NASA TECHNICAL NOTE

NASA TN D-4147

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VAPOR-PRESSURE DATA EXTRAPOLATED TO 1000 ATMOSPHERES (1.01×10^{8} N/m^{2}) FOR 13 REFRACTORY MATERIALS WITH LOW THERMAL ABSORPTION CROSS SECTIONS

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • OCTOBER 1967

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SUMMARY

With the continual increase of interest in high-temperature technology, knowledge of the vapor pressure of refractory materials is becoming essential. Such is the case in the conceptual studies of nuclear systems such as the liquid-core and gas-core nuclear rockets, where attention must be given to the vapor pressure of the materials used.

Existing vapor-pressure data were collected for 13 materials with atmospheric boiling points over 3000° K and thermal absorption cross sections less than 5 barns (5.0×10^{-28} m^2). All the data were discussed and extrapolated to 1000 atmospheres (1.01×10^8 N/m^2); with the addition of an error analysis, a temperature range at a given pressure was calculated to indicate the possible error introduced by scatter in the original data. At 1000 atmospheres (1.01×10^8 N/m^2), the element that has the highest boiling point is tungsten (9340° K), while at the same pressure niobium carbide has the highest boiling point of the compounds (8400° K).

INTRODUCTION

As interest in high-temperature technology increases, the need for predicting the vapor pressure of materials at these high temperatures and pressures becomes more important. One field of particular interest is nuclear engineering, where the systems usually involve high temperatures and pressures. One group of materials that is in frequent use in nuclear engineering concepts has low vapor pressure and low thermal absorption cross section σ. This type of material is used in gas-core (ref. 1) and liquid-core (ref. 2) nuclear-rocket concepts. In these concepts, hydrogen propellant is radiantly heated by a nuclear fuel. However, hydrogen gas at temperatures less than 5000° K can not absorb radiant heat because of its transparency. However, particles can be suspended in the hydrogen propellant to absorb the radiant heat leaving the reacting fuel and then to conduct the heat to the hydrogen propellant. If it is assumed that only the particle absorbs radiant heat, a low-vapor-pressure material is necessary to keep the vaporization at a minimum. Also the material must have a low thermal absorption cross section in order not to cause an increase in the critical mass of the system.

Two criteria were used in selecting the materials in order to limit the scope of the study. First, the materials must have an atmospheric boiling point over 3000° K. Second, they must have a thermal absorption cross section less than 5 barns (5.0×10^{-28} m^2). References 3 and 4 contain general summaries of vapor-pressure data for the elements with estimated atmospheric boiling points, and reference 5 contains the values of thermal absorption cross sections.

Vapor-pressure data for 11 elements and 2 compounds were selected and analyzed. Table I lists the materials that were chosen, their values of thermal absorption cross section, and the references from which the vapor-pressure data were taken. There are compounds which would qualify in the selection, such as some oxides and carbides of the elements chosen; however, there are insufficient vapor-pressure data available for these compounds to permit extrapolation to 1000 atmospheres (1.01×10^{8} N/m^2). Within

TABLE I. - REFRACTORY MATERIALS INVESTIGATED

Material	Thermal absorption cross section		Vapor-pressure reference
	b	m^2	
Carbon	0.00373	0.00373×10^{-28}	7
Cerium	.73	.73	9
Molybdenum	2.70	2.70	6, 10, 11
Niobium	1.16	1.16	12, 13
Niobium carbide	1.16373	1.16373	26, 27
Platinum 196	.70	.70	14, 15
Platinum 194	1.2	1.2	14, 15
Ruthenium	2.56	2.56	16, 17, 18
Silicon	.16	.16	19
Tungsten 184	2.0	2.0	22
Vanadium	5.0	5.0	23
Yttrium	1.31	1.31	9, 24
Zirconium	.185	.185	25
Zirconium carbide	.18873	.18873	28, 29

the group of materials chosen, there are several cases where more than one set of vapor-pressure data is presented, and in these cases the results are compared. This study was performed to collect, evaluate and select the best vapor-pressure data available, and then to extrapolate them to 1000 atmospheres (1.01×10^8 N/m^2). By taking into account the experimental scatter in the data points and the temperature range over which the experiment was performed, a possible temperature range was calculated for pressures of 1, 10, 100, and 1000 atmospheres (1.01×10^5, 1.01×10^6, 1.01×10^7, and 1.01×10^8 N/m^2).

COLLECTION AND EVALUATION OF VAPOR-PRESSURE DATA

Examination of the available data indicate that most experimental data were obtained at temperatures less than 3000° K and that, hence, the vapor pressures were in the range of 10^{-5} to 10^{-10} atmospheres (1.01 to 1.01×10^{-5} N/m^2). Therefore, an extrapolation of at least 7 orders of magnitude is required to reach the desired 1000 atmospheres (1.01×10^8 N/m^2).

During the collection and evaluation of vapor-pressure data, it was necessary to judge the reliability of reported vapor-pressure measurements. In the cases where more than one set of vapor-pressure data exists for a given material, each is discussed. If, for any reason, one set is preferred over the other, the reasons are discussed and only the preferred set is retained; otherwise all sets are retained. The following factors were considered:

(1) The reaction and equilibrium behavior of the system
(2) The identification of the various gaseous species in the system
(3) The experimental technique by which the vapor pressure was measured
(4) The range and scatter of the vapor-pressure data

The investigation of the general behavior of the system should reveal the following information: first, whether there is any reaction between the sample and any other part of the system. If there is a reaction, the resulting phase may vaporize and affect the vapor-pressure measurements, or it may contaminate the sample by changing its composition. The measured vapor pressure thus would not be of the pure sample but of the contaminated one. Second, the equilibrium of the system must be understood. Two factors that affect this are congruence and invariance. For congruence, a phase must vaporize to give a gas of the same composition as the liquid or solid phase. This result is demonstrated by whether the composition of the residue changes after several successive vaporizations. If the residue is always the same, the system is congruent. For invariance, the rate at which vapor leaves the sample must be constant. This condition can be established by noting the pressure in successive experiments at the same temperature.

If the pressure remains constant during the entire course of vaporization, the process is invariant.

The various gaseous species must be identified to complete any vapor-pressure experiment. Several different species may vaporize from a sample, and each must be identified and its share of the vapor pressure calculated or measured. Whenever vapor-pressure data are extrapolated, the vapor pressure of each individual species is extrapolated rather than the sum of the partial pressures of the species.

Vapor-pressure measurements on high-temperature materials are most suitably made by using either the Knudsen or the Langmuir method. Both methods require a high-vacuum system. In the Knudsen method, the sample is contained in an inert crucible that has a small, thin orifice. Equilibrium is established inside the crucible if the orifice is sufficiently small. However, all the vapor striking the orifice inlet does not leave the orifice outlet. The ratio between the rate at which vapor leaves the orifice outlet and that at which vapor strikes the orifice inlet is given by a "Clausing factor." This Clausing factor is governed only by the dimensions of the orifice. The rate of effusion through the orifice is then governed by the Clausing factor, the temperature, the vapor pressure, and the molecular weight of the effusing vapor species. In the Langmuir method, no crucible is used but rather free evaporation occurs from the entire sample surface. The vapor pressure is therefore a function of the rate at which material sublimes from the sample, the surface area and the absolute temperature of the sample, and the molecular weight of the vapor leaving the sample.

METHOD OF EXTRAPOLATION

The curve that was fitted to the data and extrapolated to 1000 atmospheres (1.01×10^8 N/m^2) can be derived from the Clapeyron equation under the assumptions that (1) the heat of vaporization is constant, (2) a volume of liquid or solid is negligible compared with that of the vapor, and (3) the vapor conforms to the ideal gas law. The resulting equation is of the form

$$\log P = \frac{A}{T} + D \qquad (1)$$

where A and D are constants, P is vapor pressure in atmospheres (N/m^2), and T is temperature in $^{\circ}K$. The majority of the selected vapor-pressure reports use equation (1) to express their vapor-pressure data mathematically and to estimate the atmospheric boiling point.

The least-squares method was used to fit the selected vapor-pressure data to equation (1). In the majority of cases, the referenced literature already reported the results using this method with equation (1). However, the vapor-pressure data were refitted to equation (1) using the least-squares method to put all the data on a common basis for comparison.

The possible error in predicting a value of vapor pressure from extrapolated data originates from three sources. First, there is the error introduced by the three assumptions used to derive the Clausius-Clapeyron equation (eq. (1)). The importance of this error cannot be assessed until additional experimental data at higher temperatures become available. Second, a systemic error may already be present in the original vapor-pressure data. Assessment of the magnitude of this type of error is also not possible. Third, there is an error caused by the random scatter of the data. This error can be estimated.

