{T_2}{273.16}\right)^{-1.5}\right] + 34.7078238 \cdot \left[1-\left(\frac{T_2}{273.16}\right)^{-1.25}\right]\right]} \tag{19}$$

Equation (19) represents the relationship used for calculating the vapor pressure vs. temperature which is shown in Figure 18. The temperature range of equation (18) is considered, i.e.: T_2=T_1.

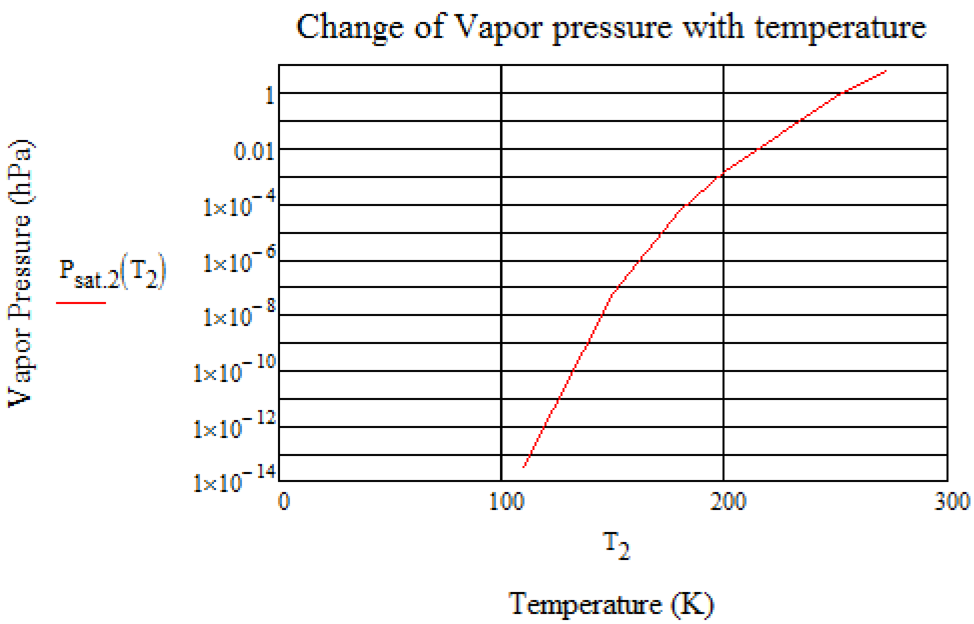

Figure 18: Vapor pressure distribution for equation (19)

$$T_3 := T_1$$

$$P_{sat.3}(T_3) := 0.01 \cdot e^{\left(9.550426 - \frac{5723.265}{T_3} + 3.53068 \cdot \ln(T_3) - 0.00728332 \cdot T_3\right)} \tag{20}$$

Similar methods to obtain Figures 17 and 18 were used to develop Figure 19.

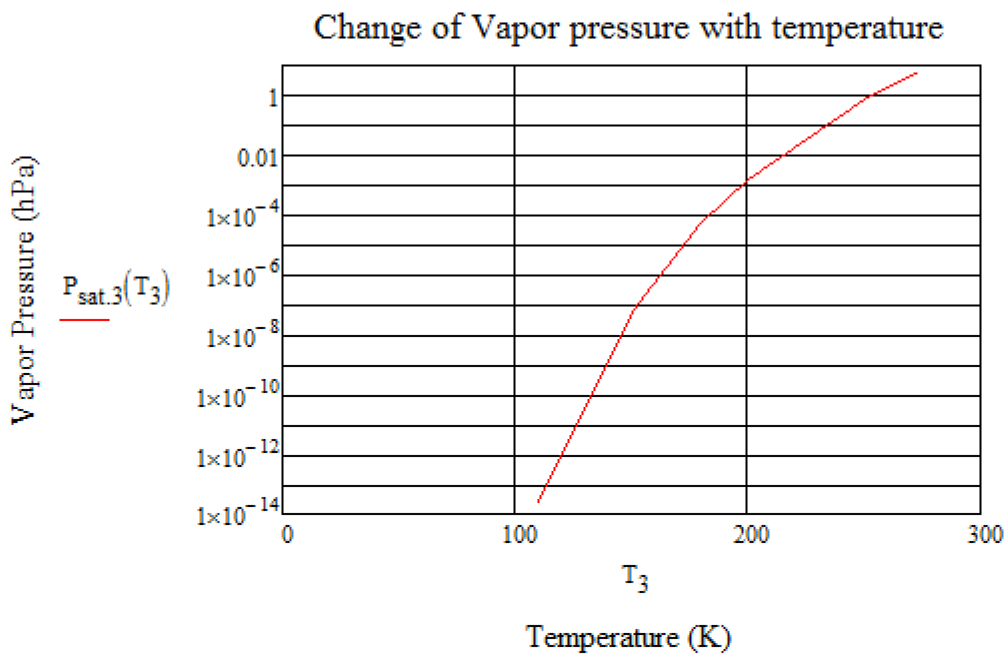

Figure 19: Vapor pressure distribution for equation (20)

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