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GRAPHITE SUBLIMATION - A LITERATURE REVIEW

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MASTER

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INTRODUCTION

The use of graphite materials in nuclear propulsion systems for space vehicles has introduced several new and interesting problems. Once a nuclear reactor has fulfilled its function the deposition of the spent engine is of critical importance. If, at the end of its mission, the reactor proceeds into space, then no earth contamination could result from its operation, and the reactor is of no further concern. If instead, it remains in some earth orbit or travels on a course that may bring it at some later time into an earth orbit, then the physical condition of the reactor must be known with reasonable accuracy. To this end a preliminary analysis of the temperature response of the reactor core and other components has been completed⁽¹⁾ for a variety of operating periods and shutdown schedules in which loss of coolant flow was considered to have occurred at initiation of shutdown.

It has been concluded from the analysis of the effect of post-operational heat on a NERVA reactor that temperatures inside the core will go to and above the temperature at which graphite sublimates under vacuum conditions. Therefore, some sublimation of fuel will occur under these conditions. The smallest preliminary estimate was 46.8 lbs. and the largest, 810.2 lbs.

When the inside of the core reaches these very high temperatures there are two processes which are important. They are:

- (1) The evaporation process from the graphite surface.
- (2) The flow of the carbon vapor thus formed out of the channels into a vacuum.

To calculate graphite sublimation rates and transport, utilizing the sublimation subroutine, NØFLØW, it is important to know graphite vapor pressures, composition of the species in the vapor and suitable values for the accommodation coefficient of the species.

Since the heat of sublimation is much higher than the specific heat of graphite--mass losses may be nearly negligible, yet energy losses significant. If the mass losses which occur

are large, then the energy loss will be very significant. It is therefore obvious that if sublimation does occur it will produce an energy sink which will be significant.

The present study represents the first step in obtaining information regarding the nature of the sublimation of graphite and its transport within the core. In this investigation an attempt has been made to obtain from the literature information about vapor pressures, identification of the species of the vapor and suitable values for the accommodation (evaporation) coefficient of the gas.

It is believed that the information included in this report should serve as initial input to predict the rates of graphite vaporization on NERVA fuel and in the development of an experimental program in the study of sublimation rates of graphite.

BACKGROUND INFORMATION

A solid, like a liquid, has a definite vapor pressure at each temperature, with increasing temperature the vapor pressure increases. The term sublimation being used to indicate direct conversion of solid to vapor without intervention of liquid. Similarly, under suitable conditions, a vapor may be condensed directly to a solid; this occurs, in general, upon cooling the vapor, provided its pressure is less than the vapor pressure of the solid at its melting point.

The change from solid to vapor, like that from liquid to vapor, or from solid to liquid, is accompanied by an absorption of heat; this is the (latent) heat of sublimation (L_s). It is related to the heats of vaporization (L_v) and of fusion (L_f) in the following manner:

$$L_s = L_f + L_v \quad (1)$$

where the three (3) values must refer to the same temperatures. In other words, the same quantity of heat (L_s) must be supplied to convert one (1) mole of solid directly to vapor as

would be required first to melt the solid (L_f) and then to vaporize it (L_v). This result is in accord with the law of conservation of energy.

The influence of temperature on the vapor pressure of a solid is given by a form of the Clapeyron equation where the rate of variation of the vapor pressure with temperature, i.e., dp/dT , is expressed by:

$$\frac{dp}{dT} = \frac{L_s}{T(V_v - V_s)} = \frac{l_s}{T(v_v - v_s)} \quad (2)$$

where V_v and V_s are the molar volumes, and v_v and v_s are the specific volumes, of vapor and solid, respectively, at the temperature T ; l_s is the heat of sublimation per gram. It is permissible here to neglect V_s in comparison with V_v , since the density of the vapor is very much less than that of the solid; hence, Equation (2) may be converted into a form:

$$\frac{d \ln p}{dT} = \frac{L_s}{RT^2} \quad (3)$$

The chief use of Equations (2) and (3) and those obtained by integration, is that they permit the value of the heat of sublimation of the solid to be calculated at any temperature from a knowledge of the sublimation vapor pressures in the vicinity of that temperature.