Figure 1 shows a schematic drawing of the error analysis used to estimate the third type of error. By using the common logarithmic coordinate of vapor pressure and reciprocal temperature, equations in the form of equation (1) are represented by straight lines. In figure 1, the lines W and X, which are visually drawn, are the boundary lines that encompass at least 90 percent of the data points. As the number of data points increases, these lines usually become parallel and equidistant from the line generated when curve fitting the data to equation (1). The diverging lines, Y and Z, encompass all possible straight lines that can be drawn through the data. These two straight lines are then extended to a pressure of 1000 atmospheres (1.01×10^8 N/m^2). The maximum error, or as it is called hereinafter, the "temperature uncertainty", is the difference at a given vapor pressure between the temperature value given by equation (1) and the values given by the two diverging lines, Y and Z. Figure 2 shows the procedure, using the set of molybdenum vapor-pressure data from reference 6. The calculated temperature uncertainty is for a given set of vapor-pressure data and reflects only the random error caused by the scatter in the data. Figure 1 shows that the magnitude of the temperature uncertainty at a given pressure is also dependent on the amount of extrapolation from the original data. Where two or more sets of data are selected, each is extrapolated to 1000 atmospheres (1.01×10^8 N/m^2). The results are then combined; the average value of A and D are found and these average values are used in the extrapolation. Also the temperature uncertainty at a given pressure includes the entire range found for all sets of data. The results of the extrapolations and error analysis are shown in table II to IV.

DISCUSSION OF MATERIALS

Carbon

Reference 7 is the most recent work on the vapor pressure of carbon with the influence of large carbon polymer species. Mass spectrographic studies were performed on carbon in the temperature range from 1800° to 2700° K. The ions observed were C_1^+, C_2^+, C_3^+, C_4^+ and C_5^+; the intensities of C_6^+/C_1^+ and C_7^+/C_1^+ were less than 5×10^{-4} at 2500° K, and no results were reported for these two species. To minimize temperature uncertainties reference 7 assumed the vapor pressure of C_1 to be known and its associated value for the heat of vaporization ΔH_0° to be equal to 169.58 kilocalories per gram atom (709.52 kJ/g-atom). A least-squares treatment was applied to the relative intensities C_n^+/C_1 to calculate $\Delta H_0^{\circ}(C_n)$ where $n \leq 5$. The ratios were divide by 2.30, 3.66, 4.96, and 6.30 for C_2 to C_5, respectively, to convert to relative pressures. A trial and error graphical method was used to calculate the temperature of the total carbon vapor pressure at 1 to 1000 atmospheres (1.01×10^5 to 1.01×10^8 N/m^2). A summation of the partial pressure of C_1 to C_5 is made in table II(a) for total carbon pressures of 1, 10, 100, and 1000 atmospheres (1.01×10^5, 1.01×10^6, 1.01×10^7, and 1.01×10^8 N/m^2). Figure 3 shows the extrapolation of the carbon species. The errors involved in C_2 to C_5 are based on a given value of C_1; therefore, any error in C_1 increases the errors of the larger carbon polymers. In addition, carbon polymers larger than C_5 start to influence the total vapor pressure in this pressure range.

In reference 8 is described a mass spectrometric study of the vapor ejected from a graphite sample that was flash heated by a focused laser beam. The relative abundance of the carbon polymer species, C_1 to C_{11} and C_{14}, at approximately 4000° K was obtained. The relative ion intensities of the various carbon species did not vary significantly for different graphite samples; however, a standard deviation of about 50 percent necessitated a large number of measurements on each carbon species. A typical averaged mass spectrum is presented in reference 8, with the extrapolated results of reference 7, and is reproduced in table II(b). The agreement between Drowart, et al. (ref. 7) and Berkowitz, et al. (ref. 8) is good considering the differences in the methods used. It is also interesting that, from the data of reference 8, the carbon species C_7 approaches the magnitude of C_4 and C_5 in importance and that at higher pressures and temperatures it may become dominant.

TABLE II. - EXTRAPOLATED VAPOR-PRESSURE DATA

(a) Data for carbon from reference 7

Partial vapor pressures of carbon										Total vapor pressure		Extrapolated temperature, $^\circ K$	Temperature uncertainty	
C_1		C_2		C_3		C_4		C_5					$^\circ K$	percent
atm	N/m^2	atm	N/m^2	atm	N/m^2	atm	N/m^2	atm	N/m^2	atm	N/m^2			
0.11	0.12×10^5	0.30	0.30×10^5	0.49	0.5×10^5	0.04	0.04×10^5	0.06	0.06×10^5	1	1.01×10^5	4100	3840 to 4380	-6 to +7
.8	.81	3.1	3.1	4.6	4.7	.6	.6	.9	.91	10	1.01×10^6	4540	4220 to 4890	-7 to +8
6	6.1	31	31	42	43	8	8.1	13	13.2	100	1.01×10^7	5070	4650 to 5540	-8 to +9
42	42.5	292	296	361	366	120	122	185	187	1000	1.01×10^8	5740	5150 to 6400	-10 to +11

(b) Relative concentrations of carbon vapor species above graphite at 4000° K

Reference	Carbon molecular species											
	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	C_{14}
7	22.2	62.5	100.0	7.8	11.1	-----	----	----	----	----	----	-----
8	37.0	31.4	100.0	2.13	7.9	0.413	1.11	0.19	0.11	0.32	0.15	0.042

Cerium

The vapor-pressure data for liquid cerium were obtained directly from Habermann, et al. (ref. 9) and consist of 19 data points in the temperature range from 1861° to 2252° K. A direct-weight-loss modification of the Knudsen effusion technique was used involving a quartz-fiber microbalance. An analysis showed the cerium to be 99.9 percent pure. The major impurities detected were tantalum, 100 parts per million (ppm); iron, 250 ppm; oxygen, 345 ppm; carbon, 200 ppm; nitrogen, 150 ppm; and traces of calcium, silicon, fluorine, and hydrogen, 95 ppm. Table II(c) indicates the results when the vapor-pressure data were extrapolated to 1000 atmospheres (1.01×10^8 N/m^2).

Molybdenum

Three references were used for the extrapolated vapor pressure of solid molybdenum. Edwards, et al. (ref. 10) used the Langmuir vacuum-evaporation method; nine

TABLE II. - Continued. EXTRAPOLATED VAPOR-PRESSURE DATA

(c) Cerium

Vapor pressure		Extrapolated temperature, °K	Temperature uncertainty	
atm	N/m^2		°K	percent
1	1.01×10^5	3 560	3480 to 3 680	-2 to +3
10	1.01×10^6	4 200	4080 to 4 430	-3 to +5
100	1.01×10^7	5 160	4940 to 5 560	-4 to +8
1000	1.01×10^8	6 670	6250 to 7 460	-6 to +12

(d) Data for molybdenum from reference 10

1	1.01×10^5	5 100	4880 to 5 350	-4 to +5
10	1.01×10^6	6 100	5740 to 6 510	-6 to +7
100	1.01×10^7	7 590	6980 to 8 320	-8 to +10
1000	1.01×10^8	10 040	8900 to 11 530	-11 to +15

(e) Data for molybdenum from reference 6

1	1.01×10^5	4 700	4590 to 5 090	-2 to +8
10	1.01×10^6	5 480	5310 to 6 090	-3 to +11
100	1.01×10^7	6 570	6290 to 7 580	-4 to +15
1000	1.01×10^8	8 180	7720 to 10 040	-6 to +23

(f) Data for molybdenum from reference 11

Vapor pressure		Extrapolated temperature, °K	Temperature uncertainty	
atm	N/m^2		°K	percent
1	1.01×10^5	4640	4500 to 4 830	-3 to +4
10	1.01×10^6	5340	5180 to 5 690	-3 to +6
100	1.01×10^7	6440	6110 to 6 910	-5 to +7
1000	1.01×10^8	7980	7430 to 8 810	-7 to +10

(g) Data for molybdenum, combined data of references 6, 10, and 11

1	1.01×10^5	4800	4500 to 5 350	-6 to +11
10	1.01×10^6	5630	5180 to 6 510	-8 to +15
100	1.01×10^7	6820	6110 to 8 320	-10 to +22
1000	1.01×10^8	8620	7430 to 11 530	-14 to +33

(h) Data for niobium from reference 12

1	1.01×10^5	4520	4360 to 4 800	-4 to +6
10	1.01×10^6	5090	4870 to 5 500	-4 to +8
100	1.01×10^7	5830	5510 to 6 440	-5 to +10
1000	1.01×10^8	6830	6340 to 7 780	-7 to +14

vapor-pressure data points were recorded in the temperature range from 2151° to 2462° K. The molybdenum sample was at least 99.957 percent pure. Spectroscopic analysis showed the presence of 0.023 percent carbon and 0.01 to 0.001 percent each of iron and silicon. In table II(d), extrapolation of the data of reference 10 to 1000 atmospheres (1.01×10^{8} N/m^{2}) is presented.

The second study (Vozzella, et al., ref. 6) also used the Langmuir method to measure the vapor pressure of solid molybdenum. An automatic recording semimicro vacuum balance and a calibrated optical pyrometer were used to obtain vapor-pressure measurements in the temperature range from 2141° to 2533° K; 12 data points are presented. An analysis of the sample showed the molybdenum to be 99.89 percent pure. Impurities amounted to 1100 ppm; oxygen, 30 ppm; carbon, 70 ppm; and traces of iron, nickel, chromium, and silicon, totaling 1000 ppm. By taking into account the spread in the data, an extrapolation to 1000 atmospheres (1.01×10^{8} N/m^{2}) yielded the results shown in table II(e).

