EVAPORATION CHARACTERISTICS OF TUNGSTEN.

By G. R. Fonda.

ABSTRACT.

Rate of evaporation from tungsten filaments at 2825° K.—Using the Langmuir method, it was found that *in vacuum* the rate of evaporation per cm² m is independent of the diameter a, 1/20 to 1/4 mm, but is over forty per cent greater for fine-grained than for very coarse-grained wires, probably because the evaporation at the boundaries of the crystals is abnormal. *In nitrogen* the rate varied from 2 to 5 per cent of that for the same wire in vacuum, and *in argon* from 1.3 to 3 per cent, increasing as the diameter decreased from 1/4 to 1/15 mm. The variation with size when gas was present is in agreement with the Langmuir theory of heat conduction for hot filaments which supposes that there is around the wire a stationary film of gas through which the evaporated atoms must diffuse. The diameter of the outer surface of this film b varies with a according to the equation: $b \log (b/a) = 0.86$; and this leads to the equation: $ma \log (b/a) = \text{const.}$, with which the experimental results agree. The constants for nitrogen and argon are inversely proportional to the molecular weights.

METHODS of measuring the rate of evaporation of tungsten in the form of filaments have been developed and studied in vacuum by Langmuir.[1] Use of his method in a further study of tungsten filaments in gases as compared with their behavior in vacuum has brought out the extent to which the rate is lowered in nitrogen and argon and also the dependence of the rate on the crystalline structure of the wire.

Drawn wire was used in all cases, both as "thoriated" and as "Non Sag." The former contains 0.6–0.8 per cent thoria and is uniformly and invariably fine grain, so much so that several crystals occur across a diameter of the wire, even in the smallest sizes. The "Non Sag" wire contains less than 0.1 per cent of impurities. In crystallization it varies from a structure as fine grained as the thoriated to one characterized by excessively large and long crystals.

Filaments in 12 cm lengths, mounted in vertical loops, were tested at constant voltage at an initial temperature of 2950° K in the case of the experiments in vacuum, and 2825° K in the case of those in gas. The gas was introduced to the lamp at a pressure cold of 51 cm. The filament temperature was determined by color match on the photometer; only the central portion of the filament was viewed in order to avoid errors from the lower temperature at the portions cooled by the leads. In

[1] Phys. Rev., 2, 329 (1913).

obtaining the final weight of the filament, 1.5 cm next each lead was rejected for the same reason, and, in the case of filaments tested in gas, 1 cm on each side of the tip. Each test was continued to burn-out of the filament and a 7-mm length on each side of the point of burn-out was also rejected, in order to avoid errors due to the molten conditions of the terminals.

RATE OF EVAPORATION.

The rate of evaporation was determined from Langmuir's equation,

$$m = 2.846 \, \frac{\sqrt{W_0} - \sqrt{W_f}}{t},$$

where W_0 = initial weight in grams per cm,
$\quad W_f$ = final weight in grams per cm,
$\quad t$ = time in seconds.

m is accordingly the rate of evaporation in grams per sq. cm per second.

The results given in Table I. are made up, with the exception of "I." and "II.", from averages from several wires of the same crystalline

TABLE I.

Rate Evaporation of Tungsten Filaments in Vacuum and in Inert Gases.

Size Filament.	Character Tungsten.	Crystalline Structure.	Rate of Evaporation gms. per sq. cm per sec. $\times (10)^9$.		
			Vacuum.	Nitrogen.	Argon.
.051 mm	Non Sag	Large	300	—	—
"	Non Sag	Small	420	21	—
.069	Thoriated I.	Small	—	13	9
.076	Non Sag II.	Large	270	17	—
.102	Non Sag	Large	360	17	—
"	Non Sag	Segregations	450	16	—
"	Non Sag	Small	470	15	—
"	Thoriated	Small	440	12	—
.127	Non Sag	Large	170	8	—
"	Non Sag	Small	330	11	—
"	Non Sag II.	Small	400	12	—
"	Thoriated	Small	350	14	—
"	Thoriated I.	Small	—	10	6
.254	Non Sag II.	Small	350	8	—
"	Thoriated I.	Small	—	6	4

character. "I." and "II." denote individual wires drawn to different sizes. By a structure of "small" crystals is meant an aggregation of crystals whose width is less than that of the wire. The designation "large" crystals refers to those whose length is greater than several diameters of the wire, varying in fact from 0.4 mm to 10 mm long.

"Segregation" refers to a wire having long crystals separated by segregations of small ones. From 6 to 18 tests were made on each wire. By the help of Langmuir's curves for the variation in rate of evaporation with temperature, and for the sake of a direct comparison, the rate of evaporation is expressed throughout in terms of its value at the constant temperature of 2825° K.

