FRACTIONAL DISTILLATION IN A LUNAR ENVIRONMENT

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The establishment of a permanent lunar base will undoubtedly employ distillation operations as a routine practice. Reclamation of vital fluids along with products from chemical processes will lend itself to fractional distillation. The lunar environment, with reduced gravity and pressure, will dictate design modifications and offer some pleasant advantages. Column area will increase to maintain the same flow rates as Earth-based counterparts. Plate efficiencies can increase, allowing shorter columns. Thermal insulation will be facilitated by the lunar atmosphere, as well as low pressure "vacuum" distillation.

INTRODUCTION

With the development of a reliable space transport system, extraterrestrial engineering is becoming a respectable field of endeavor. The detailed engineering for maintaining a space station or lunar base, along with possible manufacturing processes, presents a challenge for scientists and engineers.

The establishment of a permanent lunar base will employ separation techniques as part of routine necessity. Recycling precious body fluids, in addition to solvents and products of chemical manufacture, could lend itself to fractional distillation. The lunar environment, with reduced gravity and pressure, will offer some unique possibilities for clever designs with a concurrent struggle to overcome the hardships.

Why use an age-old process like distillation when there are many "space age" separation techniques (such as membrane technology)? Distillation uses simple, hearty equipment that operates in a dependable manner, equipment that is not easily damaged if operation is in error. Many of the construction materials could ultimately be derived from lunar sources, saving the transportation costs of Earth-based goods. Most important, distillation uses heat energy as the main driving force for separation.

On the Moon, shaft and electrical energy will be at a premium. Whether from solar, combustion, or nuclear sources, heat energy will be more abundant and more efficiently obtained than shaft or electrical energy. In the allocation of such a valuable commodity, it makes good sense to employ processes that utilize heat directly, saving the shaft and electrical energy for those processes that cannot be driven any other way. Waste heat from ongoing processes may be of a quality suitable for driving distillation, thus realizing further economy.

The lunar environment will offer some unique advantages for distillation processes. Vacuum distillation will be possible due to the cryogenic temperatures available on the Moon. With vacuum distillation lower heat loads are realized with cleaner separations and with the possiblity of breaking azeotrope systems. With a radiation barrier the distillation columns will be essentially enclosed in a giant "thermos bottle," realizing very low heat losses, so the energy injected into the processes will be used efficiently for driving the separation. The constant nature of the lunar atmosphere will facilitate the process control, resulting in consistent product output and quality. In contrast, heat loss from Earth-based columns is of major concern, especially coupled with changing weather patterns that complicate the process control.

Fractional distillation is a mature engineering field backed with years of experimentation that resulted in practical design. The approach taken here is to utilize this existing knowledge, coupled with dimensional analysis and scaling arguments, to modify the design of Earth-based columns for lunar operation.

BACKGROUND IN DISTILLATION EQUIPMENT

The anatomy of a fractional distillation process is shown in Fig. 1. The heart of the unit consists of the fractionating column, basically a tall vertical pipe where the liquid and vapor experience intimate contact and where mass transfer between phases is effective, thus achieving component separation. At the bottom of the column is the reboiler, a vat of boiling liquid from which the vapors flow upward into the bottom of the column while the condensed liquid emanating from the column flows downward into the reboiler. The heat for driving the separation is injected into the reboiler.

At the top of the column is an overhead condenser that converts the enriched vapor effluent into a liquid, rejecting heat into the environment. A portion of this liquid is tapped off as head product, the balance being returned to the top of the column as reflux. The ratio of the amount of liquid returned to the amount tapped off is called the reflux ratio and is an important quantity in the design of a distillation process.

Most distillation processes are designed to operate on a continuous basis, unlike the familiar connotations of a moonshiner's batch still for making "white lightning." A continuous feed is introduced into the column at the point where the concentration of components in the feed matches that in the column. The enriched head product is continuously withdrawn from the top while depleted bottoms are continuously removed from the reboiler.