The third study (Fries, ref. 11) on the vapor pressure of solid molybdenum also used the Langmuir method to measure vapor pressure. The apparatus used by Fries (ref. 11) was essentially the same as that used by Vozzella, et al., (ref. 6). Optical pyrometer readings recorded 12 data points in the temperature range from 2086° to 2489° K. Analysis of the sample indicated maximum impurities amounting to 1085 ppm consisting of oxygen, 45 ppm; nitrogen, 20 ppm; niobium, tungsten, and zinc, each 150 ppm; iron, 75 ppm; tantalum, zirconium, strontium, cobalt, titanium, potassium, and silicon, each 45 ppm; and trace materials amounting to 180 ppm. Fitting the data to equation (1) and extrapolating it to 100 atmospheres (1.01×10^{8} N/m^{2}) yielded the results shown in table II(f).

Since each set of data (refs. 6, 10, and 11) yields different results for the vapor pressure at 1 to 1000 atmospheres (1.01×10^{5} to 1.01×10^{8} N/m^{2}) all three sets were combined. Therefore, a vapor-pressure line was computed by averaging the least-squares line calculated in each case. The results of this procedure are listed in table II(g), along with the temperature uncertainty which was also calculated by using all three sets of data.

Niobium

Two sets of data for the vapor pressure of solid niobium are discussed herein. The first set (ref. 12) was presented in 1959. The Langmuir method was employed, and temperatures were measured under blackbody conditions by sighting with an optical pyrometer into a hole drilled into the sample. Seventeen data points were recorded in the temperature range from 2304° to 2596° K. The sample purity was 99.9 percent, but no mention was made of the types of impurities; however, the sample was thoroughly outgassed before it was heated inductively and measurements were taken. In table II(h) the data of reference 12 are extrapolated to 1000 atmospheres (1.01×10^{8} N/m^{2}).

In 1962, another experiment on niobium vapor pressures was presented, in reference 13. Again the Langmuir method was used, and temperatures were measured with an optical pyrometer, which was sighted on a blackbody hole drilled in the niobium sample. The experimenter used a high-temperature thermobalance which incorporated a new furnace design that gave stable temperatures up to 3000° K. The niobium sample purity was 99.975 percent. An analysis showed that impurities amounted to 248 parts per million; carbon, 20 ppm; oxygen, 100 ppm; nitrogen, 8 ppm; hydrogen, 5 ppm; tantalum, 100 ppm; iron, 8 ppm; and silicon, 7 ppm. The raw vapor-pressure data used in reference 13 were received from Woerner, et al. (ref. 13) and consisted of 32 data points in the temperature range from 2241° to 2588° K. A least-squares fit to equation (1) was applied, and the data were extrapolated to 1000 atmospheres (1.01×10^{8} N/m^{2}). The results are shown in table II(i).

Each set of data (refs. 12 and 13) is essentially in the same temperature range, and the resulting least-squares vapor-pressure lines are parallel. This result indicates that the experimenters are in agreement on the slope of the vapor-pressure curve but that a systemic error in the temperature or weight measurements caused a shift in the vapor pressure values. The difference in the two curves on the temperature scale is 40° K. When the results are averaged, a vapor-pressure line parallel to and between the

TABLE II. - Continued. EXTRAPOLATED

VAPOR-PRESSURE DATA

(i) Data for niobium from reference 13

Vapor pressure		Extrapolated temperature, °K	Temperature uncertainty	
atm	N/m^{2}		°K	percent
1	1.01×10^{5}	4760	4520 to 5040	-5 to +6
10	1.01×10^{6}	5430	5080 to 5840	-6 to +8
100	1.01×10^{7}	6300	5800 to 6950	-8 to +10
1000	1.01×10^{8}	7530	6750 to 8580	-10 to +14

(j) Data for niobium, combined data of references 12 and 13

1	1.01×10^{5}	4660	4360 to 5040	-6 to +8
10	1.01×10^{6}	5280	4870 to 5840	-8 to +11
100	1.01×10^{7}	6100	5510 to 6950	-10 to +14
1000	1.01×10^{8}	7220	6340 to 8580	-12 to +19

two sets of data is formed. Since there is no clear reason to prefer one set of data to the other, the results shown in table II(j) lie between the results calculated from Speiser, et al. (ref. 12) and Woerner, et al. (ref. 13).

Platinum

The first set of platinum vapor-pressure data discussed herein is presented in reference 14. The Langmuir technique was used, and the vapor pressure of solid platinum was measured in the temperature range from 1571° to 1783° K. The platinum sample was at least 99.95 percent pure, but no mention was made of the types of impurities. Only nine data points are presented by Dreger, et al. (ref. 14), and five of these are within 5° K of 1740° K; therefore, it was difficult to estimate an error throughout the temperature range investigated. The vapor-pressure curve calculated from the data of reference 14 resulted in an equation that was of the same form but numerically different from that calculated in reference 14. At 1000 atmospheres (1.01×10^{8} N/m^{2}), equation (1) predicts a temperature of 5430° K, whereas the equation calculated in reference 14 predicts 6490° K. Since Dreger, et al. (ref. 14) may not have used the least-squares method for calculating the vapor-pressure equation, or because other unmentioned factors may have entered his calculations, these data were not used for extrapolation purposes.

A second set of platinum vapor-pressure data is presented in reference 15. A microbalance was used to measure the vapor pressure of solid platinum by the Langmuir technique over the range from 1916° to 2042° K. A plot of the 18 data points shows a good distribution over the temperature range (Hampson, et al. (ref. 15)), but since the temperature range was only 125° K, the temperature uncertainty becomes quite large at 1000 atmospheres (1.01×10^{8} N/m^{2}). The platinum sample was approximately 99.7 percent pure. The major impurities were palladium, iridium, and rhodium at percentage levels of 0.01 to 0.1 percent. Copper and iron were estimated at percentage levels of 0.001 to 0.1 and silver at less than 0.001 percent. From an extrapolation to 1000 atmospheres (1.01×10^{8} N/m^{2}), vapor-pressure and temperature estimates were computed, as shown in table II(k).

Ruthenium

Survey studies were made of three references containing information on the vapor pressure of solid ruthenium. In reference 16, 24 data points for the vapor pressure of solid ruthenium in the temperature range from 2036° to 2591° K are presented. Data

TABLE II. - Continued. EXTRAPOLATED VAPOR-PRESSURE DATA

(k) Platinum

Vapor pressure		Extrapolated temperature, °K	Temperature uncertainty	
atm	N/m^2		°K	percent
1	1.01×10^5	4070	3640 to 4 740	-11 to +16
10	1.01×10^6	4780	4130 to 5 880	-14 to +23
100	1.01×10^7	5790	4760 to 7 760	-18 to +34
1000	1.01×10^8	7330	5620 to 11 400	-23 to +55

(l) Data for ruthenium from reference 16

1	1.01×10^5	4280	3960 to 4 620	-7 to +8
10	1.01×10^6	4930	4450 to 5 440	-9 to +10
100	1.01×10^7	5790	5070 to 6 610	-12 to +14
1000	1.01×10^8	7040	5900 to 8 430	-16 to +20

were taken by both the Knudsen method and the Langmuir technique. Sixteen data points were obtained by the Knudsen method, while the other eight points were obtained by the Langmuir technique. The Knudsen method employed ruthenium 103 as a radioactive tracer in the vaporizing ruthenium metal. The radioactivity of the target on which the effusion beam condensed was then compared with a previously calibrated sample.

The Langmuir evaporation studies (Panish, et al. (ref. 16)) were performed on a small cylindrically shaped pellet of ruthenium metal containing a blackbody hole for temperature measurements. The ruthenium samples were analyzed spectroscopically, and trace amounts of impurities were found; however, the types and amounts were not reported. By extrapolating the data to 1000 atmospheres (1.01×10^8 N/m^2), results for the vapor pressure of ruthenium were calculated and are shown in table II(l).

Reference 17 presents studies of the vapor pressure of solid ruthenium in the temperature range 2011° to 2330° K. By using the Langmuir technique in conjunction with a microbalance built inside the vacuum system, nine data points were obtained. The sample of ruthenium was between 99.8 and 99.98 percent pure, with the major impurities being platinum and calcium from 0.01 to 0.1 percent. Extrapolation of these nine data points yields the values given in table II(m) showing estimated temperatures for pressures up to 1000 atmospheres (1.01×10^8 N/m^2).

