LOW TEMPERATURE ENGINEERING APPLIED TO LUNAR IN-SITU RESOURCE UTILIZATION

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ABSTRACT

In support of NASA's Exploration Mission low-temperature scientists and engineers have investigated the process of extracting volatile materials form the lunar regolith, their purification/liquefaction, and storage. Volatiles such as O_2, N_2, He and water can be used to support human habitation, while H_2 and O_2 can be used as rocket fuel. Using a sorption pump, passive thermal radiators, temperature control, and a small number of storage vessels and valves, a purification and storage system can be designed to operate inside a permanently shadowed polar crater where volatiles are expected to be most abundant. The basic approach can be used as the basis for a small experiment on a prospecting mission, which will serve as a proof of concept for a much bigger cryogenic fluids facility to support NASA's human exploration effort. A similar design with sufficient radiation shielding can be operated on the Moon's surface.

KEYWORDS: lunar, cryogenic, regolith, thermal radiator.
PACS: 07.20.Mc

INTRODUCTION

In-Situ Resource Utilization (ISRU) is a key element of NASA's vision for Space Exploration. Since the Apollo missions, numerous processes for extracting lunar volatiles have been proposed [1-5]. This year, NASA has conducted an internal Exploration Systems Architecture Study covering various exploration aspects including lunar sortie and outpost missions. Another recent event is the Moon Regolith Oxygen (MoonROx) Challenge sponsored by NASA's Exploration Systems Mission Directorate and the Florida Space

TABLE 1. Average lunar volatile composition.

gas	H	He	**N**
concentration	59 ppm	21 ppm	96 ppm

Research Institute (FSRI) to extract at least five kilograms of breathable oxygen from simulated lunar soil during an eight-hour period [6].

Our knowledge of lunar regolith composition largely comes from Apollo and Luna samples. Concentrations for volatiles of interests are tabulated in Table 1. The hydrogen and helium contents are averaged from samples of six Apollo missions (A11, A12, and A14–A17), the nitrogen content is averaged over samples from the same Apollo missions and two Luna missions (L16 and L20). The oxygen content in the regolith is more difficult to quantify since it is in the form of oxides. However, it appears to be the most abundant among the volatiles. A myriad of processes have been proposed for liberating oxygen from the oxides. The process complexity and oxygen yield vary in a broad range. Examples of the processes include hydrogen reduction of Ilmenite, hydrogen sulfide reduction of Ca, Fe, and Mg oxides, carbochlorination, fluorine exchange, and ion separation.

Since its formation between 4.5 and 4.6 billions years ago, the Moon has been continuously bombarded by comets and meteorites. Water-rich comets and meteorites may have left traces of water on the Moon, especially in the permanently shadowed craters in the polar regions. There is evidence suggesting the existence of water ice on the Moon based on data from the Clementine (1994) and Lunar Prospector (1998-1999) probes [7]. The existence of water ice would make electrolysis an economical option for producing hydrogen and oxygen.

It should also be noted that in the lunar helium content, the helium 3 isotope makes up roughly 1/2600 that of helium 4. Mining helium 3 for fusion energy for future space exploration and settlement has also been proposed [8].

Utilization of lunar volatiles involves exploration, extraction, separation, and storage. The current effort at JPL has been summarized elsewhere [9]. This work focuses only on the design, construction, and demonstration of a ground-based miniature gas separation system as a proof-of-concept unit. Accordingly, the scope of this paper is confined to aspects related to separation and storage.

LUNAR ENVIRONMENT

Unlike most satellites of other planets, the Moon orbits the Earth in synchronous rotation in a plane closer to the ecliptic plane (5.1454°) than to the Earth's equatorial plane. Its rotation axis has an inclination of 1.5424° with respect to the normal of the ecliptic plane. This configuration favors the use of passive thermal radiators in the polar regions, which will be discussed later in more details. Moreover, at locations other than the polar regions, a power source based on solar energy is only available roughly 50% of the time.

Between night and day, the Moon experiences dramatic temperature swings. Its average surface temperature varies between 120 and 380 K with extremes at 40 and 394 K. This type of harsh environment imposes stringent requirements for human habitat and on equipment that demands continuous reliable operation.

The lunar atmospheric pressure is at ~ 3 x 10^{-13} kPa. This vacuum environment is advantageous to thermal insulation at cryogenic temperatures. On the downside, it also has an adverse effect on heat dissipation. Rejection of waste heat from any lunar equipment is limited to thermal radiation to space.