The design of what goes inside the column to achieve the intimate contact between vapor and liquid is somewhat of an art as well as a science. The column can be filled with plates, each having a standing pool of liquid that vapors bubble through, giving discrete or stage-wise contact. The column can be packed with irregular objects, providing continuous contact between the liquid trickling down and vapor percolating up. Presently, the most popular column design uses plates, with future trends leaning towards packed columns. This paper will deal with plate-type columns, with packed columns being the subject of another study.

There are many types of plate designs, with sieve tray plates being the most common. The sieve tray plate will be considered here initially, with the scaling arguments derived being general for most types of plate columns. Figure 2*a* shows a cross section of a

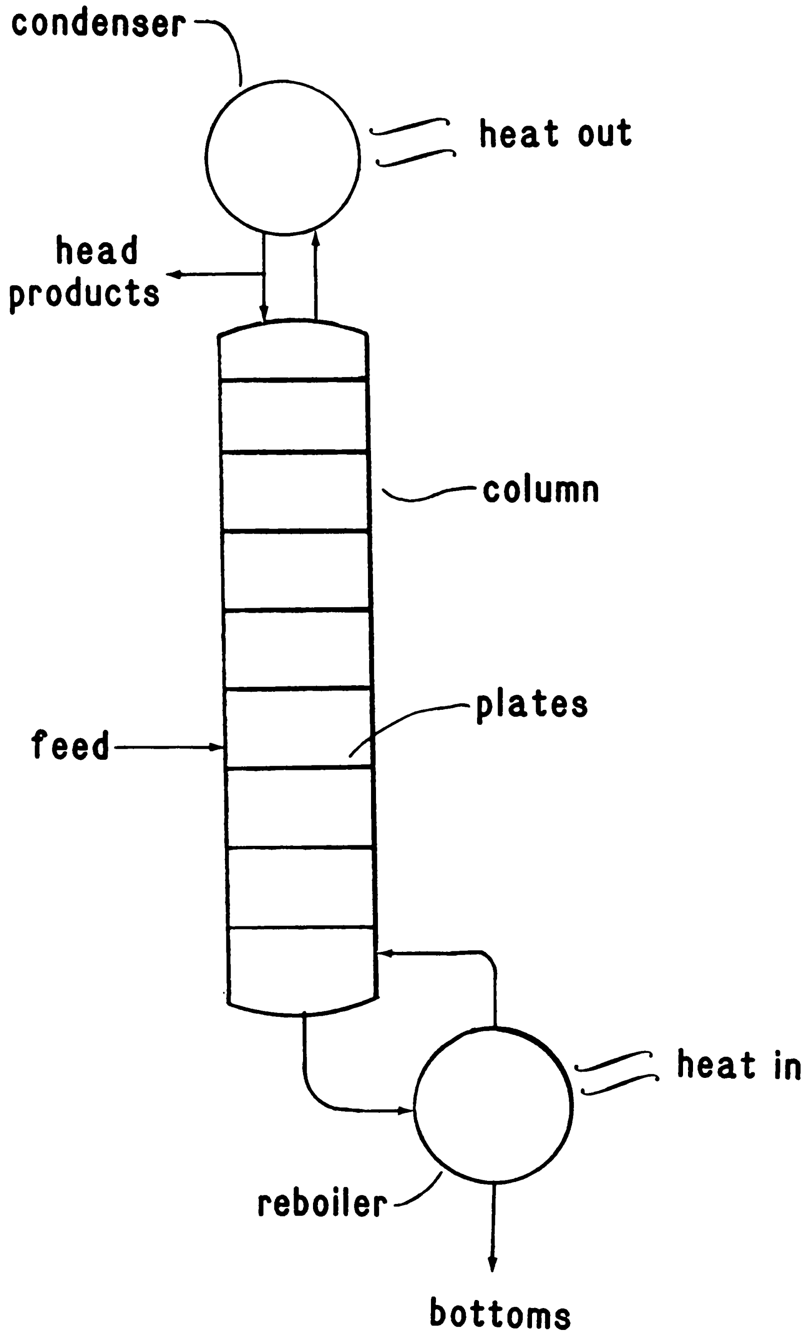

Figure. 1. Schematic of a basic fractional distillation process.