Reference 18, reports the vapor pressure of solid ruthenium in the temperature range from 1918° to 2377° K, also using the Langmuir method. A microbalance was used for weight measurements, and a calibrated pyrometer was used for temperature mea-

TABLE II. - Continued. EXTRAPOLATED

VAPOR-PRESSURE DATA

(m) Data for ruthenium from reference 17

Vapor pressure		Extrapolated temperature, ^{o}K	Temperature uncertainty	
atm	N/m^{2}		^{o}K	percent
1	1.01×10^{5}	4080	3870 to 4230	-5 to +4
10	1.01×10^{6}	4650	4340 to 4880	-7 to +5
100	1.01×10^{7}	5410	4950 to 5770	-8 to +7
1000	1.01×10^{8}	6470	5750 to 7050	-11 to +9

(n) Data for ruthenium from reference 18

1	1.01×10^{5}	4370	4010 to 4710	-8 to +8
10	1.01×10^{6}	5040	4520 to 5570	-10 to +11
100	1.01×10^{7}	5960	5180 to 6800	-13 to +14
1000	1.01×10^{8}	7280	6060 to 8730	-17 to +20

(o) Data for ruthenium, combined data of references 16 to 18

1	1.01×10^{5}	4240	3870 to 4710	-9 to +11
10	1.01×10^{6}	4870	4340 to 5570	-11 to +14
100	1.01×10^{7}	5710	4950 to 6800	-13 to +19
1000	1.01×10^{8}	6910	5750 to 8730	-17 to +26

surements. Two ruthenium samples of different purities were used. Sample 1 had a purity greater than 99.97 percent, with the major impurities being less than 0.02 percent osmium and less than 0.007 percent rhodium. Sample 2 had a purity greater than 99.8 percent, with the major impurities being less than 0.1 percent platinum and calcium. In reference 18, 42 data runs are presented using sample 1, and 52 runs are presented using sample 2. Extrapolating the data to 1000 atmospheres (1.01×10^{8} N/m^{2}), results in the vapor-pressure values presented in table II(n).

Again, all the resulting vapor-pressure equations of references 16 to 18 were averaged and extrapolated to 1000 atmospheres (1.01×10^{8} N/m^{2}). All three references overlap in the temperature range studied, and the slope of the vapor-pressure curve is approximately the same for each reference. Therefore, the result of extrapolating the combined data is a vapor-pressure curve between the two outer, or most separated, sets of data. These results are presented in table II(o).

Silicon

Silicon vaporizes in the same manner as carbon. The various silicon species each have a certain partial pressure at a given temperature and possess their own value for the heat of vaporization. The partial pressure of each silicon species must be known in order to extrapolate the silicon vapor pressure to 1000 atmospheres (1.01×10^{8} N/m^{2}).

Reference 19 describes sublimation studies of silicon with a mass spectrometer. Molecules Si_1 to Si_7 were found, and their intensities were measured at a temperature of 1660^{o} K. The heats of sublimation were measured (Honig, ref. 19) for the four most abundant species, Si_1 to Si_4. The measured heats of vaporization and the known relative intensities and total vapor pressures of the silicon species at 1600^{o} K are used to extrapolate the partial pressures of Si_1 to Si_4 to 1000 atmospheres (1.01×10^{8} N/m^{2}). The total pressure measured at 1600^{o} K was revised by Honig (ref. 19), and is reported in reference 20. Table II(p) gives the partial vapor pressures of Si_1 to Si_4 at total pressures of 1, 10, 100, and 1000 atmospheres (1.01×10^{5}, 1.01×10^{6}, 1.01×10^{7}, and 1.01×10^{8} N/m^{2}). Figure 4, in which the silicon pressures are plotted, was used to calculate the total silicon pressure graphically.

TABLE II. - Continued. EXTRAPOLATED VAPOR-PRESSURE DATA

(p) Silicon

Partial vapor pressure of silicon								Total vapor pressure		Extrapolated temperature, ^{o}K	Minimum temperature uncertanity	
Si_1		Si_2		Si_3		Si_4						
atm	N/m^{2}	atm	N/m^{2}	atm	N/m^{2}	atm	N/m^{2}	atm	N/m^{2}		^{o}K	percent
0.24	0.25×10^{5}	0.16	0.16×10^{5}	0.19	0.19×10^{5}	0.41	0.42×10^{5}	1	1.01×10^{5}	2730	2430 to 3140	-11 to +15
1.4	1.4	1.6	1.6	2.0	2	5.0	5.1	10	1.01×10^{6}	3010	2600 to 3610	-14 to +20
8	8.1	15	15.3	21	21.5	56	57	100	1.01×10^{7}	3350	2770 to 4220	-17 to +26
45	46	145	148	210	215	600	613	1000	1.01×10^{8}	3760	3000 to 4990	-20 to +33

Honig (ref. 19) performed 11 runs on Si_1, 4 on Si_2, 2 on Si_3, and 1 on Si_4. No estimate of error was possible for Si_3 and Si_4. At 1600^{o} K, the temperature at which the experiment was performed, the combined partial pressures of Si_2, Si_3, and Si_4 contribute only 5 percent toward the vapor pressure of silicon.

More recently, reference 21 presented a thermodynamic study of silicon carbide using a mass spectrometer. By measuring the partial pressure of silicon over silicon carbide, reference 21 calculates the total vapor pressure of pure silicon as 10 times lower than that presented by Honig (ref. 19). However, extrapolation to 1000 atmospheres (1.01×10^{8} N/m^{2}) was not possible since the partial pressure of each molecular species was not calculated. A more extensive study is necessary before reliable silicon vapor pressures from 1 to 1000 atmospheres (1.01×10^5 to 1.01×10^8 N/m^2) can be calculated.

Tungsten

The vapor pressure of solid tungsten is reported in reference 22, where 10 data points are recorded in the temperature range from 2574° to 3183° K. The Langmuir method was used with the aid of a vacuum microbalance. A calibrated optical pyrometer was used to measure temperatures by sighting on a blackbody hole drilled in the specimen. Results of a spectrochemical analysis indicate a maximum impurity content of 0.02 percent where molybdenum and silicon are the principal impurities. The results obtained by extrapolating these data to 1000 atmospheres (1.01×10^8 N/m^2) are shown in table II(q).

Vanadium

The vapor pressure of solid vanadium was measured in the temperature range from 1666° to 1882° K in reference 23 by the Langmuir method. The vanadium sample was

TABLE II. - Continued. EXTRAPOLATED

VAPOR-PRESSURE DATA

(q) Tungsten

Vapor pressure		Extrapolated temperature, °K	Temperature uncertainty	
atm	N/m^2		°K	percent
1	1.01×10^5	5740	5620 to 5 930	-2 to +3
10	1.01×10^6	6580	6420 to 6 880	-2 to +5
100	1.01×10^7	7730	7470 to 8 180	-3 to +6
1000	1.01×10^8	9340	8930 to 10 110	-5 to +9

(r) Vanadium

1	1.01×10^5	3510	3420 to 3 640	-3 to +4
10	1.01×10^6	4060	3920 to 4 260	-3 to +5
100	1.01×10^7	4800	4590 to 5 120	-4 to +7
1000	1.01×10^8	5880	5540 to 6 430	-6 to +9

heated by radiofrequency induction, and temperature measurements were made with an optical pyrometer that was sighted on a blackbody hole drilled in the sample. An analysis of the sample showed it to be 99.6 percent vanadium. The measured impurities were 0.2 percent carbon, 0.1 percent hydrogen, with traces of iron, silicon, manganese, copper, and calcium comprising the other 0.1 percent. No correction factor was applied to the vapor-pressure measurements resulting from these impurities. However, in several of the initial runs, gas was evolving from the sample (during heating), which would indicate outgassing of some impurities, and these runs were rejected; 12 data points were recorded. The least-squares method was used to calculate the best straight line through the data and to extrapolate it to 1000 atmospheres (1.01×10^8 N/m^2). The spread of the vapor-pressure data was also used to calculate the temperature uncertainty from 1 to 1000 atmospheres (1.01×10^5 to 1.01×10^8 N/m^2), and the results are presented in table II(r).

Yttrium

The vapor pressures of liquid yttrium from two references are discussed and compared herein. Reference 24 contains vapor-pressure data on liquid yttrium in the temperature range from 1774° to 2103° K. Rates of vaporization were measured as a function of temperature by an inductively heated, tungsten Knudsen effusion cell. Weight measurements were made with a vacuum balance, while temperatures were recorded by use of an optical pyrometer. Seven vaporization data points were recorded from the sample of yttrium, which contained about 0.4 percent calcium. However, the orifice of the Knudsen cell was not thin, and a Clausing factor of 0.36 was used in the calculations.

Reference 9 presents a vapor-pressure study of liquid yttrium. Again, the Knudsen method was used in conjunction with a quartz-fiber microbalance for weight measurements, and an optical pyrometer was used for temperature measurements. Data for 18 runs were received from Habermann, et al. (ref. 9); the data were in the temperature range from 1861° to 2252° K. The yttrium metal was better than 99.88 percent pure. The impurities were tantalum, 400 ppm; iron, 150 ppm; oxygen, 300 ppm; carbon, 150 ppm; fluorine, 100 ppm; and 65 ppm of additional impurities.

