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# Selected Values of Evaporation and Condensation Coefficients for Simple Substances

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Tables of selected data on the coefficients of evaporation and condensation far from equilibrium for simple substances are presented, together with a rationale for the exclusion or choice of data and an estimate of the precision measure.

Key words: Condensation coefficients; data evaluation; evaporation coefficients; phase change.

## 1. Definition of Coefficients of Evaporation and Condensation

The coefficient of evaporation or condensation  $\alpha$  is defined by the expression from gas kinetic theory [e.g., Loeb, 1934] for the net flux of evaporation or condensation

$$J = \frac{\alpha(p - p_{\text{eq}})}{\sqrt{2\pi mkT}} \quad (1)$$

in which  $p$  is the partial pressure of vapor in the gas phase,  $p_{\text{eq}}$  the equilibrium vapor pressure of the bulk phase at temperature  $T$  and  $m$  is the mass of the atom or molecule. A value of  $\alpha$  less than unity may arise from several sources:

- (a) A coating of impurity on the surface. Any suspicion of appreciable impurity justifies exclusion of the data.
- (b) Other gases in the vapor phase which cause a diffusion impedance for the vapor of interest. This factor must be carefully considered in assessing the data, e.g., as done by Bradley and co-workers.<sup>1</sup>
- (c) The self-diffusion and wall impedance of the vapor itself. This is defined by the Clausing factor [Clausing, 1930 and 1932].
- (d) A reduction or increase in temperature of the surface due to the heat of condensation. Any appreciable uncertainty in this quantity must lead to rejection of the data due to the strong influence of temperature on vapor pressure.
- (e) A dissociative or chemical reaction at the surface. This effect has been carefully considered by Stranski and co-workers [e.g., Knacke and Stranski, 1956]. However such complicated phenomena are beyond the scope of the present work.
- (f) An intrinsic molecular process at the surface of the substance. This is usually the process of scientific interest, because it yields information about the structure of the condensed phase and its surface.

<sup>1</sup>This complicated effect is of great practical importance in chemical engineering, and it has been carefully described by Sherwood and Cooke [1957].

Although the evaporation and condensation coefficients may be equal for some simple liquids, one cannot expect that they will be equal in all cases. This is because the mechanisms of evaporation and condensation are usually different under conditions removed from equilibrium, as reviewed by Hirth and Pound [1963]. One example is evaporation or growth of a close-packed crystal surface by the ledge mechanism.

Coefficients of condensation and evaporation are related in a very complicated way to the coefficient of thermal accommodation, extent of compliance with the cosine law for diffuse reflection, the degree of momentum accommodation, and the extent to which the cosine law would obtain due to scattering from surface asperities alone [e.g., Hirth and Pound, 1963]. However, only measured coefficients of evaporation and condensation will be considered here. Suffice it to say that in the case of substances with high binding energy, i.e., most of the examples given in the tables of the present work, the coefficient of thermal accommodation is found to be unity, as expected from the theoretical work of Cabrera [1959] and Zwanzig [1960] on a one-dimensional chain.

## 2. Experimental Methods

There are some excellent reviews relating to evaporation and condensation. Among these are the works of Burton, Cabrera and Frank [1950], Knacke and Stranski [1956], Chernov [1961], Dekeyser and Amelinckx [1959], Verma [1953], Courtney [1961], Strickland-Constable [1968], and Paul [1962]. Accordingly the experimental methods used in work on evaporation and condensation will be only briefly described here, with principal emphasis being placed on sources of error in the various methods.

### 2.1. Methods for Measuring the Evaporation Coefficient of Solids and Attendant Sources of Error

In regard to the evaporation coefficient of solids, the most important basic method is comparison of the weight loss in a free evaporation or Langmuir

experiment with that from an effusion or Knudsen experiment. The free evaporation experiment is usually conducted in a high vacuum, as is the effusion experiment. The difference is that the equilibrium vapor pressure is approached in the Knudsen effusion cell, and hence the effusion rate from the cell is related to the vapor pressure of the substance through standard expressions. On the other hand, in the Langmuir free evaporation experiment the concentration of atoms at the surface may be less than the equilibrium concentration and hence the desorption rate correspondingly lower than the gross flux at equilibrium, which gives rise to a value of evaporation coefficient  $\alpha_v$  less than unity. Many errors are possible in this method, including contamination of the surface, poor vacua, improper evaluation of the Clausing factor, uncertainty in temperature at the surface due to cooling on free evaporation, or the presence of dissociative or chemical reactions. All of these tend to reduce the evaporation coefficient from unity. A more subtle error arises from discrepancy in temperature between the Langmuir and Knudsen experiments. This is particularly true for work in which the respective experiments were conducted in different laboratories; errors of the order of 50 percent may readily arise.