portion of a column containing a sieve tray plate, while Fig. 2*b* shows the top view. A pool of liquid, usually 10–20 cm deep, stands on top of a perforated plate with holes ranging from 4–15 mm in diameter. The liquid is kept from weeping through the holes by a steady stream of vapor pushing upward, emanating from the liquid on the plate immediately below. The vapor, with intimate contact, bubbles through the pool of liquid and thereby condenses. The heat released upon condensing vaporizes a corresponding amount of liquid, which pushes upwards as vapor to bubble through the next higher

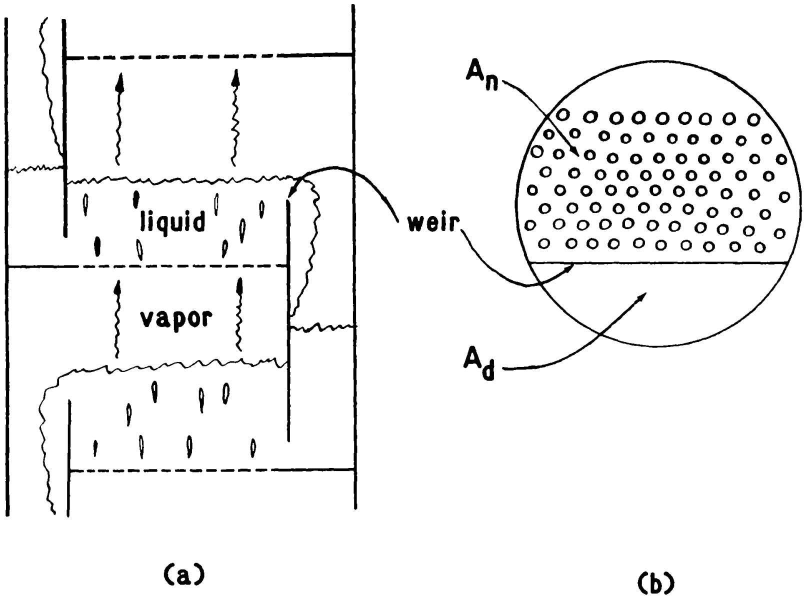

Figure 2. (a) Cross section of a column with sieve tray plates; (b) top view of a sieve tray plate.

plate. Insulation is critical in the operation, because the energy for vaporizing the liquid on a plate comes from the condensing vapors; any heat loss hinders this interplay.

The liquid level is maintained by a lip or weir, over which the liquid can splash and flow down a passage called a downer to the next lower plate. A liquid seal is provided so the vapors cannot flow "up the downer" and are forced to percolate through the sieve tray holes. The weir usually cuts some chord length of the column cross section, separating the downer area A_d, from the net area of the sieve tray, A_n (A_n is based on the sieve tray area, not the hole area), as seen in Fig. 2*b*.

To achieve a given head product purity, thermodynamics will dictate the ideal number of plates, assuming equilibrium is reached. A plate efficiency, E, is used to determine the number of real plates from this ideal case. Plate spacing is usually between 30–50 cm, so column height is then specified. Typical industrial columns may range from 1/2–2 m in diameter, 5–50 m high.

LUNAR MODIFICATIONS

Dimensional analysis and scaling arguments can be used to modify Earth-based columns for use on the Moon. The prime consideration is the reduction of gravity to one-sixth of that found on the Earth. Gravity-driven buoyant forces are responsible for moving the two-phase fluid system and will affect A_n, A_d, and E. Vapor-liquid thermodynamics will remain the same between the Earth and the Moon so that the number of ideal plates needed for a given separation will remain constant. Hydraulic similarity between Earth-based plates and Moon-based ones should be maintained through dimensional analysis so that the column operation will remain consistent with Earth-bound operations.