Vapor Pressure

The determination of the vapor pressures of highly nonvolatile substances is not easy. Thus, it is necessary to go to very high temperatures (2400-2800°K) to obtain an accurately measurable vapor pressure over graphite, and even then it is only of the order of 10^{-7} atmospheres. Two techniques commonly employed in this type of work are the Langmuir or evaporation-rate method and the Knudsen or effusion-cell method. These will be discussed in the following section:

1. The Evaporation-Rate Method - When a substance is at equilibrium with its vapor, the rates of condensation and evaporation must necessarily be equal. The rate of

condensation of a gas is related to its pressure by an equation (see below) derived from the kinetic molecular gas theory. An identical equation must accordingly relate the evaporation rate and the equilibrium vapor pressure.

In the Langmuir method, the solid is heated in a vacuum so complete that an atom, once evaporated, has a negligible chance of recondensing. The solid-vapor reaction is thus entirely unidirectional; its rate is determined by the rate of evaporation alone, which can be calculated directly from the rate of weight loss of the sample. The evaporation rate is a constant at a given temperature, unaffected by a departure from equilibrium conditions. Hence, the rate measured in vacuo is the same as the rate at equilibrium and can be used to calculate the equilibrium vapor pressure.

The combined weight of the gas molecules which collide with or pass through unit area in unit time can be derived from kinetic theory and is given by $P \sqrt{M/2 \pi RT}$. It is not a priori certain that all gas molecules colliding with the surface of the corresponding solid actually stick. A so-called sticking or accommodation coefficient α is therefore introduced when the above expression is applied to the condensation rate. We have

$$\text{rate of condensation (g/sec)} = r_c = \alpha A P \sqrt{M/2 \pi RT} \quad (4)$$

$$\text{rate of evaporation (g/sec)} = r_{ev} = \alpha A P_{eq} \sqrt{M/2 \pi RT} \quad (5)$$

where A is the surface area of the sample.

Evidently, α must be known if P_{eq} is to be calculated from the evaporation rate. In most evaporations it is taken as unity. A coefficient less than one can be interpreted as being due to an energy barrier in the evaporation-condensation process. In fact, it can be shown that $\alpha \sim \exp(-\Delta H^*/RT)$, where ΔH^* is the height of the barrier. Condensation processes in which the gas species is closely related to the solid species would be expected to have no barrier; the gas molecules or atoms can simply "fall into place" on the solid surface. Thus, every molecule that hits condenses, and $\alpha = 1$.

If the condensation requires the formation of high energy intermediate states, as might happen, for instance, if the gas species were quite different from the solid species, a barrier would be predicted. It will be shown later that the value of α in the carbon vapor equilibrium has been a major bone of contention between workers in the field. Suggested values vary from 1 to 10^{-4} . From Equation (5) it is seen that proponents of a small value would obtain high vapor pressures from their experiments, corresponding to small heats of vaporization while the assumption $\alpha \cong 1$ would yield a large heat of vaporization.

2. The Equilibrium Method - The sample is heated in a closed container called a Knudsen cell so that the equilibrium pressure can build up, and the vapor is allowed to leak into vacuum through a small orifice in the cell wall. It follows from the theory discussed above that:

$$\text{rate of effusion} = r_{\text{eff}} = \chi P \sqrt{M/2 \pi RT} \quad (6)$$

where χ is the area of the orifice. This method avoids the uncertainty introduced by the accommodation coefficient α in Equation (4), for if the orifice is properly designed all gas molecules entering it will pass through. The question remains whether the pressure, for the leakage of vapor may be enough to prevent the equilibrium pressure from ever building up.

The flux balance in the effusion cell is represented by the equation:

$$\begin{aligned} \text{evaporation rate} &= \text{condensation rate} + \text{effusion rate} \\ r_{\text{ev}} &= r_{\text{c}} + r_{\text{eff}} \end{aligned} \quad (7)$$

The condition for solid-vapor equilibrium, and hence for $P = P_{\text{eq}}$ in Equation (6), is that $r_{\text{ev}} = r_{\text{c}}$. To the extent that r_{eff} disturbs this equality the pressure determined from the effusion rate will be less than the equilibrium pressure. The importance of r_{eff} relative to r_{c} in Equation (7) is thus the critical factor. Comparison of Equations (4) and (6) shows the ratio $r_{\text{eff}}/r_{\text{c}}$ is given by $\chi/A\alpha$ or σ/α where σ is the ratio of orifice size to the area of the sample:

$$\sigma = \chi/A \quad . \quad (8)$$

The condition that $P = P_{eq}$ is satisfied if $\sigma/\alpha \ll 1$. In other words, if the effusion rate is to be a measure of the equilibrium pressure, the limitation on orifice size is the more stringent the smaller the value of α . The restriction that α places on σ can be explained alternatively as follows. It has been shown that a small α corresponds to an energy barrier in the evaporation process, i.e., to a sluggish evaporation-condensation equilibrium. Such a sluggish system will be much less able to withstand the constant draining away of vapor by effusion than will a highly resilient system with $\alpha = 1$. Hence, the necessity for smaller orifices for systems with small α . Measurements with too large an orifice will yield vapor pressures less than the equilibrium value, corresponding to an erroneously high heat of sublimation.