In Langmuir experiments, the evaporation coefficient  $\alpha_v$  is sometimes estimated to be unity if the calculated third-law values for the standard enthalpy of vaporization  $\Delta H_0^\circ$  is constant for the range of temperatures studied. However,  $\Delta H_0^\circ$  is a function of  $kT \ln \alpha_v + \text{a constant}$  and hence over the usual limited temperature range of most experiments, the third-law test is not precise. Accordingly, all results obtained by this method were rejected.

Another source of error, recognized and carefully described only recently by Winterbottom and Hirth [1962] and Winterbottom [1967], arises from neglect of surface diffusion through the orifice in Knudsen experiments. This factor may reduce the evaporation coefficient by an amount typically of the order of 5 percent. It has never been considered in any measurement of evaporation coefficient, including the works cited in the present review.

An interesting variant of the Knudsen weight-loss method was introduced by Volmer [1931] and Neumann and Völker [1932] in which the momentum transfer due to evaporation from holes on opposite sides of a torsion balance beam was measured and related to the equilibrium vapor pressure. A clever adaptation of this method was carried out by Holden, Speiser and Johnson [1948] to permit direct determination of the evaporation coefficient. In this apparatus the holes on one side of the torsion balance beam were replaced by a flat surface from which free evaporation occurred. Wessel [1951]

further improved the method by constructing the torsion balance beam of the substance to be investigated in the form of a hollow box with a hole on one side and none on the other. This change tended to make the temperatures on opposite ends of the balance beam more nearly the same.

Another valuable new method for measuring thermal beam flux in Langmuir and Knudsen evaporation experiments is mass spectrometry, as developed by Rothberg, Eisenstadt, and Kusch [1959] and by Burns, Jason, and Inghram [1967]. This method permits direct determination of the evaporating species.

In the method of Bradley and Shellard [1949], small beads of solid are evaporated in air, and the rate determined gravimetrically. The evaporation coefficient is determined from a careful analysis of the effect of gaseous diffusion and comparison of the rate in air with the rate from Knudsen experiments. This method is thought to give accurate results. In a free evaporation experiment they should lie even closer to unity than shown in the tables.

It is interesting to note that no authors attempt to estimate the surface cleanliness. Only a few use single crystals and attempt to specify the surface orientation. Only one, Loew [1964], has specified the degree of surface imperfection in terms of dislocation density.

Finally one notes that research on evaporation of solids is beset with a special, often intangible difficulty: due to the slowness of diffusion in solids, a layer of nonvolatile impurity may rapidly accumulate at the surface, even though the initial specimen is very pure.

## 2.2. Methods for Measuring the Evaporation and Coefficient of Liquids and Attendant Sources of Error

Some of the experimental methods for determination of the evaporation coefficients of liquid are the same as for solids. Thus the basic Langmuir-Knudsen method described in the preceding section may be applied to liquids of low vapor pressure such as glycerol. Also, the method employed by Bradley and Shellard [1949] for evaporation of solid beads in air, as described above, was originally developed for small droplets of liquid by Birks and Bradley [1949].

However, due to the high vapor pressure of most liquids, other special and often ingenious methods had to be developed. Perhaps the first of these was the method introduced by Alty and Mackay [1935] for the study of water. They evaporated a small drop of water, as it was being formed on a volumetric pipette tip, into a vacuum. When the drop was fully formed, it fell from the tip whereupon it was collected and weighed to determine the loss by evaporation. The surface tension could also be deduced from the drop weight and hence the sur-

face temperature of the evaporating drop and the vapor pressure of the liquid at this temperature. Again, many errors are possible in this method and the special methods to be described in the following, including contamination of the surface, poor vacuum, improper evaluation of the Clausing factor for self-diffusion impedance of the vapor, and surface cooling. However, due to the rapid evaporation rate and low thermal conductivity of most liquids, the principal difficulty would appear to arise from surface cooling. In fact, Littlewood and Rideal [1956] have criticized the experiment of Alty and Mackay on the grounds that the surface tension of an evaporating surface is not the same as that of a surface at equilibrium and therefore that there was an error due to surface cooling.

There have been other elaborate attempts to measure the surface temperature directly by small thermocouples. The most outstanding effort was probably that of Bucka [1950], who evaporated ethanol into an evacuated vessel and measured the surface temperature as the surface passed the thermocouple. The evaporation rate was obtained from the pressure rise, and the evaporation coefficient determined by comparison with the gross evaporation flux corresponding to the equilibrium vapor pressure.

Perhaps a more reliable method is that of Von Bogdandy, Kleist, and Knacke [1955], who evaporated liquids (see table 2) of differing enthalpy of vaporization and thermal conductivity from copper and glass capillary tubes of variable inside diameter into an evacuated vessel and measured the pressure rise.