In the design of a distillation column, the feed rate and desired component separation are given; column pressure, temperature, number of ideal plates, and reflux ratio are then specified from a blend of thermodynamic and economic arguments. With these parameters fixed, the internal flow rates of vapor and liquid are also known. The column diameter is dictated by the A_n and A_d required to handle these internal flows, and the height is specified by the number of real plates calculated from the ideal number and E.

The net column area A_n is correlated to the internal volumetric gas (vapor) flow rate Q_G. The gas velocity V_F is defined as Q_G/A_n and is given by Treybal (1980) as

$$V_F = C_F \sqrt{\frac{\rho_L - \rho_G}{\rho_G}} \tag{1}$$

where ρ_L and ρ_G are the liquid and gas phase densities and C_F is the flooding coefficient, a constant determined from the details of plate geometry.

Equation (1) has no theoretical derivation; it is based on empirical correlation of experimental data for the prevention of droplet entrainment in the rising vapor. Realizing that such criterion is based on a balance of forces experienced by the droplets, it is recognized that the $(\rho_L - \rho_G)/\rho_G$ term in (1) is due to gravity-driven buoyant force between the liquid droplet and the gas. The density term must be multiplied by g, the acceleration due to gravity, in order to render the quantity into a proper buoyant force, which would certainly result if a theoretical derivation of (1) could be undertaken. Since (1) is developed empirically from Earth-based data, the acceleration due to gravity, which is not considered a separate parameter, would be buried in the flooding coefficient by the mechanics of the correlation process. It is not expected to find the gravitational acceleration anywhere in the equation. Therefore, the effect of gravity must enter in the flooding coefficient, resulting in V_F being proportional to $\sqrt{g}$.

The terminal velocity of a bubble in liquid (or a droplet in gas) has a well-known solution (Bird *et al.*, 1960) and can be used to reinforce the arguments applied (1), realizing that such analysis is an oversimplification of the actual flooding process. Considering a sperical-shaped bubble

$$F_d = \frac{\pi \rho_L V_B^2 d^2 \theta}{8} \tag{2}$$

will be the drag force F_d, where V_B is the bubble velocity, d is the diameter, and θ is the drag coefficient. The buoyancy force F_b will be as follows

$$F_b = \frac{(\rho_L - \rho_G)\, g \pi d^3}{6} \tag{3}$$

Equating the drag force to buoyant force and solving for the bubble velocity gives

$$V_B = \sqrt{\frac{4\ dg}{3\theta}\left(\frac{\rho_L - \rho_G}{\rho_L}\right)} \tag{4}$$

For Reynold's numbers greater than 10, which applies to the flow regimes found in plate-type columns, the drag coefficient is constant.

This balance is essentially the same for a droplet falling in gas, except that the density term is $(\rho_L - \rho_G)/\rho_G$ because the drag force in (2) is based on the external flow of the medium around a sphere. When applied to a falling droplet, (4) is remarkably similar in form to (1). For the onset of flooding, the gas velocity V_F must be of the order of the droplet velocity, which yields V_F proportional to $\sqrt{g}$ the same as the result deduced from the empirical correlation in (1). Substituting Q_G/A_n for V_F and solving for A_n gives the proportion

$$A_n \propto \frac{Q_G}{\sqrt{g}} \tag{5}$$

For the specified feed, reflux ratio, and column pressure, Q_G will be essentially the same between the Earth and the Moon, so the net area ratio will scale as

$$\frac{A_n\big|_M}{A_n\big|_E} = \sqrt{\frac{g_E}{g_M}} \tag{6}$$

where the subscripts E and M differentiate between the Earth and the Moon.