The above discussion shows that the value of the accommodation coefficient is a key to the interpretation of both evaporation and effusion experiments. In both cases high heats of sublimation are associated with the assumption that $\alpha \cong 1$, and low heats with $\alpha \ll 1$ (energy barrier).

A tacit assumption underlying both evaporation and equilibrium methods is that the vapor consists of one molecular species only. Measurements made under conditions such that two or more species exist in the vapor may give rise to erroneous interpretations, especially if the energy is for sublimation to a species which is relatively rare under the conditions of the experiment. As regards carbon, the sublimation energy is to the simple carbon atom C_1 . But other species such as C_2 and C_3 are known to exist. In evaporation and effusion rate experiments it is essential to know what fraction of the evaporating or effusing material is in the form of the species of interest, so that the experimental rates substituted in Equations (4) and (6) can be corrected accordingly. This fraction will not be the same for the two types of experiments if the species have different accommodation coefficients. In that case, the evaporation rates (Equation (5)) will not be in the same ratio as the equilibrium partial vapor pressures, whereas the effusion rates will (neglecting the difference in molecular weight). In short, the vapor coming off during an evaporation-rate experiment may have a composition

entirely different from that leaving an effusion cell, just as the products of an organic reaction as determined by the rates of competing reactions may be entirely different from those prevailing in the equilibrium mixture.

3. Mass Spectrograph Method - As long as uncertainties in the vapor composition and accommodation coefficients persisted, it seemed unlikely that any value for the sublimation energy would gain universal acceptance; and unfortunately, the one uncertainty could not be effectively attached until the other had been resolved. It was at this time that a new technique was discovered which gave promise of solving or circumventing these difficulties and of providing the ultimate answer to the vexing problem.

This new approach was provided by the mass spectrograph. The use of this instrument in effusion and evaporation experiments was first reported by Chupka and Inghram⁽²⁾ and Honig⁽³⁾. A portion of the evaporating molecules passes into the ionization chamber of a mass spectrograph. In this way the different species in the carbon vapor can be detected and measured separately. In addition to getting the composition problem, the method avoids another difficulty associated with the usual effusion experiments. The rate of effusion is determined from the weight of carbon vapor condensing on a cooled target placed near the orifice of the effusion cell.

The mass spectroscopic method has difficulties of its own which will not be expounded upon. The method has not yet been refined to the point where the influence of such errors can accurately be evaluated. In general, though the effect of the errors would be to increase the observed vapor pressures, and hence gain erroneously low sublimation energies.

With the above mentioned in mind, the best values from the literature will be reviewed.

In 1948 the important paper of Brewer, Gilles and Jenkins⁽⁴⁾ appeared, reporting on the first equilibrium vapor pressure measurements by the effusion method. They used a graphite-lined Knudsen cell at 2600°K with an orifice ratio (σ) of 1/600. The effusion rate was determined from the weight of carbon deposited on a platinum surface near the mouth of the

cell. The authors offered evidence that C_2 was essentially absent from the effusing vapor. Assuming that C_1 was the sole effusing species and that equilibrium with respect to this species had been achieved within the cell, they found that their results were compatible only with a high (170 kcal.) value for the sublimation energy.

This estimate was reinforced shortly after by the publication in Belgium of the vapor pressure measurements of Goldfinger, et al⁽⁵⁾ (1953). Their effusion cell results agreed reasonably well with those of Brewer when they used a cell with σ close to Brewer's value. The novel feature of their experiments was that when the orifice was made smaller, reducing σ to 1/24,000, the effusion rate per orifice area increased enormously, indicating a higher pressure in the cell. Their results with very low σ pointed unequivocally to a sublimation energy of 141 kcal. With the larger orifice, the vapor had evidently not attained its equilibrium pressure, and the measurements had given erroneously high sublimation heats. If escape from a hole only 1/600 the area of the evaporating surface was sufficient to upset the solid vapor equilibrium completely, the authors argued that the evaporation-condensation rate must be extremely sluggish; hence, the accommodation coefficient α must be $\ll 1$, in fact, around 10^{-3} . This conclusion coincided with a conception of the evaporation process that had been widely accepted ever since an early publication of Herzberg, Herzfeld and Teller⁽⁶⁾, which hypothesized an unusual type of energy barrier to C_1 sublimation arising from the hexagonal structure of graphite crystal planes. It was in direct conflict with the α of about unity assumed by Marshall and Norton⁽⁷⁾, as well as Brewer⁽⁴⁾.