Trevoý [1953] and Hickman [1954] measured the free evaporation rate from freshly created (moving) surfaces of glycerol and water, respectively, into a vacuum and reported much higher evaporation coefficients than those obtained by other workers using "still" surfaces. Supposedly, the problem of surface cooling had been obviated, as assumed by Littlewood and Rideal [1956]. Trevoý and Hickman interpreted their results to mean that the motion of the liquid provided a clean, unoriented surface, for which the evaporation coefficient is essentially unity.

The results of Trevoý and of Hickman have been challenged by Heideger and Boudart [1962], who evaporated stirred and unstirred glycerol from an open container and from an effusion cell into an evacuated vessel and observed the pressure rise. They determined the equilibrium vapor pressure as the terminal pressure in the system. Heideger and Boudart found that the stirring had no effect on the evaporation coefficient, which was of the order of 0.05–0.15.

Wyllie's [1948] value of 0.052 for glycerol has been excluded from consideration by Burrows' [1947] calculation of the Clausing factor for that

apparatus. Burrows estimates that proper consideration of the Clausing factor for Wyllie's experiment would raise the evaporation coefficient to at least 0.5.

### 2.3. Methods for Measuring the Condensation Coefficient of Solids and Attendant Sources of Error

The author has been unable to find highly reliable data for the condensation coefficient of liquids. In general, for the case of solids, a thermal beam of the vapor to be condensed is projected onto the substrate surface, which is maintained at a fixed temperature. The amount condensed may be measured by chemical analysis, gravimetry, observation of crystal dimensions or, more recently, by a crystal oscillator as done by Bachmann and Shin [1966]. Also, radioactive tracers may be used, as in the work of Devienne [1953 a, b]. Sometimes the vapor beam is calibrated by deposition on a cold surface, upon which all of the incident vapor is assumed to condense, as in the work of Rapp et al. [1961]. In other cases, the vapor flux is calculated from the vapor pressure of the material at the vapor source as in the work of Hock and Neumann [1954]. Chupka and co-workers [1963] used a mass spectrometer to monitor both impinging and reflected fluxes at metal surfaces. In the recent paper by Bachmann and Shin, an ionization gauge was used to monitor the vapor beam flux. All of these methods are fairly precise.

However, a principal difficulty arises in connection with specification of the substrate. If the substrate is different from the condensing material, a problem arises relating to the adsorption and heterogeneous nucleation of condensate on the substrate. This is a large field in itself and could be the subject of another monograph. If the substrate is of the same material and the supersaturation is low, a probable rate controlling process in a "clean" system with sources of monatomic (or multiatomic) steps at the surface is surface diffusion of ad molecules to these steps. As discussed by Hirth and Pound [1963], the density of these step sources can have an effect on crystal growth rate and hence the evaporation coefficient. A more important effect may well be the "poisoning" of the step sinks by minute amounts of adsorbed impurity. In any case, for one reason or another, the data on various systems by various methods are at present by no means wholly compatible. Indeed growth rate of crystals at low supersaturation could well be the topic of a separate paper, as it has been many times in the past [for example, see the classic paper of Burton, Cabrera, and Frank, 1950]. Therefore, the writer has arbitrarily excluded from consideration the topic of crystal growth at low supersaturations. Attention will be restricted to condensation coefficients in growth at high supersaturations where it is expected that "clean" step sinks arising from nucleation of

crystallites will be abundant on the solid surface.

One notes that the analogous difficulty is apparently not as severe for evaporation at low undersaturations. Evidently there are more sources for steps operative in this case, e.g., crystal and grain-boundary edges.

### 3. Criteria for Selection of Data

In regard to the evaporation coefficients, all results which did not appear to meet the following criteria were arbitrarily rejected:

- (a). There should be no serious doubt about the cleanliness of the evaporating surface with respect to impurities from either vapor or evaporating solid which might either impede or facilitate evaporation.
- (b). Any appreciable Clausius factor to account for the impedance of vapor transport arising from diffusion through a foreign gas or self-diffusion in the vapor should be duly considered.
- (c). The surface temperature should be known with reasonable certainty.
- (d). There should be no worry about the existence of any appreciable discrepancy in temperature between the Knudsen and Langmuir experiments, especially in cases where they were performed in separate laboratories.
- (e). There should be no reason to suspect the existence of any appreciable dissociative or chemical reaction on evaporation.
- (f). The techniques should appear plausible and reasonably consistent with the precision measure claimed for them.
- (g). The results should appear to be self consistent.
- (h). The paper should be sufficiently complete to yield at least the necessary information for comparison with the above criteria.

In regard to the condensation coefficients, all results which did not meet the following criteria were arbitrarily rejected:

- (a). The substrate should consist of the condensing substance itself.
- (b). The supersaturation should be sufficiently high that there is an abundance of monatomic step sinks.
- (c). There should be no serious doubt about the cleanliness of the surface of condensation with respect to impurities from the vapor which might impede the condensation.
- (d). The surface temperature should be known with reasonable certainty.

and criteria (e) to (h) above.

