

of longitudinal moments of inertia. From the calculated values of ω_1 , ω_2 , and ω_3 , one can next obtain the attitude at any time by use of the formula for the Hamilton-Cayley-Klein parameters.² Since these parameters are given in terms of the history of $\omega(t)$, we have formally integrated the motion for a new class of problems. A last detail of interest is that the coning angle ψ of the vehicle about its angular momentum vector \mathbf{h} is constant; the component of angular velocity normal to the symmetry axis changes inversely in length as the magnitude of the longitudinal moment of inertia (only the coning rate p varies).

Example

Take the case of one particle executing $\beta_3^1(t) = a \sin t$, $\beta_3^0 = 0$, where β_3^1 is the displacement of the particle from the vehicle's origin, so

$$r_3^1 = \beta_3^1 - m^1/(m^0 + m^1)\beta_3^1 = m^0/(m^0 + m^1)a \sin t$$

$$r_3^0 = -m^1/(m^0 + m^1)\beta_3^1 = -m^1/(m^0 + m^1)a \sin t$$

$$m^0(r_3^0)^2 + m^1(r_3^1)^2 = m^0 m^1/(m^0 + m^1)a^2 \sin^2 t = \mu \sin^2 t$$

From (9) and (10),

$$e^{\theta(t)} = I_0/(I_0 + \mu \sin^2 t)$$

$$\phi(t) = \{I_3 s/[I_0(I_0 + \mu)]^{1/2}\} \tan^{-1}\{[1 + (\mu/I_0)]^{1/2} \tan t\} - st$$

Setting $\alpha = \mu/I_0$, $\beta = (1 + \alpha)^{1/2}$, and $\gamma = I_3/I_0$, we have

$$e^{\theta} = (1 + \alpha \sin^2 t)^{-1}$$

$$\phi = s[(\gamma/\beta) \tan^{-1}(\beta \tan t) - t]$$

With these functional relations, we now use (8) to get the angular velocity. Assume that $a = 15$ ft, $I_0 = 500$ slug ft², $I_3 = 100$ slug-ft², $m^0 = 20$ slug, $m^1 = 1$ slug, and $s = 1$ rad/sec. A pair of graphs (Figs. 1 and 2) is shown of (8) for the foregoing with $\omega_1(0) = 1$ and $\omega_2(0) = 0$, and a comparison is made with the free-body case.

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Evaporation of Electroplated Cadmium in High Vacuum

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Introduction

CADMIUM or zinc platings are often used in missiles as protection against corrosion due to moisture, propellants, and decomposition products of lubricants and propellants.¹

Cadmium-plated articles have also been used in space vehicles. The question has arisen concerning the desirability and feasibility of using cadmium in the space environment.² Critics have claimed that the vapor pressure of cadmium is such that it is sublimed and redeposited on critical vehicle areas in the space environment. Proponents of cadmium plating maintain that the volatilization and/or redeposition is not significant. This study was undertaken to determine a few of the properties of electroplated cadmium in a simulated space environment.

Background

The rate of evaporation of an inorganic material in a vacuum is given by the Langmuir equation³

$$G = P_v(M/T)^{1/2}/17.14 \quad (1)$$

where G is the rate of evaporation in grams per (centimeter)²-seconds, P_v is the vapor pressure of the material in millimeters of mercury, M is the molecular weight of the material in the gas phase, and T is the temperature in degrees Kelvin. Gloria, Stewart, and Savin⁴ found that the evaporation of cadmium in a vacuum is described by the Langmuir equation when the vapor pressure P_v is given as^{4,5}

$$\log_{10} P_v = 8.564 - 5693.1/T \quad (2)$$

The vapor pressure obtained using this equation is somewhat higher than that cited by Honig.⁶ Furthermore, it has been shown for related materials, and indicated for cadmium,⁷ that the oxide generally present on plated cadmium decreases the evaporation rate. Thus, the G for plated cadmium articles can be expected to be less than that predicted by Eqs. (1) and (2).

The Langmuir equation may also be used to obtain the rate of condensation if it is modified by multiplying it by the "sticking" coefficient α . Values of α from 0.001 to 0.6 have been obtained on contaminated and relatively clean surfaces.^{8,9} Knudsen¹⁰ found that cadmium vapor condensed completely on glass at 78°K. Rapp, Hirth, and Pound¹¹ obtained values of one for α at high cadmium supersaturation at room temperature on clean metal surfaces.

