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DESIGN OF EQUIPMENT FOR VAPOR PHASE PROCESSING OF METALS, K. Eric Drexler (MIT, Cambridge, Mass.) and H. Keith Henson (Analog Precision, Tucson, Arizona).

Introduction: Among the operations to be performed on lunar materials are metal separation and fabrication. If the metals to be separated are in reduced form, or if the object to be fabricated locally resembles a curved sheet, then candidate processes include distillation and vapor deposition. Both the separation factors per stage in the first case, and the materials properties attainable in the second are promising. The goal then is the design of a light-weight, direct solar heated metal evaporator for use in space, as this is the key technology in both systems.

Major design problems and proposed solutions: Containment of vapor to prevent deposition on sun concentrating optics; construct furnace with absorber cavity separated from vapor filled cavity by a conductive diaphragm (see fig. 1; mirror, vapor nozzle, condensation system, gas recirculation, and means for adding metal not shown). Mechanical strength of diaphragm at circa 2700°K; use pyrolytic graphite (short term strength greater than 20 kg/mm^2 (1)). Diaphragm evaporation and creep; fill outer cavity with gas to balance pressure load and retard evaporation. Gas containment; construct a dome-like fused alumina window outside aperture. Diffusion and condensation of carbon vapor on window; circulate gas through aperture into cavity. Diaphragm conductivity; machine interlocking grooves in graphite. Corrosion by molten metal; make use of zero-g and some combination of surface tension, induction, dynamic feed, and cold metal tabs to avoid contact of dissimilar materials. Metal vapor reactions with graphite; reasonable operating conditions (temperature differences, pressures) can make carbides unstable at walls and diaphragm (see fig. 2).

System Parameters and Relationships:

D = diameter of furnace (m)
$D^2 * A_W$ = area of external walls (m^2)
$D^2 * A_D$ = area of diaphragm (m^2)
$D^2 * A_m$ = area of exposed metal (m^2)
f = fract. wall area behind diaphragm
t = mirror reflectivity* window transmissivity
e_D = emissivity of diaphragm
e_m = emissivity of molten metal
C = conductivity of diaphragm (W/m^2-K)
K = quality of insulation for specified conditions (W-kg/m^4)
$\sigma = 5.67 * 10^{-8}$ (W/m^{2}K^4)
$\dot{m}$ = metal vapor mass flow (kg/s)
P_m = pressure of metal vapor (N/m^2)
ΔH = heat to vaporize metal (J/kg)
M = molecular weight of metal (kg/mole)
$P_m = \Delta H * \dot{m}$ = useful power (W)
P_W = power leaving through walls (W)
P_n = power radiated through nozzle (W)
P_a = power entering through aperture (W)
A_a = area of aperture (m^2)
A_n = area of nozzle (m^2)
T_a = av. focal temp. at aperture (K)
T_{C1} = temp. of ext. cavity rad. field (K)
T_{D1} = temp. of ext. surface of dia. (K)
T_{D2} = temp. of inner surface of dia. (K)
T_{C2} = temp of inner cav. rad. field (K)
T_m = temperature of metal (K)

Approximating (conservatively) the radiative transfer beteen two surfaces as transfer from the first surface to an isotropic radiation field, and then from the field to the second surface, the following relations describe the major thermal differences and power flows in the system:

$$T_{C2} = \left(\frac{P_m}{\sigma e_m A_m D^2} + T_m^4\right)^{\frac{1}{4}}; \qquad T_{D2} = \left(\frac{P_m+P_n+fP_w}{\sigma e_D A_D D^2} + T_{C2}^4\right)^{\frac{1}{4}}$$

$$T_{D1} = \left(T_{D2} + \frac{P_m+P_n+fP_w}{CA_D D^2}\right); \qquad T_{C1} = \left(\frac{P_m+P_n+fP_w}{\sigma e_D A_D D^2} + T_{D1}^4\right)^{\frac{1}{4}}$$

or:

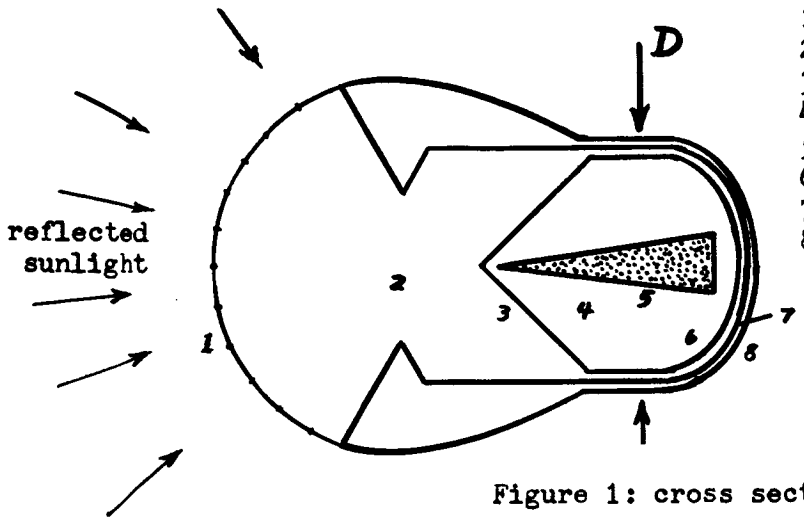
$$T_{C1} = \left(\frac{P_m+P_n+fP_w}{\sigma e_D A_D D^2} + \left(\frac{P_m+P_n+fP_w}{CA_D D^2} + \left(\frac{P_m+P_n+fP_w}{\sigma e_D A_D D^2} + \frac{P_m}{\sigma e_m A_m D^2} + T_m^4\right)^{\frac{1}{4}}\right)^4\right)^{\frac{1}{4}}$$