In extrapolating the vapor-pressure data, only the data of reference 9 were used. The advantages of this set of data were the following. First, the orifice in the Knudsen cell was much thinner than that used in reference 24. This led to a Clausing factor of 0.9666 compared with 0.36 in reference 24. Second, 18 data points were received from Habermann, et al. (ref. 9) compared with 7 presented in reference 24. Table II(s) shows the results of extrapolating the data of reference 9 to 1000 atmospheres (1.01×10^{8} N/m^{2}), along with the calculated temperature uncertainty.

Zirconium

Extrapolated vapor-pressure data for zirconium are based on the experiment described in reference 25. The vapor pressure of solid zirconium was measured between 1949° and 2054° K by a modified method of the Langmuir technique. The zirconium sample was heated inductively by high-frequency current, while temperature measurements were taken from optical pyrometer readings. Weight loses were determined by two methods: first, by collecting and analyzing the evaporated film and, second, by direct measurement of the sample weight loss.

The zirconium sample contained 0.99 atom percent hafnium, 0.05 atom percent tungsten, and 0.37 atom percent of other impurities, which included mostly silicon and

TABLE II. - Continued. EXTRAPOLATED VAPOR-PRESSURE DATA

(s) Yttrium

Vapor pressure		Extrapolated temperature, °K	Temperature uncertainty	
atm	N/m^{2}		°K	percent
1	1.01×10^{5}	3 480	3 410 to 3 590	-2 to +3
10	1.01×10^{6}	4 170	4 050 to 4 390	-3 to +5
100	1.01×10^{7}	5 210	5 000 to 5 630	-4 to +8
1000	1.01×10^{8}	6 950	6 530 to 7 850	-6 to +13

(t) Zirconium

1	1.01×10^{5}	4 700	4 440 to 5 240	-6 to +11
10	1.01×10^{6}	5 580	5 170 to 6 450	-7 to +16
100	1.01×10^{7}	6 850	6 180 to 8 370	-10 to +22
1000	1.01×10^{8}	8 860	7 690 to 11 940	-13 to +35

(u) Niobium carbide (data from ref. 26)

1	1.01×10^{5}	6 180	5 880 to 6 880	-5 to +11
10	1.01×10^{6}	7 620	7 120 to 8 880	-7 to +16
100	1.01×10^{7}	9 940	9 020 to 12 500	-9 to +26
1000	1.01×10^{8}	14 250	12 320 to 21 130	-14 to +48

and aluminum. The temperature range of the experiment was only 105° K, and even though a plot of the data shows a good distribution over the temperature range, the extrapolation of the data to 1000 atmospheres (1.01×10^{8} N/m^2) predicts a large temperature uncertainty. Table II(t) summarizes the extrapolation of the least-squares curve fit and the possible temperature variation with pressure.

Niobium Carbide

The vaporization behavior of solid niobium carbide was observed experimentally by Fries (ref. 26). The Langmuir method was used to measure the vapor pressure of niobium carbide, and eight data points were recorded over the temperature range from 2260° to 2940° K. The samples were heated inductively, and temperature measurements were made by sighting into a blackbody hole drilled into the sample. Weight measurements were made of the samples before and after each run in order to calculate weight loss.

Analysis of the sample indicated a nearly stoichiometric compound $NbC_{0.924}$, with 0.88 percent free carbon, 0.5 percent oxygen, 0.31 percent nitrogen, and traces of tungsten and tantalum at 500 to 1000 ppm and of zirconium, zinc and molybdenum at 100 to 300 ppm. The nearly stoichiometric niobium carbide was observed to vaporize noncongruently and to lose carbon preferentially, and it was assumed that the carbon vapor leaving the sample was monatomic. A fair amount of scatter occurred in the eight data points which when extrapolated to 1000 atmospheres (1.01×10^{8} N/m^2) created a large temperature uncertainty at a given pressure. The extrapolations are listed in table II(u) for pressures from 1 to 1000 atmospheres (1.01×10^{5} to 1.01×10^{8} N/m^2).

TABLE II. - Continued. EXTRAPOLATED

VAPOR-PRESSURE DATA

(v) Calculated vapor pressures from reference 27

Partial vapor pressure				Total vapor pressure of niobium carbide		Calculated temperature, °K
Niobium		Carbon				
atm	N/m^2	atm	N/m^2	atm	N/m^2	
0.09	0.09×10^{5}	0.91	0.92×10^{5}	1	1.01×10^{5}	4810
1.0	1.01	9.0	9.1	10	1.01×10^{6}	5620
14	14.2	86	87	100	1.01×10^{7}	6730
170	172	830	842	1000	1.01×10^{8}	8400

The vapor pressure of niobium carbide was also studied analytically in reference 27. Experimentally measured vapor-pressure data of niobium and carbon were used in thermodynamic formulation to calculate the partial pressure of niobium and carbon over niobium carbide. Table II(v) indicates the results of these calculations for total pressures of 1, 10, 100, and 1000 atmospheres (1.01×10^5, 1.01×10^6, 1.01×10^7, and 1.01×10^8 N/m^2).

There are several possible reasons why the data of Fries (ref. 26) and the analytical approach of Kaufmann, et al. (ref. 27) differ by $1\frac{1}{2}$ orders of magnitude.

(1) Fries (ref. 26) assumed that only monatomic carbon vaporized from the niobium carbide sample. Monatomic carbon is the major constituent of the vapor in the temperature range of the experiment performed by Fries (ref. 26) but polyatomic species are always present, and at higher temperatures they are dominant.

(2) Fries (ref. 26) was unable to measure the partial pressure of niobium. In the temperature range of the experiment, the partial pressure of niobium may not have influenced the total vapor pressure; however, the partial pressure of niobium must be known to extrapolate the data to 1000 atmospheres (1.01×10^8 N/m^2).

(3) The data used by Kaufman, et al. (ref. 27) had to be extrapolated to higher pressures. A certain amount of error is always present with experimental data, and this error is enlarged when the data are extrapolated.

The extrapolation of vapor-pressure data must be done very carefully with full knowledge of the type of experiment and the errors involved. As shown in reference 26, the data may be entirely valid for the temperature range in which they were obtained, but meaningful extrapolation to higher pressures may not be possible. It was decided that the analysis of Kaufman, et al. (ref. 27) predicts more accurately the vapor pressure of niobium carbide from 1 to 1000 atmospheres (1.01×10^5 to 1.01×10^8 N/m^2) than does the extrapolation of the data of Fries (ref. 26); therefore, only the analysis of reference 27 is recommended. The partial pressures of niobium and carbon, in addition to the total pressure of niobium carbide calculated from reference 27, are shown in figure 5.

Zirconium Carbide

The vaporization of solid zirconium carbide is discussed in references 28 and 29. The Langmuir method was used, and temperatures were measured with an optical pyrometer, which was sighted on a blackbody hole drilled in each specimen. The specimens were made from hot-pressed zirconium carbide powder containing 2.13 percent impurities. Analysis of the impurities showed 1.1 weight percent free carbon, 0.58 weight percent silicon, 0.30 weight percent niobium, and 0.05 weight percent each of boron, iron, and molybdenum. Most impurities near the surface were evaporated during

TABLE II. - Concluded. EXTRAPOLATED VAPOR-PRESSURE DATA

(w) Zirconium carbide

Partial vapor pressure				Total vapor pressure of zirconium carbide		Extrapolated temperature, $^{\circ}K$	Temperature uncertainty	
Zirconium		Carbon					$^{\circ}K$	percent
atm	N/m^2	atm	N/m^2	atm	N/m^2			
0.73	0.74×10^5	0.27	0.27×10^5	1	1.01×10^5	4940	4620 to 5420	-6 to +10
7.3	7.4	2.7	2.74	10	1.01×10^6	5610	5150 to 6330	-8 to +13
73	74	27	27.4	100	1.01×10^7	6570	5890 to 7670	-10 to +17
730	740	270	274	1000	1.01×10^8	7930	6870 to 9730	-13 to +23

the early heatings and all the reliable vapor-pressure measurements were obtained thereafter. Observations of the specimen and the sublimate during the course of the experiment indicate that the vaporization of stoichiometric zirconium carbide is congruent; that is, no change of the specimen surface composition occurs as the vaporization process proceeds. For this experiment, 31 runs were performed. Both the partial pressure of zirconium and the partial pressure of carbon are reported in the temperature range from 2246° to 2898° K. Partial pressures of zirconium and carbon were extrapolated separately to 1000 atmospheres (1.01×10^8 N/m^2). These two extrapolated curves were then added to give a total pressure for a given temperature, for pressures up to 1000 atmospheres (1.01×10^8 N/m^2). The results are listed in table II(w) and are shown in figure 6. The partial vapor pressure of carbon that is extrapolated is the sum of all the carbon species. Therefore, since the larger carbon polymers (C_2 to C_5) become dominant at higher temperatures, the error of the carbon vapor-pressure extrapolation increases with temperature.

In figure 7 are plotted the vapor pressures of all the materials chosen from 1 to 1000 atmospheres (1.01×10^5 to 1.01×10^8 N/m^2).