Goldfinger also considered the C_2 problem. On the basis of Herzberg's latest spectroscopic value for D_{c2} and his own estimate of (140 kcal.), the C_2 pressure was calculated to be a good deal higher than assumed by Brewer, but still less than C_1 pressure. Goldfinger believed that Marshall and Norton owed their high sublimation energy value in part to having mistakenly measured the evaporation of C_2 rather than C_1 . After correction for the presence of C_2 and the low α value of C_1 , their results could be brought in line with the low sublimation energy value advocated by Goldfinger.

To the assertion of Goldfinger, et al⁽⁵⁾, that "the results of Brewer, Gilles and Jenkins seem to be the only direct evidence for the high value", Brewer⁽⁸⁾ replied that "all other new data reported, be as close to or closer to 170 than to 141". After pointing out certain inconsistencies in the experimental approach to their work, Brewer suggested that the high pressure they observed might be a result of incomplete outgassing of the sample. Brewer also pointed out certain inconsistencies in Goldfinger's results which indicated that experimental errors may account for the observed variation. These errors, Brewer claims, were due to the "tar effect". Long heatings at very high temperatures are necessary to obtain graphite samples which do not give spuriously high vapor pressure values^(4,7). The highest heating reported for the samples was 2100°K which would be much too low to eliminate the "tar effect". The entire theoretical basis for the low C_1 accommodation coefficient was regarded with some skepticism, partly because of analogies with other elements and partly because of independent experimental evidence attesting α for C_1 , not far from unity.

Composition of the Vapor

The considerable discrepancy between the carbon vapor pressures obtained by different investigators reflects the complex nature of the sublimation of carbon. It is due to the complex composition of its vapor and the fact that the accommodation coefficient is not unity.

The introduction of the mass spectrograph in effusion and evaporation rate experiments gave promise in solving or circumventing the problems which existed in determination of vapor composition and accommodation coefficients. This new approach was first reported by Chupka and Inghram⁽²⁾. A Knudsen cell together with mass spectrometric analysis of the effusing vapor showed C_1 , C_2 and C_3 as important species in the effusion cell ($\sigma = 1/1500$) experiments. This work very strongly supports a value of 170.4 kcal/mole for the heat of sublimation of carbon. The discovery of considerable amounts of higher molecular weight (48 to 60) species in the effusing vapor was prominent, but not constant with time. It was not determined whether any fraction of the mass 48 to 60 peaks were C_4^+ or C_5^+ .

A study done by Thorn and Winslow⁽⁹⁾ carried out by the mass spectrometer method for vaporization from an open surface reported the vapor composition is characterized by the ratio $C_1:C_2:C_3 = 1:0.5:1.6$.

In 1959 Drowart, et al,⁽¹⁰⁾ carried out an investigation using the mass spectrometric method in which carbon was vaporized from tungsten and tantalum effusion chambers with an orifice to chamber cross-section ratio of 1/100,000. Measurements showed the ions C_1^+ , C_2^+ , C_3^+ , C_4^+ , C_5^+ , C_6^+ and C_7^+ to be present in the carbon vapor, the content of the latter two ions being less than $5 \times 10^{-4}\%$ at 2500°K. It was found that $C_1:C_2:C_3:C_4:C_5 = 1:2.85:4.5:0.35:0.5$.

Accommodation and Evaporation Coefficients

Knudsen introduced a coefficient of evaporation and a coefficient of accommodation in his studies on evaporation in vacuum. The latter term was used to describe the parameter that characterizes the change in the energy state of the molecules during the transition from the condensed phase to the gaseous phase on evaporation. The coefficient of evaporation was defined as the ratio of the measured evaporation rate in vacuum to the hypothetical equilibrium rate of evaporation calculated at equilibrium vapor pressure from the following equation:

$$G = P \sqrt{M/2\pi RT} \quad (9)$$

The value G is the mass per cm^2 of surface which the substance loses per unit time for evaporation at temperature T in a vacuum. There was thus introduced into the calculation formulas which link the vapor pressure to the rate of evaporation, a coefficient α , which is equal to unity in the majority of studies on the determination of vapor pressure.