Finally, in no case were results admitted to the tables merely because they were in agreement with other data.

The author is painfully aware that he may have misinterpreted papers of great value and thus wrong-

fully rejected them from his tables of selected data. Also, there is little doubt that important omissions occur in the Bibliography, especially in regard to the more recent literature. He hopes that the authors of such articles will communicate to him the nature of his errors and omissions.

### 4. Discussion of Tables of Selected Data

The data selected according to the above criteria for Coefficients of Evaporation of Solids, Coefficients of Evaporation of Liquids, and Coefficients of Condensation of Solids are presented in tables 1, 2, and 3, respectively. The column headings are probably self-explanatory. The descriptions under the column labeled "Technique" will best be understood by reference to the section on Experimental Methods. The column labeled "Surface Condition" in table 2 was occasioned by the controversy between Trevoy [1953] and Heideger and Boudart [1962] in which Trevoy maintains that the evaporation coefficient of glycerol tends to be very considerably enhanced at moving surfaces. A similar disparity exists between the results of Alty and Mackay [1935] and Hickman [1954] for the case of water, as noted above.

In the footnotes to the tables some reservations are expressed as to the reliability and interpretation of some of the data. However, none of these reservations seem particularly serious.

Finally, it will be noted that there are more columns available in the tables than there are corresponding items of information. It is hoped that this representation will encourage future investigators to seek such missing information.

### 5. Principal Conclusions to be Drawn from the Tables

- (1) The evaporation coefficient for the "clean" surface of most simple polycrystalline solids approaches unity. The principal exception would appear to be rhombic sulfur.
- (2) The evaporation coefficient for the "clean" surfaces of single crystals of simple solids seems to be significantly, but not greatly, lower than unity.
- (3) The evaporation coefficient of "clean" surfaces of most simple liquids approaches unity. Ethanol appears to be a notable exception. The status of water and glycerol are still moot, as is the effect of a "moving" versus a "still" surface.
- (4) The condensation coefficient for growth of metals at high supersaturation is unity.

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Table 1. Selected values of measured evaporation coefficients,  $\alpha_e$ , for solids

Substance	Purity	Orientation	Surface imperfection	Surface cleanliness	Vacuum	Temperature	Technique	Evaporation coefficient, $\alpha_e$	Authors
Beryllium, solid.	Fairly high; vacuum cast; sintered.	Polycrystalline.	Unstated.	Unstated; probably fair.	Unstated; probably $10^{-6}$ torr.	1171–1552 K $\pm 1^\circ$ .	Langmuir-Knudsen torsion balance.	$1.0 \pm 0.02$ .	Holden et al. [1948].
Boron, solid; liquid.	Unstated; probably fair.	Polycrystalline; liquid (Still).	Unstated.	Unstated; probably fair.	Unstated; probably $< 10^{-8}$ torr.	Melting Point, $2403 \pm 40$ K.	Mass spec. Langmuir-Knudsen on liq.	$0.98 \pm 0.02$ .	Burns et al. [1967].
Cadmium, solid.	Unstated; probably fair.	Polycrystalline.	Polished.	Unstated; probably fair.	$10^{-6}$ torr.	Just below mp, $586 \pm 3$ K.	Langmuir-Knudsen torsion balance.	$0.996 \pm 0.002$ .	Wessel [1951].
Carbon.	Unstated; Acheson graphite.	Polycrystalline.	Unstated.	Unstated; probably fair.	$10^{-8}$ torr.	2357–2870 K $\pm 10^\circ$ .	Langmuir-Knudsen.	$1 \pm 0.1$ .	Marshall and Norton [1950].
Cesium Bromide, solid.	Unstated; Harshaw.	Single crystal <sup>a</sup> but unknown orientation.	Unstated.	Unstated; probably fair.	Unstated; probably $< 10^{-8}$ torr.	785–830 K $\pm 5^\circ$ .	Mass spec. Langmuir-Knudsen.	$0.27 \pm 0.1$ .	Rothberg et al. [1959].
Cesium Iodide, solid.	Unstated; Harshaw.	Single crystal <sup>a</sup> but unknown orientation.	Unstated.	Unstated; probably fair.	Unstated; probably $< 10^{-8}$ torr.	757–772 K $\pm 5^\circ$ .	Mass spec. Langmuir-Knudsen.	$0.36 \pm 0.1$ .	Rothberg et al. [1959].
Chromium, solid.	A. D. Mackay, Inc., 99.9%.	Polycrystalline.	Unstated.	Unstated; probably fair.	Unstated; probably $< 10^{-7}$ torr.	1318–1563 K $\pm 3^\circ$ .	Langmuir-Knudsen.	$0.9 \pm 0.1$ .	McCabe et al. [1956].
Ice.	Unstated; probably fair.	Polycrystalline.	Unstated.	Unstated; probably fair.	$10^{-5}$ torr.	188–213 K $\pm 0.6^\circ$ .	Langmuir-Equil. Vap.	$0.9 \pm 0.1$ .	Tschudin [1946].
Iron, solid.	Unstated; probably fair.	Polycrystalline.	Unstated.	Unstated; probably fair.	$10^{-5}$ torr.	1540–1740 K $\pm 15^\circ$ .	Langmuir-Knudsen.	$1 \pm 0.2$ .	Wessel [1951].
Iron, solid.	Fisher Electrolytic; probably fair.	Polycrystalline.	Unstated.	Unstated; probably fair.	Unstated; probably $< 10^{-7}$ torr.	1358–1520 K $\pm 3^\circ$ .	Langmuir-Knudsen.	$0.9 \pm 0.1$ .	McCabe et al. [1956].
Lanthanum Fluoride, solid.	99.6%.	Macroscopically (0001).	Polished.	Unstated; probably fair.	$10^{-8}$ – $10^{-9}$ torr.	1340–1650 K $\pm 5^\circ$ .	Torsion Knudsen-Torsion Langmuir.	$0.95 \pm 0.1$ .	Mar and Searcy [1967].
<i>n</i> -C <sub>17</sub> H <sub>36</sub> .	Refractive indices and densities of liquid and X-ray diffraction of solid indicated good purity.	Polycrystalline.	Unstated.	Unstated; probably fair.	0.1 torr (of air).	15–22° C $\pm 0.01^\circ$ .	Evap. of beads in air and Knudsen.	$0.95 \pm 0.05$ <sup>b</sup> .	Bradley and Shellard [1949].
<i>n</i> -C <sub>18</sub> H <sub>38</sub> .	Refractive indices and densities of liquid and X-ray diffraction of solid indicated good purity.	Polycrystalline.	Unstated.	Unstated; probably fair.	0.1 torr (of air).	15–28° C $\pm 0.01^\circ$ .	Evap. of beads in air and Knudsen.	$1.00 \pm 0.05$ <sup>b</sup> .	Bradley and Shellard [1949].
Potassium Chloride.	Unstated; probably high.	Single crystal, macroscopically (100) and (100) plus (111).	Polished.	Unstated; probably fair.	Unstated; probably $10^{-7}$ torr.	672–738 K $\pm 0.1^\circ$ .	Langmuir-Knudsen.	$0.72 \pm 0.15$ <sup>c</sup> .	Bradley and Volans [1953].