The attractive forces between the condensed atoms of cadmium and glass are exceptionally weak.¹² Furthermore, Sennett et al.¹³ found that a critical flux density must be exceeded for condensation to take place, and this condensation proceeded after the apparently instantaneous appearance of particles having an approximate size of 200°A. Bueche¹⁴ found that the glass must be near liquid air temperature (-233°F) before cadmium could be deposited uniformly. Fraser¹⁵ has suggested that condensation is normal (no critical flux density) if the substrate is perfectly clean, i.e., no adsorbed gases or other contamination.

An interesting phenomenon reported by Palatnik and Gladkikh^{16, 17} may prove to be an acceptable explanation of some of the anomalies related to the condensation of metals in vacuums. They found¹⁶ that the transition of the condensation mechanism from vapor \rightarrow crystal to vapor \rightarrow liquid (\rightarrow crystal) at high vapor concentrations in a vacuum is a "step rule." The second mechanism of condensation was found to begin at a temperature θ_2 (degrees Kelvin), which was given, for the metals studied (including cadmium), by the relationship $\theta_2/T_s = \frac{1}{3}$, where T_s is the melting point of the metal in degrees Kelvin. Furthermore, they found that there is an increasingly broad temperature region, at low vapor concentrations, in which no metal is condensed.¹⁷

Apparatus and Experimental Procedure

A schematic of the apparatus used for the vaporization and redeposition studies is shown in Fig. 1. The samples were 4 in.², $\frac{1}{16}$ in., or $\frac{1}{8}$ in. thick, cold-rolled 1020 steel having an electro-

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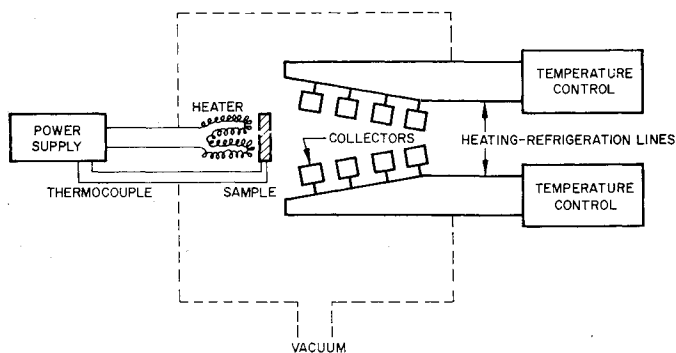


Fig. 1 Schematic of test system for cadmium vaporization and condensation studies.

plated coating of cadmium (from a cyanide bath) 1 to 3 mils thick on one 4-in.² surface. A thermocouple was embedded in the edge of the sample, the sample degreased and then placed on the hot plate shown in Fig. 1. The samples were weighed before and after the runs.

The collectors (for redeposition studies) were glass microscope slides cut in 1-in. strips and mounted in the copper mounts with brass screws and washers. The collectors were supported on copper tubing in such a manner as to be in hemispheres over the sample, the radii (inches) being 2.75, 6.75, 9.5, and 12.5, with opposing collectors being on the same cooling system.

The system pressure was reduced to less than 10^{-6} mm Hg before a run was started, and was kept below 10^{-5} mm Hg during a run. The samples generally had attained their operating temperature within 30 min and were at temperature from 20 to 167 hr.

Results and Discussion

Evaporation

The experimentally determined rate of evaporation of plated cadmium G is plotted vs reciprocal temperature in Fig. 2 and compared with the curve for G_T , the theoretical flux density calculated from Eqs. (1) and (2). The average ratio G/G_T is about 0.02, but for one sample it was only 0.001. The data are for samples of both thick, rough, dull, nonreflective coatings and for thin, bright, reflective coatings. All of the bright, reflective coatings exhibited the phenomenon of change from a bright surface to milky-appearing surface as the samples were raised through the temperature region 180° to 200°F.