CONCLUDING REMARKS

Existing vapor-pressure data were collected from the literature for 11 elements and 2 compounds. The materials chosen had a thermal neutron absorption cross section less than 5 barns (5.0×10^{-28} m^2) and an atmospheric boiling point over 3000° K. The data were curve fitted to an equation of the following form:

$$\log P = \frac{A}{T} + D$$

TABLE III. - CALCULATED CONSTANTS OF VAPOR PRESSURE EQUATION (EQ. (1))

Material	Constants		
	A	D	
		Pressure in atm	Pressure in N/m^2
Carbon$_1$	-37 067	8.078	13.084
Carbon$_2$	-42 798	9.924	14.930
Carbon$_3$	-41 115	9.720	14.726
Carbon$_4$	-50 165	10.818	15.824
Carbon$_5$	-50 820	11.132	16.138
Cerium	-22 816	6.419	11.425
Molybdenum	-32 468	6.768	11.774
Niobium	-39 308	8.444	13.450
Platinum	-27 546	6.747	11.753
Ruthenium	-32 927	7.766	12.772
Silicon$_1$	-22 951	7.790	12.796
Silicon$_2$	-29 509	10.009	15.015
Silicon$_3$	-30 383	10.393	15.399
Silicon$_4$	-31 913	11.266	16.272
Tungsten	-44 680	7.790	12.796
Vanadium	-26 134	7.441	12.447
Yttrium	-20 821	6.001	11.007
Zirconium	-30 158	6.399	11.405
Zirconium over zirconium carbide	-38 591	7.729	12.735
Carbon over zirconium carbide	-38 591	7.289	12.295
Niobium over niobium carbide	-37 048	6.649	11.655
Carbon over niobium carbide	-33 368	6.880	11.886

where A and D are constants, P is vapor pressure, and T is temperature. This equation has the form of a straight line when log P is plotted as a function of reciprocal temperature. The constants A and D were obtained for each of the materials discussed herein and are listed in table III. Selection of the constant D depends on whether pressure is expressed in atmospheres or newtons per square meter.

Equation (1) was used to extrapolate the vapor-pressure data to 1000 atmospheres (1.01×10^8 N/m^2). Whatever limitations exist in using the preceding equation for extrapolating vapor-pressure data exist in the extrapolations presented herein. An error anal-

TABLE IV. - RANGE OF VAPOR-PRESSURE DATA AND SUMMARY OF VAPOR-PRESSURE EXTRAPOLATION

Material	Pressure range		Vapor pressure			
	atm	N/m^2	1 atm; 1.01×10^{5} N/m^2	10 atm; 1.01×10^{6} N/m^2	100 atm; 1.01×10^{7} N/m^2	1000 atm; 1.01×10^{8} N/m^2
			Extrapolated boiling point, °K			
Carbon	$1\ \times10^{-12}$ to $2\ \times10^{-5}$	$1\ \times10^{-7}$ to 2	4100	4540	5070	5740
Cerium	1.6×10^{-6} to 2.1×10^{-4}	1.6×10^{-1} to 2.1×10^{1}	3560	4200	5160	6670
Molybdenum	4.3×10^{-9} to $1\ \times10^{-6}$	4.4×10^{-4} to $1\ \times10^{-1}$	4800	5630	6820	8620
Niobium	7.6×10^{-10} to 2.4×10^{-7}	7.7×10^{-5} to 2.4×10^{-2}	4660	5280	6100	7220
Niobium carbide	--------------------	(a)	4810	5620	6730	8400
Platinum	1.7×10^{-8} to 2.3×10^{-7}	1.7×10^{-3} to 2.3×10^{-2}	4070	4780	5790	7330
Ruthenium	2.3×10^{-10} to 1.7×10^{-5}	2.3×10^{-5} to 1.7	4240	4870	5710	6910
Silicon	1.3×10^{-9} to 1.3×10^{-6}	1.3×10^{-4} to 1.3×10^{-1}	2730	3010	3350	3760
Tungsten	2.5×10^{-10} to 5.4×10^{-7}	2.5×10^{-5} to 5.5×10^{-2}	5740	6580	7730	9340
Vanadium	5.4×10^{-9} to 3.5×10^{-7}	5.5×10^{-4} to 3.6×10^{-2}	3510	4060	4800	5880
Yttrium	6.0×10^{-6} to 2.6×10^{-4}	6.1×10^{-1} to 2.6×10^{1}	3480	4170	5210	6950
Zirconium	8.5×10^{-10} to 5.3×10^{-9}	8.6×10^{-5} to 5.4×10^{-4}	4700	5580	6850	8860
Zirconium carbide	1.3×10^{-10} to 2.8×10^{-6}	1.3×10^{-5} to 2.8×10^{-1}	4940	5610	6570	7930

[a] Analysis.

TABLE V. - BOILING-POINT TEMPERATURES OF SELECTED REFRACTORY MATERIALS

(a) At 1000 atmospheres (1.01×10^{8} N/m^{2})

Temperature, °K	Thermal absorption cross section, σ		
	$\sigma \leq 1.0$	$1.0 < \sigma \leq 2.0$	$2.0 < \sigma \leq 5.0$
9000 to 10 000	----------------	Tungsten 184	-----------
8000 to 9 000	Zirconium	Niobium carbide	Molybdenum
7000 to 8 000	Zirconium carbide Platinum 196 ----------------	Yttrium Niobium Platinum 194	----------- ----------- -----------
6000 to 7 000	Cerium	--------------	Ruthenium
5000 to 6 000	Carbon	--------------	Vanadium
<5000	Silicon	--------------	-----------

(b) At 100 atmospheres (1.01×10^{7} N/m^{2})

7000 to 8 000	----------------	Tungsten 184	-----------
6000 to 7 000	Zirconium Zirconium carbide	Niobium carbide Niobium	Molybdenum -----------
5000 to 6 000	Platinum 196 Cerium Carbon	Platinum 194 Yttrium --------------	Ruthenium ----------- -----------
4000 to 5 000	----------------	--------------	Vanadium
<4000	Silicon	--------------	-----------

ysis was used to find the temperature uncertainty in the extrapolated vapor pressure due to the scatter of the original data. The vapor-pressure data were generally taken in the range from 10^{-10} to 10^{-5} atmospheres (1.01×10^{-5} to 1.01 N/m^{2}), and table IV summarizes the results by showing, for each chosen material, the range of the original data and the predicted boiling points at 1, 10, 100, and 1000 atmospheres (1.01×10^{5}, 1.01×10^{6}, 1.01×10^{7}, and 1.01×10^{8} N/m^{2}).

In tables V(a) and (b), the refractory materials are grouped according to boiling point ranges and thermal absorption cross sections. At 1000 atmospheres (1.01×10^{8} N/m^{2}) the element that has the highest boiling point is tungsten (9340° K), while at the same pressure niobium carbide has the highest boiling point of the compounds (8400° K).

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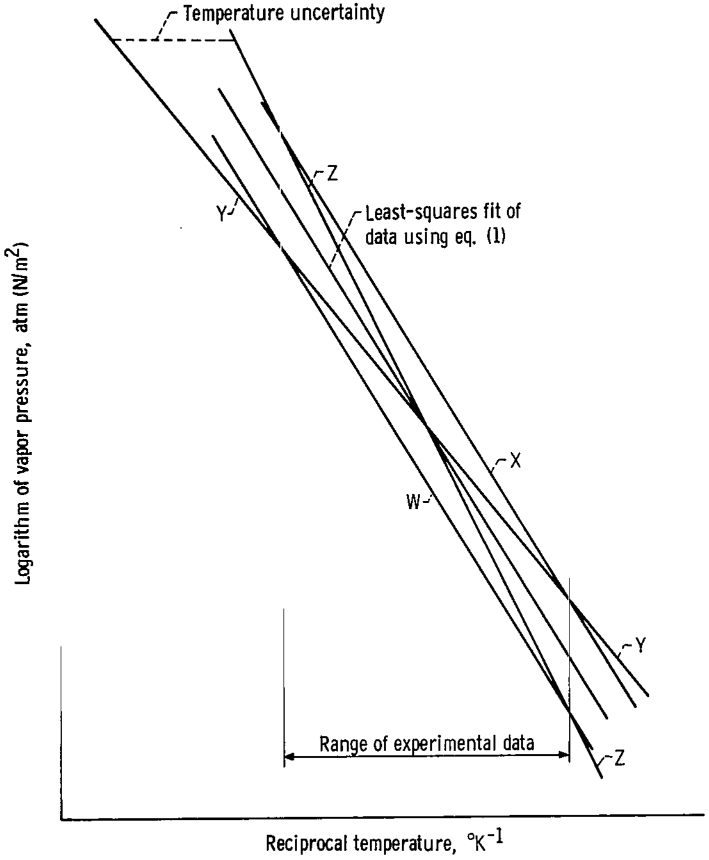

Figure 1. - Schematic drawing of visual error analysis.