The scaling of downer area A_d will be dictated by the effects of gravitational forces on liquid flowing downwards in a closed conduit. Considering laminar flow in a vertical pipe, the liquid flow rate Q_L can be expressed (Bird *et al.*, 1960) as

$$Q_L = \frac{(\pi R^2)^2\ \rho_L g}{\pi 8 \mu_L} \tag{7}$$

where R is the radius and μ_L is the liquid viscosity. In general, for a closed conduit, Q_L will be proportional to gA_d^2. For a fixed volume of liquid flow, A_d will be as follows

$$A_d \propto \frac{1}{\sqrt{g}} \tag{8}$$

which gives the scaling ratio

$$\frac{A_d|_M}{A_d|_E} = \sqrt{\frac{g_E}{g_M}} \tag{9}$$

From (6) and (9), the lunar values of A_n and A_d increase by a factor of 2.45 in order to compensate for the one-sixth lunar gravity. For an earthly column 1 m in diameter, the corresponding lunar column would be 1.6 m.

The formation of bubbles with their corresponding interfacial surface area and rising velocity are the most important hydraulic concerns that affect plate efficiency. On a real plate, bubble-liquid interactions are complex. A simplified approach will be used to evaluate the major role of gravitational forces where single bubbles are rising in a body of liquid.

Assuming each plate is well mixed, the efficiency can be expressed as the proportion (Treybal, 1980)

$$E \propto 1 - e^{-k_L ah/V_B} \tag{10}$$

where E is called the Murphree plate efficiency, k_L is the bubble mass transfer coefficient base on the liquid phase, V_B is the bubble velocity, a is the total interfacial surface area, and h is the plate liquid depth. Equation (10) yields the ratio

$$\frac{\ell n\,(1 - E)|_M}{\ell n\,(1 - E)|_E} = \left(\frac{a_M}{a_E}\right)\left(\frac{h_M}{h_E}\right)\left(\frac{k_L|_M}{k_L|_E}\right)\left(\frac{V_B|_E}{V_B|_M}\right) \tag{11}$$

Based on penetration theory, k_L for a rising bubble is equal to (Treybal, 1980)

$$k_L = \left(\frac{D_{ab}}{\pi t}\right)^{1/2} \tag{12}$$

where D_{ab} is the diffusion coefficient and t is a fluid packet-bubble contact time. The contact time will be proportional to bubble diameter divided by bubble velocity, which gives

$$k_L \propto \left(\frac{V_B}{d}\right)^{1/2} \tag{13}$$

The diffusion coefficient is independent of gravity, thus being dropped as an argument. Equation (13) yields the mass transfer coefficient ratio

$$\frac{k_L|_M}{k_L|_E} = \left(\frac{d_E}{d_M}\right)^{1/2} \left(\frac{V_B|_M}{V_B|_E}\right)^{1/2} \tag{14}$$

which combined with (11) gives

$$\frac{\ell n\,(1 - E)|_M}{\ell n\,(1 - E)|_E} = \left(\frac{a_M}{a_E}\right)\left(\frac{h_M}{h_E}\right)\left(\frac{d_E}{d_M}\right)^{1/2} \left(\frac{V_B|_E}{V_B|_M}\right)^{1/2} \tag{15}$$

The rising velocity of a bubble has already been evaluated in (4) and is proportional to $\sqrt{dg}$.

The ratio of bubble velocity between the Earth and the Moon will be as follows

$$\frac{V_B|_M}{V_B|_E} = \sqrt{\left(\frac{g_M}{g_E}\right)\left(\frac{d_M}{d_E}\right)} \tag{16}$$

where the bubble diameter ratio has been included as a possible adjustable parameter.

