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ISOTOPIC SEPARATION OF $^{3}He/^{4}He$ FROM SOLAR WIND GASES EVOLVED FROM THE LUNAR REGOLITH

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Isotopic Separation of $^3He/^4He$ From Solar Wind Gases Evolved From the Lunar Regolith

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Abstract

The potential benefits of ^3He when utilized in a nuclear fusion reactor to provide clean, safe electricity in the 21st century for the world's inhabitants has been documented. Unfortunately, ^3He is scarce on earth. Large quantities of ^3He, perhaps a million tonnes, are embedded in the lunar regolith, presumably implanted by the solar wind together with other elements, notably ^4He, H, C and N. Several studies have suggested processing the lunar regolith and recovering these valuable solar wind gases. Once released, these gases can be separated for use. The separation of helium isotopes is described in this paper.

^3He constitutes only 400 at.ppm of lunar He, too dilute to separate economically by distillation alone. A 'superfluid' separator is being considered to pre-concentrate the ^3He. The superfluid separator consists of a porous filter in a tube maintained at a temperature of 2.17 K or less. Although the ^4He, which is superfluid below 2.17 K, flows readily through the filter, the ^3He is blocked by the filter, and becomes enriched at the feed end. ^3He can be enriched to about 10% in such a system.

The enriched product from the superfluid separation serves as a feed to a distillation apparatus operating at a

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pressure of 9 kPa, with a boiler temperature of 2.4 K, and a condenser temperature of 1.6 K. Under constant flow conditions, a 99.9% enriched ^{3}He product can be produced in this apparatus. The heat rejection loads of the refrigeration equipment necessary to cool the separation system are such that the separation operations would be conducted during the lunar nights.

Introduction

It has been noted that perhaps a million tonnes of ^{3}He, an isotope which has great potential as a fuel for nuclear fusion, exist embedded in the lunar regolith. (Wittenberg, et al., 1986) The recovery of this ^{3}He from lunar regolith requires an enrichment from its initial concentration of approximately 400 at. ppm. in total He to a final value near 100%. Enrichment is necessary, first, to reduce the quantity of material that must be transported from the lunar surface to Earth; and secondly to remove ^{4}He, which will not burn in a fusion reaction.

Although, in principle, it is possible to accomplish the entire enrichment in a single apparatus, e.g., a distillation column, this is not efficient because of the range of concentrations covered in the separation. It is common practice in separations which cover a wide range of concentrations (here, 4 x 10^{-2}% to 100%) to configure the separation equipment into an array or cascade of separating devices. Assuming, as in the present case, that the desired product is initially very dilute, the material to be separated is fed to the cascade near its waste end. A short (i.e., few stages) wide (high flow capacity) stripping section is employed to remove the desired product from the waste, and a longer, narrower enriching section connects the feed with the product withdrawal end. There may be several sections to the cascade, each of a different width, corresponding to the flow at different concentrations. Such a design maximizes the amount of separated product for a given energy input.

In the present case, it is proposed to employ two entirely different separation methods for the production of the enriched ^{3}He. The stripping operation and the initial ^{3}He enrichment employ a superfluid separation, utilizing the fact that at temperatures below 2.17 K ^{4}He is superfluid with zero viscosity (within limits) whereas ^{3}He is not. A practical limit to the enrichment that can be achieved in the superfluid filter is of the order of 1 to 10% ^{3}He in total He. This represents a concentration of 25 to 250 times the original ^{3}He concentration in the lunar helium.

The remaining separation can be achieved by cryogenic distillation. Continuous cryogenic distillation of helium isotopes has been accomplished with starting concentrations on the order of 5% ^{3}He, and product concentrations and flow rates in excess of 99.9% and 3 liters per hour of ^{3}He, respectively. Thus, the problem becomes one of estimating the scale of the separation apparatus which might be used in a lunar environment. Figure 1 shows how the principal elements of the separation system are configured.