Thorn and Winslow⁽⁹⁾ obtained rates of evaporation and evaporation coefficients by the Knudsen cell method. This was done by a direct comparison of the rate of deposition from a cell and a surface which produced an "apparent" evaporation coefficient, which had to be corrected for relative geometries of the orifice and orific edge area. A plot of the reciprocal apparent temperature vs. time of deposition, for the simultaneous determinations of the evaporation and effusion rates were used. The evaporation coefficient was then calculated simply

from the ratios of the slopes of those lines which had been corrected for the temperature gradient across the wall with an assumed heat of sublimation of 170 kcal/mole. The evaporation coefficients were found to be, respectively, 0.37, 0.34 and 0.08. The mean evaporation coefficient is 0.15. The mean standard heat of sublimation of 0°K is 170 kcal/mole.

Burns, Jason and Inghram⁽¹¹⁾ determined, by means of the mass spectrometer, the evaporation coefficient of graphite for individual gaseous species, as a function of crystal orientation. The symbols α_i^c and α_i^a refer to the evaporation coefficients for pyrolytic graphite of the i^{th} species, from a crystal face which is perpendicular to the c or a axis, respectively. The evaporation coefficients at Temp = 2500°K are:

		α_i^c	α_i^a
C_1^+	=	0.14	0.23
C_2^+	=	0.26	0.38
C_3^+	=	0.03	0.04

This gives an overall evaporation coefficient of $\alpha^c = 0.07$ and $\alpha^a = 0.12$. The fact that the Thorn and Winslow⁽⁹⁾ value is somewhat higher has been explained by a different grade graphite which was rougher and more porous than the graphite used by Burns, et al.

According to Brewer,⁽⁸⁾ the accommodation coefficient for a monatomic molecule is 0.3, it lies between 0.5 and 1 for diatomic molecules and is 0.1 for triatomic molecules. For more complex molecules the coefficient α is insignificant. Thus, the aforementioned data are in reasonably good accord with Brewer's prediction.

One of the most recent publications available on the vapor pressure of carbon molecules over graphite was done by Vidale⁽¹²⁾. These data are based primarily on the recent study by Drowart, et al⁽¹⁰⁾ which generally confirms most of the recent studies utilizing mass spectrometric studies.

It assumes, therefore, that five molecular species are significant components of the vapor in equilibrium with the solid phase: C_1 , C_2 , C_3 , C_4 and C_5 .

Vapor pressure of carbon atoms were obtained by fitting the data from Stull and Sinke⁽¹⁵⁾ from 2500–3000°K to the following equation:

$$\log P_{c_1} = 8.115 - 37,170/T \quad (10)$$

$$\log P_{c_2} = 9.605 - 42,490/T \quad (11)$$

$$\log P_{c_3} = 9.571 - 40,210/T \quad (12)$$

$$\log P_{c_4} = 10.184 - 49,170/T \quad (13)$$

$$\log P_{c_5} = 10.889 - 50,400/T \quad (14)$$

It assumes the vapor pressure curves given by Drowart are correct and may be extrapolated linearly up to 4100°K. This implies, among other things, that the ionization cross-section used by Drowart is correct at all temperatures. Vapor pressure values for the last four molecules are considerably less certain.

Figure 1 shows the best theoretical and experimental vapor pressure data reported in the literature for the sublimation of graphite utilizing the Knudsen cell method. In view of the large discrepancies in the experimental data of Brewer and Goldfinger, the empirical vapor pressure of Vidale are usable.

Table I lists sublimation rates and heats of vaporization of graphite using the best available experimental results utilizing the Langmuir method. The information in Table I are based on experimental vapor pressure measurements obtained from rate of evaporation experiments of graphite in a vacuum. The heats of vaporization and sublimation rates predicated by Vidale are in good agreement with those of Hoch, et al,⁽¹³⁾ and Marshall and Norton⁽⁷⁾.

With the latest paper of Goldfinger,⁽¹⁴⁾ the new mass spectrographic findings concerning the composition of carbon vapor, including the existence of C_5 , has led to a re-interpretation of his earlier results, which are now presented as support for, rather than evidence against, the 170 kcal value for heat of vaporization.