Depending on the duration of the mission, protective measures against cosmic rays, solar flares, and solar wind (inflatable gas containment structure would be vulnerable) should be thoroughly evaluated before deploying any lunar surface structures.

The Moon is also covered with a layer of very fine dust of micron-sizes, which could cause performance degradation or even detrimental damage to lunar surface equipment, and could potentially pose serious health hazard to astronauts.

SEPARATION TECHNOLOGIES

Ground-based separation technologies have matured over the years. Widely used methods include adsorption, diffusion, and distillation [11-14]. Based on the operating temperature, these methods can be classified in two major categories: cryogenic and non-cryogenic with distillation falling in the former and adsorption and diffusion the latter.

Adsorption

Several techniques based on adsorption have been commercialized over the past twenty years or so. These techniques use physical properties to separate and purify gases and include pressure swing adsorption (PSA), vacuum swing adsorption (VSA), pressure and vacuum swing adsorption (PVSA), and temperature swing adsorption (TSA). The PSA, VSA and PVSA processes operate at mostly ambient temperatures and involve the use of adsorbents that adsorb specific constituents at higher partial pressures and desorb at lower pressures, and the TSA process uses adsorbents to adsorb specific constituents at lower temperatures and desorb at higher temperatures. The adsorption process is flexible in cycle time. However, good knowledge of gas composition and adsorbent characteristics is critical.

Diffusion

In a diffusion process, gas constituents are separated by difference in permeation rates through membranes as selective gas diffuses through membrane from retentate side to permeate side. Higher operating temperatures increase permeability but reduce selectivity. Metal, ceramic, and polymer membranes made in various shapes have been used for diffusion separation. They are highly modular and system cost is mostly proportional to unit capacity. In certain applications, other methods have to be implemented either prior to or after the diffusion separation process since some contaminants cannot be completely removed by the membrane process unless their levels are tolerable.

Distillation

Distillation or cryogenic separation has been commercialized since early 20th century. It relies on differences in boiling points to separate and purify gases. Distillation columns are used to separate gases at various temperature levels. It is considered as the most cost effective approach for large plants for high purity products. Compared to processes utilizing adsorption and diffusion, cryogenic separation is less reliable and occasional warm-up is required for lines clogged by frozen contaminants.

Comparison and Selection of Separation Techniques

Each separation technology has its advantages and disadvantages. Selection of separation techniques for ground-based facilities highly depends on the desired production rate. The current effort is inclined toward a hybrid system with passive cooling and adsorption for gas separation, liquefaction, and storage. The selection of a cryogenic passive thermal radiator system is a logical choice to take advantage of the lunar thermal environment, minimize the need for electricity, and more effectively store volatiles of appreciable quantities.

Again, this approach is targeted at a small demonstration unit. Continuous operation of a large-scale liquefaction system would definitely require considerable amount of electric power, which has to be dealt with at a later time.

DEVELOPMENT STATUS

The most immediate development effort is focusing on two tasks:

- Design and analysis of a passive, cryogenic thermal radiator system for lunar application
- Development and demonstration of a ground-based miniature gas separation system.

Successful completion of these tasks will prove the readiness of key technologies required for a flight unit in the future.

Cryogenic Thermal Radiator

Sun shields and thermal radiators have been routinely used in spacecrafts for thermal control and management [10]. Cryogenic thermal radiator can be used for liquefying and pre-cooling of the lunar volatiles. Preliminary study indicates that nitrogen liquefaction can be achieved by the use of passive radiator alone in the lunar environment within reasonable size limits. The radiator needs a minimum of three stages (warm, intermediate, and cold) assuming that it takes a conical V-groove configuration and that the warm stage is exposed to the sun on one side. The size of the radiator depends on the temperature of the incoming gas upon extraction and the intended gas production rate. The location of the radiator also plays a crucial role on radiator sizing. Ideally the radiator should be deployed in the polar regions. Any location of lower latitude would adversely affect the overall size of the radiator system as it becomes more difficult to point the radiator in the normal direction of the ecliptic plane (away from the sun) as indicated in FIGURE 1.