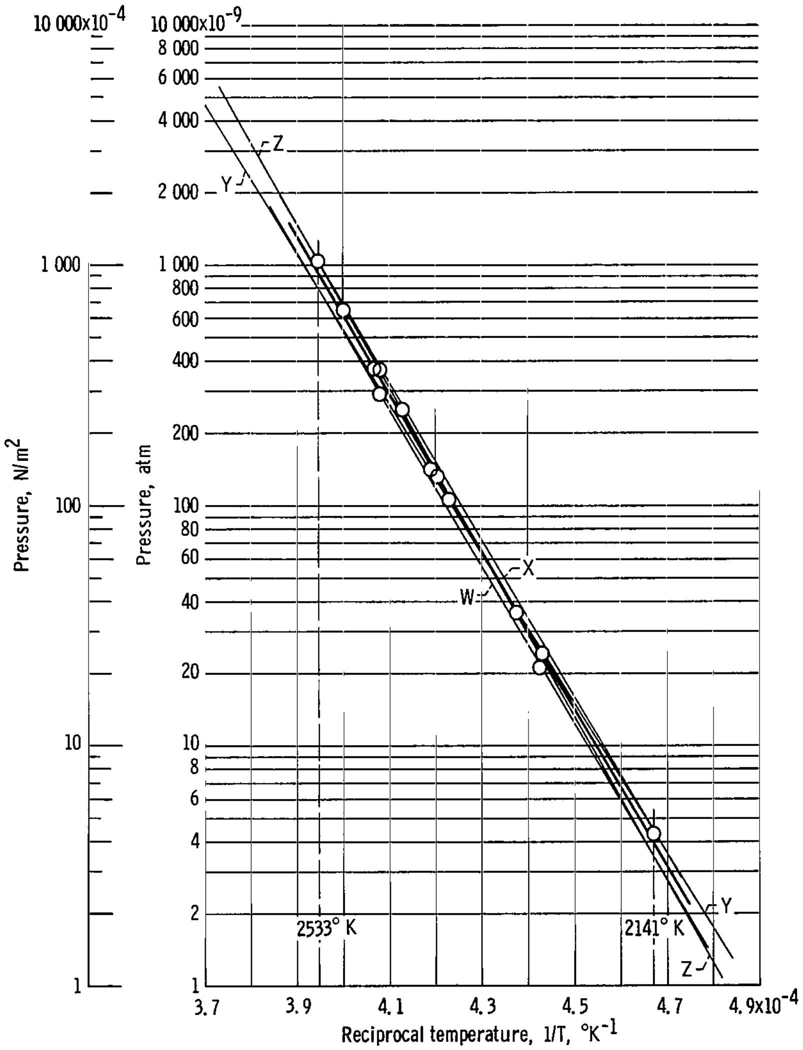

Figure 2. - Method of extrapolation using molybdenum vapor pressure data from reference 6.

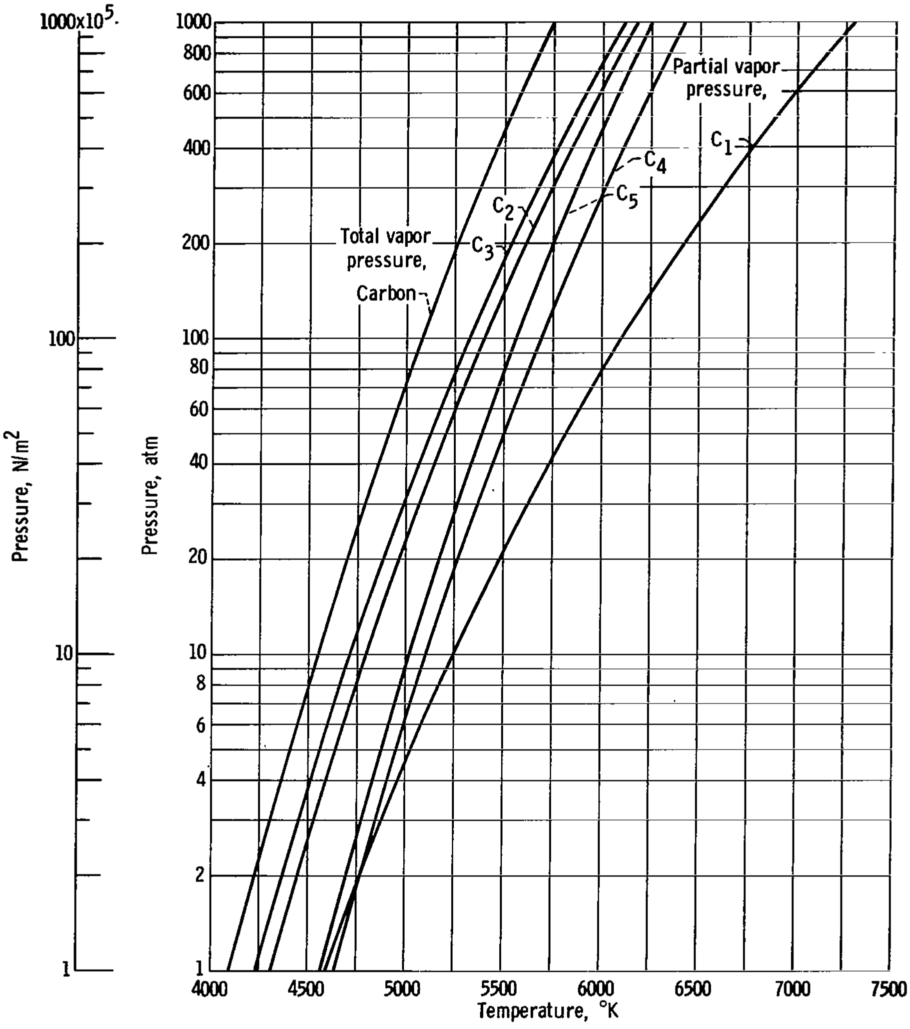

Figure 3. - Extrapolated vapor pressure of carbon (data from ref. 7).

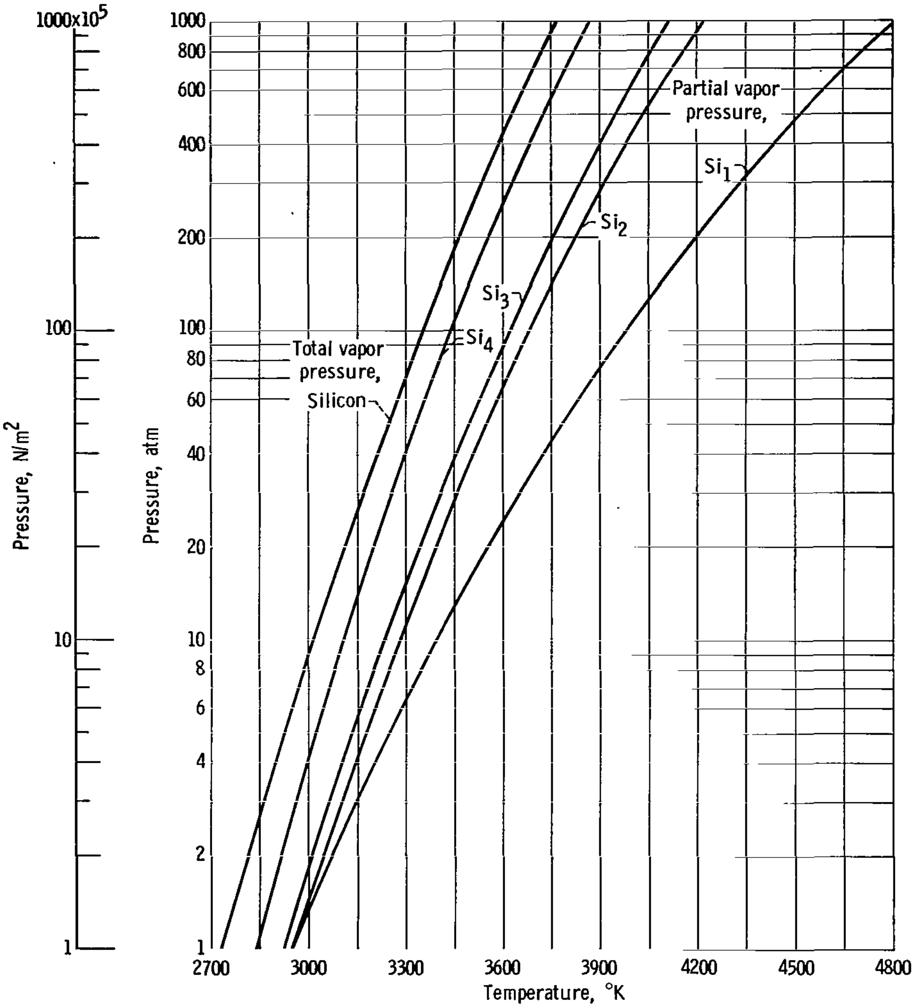

Figure 4. - Extrapolated vapor pressure of silicon (data from ref. 19).