Table 1. Selected values of measured evaporation coefficients,  $\alpha_v$ , for solids — Continued

Substance	Purity	Orientation	Surface imperfection	Surface cleanliness	Vacuum	Temperature	Technique	Evaporation coefficient, $\alpha_v$	Authors
Potassium Chloride.	Unstated; probably high.	Single crystal, macroscopically (100) and (100) plus (111) and (100) plus (110).	Polished.	Unstated; probably fair.	Unstated; probably $10^{-7}$ torr.	672–788 K $\pm$ 0.1°.	Langmuir-Knudsen.	0.63 $\pm$ 0.015°.	Bradley and Volans [1953].
Potassium Per-rhenate, solid.	Unstated.	Single crystal, macroscopically basal plane.	Irregular surface.	Unstated.	Unstated; probably $10^{-6}$ torr.	746–768 K $\pm$ 1°.	Langmuir-Knudsen.	0.7 $\pm$ 0.1.	Neumann and Costeau [1939].
Silver, solid.	Unstated.	Polycrystalline.	Unstated.	Unstated; probably fair.	$10^{-5}$ torr.	Just below mp, 1234 $\pm$ 3 K.	Torsion balance.	> 0.92.	Wessel [1951].
Silver, solid.	Spectrographically pure.	Polycrystalline.	Unstated.	Unstated; probably fair.	$5 \times 10^{-6}$ torr.	1103 $\pm$ 1 K.	Langmuir-Knudsen.	0.9 $\pm$ 0.2.	Lowe [1964].
Silver, solid.	Spectrographically pure.	Complex plane.	Unstated.	Unstated; probably fair.	$5 \times 10^{-6}$ torr.	1103 $\pm$ 1 K.	Langmuir-Knudsen.	0.8 $\pm$ 0.2.	Lowe [1964].
Silver, solid.	Spectrographically pure.	Single crystal, (111) plane (epitaxial film).	Dislocation density $1.6 \pm 0.5 \times 10^7/\text{cm}^2$ .	Unstated; probably fair.	$5 \times 10^{-6}$ torr.	1103 $\pm$ 1 K.	Langmuir-Knudsen.	0.85 $\pm$ 0.2.	Lowe [1964].
Silver, solid.	Spectrographically pure.	Single crystal, (111) plane (epitaxial film).	Dislocation density $1.6 \pm 0.5 \times 10^7/\text{cm}^2$ .	Unstated; probably fair.	$5 \times 10^{-6}$ torr.	1198 $\pm$ 1 K.	Langmuir-Knudsen.	0.54 $\pm$ 0.2.	Lowe [1964].
Sodium Chloride.	Unstated; probably fair.	Single crystal, macroscopically (100).	Pitted, increasing with increasing undersaturation.	Unstated; probably fair.	$10^{-5}$ torr.	853 $\pm$ 5 K.	Torsion balance with various effusion orifice sizes.	0.4 $\pm$ 0.05 at largest orifice size corresponding to free evaporation.	Jaekel and Peperle [1961].
Sulfur, rhombic.	Unstated; probably high.	Single crystal, macroscopically bipyramidal planes.	Some pits.	Unstated; probably fair.	Unstated; probably $10^{-6}$ torr.	288.3–306.8 K $\pm$ 0.1.	Langmuir-Knudsen.	0.73 $\pm$ 0.05.	Bradley [1951].
Sulfur, rhombic.	Unstated; probably high.	Polycrystalline.	Unstated.	Unstated; probably fair.	$10^{-7}$ torr.	288.3–305.7 K $\pm$ 0.1.	Langmuir-Knudsen.	0.70 $\pm$ 0.05.	Bradley [1951].

