

# VAPORIZATION DURING IMPACTS INTO PLANETARY REGOLITHS: APPLICATION TO THE MOON AND MERCURY; Mark J. Cintala, Code SN21, NASA JSC, Houston, TX 77058

Although impact vaporization in planetary regoliths has been studied in the past,<sup>1,2</sup> the discovery of sodium and potassium in the lunar<sup>3</sup> and mercurian<sup>4</sup> "atmospheres" has revived interest in the process. Recent work has treated the contribution that impact vaporization can make to the atmospheres of these planets;<sup>5,6</sup> aspects of vapor generation from and deposition on exposed surface materials are addressed here.

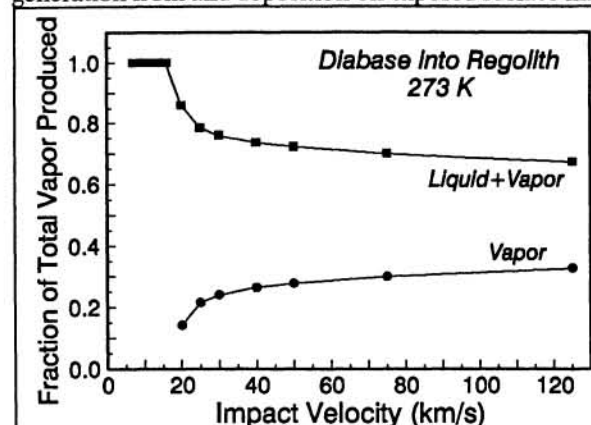


Figure 1. Relative contributions of the liquid+vapor and pure-vapor fields to the total vapor produced by impacts at the indicated velocities.<sup>11</sup> Note that the liquid+vapor field accounts for a minimum of 67 percent of the total vapor produced at any velocity relevant to this study.

vapor will not be free to escape the crater as an unconfined gas. Depending on cooling rates, viscosities, and other factors, the fate of the trapped fraction could then range from resorption to vesicle formation. While volatilization of trapped solar-wind gases has been suggested as a source of vesicles in lunar agglutinates,<sup>9,10</sup> trapped impact vapor such as that described here could also perform the same function.

**Lunar and Mercurian Impact Vapor:** Typical impact velocities at Mercury will be higher than at the Moon,<sup>11</sup> implying higher shock stresses and greater volumes of impact vapor. In addition, the impact origins of this vapor will be somewhat different on each planet, as more of the pure-vapor phase should occur on Mercury. The differential distribution of the vapor component contributed by the liquid+vapor field, for example, can be found by convolving the relevant impact-velocity distribution with a polynomial describing the relative volume of vapor generated in the mixed-phase field as a function of velocity.<sup>11</sup> Such curves are plotted in Fig. 2 for both the liquid+vapor and pure-vapor components. Integration of each of the curves over the permissible velocity ranges<sup>11</sup> reveals that the liquid+vapor state would contribute almost 84 percent of all lunar impact-vapor, and almost 78 percent of that on Mercury. Conversely, only about 16 and 22 percent of all vapor would be contributed

by the pure-vapor phase on the Moon and Mercury, respectively, a difference caused primarily by the higher impact velocities on the latter. (It should be noted that the difference in surface temperature between the Moon and Mercury [273 vs. 400 K, respectively, as used here] has a negligible effect vapor production.) It is apparent, then, that only a relatively small fraction of the total vapor produced might actually be available for behavior as an unconfined gas.

**Vapor Deposition on Regolith Constituents:** The deposition of impact vapor can be examined by considering two cases: one in which no regolith mixing occurs, and one that includes the effects of mixing. **No Regolith Mixing:** In this extreme case, the rate of vapor deposition is simply equal to the rate of vapor generation times the efficiency

**Generation of Impact Vapor:** Vapor can originate from two separate zones in the highly shocked region near an impacting projectile: (a) material completely vaporized by the shock process, and (b) that shocked to somewhat lower pressures, resulting in a mixed-phase region containing both liquid and vapor. As the shock stress decays with distance from the impact point,<sup>7</sup> the vapor component in this latter zone will decrease accordingly. Due to the exceedingly high shock stresses required to vaporize silicates<sup>7</sup> and because significantly less internal energy is required to form only partially vaporized material,<sup>8</sup> the mass of the vapor component from the liquid+vapor field will generally be greater than that of the entire pure-vapor phase (Fig.1). Much of the volume of liquid+vapor, particularly that closer to the impact point and hence with a larger vapor component, will be driven downward into the pure liquid field, "diluting" the vapor in the liquid. Thus, it is very likely that much of the total volume of

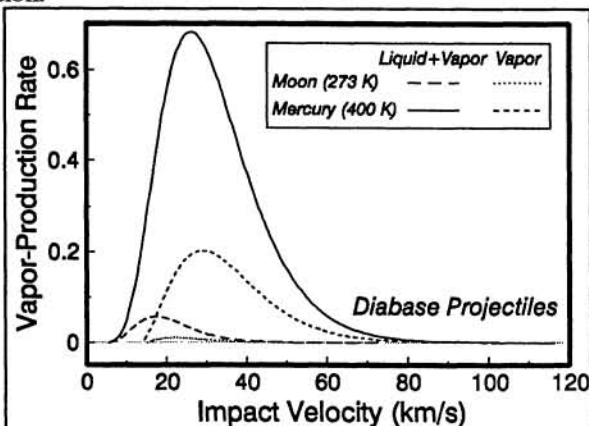


Figure 2. The relative production rates of impact vapor for the liquid+vapor and vapor fields as a function of impact velocity. Since this is a differential distribution, the ordinate has units of projectile volumes/(cm<sup>2</sup>s<sup>2</sup>km/s).