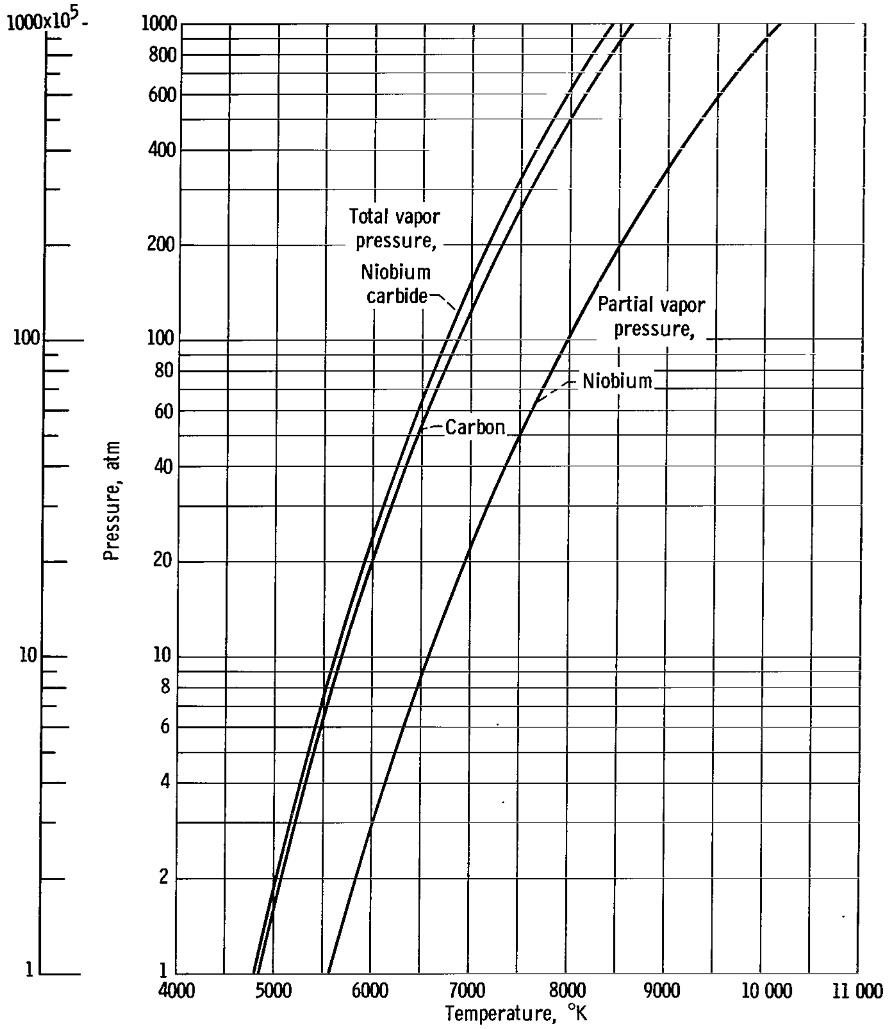

Figure 5. - Extrapolated vapor pressure of niobium carbide.

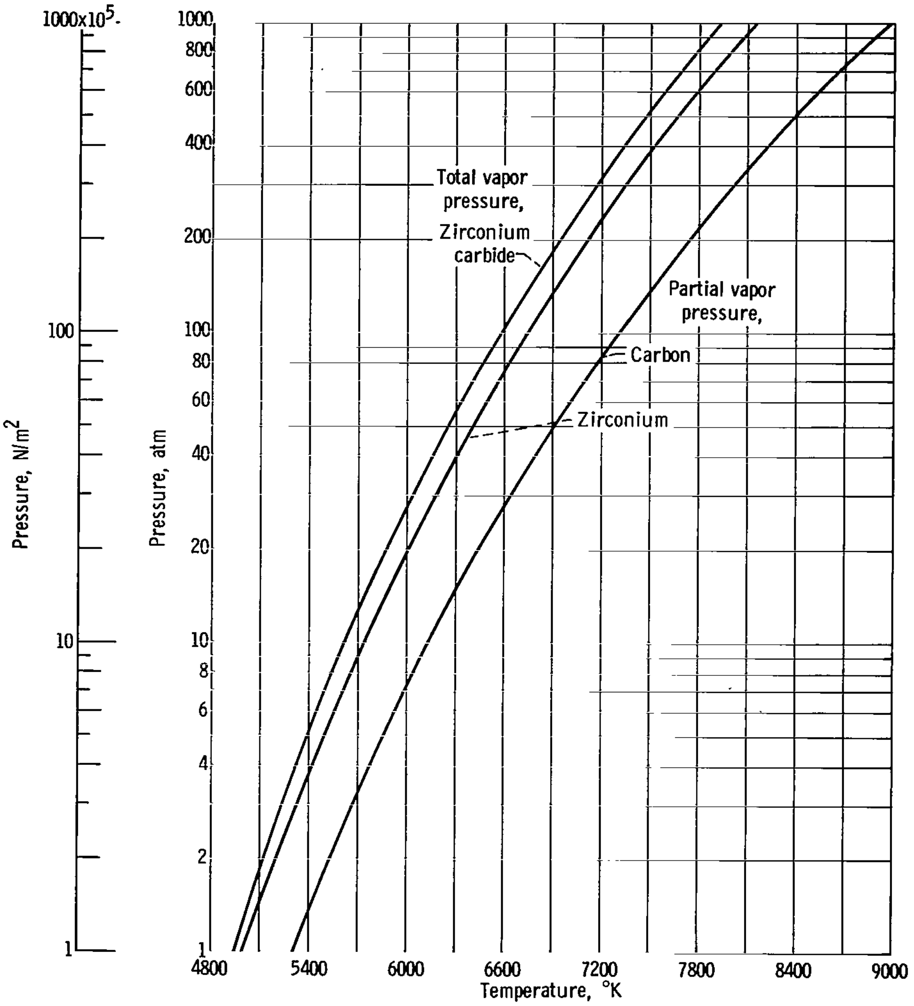

Figure 6. - Extrapolated vapor pressure of zirconium carbide (data from ref. 29).

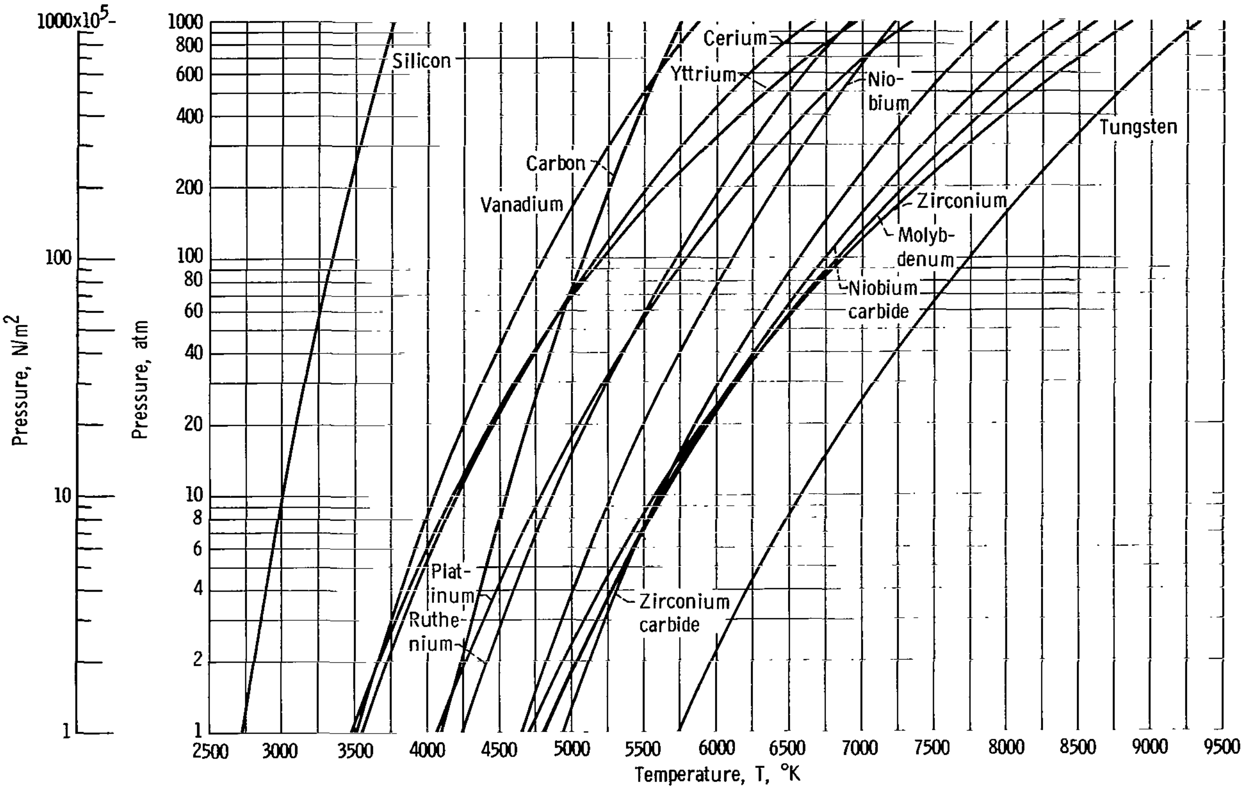

Figure 7. - Extrapolated vapor pressure data of selected refractory materials.

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