<sup>a</sup> Hirth and Pound [1963] later examined the specimens and observed that the surfaces had formed low-index planes in macroscopic steps or facets.

<sup>b</sup> The impedance due to diffusion through air was carefully considered. The evaporation

coefficient in a higher vacuum should also be unity.

<sup>c</sup> Miller and Kusch [1956, 1957] report that approximately 10% dimer exists in the vapor over potassium chloride, and this could have an effect on the evaporation coefficient.

TABLE 2. Selected values of measured evaporation coefficients,  $\alpha_v$ , for liquids

Substance	Purity	Surface condition	Surface cleanliness	Vacuum	Temperature	Technique	Evaporation coefficient, $\alpha_v$	Authors
Boron, solid; liquid.	Unstated; probably fair.	Polycrystalline, liquid (Still).	Unstated; probably fair.	Unstated < $10^{-8}$ torr.	Melting point $2403 \pm 40$ K	Mass spec. Langmuir-Knudsen on liq.	$0.98 \pm 0.02$ .	Burns et al. [1967].
Carbon tetrachloride.	Unstated.	Still.	Unstated; probably fair.	$\sim 25$ torr (of substance).	$0 \pm 0.1^\circ$ C.	Nonequil. evap. and vapor pressure.	$0.99 \pm 0.02$ .	Von Bogdandy et al. [1955].
Di- <i>n</i> -butyl phthalate.	Washed with $\text{Na}_2\text{CO}_3$ , vacuum distilled, molecular distillation. Refractive index and density given. Probably quite pure.	Still.	Unstated; probably fair.	$0.14$ – $84.6$ torr (of gas).	$15.00$ – $35.00^\circ$ C $\pm 0.01$ .	Evap. of drops in gases and Knudsen.	$1.0 \pm 0.05^a$ .	Birks and Bradley [1949].
Ethyl alcohol.	"Absolute".	Still.	Unstated; probably fair.	$\sim 20$ torr (of substance).	$12.40$ – $15.50^\circ$ C $\pm 0.03^b$ .	Nonequil. evap. and vapor pressure.	$0.024 \pm 0.002^b$ .	Bucka [1950].
Ethyl alcohol.	$> 99.9\%$ .	Still.	Unstated; probably fair.	$\sim 16$ torr (of substance).	$0 \pm 0.1^\circ$ C.	Nonequil. evap. and vapor pressure.	$0.036 \pm 0.003$ .	Von Bogdandy et al. [1955].
Glycerol.	Distilled.	Moving.	Unstated; probably fair.	$10^{-5}$ torr residual gas.	$18.0$ – $70.0^\circ$ C $\pm 0.1^c$ .	Langmuir and vapor pressure.	$1.0 + 0.15$ .	Trevo [1953].
Glycerol.	Well distilled.	Still and moving.	Unstated; probably fair.	Unstated; probably $10^{-5}$ torr residual gas (and $10^{-5}$ torr of substance), <sup>d</sup>	$13$ – $25^\circ$ C $\pm 0.1^e$ .	Nonequil. and equil. evaporations.	$0.05$ – $0.15^c \pm 0.01$ .	Heideger and Boudart [1962].
Mercury.	Unstated; probably high.	Still.	Unstated; probably high.	Unstated; probably $10^{-5}$ torr.	$19.5 \pm 0.05^\circ$ C.	Langmuir-Knudsen...	$0.96 \pm 0.01$ .	Knudsen [1915].
Mercury.	Unstated; probably high.	Still.	Fairly high.	$10^{-5}$ torr.	$-37$ to $+59^\circ$ C $\pm 0.2^e$ .	Langmuir-Knudsen...	$1.0 \pm 0.05$ .	Volmer and Estermann [1921].
<i>n</i> - $\text{C}_{17}\text{H}_{36}$ .	Refractive indices, densities, and X-ray diffraction of solid indicated good purity.	Still.	Unstated; probably fair.	$0.1$ torr (of air).	$22$ – $40^\circ$ C $\pm 0.01^e$ .	Evap. of drops in air and Knudsen.	$0.95 \pm 0.05^a$ .	Bradley and Shellard [1949].
<i>n</i> - $\text{C}_{18}\text{H}_{38}$ .	Refractive indices, densities, and X-ray diffraction of solid indicated good purity.	Still.	Unstated; probably fair.	$0.1$ torr (of air).	$28$ – $40^\circ$ C $\pm 0.01^e$ .	Evap. of drops in air and Knudsen.	$0.95 \pm 0.05^a$ .	Bradley and Shellard [1949].
Potassium, liquid.	Unstated; probably high.	Still.	Unstated; probably fair.	Unstated; probably $10^{-6}$ torr.	$66.7$ – $119.3^\circ$ C $\pm 0.1^e$ .	Langmuir-Knudsen...	$0.95 \pm 0.05$ .	Numann [1954].
Tin Chloride, $\text{SnCl}_2$ .	Merck analytical, dehydrated with HCl gas. Distilled five times.	Still.	Unstated; probably fair.	$\sim 1$ torr (of Substance).	$350 \pm 0.1^\circ$ C.	Nonequil. evap. and vapor pressure.	$0.96 \pm 0.07$ .	Von Bogdandy et al. [1955].
Tridecyl Methane.	Refractive indices, densities, and dielectric constants indicated good purity.	Still.	Unstated; probably fair.	$0.17$ torr (of Air).	$25$ – $35^\circ$ C $\pm 0.1^e$ .	Evap. of drops in air and Knudsen.	$0.98 \pm 0.03^a$ .	Bradley and Waghorn [1951].