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with which vapor is retained by each planet. In both of these examples, it will be assumed conservatively that all of the specified vapor component will be remain on the planet. The rates of vapor generation determined elsewhere<sup>11</sup> then yield deposition rates of  $1.97 \times 10^{-9}$  and  $4.04 \times 10^{-8}$  g/cm<sup>2</sup>-yr for the Moon and Mercury, respectively. If the deposited layers were to possess a density of 3 g/cm<sup>3</sup>, these values would represent growth rates of 6.57 and 13.5  $\mu\text{m/My}$ , respectively. These are extremely high values, and imply vapor coatings with thicknesses that have never been observed on lunar-regolith grains.<sup>12</sup> Even if the only source of deposited vapor were the pure-vapor field, the rates of deposition would still be unrealistically high at 1.06 and 3.01  $\mu\text{m/My}$ . **Regolith Mixing:** Morris<sup>13</sup> has provided a relationship between the depth  $D$  of *in situ* reworking and the time of exposure  $t$  of a lunar soil. Rewriting his equation slightly,

$$D = 2.2 \left( \frac{t}{t_N} \right)^{0.45} \quad (1)$$

The original equation requires  $t$  to be expressed in millions of years; thus, with  $t$  in years,  $t_N$  is equal to  $10^6$  yr for the Moon. Since the impact flux at Mercury is about 5.5 times higher than at the Moon,<sup>11</sup> the mixing rate for Mercury is approximated here by assuming a value for  $t_N$  of  $1.82 \times 10^5$  yr. In each case,  $t \geq t_N$ . Because "average" craters formed on the two planets will differ in volume by only a few percent,<sup>14</sup> the depths of mixing should be similar; the coefficient will therefore remain unchanged. Taking the density of the regolith to be 1.8 g/cm<sup>3</sup>, eq. (1) can be used to find the total mass in a column of regolith mixed -- and therefore exposed to the surface -- in a given period of time. Using the specific surface area of  $2.1 \times 10^3$  cm<sup>2</sup>/g as found for an Apollo 14 regolith,<sup>15</sup> the thickness of the vapor deposits can then be found as a function of time, and are plotted in Fig. 3.

(The time scale chosen for this illustration comes from the summary of Taylor,<sup>16</sup> which gives exposure ages for lunar soils ranging from  $10^6$  to  $4 \times 10^8$  yr on the basis of rare-gas abundances. Other means of reckoning exposure ages indicate that the upper end of this range is an extreme limit for exposure to any impact vapor.) Even in the unlikely cases of the longest times near the surface and the deposition of all of the impact vapor, the coatings on lunar regolith grains will be very thin. The potential for substantial vapor deposits on Mercury, while somewhat more favorable than on the Moon, is still low. In the best of circumstances, much less than a micrometer of vapor coating would result, and even this would require residence times at the surface that, given the high flux at Mercury, would be even more unrealistic than at the Moon.

**Implications:** It has been suggested that impact-vapor deposits could contribute to the darkening of the lunar<sup>17</sup> and mercurian<sup>18</sup> surfaces. Indeed, experimental results demonstrate that vapor-deposited films absorb efficiently at visible and infrared wavelengths.<sup>17</sup> In all of the experimental examples of this effect, however, the vapor coatings have been on the order of a micrometer thick or greater. Fig. 3 indicates that such thickness are unlikely to exist on the Moon, and would occur on Mercury only under extreme and improbable conditions. Thus, on average, it appears that vapor deposits would play a secondary role to other darkening mechanisms.<sup>14</sup>

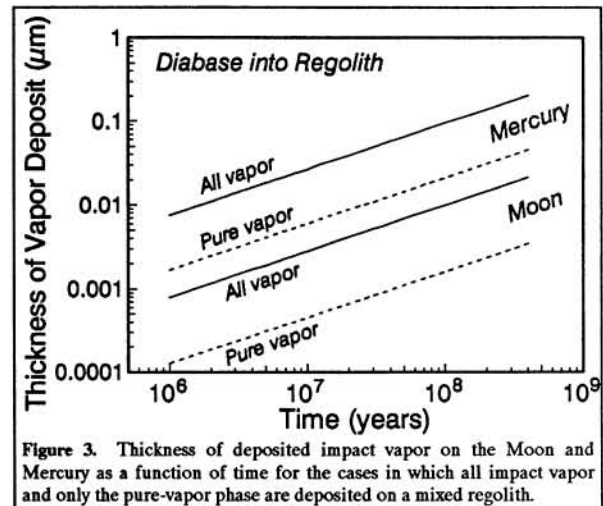


Figure 3. Thickness of deposited impact vapor on the Moon and Mercury as a function of time for the cases in which all impact vapor and only the pure-vapor phase are deposited on a mixed regolith.

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