Superfluid Separation

At temperatures below 2.17 K, ^{4}He becomes superfluid and at lower temperatures, mixtures of ^{3}He and ^{4}He also exhibit superfluid properties. In this state, the mixture behaves as if there were two fluids occupying the same volume. One is a superfluid, having zero entropy and capable of moving without friction through the other fluid or through fine orifices. The concentration of this fluid increases with decreasing temperature and with decreasing ^{3}He concentration in the mixture. The other fluid is "normal" and is comprised of a mixture of the ^{3}He and the non-superfluid fraction of the ^{4}He. This normal fluid exhibits ordinary properties of viscosity.

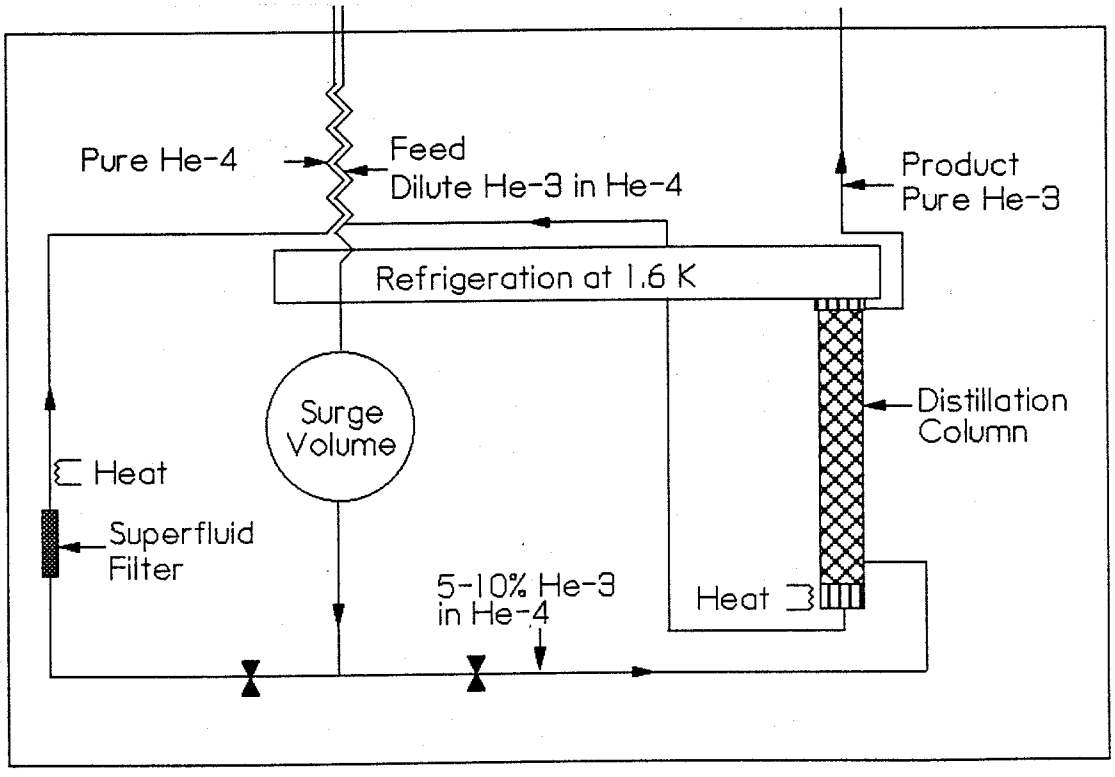

Figure 1 Combined superfluid and distillation system for separating ^{3}He from very dilute ^{3}He/^{4}He mixtures.

If a temperature gradient is imposed on this two-fluid mixture, a flow is immediately established. At the high temperature end of the gradient, the superfluid component of the mixture is less concentrated than at the cold end; hence superfluid ^{4}He immediately flows from the cold end to the warm end to reduce the concentration gradient. This is known as the thermomechanical pressure effect or "fountain" effect. Maintaining mass balance requires that normal ^{4}He flow in the opposite direction. This flow carries heat away from the heat source and in addition, any ^{3}He is swept along with the normal ^{4}He because of the collisions between them. This effect alone has been shown to be sufficient to separate helium isotope mixtures. Hendry and McClintock (1987) used this method to produce large quantities of extremely pure ^{4}He, albeit from very low ^{3}He concentrations. Whether this method can be used effectively to enrich ^{3}He beyond a fraction of a percent remains to be demonstrated.