Consider a bubble forming from gas percolating upwards through a plate hole into a body of liquid. It is important to determine the dependence of bubble mass (hence surface area) to hole diameter and the acceleration due to gravity coupled with the governing fluid properties. In the flow regime for bubble formation typically found on plates, surface tension has the dominating effect with the dependence of fluid viscosity being small. Using the Buckingham Pi method of dimensional analysis, the dimensionless pi group that arises is as follows

$$\pi = \frac{Mg}{\sigma D} \tag{17}$$

where M is the bubble mass, σ is the vapor-liquid surface tension, and D is the plate hole diameter. In order to assure hydraulic similarity, this dimensionless group is held constant between the Earth and the Moon, giving

$$\left.\frac{Mg}{\sigma D}\right|_E = \left.\frac{Mg}{\sigma D}\right|_M \tag{18}$$

There are several possibilities for juggling the parameters described in (15), (16), and (18) in order to scale the plates and determine their efficiencies.

Case I. Constant Bubble Mass

The most likely choice is to maintain constant bubble mass between the Earth and the Moon, which will assure the same bubble diameter and interfacial surface area for mass transfer. The velocity ratio from (16) will then be the following:

$$\frac{V_B|_M}{V_B|_E} = \left(\frac{g_M}{g_E}\right)^{1/2} \tag{19}$$

and

$$\frac{\ell n\,(1 - E)|_M}{\ell n\,(1 - E)|_E} = \left(\frac{h_M}{h_E}\right)\left(\frac{g_E}{g_M}\right)^{1/4} \tag{20}$$

will be the plate efficiency.

The bubble velocity will be 41% less than that on the Earth due to the one-sixth gravity on the Moon. For the same liquid depth on the plates the contact time will be longer, thus increasing the efficiency and requiring fewer plates for a given separation and a corresponding reduction in column height. The liquid depth could be reduced on lunar plates to maintain the same efficiency, so the number of plates would remain unchanged with plate spacing being reduced. From consideration of plate maintenance and column operation the standard spacings are the most practical, so liquid depth should be kept the same, realizing a shorter column from the increased efficiency. For constant liquid depth, Table 1 shows typical Earth plate efficiencies and their corresponding lunar efficiencies given by (20), which are enhanced by an average of 25%.

Table 1. Earth and Lunar Plate Efficiencies for Constant Bubble Mass and Liquid Depth

$E\|_E$	$E\|_M$
0.4	0.55
0.5	0.66
0.6	0.76
0.7	0.85
0.8	0.92

If bubble mass is to remain the same, (18) can be used to determine the hole diameter in the lunar plates, yielding

$$\frac{D_M}{D_E} = \frac{g_M}{g_E} \tag{21}$$

According to (21), the plate hole diameter for equal bubble masses will have to be six times smaller on the Moon; instead of holes 4–15 mm in diameter, the corresponding lunar perforations will be 0.67–2.5 mm. The pressure drop caused by the smaller holes could possibly increase, preventing the column from operating under vacuum conditions. From Treybal (1980), the pressure drop due to the perforated plate P, is proportional to

$$P \propto \frac{V_h^2}{g} \tag{22}$$

where V_h is the gas velocity through the holes. For holes placed on the corners of equilateral triangles and for equivalent hole diameter to pitch ratios, the increased value of A_n can increase the available hole area, decreasing the gas hole velocity. This can result in a pressure drop on the same order as Earth-based plates. In some instances it may be impossible to specify the smaller holes needed for constant bubble mass without dramatically increasing the pressure drop, making Case I an impractical approach.

Case II. Constant Plate Hole Diameter

For pressure drop consideration, the hole diameter in the plates will remain the same between the Earth and the Moon. From (18) the bubble mass ratio will then be as follows

$$\frac{M_M}{M_E} = \frac{g_E}{g_M} \tag{23}$$

which corresponds to lunar bubbles with six times the mass of earthly ones.