Aside from geometry considerations, the optical properties of the radiator surfaces are also critical to the performance of the radiator. Since the beginning of the space age, significant effort has been devoted to development and qualification of surface coating/finish techniques in a broad temperature range [14-18]. The optical properties for a radiator surface,

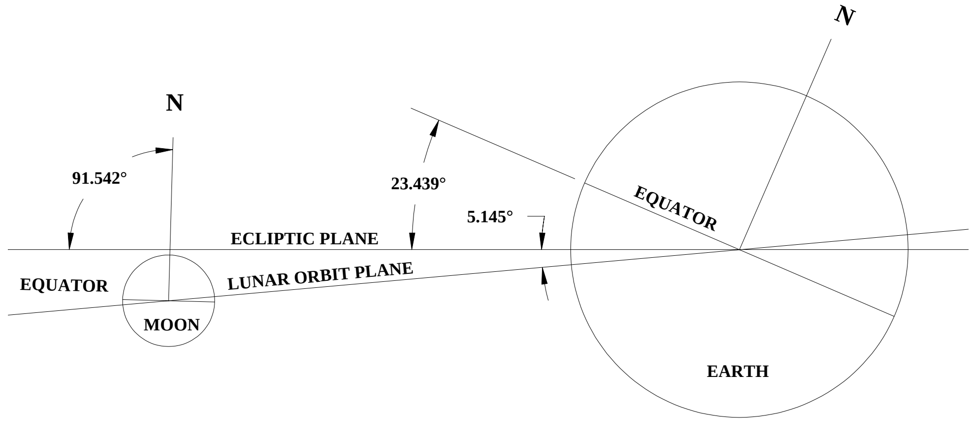

FIGURE 1. Schematic of lunar orbit plane with respect to the ecliptic plane.

especially the absorbtance and emittance, are to be tailored according to their operating temperature using the transcendental equation

$$\lambda_{\max} T = \frac{C_2}{5} \frac{1}{1 - e^{-C_2 / \lambda_{\max} T}} . \tag{1}$$

The solution of which gives the wavelength λ_{max} at the emissive power peak for any given temperature T. The Planck's spectral energy distribution constant C_2 in the equation has a value of 14388 µm-K. The solution of the equation yields one form of the Wien's displacement law as $\lambda_{\max} T = C_3$ with C_3 = 2897.8 µm-K. Wavelength values corresponding to maximum emissive power are tabulated in TABLE 2 at temperature levels of interest. For the radiator system under discussion, since the warm stage is primarily used as a sun shield, light-weight structure options should be considered. Coatings providing low solar absorptance and high infrared (IR) emittance, or low α/ε ratios, are ideal for the sun-facing outer surface. Similarly, the space-facing surface of the cold stage needs a coating or finish with high IR emittance. The rest of the surfaces would be mostly facing one another and therefore require low IR emittances in their respective wavelength ranges.

Parametric finite element models in I-DEAS TMG are being developed to simulate the lunar environment and cryogenic radiator performance. Results of the analysis will be applied to the design of the ground-based miniature gas separation demo unit.

Ground-Based Miniature Gas Separation Demo Unit

Design and construction of a ground-based miniature gas separation system is underway

TABLE 2. Wavelength values for maximum emissive power at typical temperatures.

T (K)	3.19	4.21	20.27	27.09	77.36	87.28	90.18	111.7
λ_{max} (µm)	908.4	687.7	143.0	107.0	37.5	33.2	32.1	25.9

at JPL for demonstration purpose. The system will be housed in a vacuum chamber where lunar thermal environment will be simulated by the use of a two-stage cryocooler. Gas constituents will be mixed proportionally based on current knowledge of their composition in lunar regolith. The system will be capable of liquefying all gas constituents except helium which will be stored in an adsorbent bed. For simplicity, there will be no "ortho/para" conversion catalyst beds in the system. This is justified by the small quantity of hydrogen gas involved for the demonstration process.

Based on the above-mentioned results of finite element analysis for the passive cryogenic radiator system, one or more temperature stages will be established corresponding to each radiator stage using Proportional, Integral, and Derivative (PID) algorithms. Through the use of heat exchangers, the gas stream will be brought to a lower temperature at each temperature stage with sensible heat for every gas constituent being removed. Temperature stages for liquefaction will condense oxygen, nitrogen and hydrogen at their respective saturation temperatures. The coldest temperature stage is expected to reach ~10 K, which will be used to cool the charcoal adsorbent for helium storage.

SUMMARY

Lunar ISRU is a key element of NASA's vision for Space Exploration. Volatiles separated from lunar regolith can be used for human habitat life support and as fuels for the return journey of lunar vehicles and other space vehicles such as those for Mars missions to substantially reduce their earth-to-orbit mass. The current effort focuses on development of a ground-based miniature gas separation system utilizing a cryogenic thermal radiator. This unit should serve as a prototype of a flight unit in a future perspective mission.

ACKNOWLEDGEMENTS

This work is carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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