Because of the zero viscosity of the superfluid, it is also possible to separate the helium isotopes by forcing the superfluid mixture through a fine filter. With pore sizes on the order of 1μm or less, the ^{3}He can be almost completely blocked while substantial flow of the superfluid ^{4}He is permitted. At some concentration of ^{3}He, however, depending upon the temperature, the ^{4}He in the mixture loses its superfluid properties, shutting off the separation process. Listerman (1969) investigated the equilibrium behavior of a superfluid separator and found that ^{3}He concentrations as high as 23% could be achieved.

The force necessary to drive the superfluid through a filter can come either from an externally imposed pressure differential or from a temperature differential across the filter. The first case is analogous to the reverse osmosis process used in water desalination. In the latter case, as one end of the filter is heated, the fountain effect causes the superfluid ^{4}He to flow to the heated end of the filter. The ^{3}He, being viscous, remains behind the filter. As the ^{3}He becomes more concentrated, depleting the superfluid component behind the filter, the thermal gradient must be increased to maintain the flow.

Listerman found that at a temperature of 1.6 K for the mixture, ^{3}He concentrations as high as 13% could be achieved when the warm end of the filter was at 2.17 K. With the warm end at 2.10 K, the enrichment was 10%. Although with lower mixture temperatures, even higher concentrations could be achieved, we shall use 10% as a working value. It is to be expected that in practice the enrichment will be limited to a value which permits an adequate flow through the superfluid separator.

Sizing the Separation System

We start from the position of designing an initial trial separator to supply ^3He to a single 1000 MWe terrestrial fusion reactor. Scaling the system to provide larger separative capacity is expected to be straightforward for capacities up to perhaps 10,000 MWe.

The D-^3He reaction releases 18.3 MeV of energy per fusion, equivalent to 6×10^5 GJ (or approximately 10 MWe year) per kg of ^3He. This corresponds to a flow rate of 3.2×10^{-3} g ^3He/sec or 1×10^5 g ^3He/yr for the 1000 MWe plant. With a starting concentration of one atom of ^3He in 2500 of ^4He, (1 in 3333 by weight) it becomes necessary to process the initial feed mixture at an average rate of approximately 10.6 grams per second. Because this separation requires that all of the helium feed mixture be refrigerated to a temperature of 2 K or less, it is assumed that the refrigeration and separation apparatus will operate only during the lunar night, when waste heat from the refrigerator can be most effectively dissipated into space. This limits the operating time to perhaps 4000 hours out of the 8800 in a calendar year, thereby increasing the average flow rate to the vicinity of 24 grams of helium feed per second during the enrichment operation. On the assumption that the initial enrichment provided by the superfluid filter is between 25 and 250 to one, the feed rate to the

TABLE I

	Superfluid Separator	Distillation Enricher
Feed Flow	24 gm/sec	0.1-1 gm/sec
Feed Concentration	4×10^{-2}% ^3He	10-1 % ^3He
Product Flow	0.1-1 gm/sec	0.0072 gm/sec
Prod. Concentration	10-1 % ^3He	99 % ^3He
Waste Flow	23 gm/sec	0.1-1 gm/sec
Waste Concentration	$<4 \times 10^{-3}$% ^3He	4×10^{-2}% ^3He

distillation apparatus can be expected to be between 0.1 and 1.0 gm/sec. The flow rates and concentrations in the two separation units are summarized in Table I. It should be noted that the distillation waste stream enrichment is the same as that of the feed to the superfluid separator.

We can estimate the dimensions and operating conditions of the superfluid separator from experiments (Srinivasan and Hoffman, 1985; Mills and Urbach, 1990) using the fountain effect as the basis of a pump for superfluid helium. Mills and Urbach measured the flow through a porous filter at rates approximating those required by the present application. With a 6 W heat input, they were able to obtain flow rates exceeding 10 gm/sec through a 460 cm^2 porous filter with a maximum pore diameter of 0.5 μm. Larger flow rates (20 gm/sec) were achieved, but at disproportionately higher heat inputs. The operating temperature at the cold end of the filter was 1.8 K.