SUMMARY

The most favored value of heat of vaporization, starting with 124 kcal in the thirties, was gradually shifting to 170 kcal by the late forties; there was then an interlude during which an intermediate value gained a brief ascendancy, followed by a vigorous come-back of the highest value. The swing to 170 kcal, sparked by the mass spectroscopic results, has gained momentum on all sides. The empirical predictions of Vidale⁽¹²⁾ using the best experimental values obtained must be considered as the best source for initial input data for vapor pressures, sublimations rates and heats of vaporization of graphite at this writing.

The lack of correspondence between the data obtained by various investigators for the heat of sublimation and the vapor pressure of carbon prevents giving any single figure for evaporation coefficients. Table II summarizes the best values from the literature for evaporation coefficients. The values of Burns, et al,⁽¹¹⁾ will be used as input data for evaporation coefficients of C_1 , C_2 and C_3 in the initial studies. C_1 , C_2 and C_3 are the three important species which will be considered. C_4 and C_5 will be considered and will have evaporation coefficient values of unity.

It follows from what has been said that vapor pressure data for graphite requires experimental verification with the allowance for the vapor composition and for the vaporization coefficient of carbon. Experimental data as obtained on NERVA fuel should be obtained to give a really definitive idea of the rates of evaporation. When these data become available, they should be readily incorporable in any computer program evaluating graphite vaporization.

CONCLUSION

A literature search of information regarding the nature of the sublimation of graphite, the composition of the species in the vapor and the values for the accommodation (evaporation) coefficient of the gas species has been completed. Considerable discrepancy exists

between the carbon vapor pressures and rates of sublimation obtained by different investigators. These discrepancies exist due to the complex composition of carbon vapor and the apparent fact that the evaporation coefficient is not unity. The mass spectrograph did solve or circumvented these difficulties in such a way that reliable data for composition of species, accommodation coefficients, etc. can be determined.

Graphite vaporizes in the form of molecules consisting of C_1 , C_2 , C_3 , C_4 , C_5 , C_6 and C_7 . The vaporization rate of each type of molecule is different and the vaporization coefficient is not equal to unity. The suggested values of Burns, Janson and Ingram (see Table II) will be used. For the more complex molecules the coefficient is insignificant.

In view of the large discrepancies in experimental data, the theoretically predicted vapor pressures of Vidale will be used in the NØFLØW sublimation program. Additional information will be supplied by experimental investigations carried out on NERVA fuel.

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TABLE I
SUBLIMATION RATES AND HEAT OF VAPORIZATION OF GRAPHITE

Temp. °K	Sublimation Rates			Heat of Vaporization		
	Vidale ⁽¹²⁾ g/cm ² sec	Hoch, et al ⁽¹³⁾ g/cm ² sec	Marshall & Norton ⁽⁷⁾ g/cm ² sec	Vidale ⁽¹²⁾ k cal/mole	Hoch, et al ⁽¹³⁾ k cal/mole	Marshall & Norton ⁽⁷⁾ k cal/mole
2267	4.423 x 10 ⁻⁸	0.649 x 10 ⁻⁸	---	177.0	173.9	----
2357	2.587 x 10 ⁻⁷	----	2.35 x 10 ⁻⁸ 1.65 x 10 ⁻⁸	178.5	----	176.6
2482	1.798 x 10 ⁻⁶	2.098 x 10 ⁻⁷	1.38 x 10 ⁻⁷ 2.00 x 10 ⁻⁷	179.5	173.0	174.9
2550	4.926 x 10 ⁻⁶	0.736 x 10 ⁻⁶	0.604 x 10 ⁻⁶	178.0	171.4	175.6
2734	5.934 x 10 ⁻⁵	1.081 x 10 ⁻⁵	0.346 x 10 ⁻⁵	181.0	169.5	176.3
2870	2.487 x 10 ⁻⁴	----	0.174 x 10 ⁻⁴	181.5	----	175.0
				av. 179.2	av. 172.0	av. 176.0

TABLE II
EVAPORATION COEFFICIENT OF GRAPHITE

<u>Burns, Jason, Inghram⁽¹¹⁾</u>		<u>Thorn and Winslow⁽⁹⁾</u>	<u>Brewer⁽⁴⁾</u>
α^c	α^a		
$C_1^+ = 0.14$	0.23	$C_1 = 0.37$	$C_1 = 0.30$
$C_2^+ = 0.26$	0.38	$C_2 = 0.34$	$C_2 = 0.5 \text{ to } 1$
$C_3^+ = 0.03$	0.04	$C_3 = 0.08$	$C_3 = 0.10$

FIGURE 1
 THE VAPOR PRESSURE OF C_n OVER GRAPHITE