$$P_n = \sigma T_{C2}^4 A_n; \qquad A_n = \frac{\dot{m}}{8.06*10^{-3} p_m (M/T_{C2})^{\frac{1}{2}}}$$

$$P_a = \left(P_m + P_h + P_w\right); \qquad A_a = \frac{P_a}{\sigma(T_a^4 - T_{C1}^4)}$$

$$\text{mirror area} = \frac{P_a T_a^4}{1350*t(T_a^4 - T_{C1}^4)}$$

System productivity: $K = 9.5*10^5$ for carbon black at 2600°K (3); insulation thickness must be optimised with respect to mirror specific mass. Fused alumina should give $t = 0.75$ with a mass of $2.5*10^{-5}$ kg/W if operated at 1400°K (3,4). In the following, pressure vessel mass is taken as 1 kg/m^3, mirror as 0.5 kg/m^2 (5), diaphragm as 20 kg/m^2, furnace lining as 5 kg/m^2, and the metal as iron. For a system of D = 15 m, T_m = 2400°K, and $\dot{m}$ = 10 kg/s, maximum temperature in the system is 2700°K, with mirror mass of 190 tons, insulation of 33 tons, window of 10 tons, and a total mass (including other components) of 250 tons. Such a system processes its own mass in under 8 hrs., and over 1000 times its mass in a year, with mass scaling closely with throughput. The most sensitive parameter of uncertainty is mirror specific mass; a factor of four variation varies optimised system mass by a factor of two.



1-window dome
2-aperture
3-diaphragm
4-vapor filled cavity
5-liquid metal retainer
6-vapor containing wall
7-carbon black insulation
8-pressure vessel

Figure 1: cross section of metal evaporator

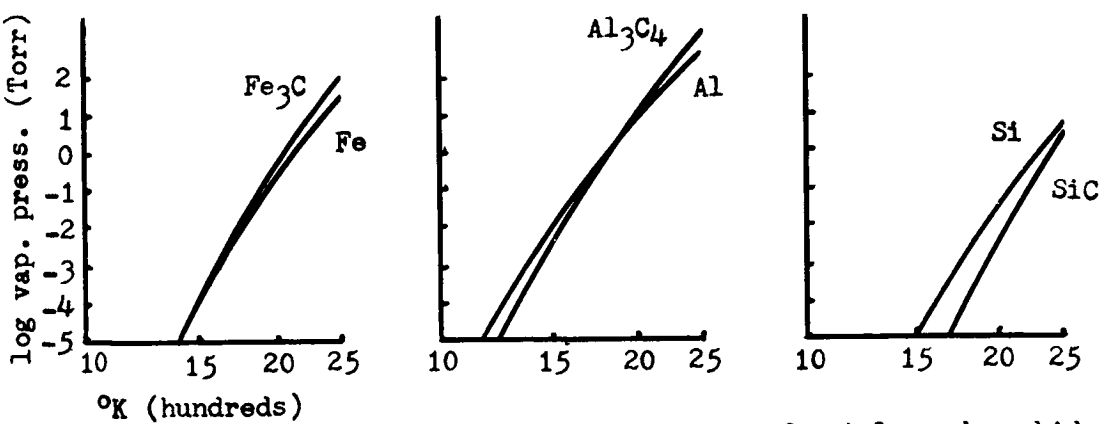


Figure 2: vapor pressures of metals and carbides(2). If the metal vapor pressure at equilibrium over a carbide is greater than ambient, the carbide will not form. In most systems, the carbide pressure will be elevated by greater temperature, while the ambient will be reduced by vapor leaving the system, hence graphite should remain the stable phase where used.

Conclusion: Distillation and vapor deposition are promising means of refining and fabricating lunar materials in space. The design of equipment to accomplish this has been considered from the standpoints of system mass, energy flows, short term materials strengths, evaporation kinetics, and gross materials compatibility. While preliminaries look promising, work remains to be done on the design of metal retention systems, component joining techniques, residual loads due to operational fluctuations and flows, and lifetime from creep and local evaporation-deposition mechanisms. If these are solved properly, such equipment should find wide application in lunar utilization.

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