We estimate, using the above values for mass and heat flow per unit area, that a superfluid filter required for the superfluid separation of ^3He from ^4He will need to be on the order of 1100 cm^2 and that a heat input of approximately 14 W will suffice to drive the process. Gistau and Claudet (1985) describe a 300 W, 1.75 K refrigerator, far exceeding this requirement. Other refrigerators have been constructed with multi-KW cooling capacities at 4.2K.

With an operating temperature of 1.6 K at the cold end of the filter, and 2.0 K at the heated end of the filter, the ^3He enrichment should reach 10%. The degree of depletion of ^3He in the waste stream will depend upon the average pore size, as will the actual size of the filter. With decreasing pore size and increasing filter thickness, the ^3He flow through the filter will be decreased.

The Distillation Separator

Pettit (1988) has discussed the concept of distillation in a lunar environment with plate columns. He notes that the limiting volumetric vapor flow V_F in the column, which is in turn determined by the flow rate at which droplets become entrained in the rising vapor, is given by

$$V_F = C_F \sqrt{\frac{\rho_L - \rho_V}{\rho_V}}$$

where ρ_L and ρ_V refer to the liquid and vapor densities. C_F is the flooding coefficient, determined by details of the column geometry. The lunar and terrestrial gravitational accelerations are g_L and g_E. Pettit generalizes this to

$$V_{FL} = V_{FE} \sqrt{\frac{g_L}{g_E}} = C_F \sqrt{\frac{\rho_L - \rho_V}{\rho_V}} \sqrt{\frac{g_L}{g_E}} .$$

In the case of helium isotope distillation, the relatively small size of the separation tower indicates the use of packed columns. For the present purposes, it is assumed that although Pettit's generalized expression is derived for plate columns, it is also correct for packed columns. Thus, the diameter of a packed distillation column required for a given separation is inversely proportional to the local gravitational acceleration.

It has been demonstrated that mixtures of ^{3}He and ^{4}He can be quickly and easily separated using packed columns on a scale that does not differ greatly from the present one (Wilkes, 1972). Enrichment of the ^{3}He in a mixture of 7-10% ^{3}He in total He to over 99.9% was achieved in a single, 9 mm i.d. packed column at a feed rate of approximately 50 STP liters per hour, while simultaneously stripping the ^{4}He stream to less than 0.01% ^{3}He. This column operated at a pressure of 8.7 kPa (66 torr) with a condenser temperature of 1.6 K and a reboiler temperature of 2.4 K. The column length was 30 cm long, and was calculated to comprise at least 15 stages of separation. The power supplied to the reboiler during this separation was 40 mW, indicating a reflux ratio of approximately 20.

Neglecting the gravitational correction, and assuming no losses as a result of scaling to a much larger column diameter, one finds that a column diameter between 5.7 cm (assuming 10% ^{3}He feed) and 18 cm (1% ^{3}He) should suffice for the separation. This and other distillation column parameters based upon a feed concentration of 10% ^{3}He are given in Table II. The reboiler input scales directly, so

TABLE II

Still Type	Existing Version	Large Terrestrial	Large Lunar
Feed % ^{3}He	7-10	10	10
Feed rate, gm/sec	2.5×10^{-3}	0.1	0.1
Boilup rate	40 mW	1.6W	1.6W
Diameter	0.9 cm	5.7 cm	14 cm
HETP	$\leq$ 2 cm	6 cm	6 cm
Length	30 cm	90 cm	90 cm
Condenser Temp.	1.6 K	1.6 K	1.6 K
Pressure	8.7 kPa	8.7 kPa	8.7 kPa

that a heat input of 1.6 W will be required. Applying a gravitational correction of 2.45 ($\sqrt{6}$) yields the diameters given in column three of Table II.

Conclusions

Enrichment of ^{3}He recovered from lunar sources to concentrations near 100% can be achieved by a combination of superfluid separation and cryogenic distillation. The scale of the apparatus required to supply ^{3}He for a terrestrial D-^{3}He fusion reactor is well within current cryogenic equipment manufacturing standards.

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