TABLE 2. Selected values of measured evaporation coefficients,  $e_v$ , for liquids—Continued

Substance	Purity	Surface condition	Surface cleanliness	Vacuum	Temperature	Technique	Evaporation coefficient, $e_v$	Authors
Triheptyl Methane.	Refractive indices, densities, and dielectric constants indicated good purity.	Still.	Unstated; probably fair.	0.17 torr (of Air).	25–35° C ± 0.1°.	Evap. of drops in air and Knudsen.	0.98 ± 0.03 <sup>a</sup> .	Bradley and Waghorn [1951].
Water.	Unstated.	Still.	Unstated; probably fair.	5–10 torr (of Substance).	14.24–19.04° C ± 0.02°.	Nonequil. evap. and vapor pressure.	0.086 ± 0.002 <sup>b</sup> .	Aly and Mackay [1955].
Water.	Distilled.	Moving.	Unstated; probably fair.	1–7 torr (of Substance).	4.0 ± 1° C.	Langmuir and vapor pressure.	> 0.24 <sup>b</sup> .	Hickman [1954].

<sup>a</sup> The impudence due to diffusion through gases was carefully considered. The evaporation coefficient at higher vacua should also be unity.

<sup>b</sup> Inadequate consideration was given to the problem of gaseous diffusion. Hence this value is probably too low.

<sup>c</sup> A function of system pressure, lower for higher partial pressures of glycerol.

TABLE 3. Selected values of measured condensation coefficients,  $\alpha_c$ , for solids