As a check, 99.999% cadmium, in the form of a rod cut in half along its axis, was evaporated. At a temperature of 300°F, G was 1.2×10^{-8} g/cm²-sec, which agrees well with $G/G_T = 0.02$ from Fig. 2. In order to remove any surface contamination (e.g., oxides),¹⁸ the sample was heated to about 500°F for a short time. Then, without opening the system, the temperature was decreased to 400°F and held at this temperature for 22 hr; the G obtained was 1.1×10^{-5} g/cm²-sec, which agrees well with G_T for pure cadmium. It

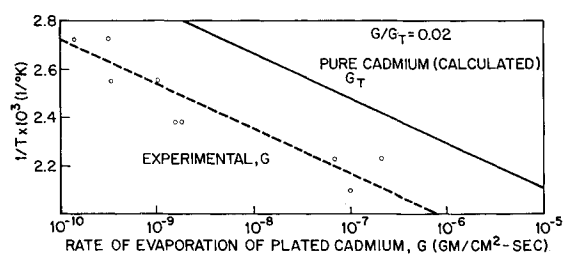


Fig. 2 Rate of evaporation of plated cadmium in 10^{-6} - 10^{-7} mm Hg vacuum.

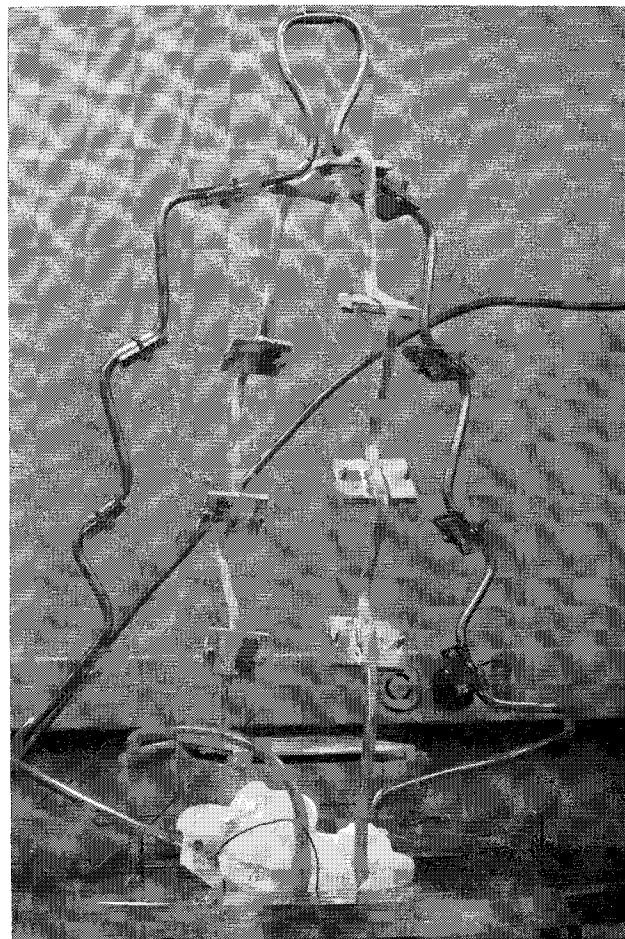


Fig. 3 Illustration of cadmium condensation resulting when the collectors attained temperatures of about 158°F.

is generally considered that plated cadmium contains, as an impurity, its oxide. It has been demonstrated, both here and in other laboratories,^{7, 18} that the presence of the oxide decreases the rate of evaporation.

Condensation

The rate of condensation of cadmium was not obtained. Under the conditions of this study cadmium either did not condense, or condensed anomalously on all the collectors.

With half of the collectors at 68°F and half at 23°F, no cadmium was visible on any collector after runs during which the sample temperature was equal to or less than 300°F. At sample temperatures of 350° and 400°F, there was considerable variation between individual collectors as to when cadmium first became visible and as to the amount of coverage of the collector. At 350°F, cadmium was visible on at least one collector after $\frac{1}{2}$ hr in one run and after 4 hr in another. At 400°F, cadmium was visible on at least one collector after $\frac{3}{4}$ hr. The fraction of the collector area, rendered opaque by condensing cadmium, was anomalous with respect to temperature and with respect to location of the collector. Whereas microscopic examination of the collectors indicated cadmium crystals scattered over the surface, visual examination indicated clear areas and opaque areas with no intermediate ranges; no interference colors were apparent. Furthermore, microscopic examination indicated that the coating was approximately 3- μ hexagonal crystals of cadmium.