It follows from (23) that

$$\frac{d_M}{d_E} = \left(\frac{g_E}{g_M}\right)^{1/3} \tag{24}$$

is the bubble diameter ratio. The interfacial surface area can be approximated by the area of a single bubble times the number of bubbles. For a fixed Q_G, the number of bubbles, N, will scale inversely with the bubble mass

$$\frac{N_M}{N_E} = \frac{g_M}{g_E} \tag{25}$$

which gives an interfacial surface area ratio of

$$\frac{a_M}{a_E} = \left(\frac{d_M}{d_E}\right)^2 \left(\frac{N_M}{N_E}\right) = \left(\frac{g_M}{g_E}\right)^{1/3} \tag{26}$$

Using (16) and (24), it follows that

$$\frac{V_B\big|_M}{V_B\big|_E} = \left(\frac{g_M}{g_E}\right)^{1/3} \tag{27}$$

will be the bubble velocity ratio.

For constant hole diameter, the lunar plates will produce bubbles with 1.8× the diameter and 55% of the rising velocity and interfacial surface area. Combining (15), (24), (26), and (27) gives

$$\frac{\ell n\,(1 - E)\big|_M}{\ell n\,(1 - E)\big|_E} = \left(\frac{g_M}{g_E}\right)^{1/3} \tag{28}$$

for constant liquid depth. Table 2 shows the lunar plate efficiencies given by (28). The efficiencies decrease by an average of 34%, primarily the result of a significant decrease in the surface area due to the larger bubble diameter.

Table 2. Earth and Lunar Plate Efficiencies for Constant Plate Hole Diameter and Liquid Depth

$E\big\|_E$	$E\big\|_M$
0.4	0.25
0.5	0.32
0.6	0.40
0.7	0.48
0.8	0.59

Case III. Constant Bubble Velocity

Another scaling criterion would be to maintain constant bubble velocity between the Earth and the Moon. From (16), the lunar bubble diameter would have to be 6× larger, which corresponds to a bubble with 216× the mass. Equation (18) dictates a lunar plate hole 36× larger, which does not yield a practical engineering design.

THE LUNAR ENVIRONMENT

The lunar atmosphere has a pressure of 10^{-12} torr, which for most considerations is a total vacuum. One would initially think the way to maintain a vacuum distillation process is to utilize the lunar atmosphere as a giant sink, but there are several reasons why this cannot be done. Purging materials into the lunar atmosphere would be a dreadful waste of resources; these materials, especially organics, will be too valuable to lose even a few percent. The void of the lunar atmosphere itself is also a valuable resource (it is noteworthy to point out that the absence of anything can be a resource). Many scientific investigations can capitalize on the combination of a gravitational setting with a vacuum environment, and the scientific value of a lunar base would significantly decrease if this atmosphere were to be contaminated.

Vacuum distillation will be maintained through the use of the cryogenic temperatures available on the Moon. Temperatures as low as 59 K can be obtained through radiation into space. The column pressure is specified by the lowest temperature available in the overhead condenser; in a lunar environment this will correspond to as low a column pressure as desired. Even "fixed gases" like oxygen, nitrogen, and carbon dioxide can be condensed, eliminating the need for vacuum pumps. The extra cost for vacuum distillation will be in the capital equipment needed to handle the radiation heat loads.

An example of a lunar distillation process would be the production of ethanol from fermentation of organic wastes. The column pressure would be maintained so the fermenter functions as a reboiler, where the alcohol is continuously boiled off at a temperature for optimum yeast growth. The azeotrope could be broken under the low pressure so absolute alcohol would be produced. A two-stage overhead condenser would first remove the condensable vapors, with a second-stage cryogenic condenser that condenses the carbon dioxide (as a solid) and any other fixed gases.

SUMMARY

The establishment of a permanent lunar base will offer some interesting possibilities for the design of distillation processes. The lunar environment will make possible convenient vacuum distillation and will facilitate column insulation. For a lunar column, the net plate and downer areas will increase by a factor of 2.45. The lunar plate efficiencies will either increase by about 25% (for constant bubble mass) or decrease by 34% (for constant hole diameter), the choice depending on the imposed engineering constraints.

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