It is noticeable that the rate in both vacuum and in gas tends to increase with increase in the number of grain boundaries. This is in accord with results obtained by Rosenhain and Ewen,[1] in the case of silver, copper and zinc, for differences in crystalline size, and the explanation would seem to lie in the presence of larger amounts of a more volatile phase in small grain metals, as suggested by those authors. If one assumes with them the presence of amorphous tungsten between the grains, then there will be present in the wire two phases of differing vapor pressure; for the amorphous one, like all undercooled liquids, must have a higher vapor pressure than the crystalline. If the intergranular material is made up rather of insoluble impurities, then in general these also will have a higher vapor pressure. In fact pronounced channels develop between the grains as the filaments are burned, illustrating the abnormal evaporation that takes place at the boundaries.

It is noticeable also for wires of the same crystalline character that the evaporation per unit area in vacuum is approximately the same independent of the diameter, and is therefore purely a function of the exposed surface. In a gas, however, a decided influence is exerted by the wire diameter.

It is true that the rates of evaporation in gas are decidedly lower than those in vacuum, but the extent to which they are lowered varies with the diameter of the wire. In nitrogen, for instance, the rate for the largest wire of 0.254 mm diameter is only 2 per cent of that for the same wire in vacuum, but it rises to 6 per cent for the smaller wire of 0.069 mm diameter. In argon the rate is still lower, but again the same dependence on diameter is shown, the range this time lying between 1.3 and 3.9 per cent of the rate in vacuum for diameters of 0.254 and .069 mm respectively.

Incidentally it should be noticed that the ratio between the rates in argon and in nitrogen is 0.69, 0.60, and 0.67, for three different sizes of wire; and that this fairly constant value is approximately the same as the inverse ratio of their molecular weights, 0.70.

The dependence of the rate of evaporation on wire diameter in gas and not in vacuum is of particular interest, and an explanation for it has

[1] J. Inst. Metals, 8, 149–170, 1912.

been found in the diffusion phenomena which take place in gas, as suggested by the relationship between the rate and the molecular weight of the gas. In vacuum an atom of tungsten, on evaporation from the filament, proceeds in an unimpeded path to the bulb, so that the diameter of the filament should in fact have no effect on the rate.

For the experiments in gas Dr. Langmuir made the suggestion that the same phenomenon was involved as described by him for the heat loss from a wire in a gas [1] and calculation on this assumption proved to give very good agreement. His theory calls for a relatively stationary film of gas of definite diameter about a wire, through which the heat is conducted away from the filament. Outside of this film another distinct zone occurs in which the heat is carried away by convection currents. The application to the present work lay in the hypothesis that tungsten atoms evaporating from a filament in a gas should obey the same law of diffusion while within this stationary film of gas, free to return to the filament as well as to move to the outer edge of the film from which they would be carried to the bulb by convection currents of gas. Their actual evaporation then would depend on the balance between these two courses of diffusion and would be determined by the factor $\log b/a$, where a is the diameter of the filament, and b that of the gas film.

This is seen by examination of Langmuir's equation for heat loss

$$W = \frac{2\pi l}{\log b/a} \, (\phi_2 - \phi_1)$$

or, for unit length of filament at constant temperature in the same gas,

$$W = \frac{\text{const.}}{\log b/a} \, .$$

The rate of evaporation, m, is in terms of grams per sq. cm. When expressed in the same units as the heat loss, grams per unit length of filament, it becomes proportional to ma. If the thickness of the film of gas determines both the heat loss and the rate of evaporation, then ma should be proportional to W, and the condition should hold

$$ma \log b/a = \text{const.}$$

In Table II. the diameter of this film is calculated for the different sizes of wire from Langmuir's equation $\log b/a = 2B/b$. B is the thickness of the film over a plane surface, and the same value of 0.43 cm is used here as for heat conduction in nitrogen. The product $ma \log b/a$ is given at the end of the table for three different cases, each dealing with fila-

[1] PHYS. REV., 34, 410 (1912).

ments from the same wire drawn to different sizes. The first two cases are for the same wire in argon and in nitrogen, and the third case is for a different wire in nitrogen.

TABLE II.

Filament Diameter a, cm.	Diameter Gas Film b, cm.	log b/a.	$m(10)^9$.			ma log $b/a(10)^{11}$.		
			I(A).	I(N).	II(N).	I(A).	I(N).	II(N).
0.0069	0.241	3.57	9	13	—	22	32	—
.0076	.246	3.50	—	—	17	—	—	45
.0123	.276	3.11	6	10	12	23	38	46
.0254	.333	2.58	4	6	8	26	39	52

With each wire the product shows a satisfactory constancy for the different sizes, so that this hypothesis for the mechanism of evaporation of a filament in a gas seems a perfectly reasonable one. This is particularly so as the thickness of gas film necessary to assume as basis for this hypothesis is the same as already developed in explanation of the heat conduction from wires in gases.

I desire to express to Dr. Langmuir my gratitude for his interest and suggestions.