Using the experimentally determined G , the distance of the collector from the sample, and the temperatures of condensation and no condensation, the flux density at the collectors can be calculated assuming hemispherical distribution. The

calculated critical condensation flux density at the collector for condensation of cadmium is indicated to be between 0.81×10^{-9} and 1.14×10^{-9} g/cm²-sec for collector temperatures of 23° and 68°F.

At (relatively) high cadmium flux densities (e.g., $G = 10^{-8}$ g/cm²-sec), cadmium condensed on aluminum (placed in the system for shielding purposes) at something above room temperature. Condensation was indicated on the copper (e.g., $G = 5 \times 10^{-8}$ g/cm²-sec) at about 100°F, with strong condensation at 130°F. Figure 3 is a picture showing the manner of cadmium condensation when maximum temperatures of about 158°F were attained on one-half of the collectors.

Collectors cleaned in various manners, or deliberately soiled, were tried. In general, little difference was found in uniformity, or lack of uniformity of condensation, except for silicone grease and finger grease, both of which prevented cadmium condensation as illustrated by the two half-coated collectors in Fig. 3.

Conclusions

Electroplated cadmium has an apparent rate of evaporation (G) in high vacuum that is about 0.02 times that of the calculated rate for pure bulk cadmium (G_T); by study of the plating conditions, surface, and/or post-plating treatment, this factor might be decreased to 0.001.

The results obtained in this work tend to support the view of Sennett et al.¹³ that a certain critical flux density is necessary for condensation, not only for glass, but for other materials as well. Extrapolation of the data presented by Palatnik and Gladkikh¹⁶ indicates that the mechanism and condensation anomaly presented by them very probably explain the so-called anomalous results obtained in this work and by Sennett et al.¹³

No final conclusions can be drawn as to the applicability of electroplated cadmium in the space environment, but the case for use of cadmium under space environmental condition appears somewhat more favorable than some have thought. The following areas need further study: 1) Why does electroplated cadmium have a lower G than pure bulk cadmium? 2) What conditions affect its G ? 3) What are the effects of surface upon the condensation? 4) How much does the surface and its cleanliness affect the critical condensation rate? 5) Is the critical condensation rate explained by the mechanism presented by Palatnik and Gladkikh?¹⁶

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Titanium, Zirconium, and Yttrium Hydrides as Space Shielding Materials

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THE neutron and proton attenuation properties of hydrogen are well established and documented. Water is an ideal neutron shielding material with regard to cost and hydrogen content, but it is not ideal with regard to physical and mechanical properties and containment considerations. Organic hydrogenous materials are subject to large volume changes associated with the liquid-solid phase change, and materials such as polyethylene frequently exhibit excessive distortion and swelling under high-temperature radiation.

Metal hydrides have numerous merits; LiH is an excellent neutron-proton shield material, and its physical chemistry, fabrication, and postfabrication properties have been investigated extensively. Hydrided titanium, zirconium, and yttrium have some physical and mechanical property advantages, which make them superior to LiH for certain applications. Some general information on metal hydrides and other hydrogenous shield materials is presented in Table I, which confirms the high-temperature advantages of Ti, Y, and Zr hydrides. Titanium and zirconium have hydrogen contents equivalent to or greater than water and most organics, are more effective as gamma shielding materials than water and organics, are metallic in nature, are fabricable, and retain enough strength to be considered as self-supporting structures in simple geometric shapes (e.g., slabs, right circular cylinders, or hexagons) at elevated temperatures (> 500°C). In addition, certain shield configurations, e.g., the spherical shield for a point source, amplify the importance of high N_H values [$(H \text{ atoms/cm}^3) \times 10^{-22}$], which can result in distinct weight savings. This note reviews recent, previously unpublished data for several metal hydrides of Ti, Y, and Zr as shield materials for space nuclear powerplants. Fabrication techniques and engineering design data are included.

Titanium Hydride

Titanium hydride has the highest useful hydrogen content per unit volume (to 0.16 g H/cm³) of any known, thermally

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