Condensing substance	Purity of condensing substance	Vapor temperature	Vapor beam flux	Substrate surface	Substrate surface orientation	Substrate surface cleanliness	Vacuum	Substrate temperature	Super-saturation ratio $p/P_{eq}$	Technique	Condensation coefficient	Authors
Cadmium	99.9%	Unstated.	$1.6 \times 10^6$ to $1.9 \times 10^6$ atoms/cm <sup>2</sup> .sec.	Cadmium.	Polycrystalline cadmium.	Unstated; probably good.	$10^{-8}$ to $10^{-4}$ torr (residual gas).	291.1–296.1 K $\pm 0.02^\circ$ .	$2 \times 10^7$ .	Measurement of mass by chemical analysis.	$1.00 \pm 0.03$ .	Rapp et al. [1961].
Gold	99.999%	Unstated.	$4 \times 10^{-4}$ mono-layers/sec.	Gold single crystal and polycrystalline.	Macroscopically (100) $\pm 2^\circ$ and polycrystalline.	Unstated; probably good.	$< 10^{-8}$ torr (residual gas).	375–900 K $\pm 35^\circ$ .	Unstated; probably high.	Measurement of mass by quartz micro-balance.	$1.0 \pm 0.1$ .	Schwoebel [1964].
Gold	Unstated.	Unstated.	$3.13 \times 10^{13}$ and $3.6 \times 10^{13}$ atoms/cm <sup>2</sup> .sec.	Gold on SiO <sub>2</sub> .	Polycrystalline on SiO <sub>2</sub> .	Unstated; probably good.	$10^{-7}$ torr (residual gas).	297 and 452 K $\pm 1^\circ$ .	Unstated; probably high.	Ionization gauge for flux and crystal oscillator for deposit.	$1.00 \pm 0.05$ (for greater than 20Å mean thickness).	Bachmann and Shin [1966].
Gold	Unstated; probably fair.	Unstated.	Unstated.	Gold.	Polycrystalline.	Flashed by heating to high temp.	$10^{-6}$ torr.	$1100^\circ \pm 20$ K.	Unstated; probably high.	Mass spectrometry.	$> 0.99$ .	Chupka et al. [1963].
Platinum	Unstated; probably fair.	Unstated.	Unstated.	Platinum.	Polycrystalline.	Flashed by heating to high temp.	$10^{-4}$ torr.	$1500^\circ \pm 20$ K.	$\sim 10^4$ .	Mass spectrometry.	$> 0.998$ .	Chupka et al. [1963].
Platinum	Unstated; probably fair.	Unstated.	Unstated.	Platinum.	Polycrystalline.	Flashed by heating to high temp.	$10^{-4}$ torr.	$600^\circ \pm 20$ K.	$\sim 10^3$ .	Mass spectrometry.	$> 0.998$ .	Chupka et al. [1963].
Potassium	Unstated.	334.1–340.1 K $\pm 0.1^\circ$ .	Corresponding to 6.9 $\times 10^{-7}$ to $13 \times 10^{-7}$ torr.	Single crystals of potassium.	Unstated.	Unstated.	Unstated.	284.1 to 333.6 K $\pm 0.1^\circ$ .	1.4 to 520.	Measurement of crystal dimensions.	$0.98 \pm 0.05$ .	Hock and Neumann [1954].
Rhodium	Unstated; probably fair.	Unstated.	Unstated.	Rhodium.	Polycrystalline.	Flashed by heating to high temp.	$10^{-6}$ torr.	$1530^\circ \pm 20$ K...	Unstated; probably high.	Mass spectrometry.	$> 0.99$ .	Chupka et al. [1963].
Silver	Unstated.	1173–1223 K.	$1.3 \times 10^{14}$ to $4.5 \times 10^{14}$ atoms/cm <sup>2</sup> .sec.	Silver.	Polycrystalline.	Unstated; probably good.	$7 \times 10^{-5}$ to $6 \times 10^{-10}$ torr (residual gas).	$447^\circ \pm 30$ K...	$10^6$ to $10^9$ .	Measurement of mass by chemical analysis.	$1.00 \pm 0.02$ .	Rapp et al. [1960].
Silver	Unstated.	Unstated.	$3.8 \times 10^8$ and $4.4 \times 10^8$ atoms/cm <sup>2</sup> .sec.	Silver on SiO <sub>2</sub> .	Polycrystalline on SiO <sub>2</sub> .	Unstated; probably good.	$10^{-8}$ torr (residual gas).	296 and 447 K $\pm 1^\circ$ .	$2 \times 10^{18}$ and $3 \times 10^{15}$ .	Ionization gauge for flux and crystal oscillator for deposit.	$1.00 \pm 0.05$ (for greater than 10Å mean thickness).	Bachmann and Shin [1966].

TABLE 5. Selected values of measured condensation coefficients,  $\alpha_v$ , for solids - Continued

Condensing substance	Purity of condensing substance	Vapor temperature	Vapor beam flux	Substrate surface	Substrate surface orientation	Substrate surface cleanliness	Vacuum	Substrate temperature	Supersaturation Ratio $p/p_{eq}$	Technique	Condensation coefficient	Authors
Tungsten.	Unstated; probably fair.	Unstated.	Unstated.	Tungsten.	Polycrystalline.	Flashed by heating to high temp.	$10^{-6}$ torr.	$2200^\circ \pm 20$ K.	Unstated; probably high.	Mass spectrometry.	$0.998 \pm 0.0005$ .	Chupka et al. [1963].
Tungsten.	Unstated; probably fair.	Unstated.	Unstated.	Tungsten.	Polycrystalline.	Flashed by heating to high temp.	$10^{-6}$ torr.	$900^\circ \pm 20$ K.	Unstated; probably high.	Mass spectrometry.	$0.998 \pm 0.0005$ .	Chupka et al. [1963].
Zinc.	99.98%.	Unstated.	$8.3 \times 10^{15}$ atoms/cm <sup>2</sup> -sec.	Zinc.	Polycrystalline zinc.	Unstated; probably good.	$6 \times 10^{-8}$ torr (residual gas).	$341.1^\circ \pm 0.2$ K.	$8 \times 10^6$ .	Measurement of mass by chemical analysis.	$0.96 \pm 0.03$ .	Rapp et al. [1961].