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SUBJECT CATEGORY: ~~ISOTOPE SEPARATION - GAS CENTRIFUGE METHOD C-24~~

TID-13673

UNION CARBIDE

UNION CARBIDE NUCLEAR COMPANY

POST OFFICE BOX P, OAK RIDGE, TENNESSEE

MASTER

Date November 29, 1960

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Date: 03/09/2021

Subject THE MAXIMUM SEPARATIVE CAPACITY OF A GAS CENTRIFUGE

KOA-748 (Revised)

The maximum rate at which separative work can be produced by a gas centrifuge, termed the maximum separative capacity of the centrifuge, can be computed from the equation

$$\delta U(\max) = \frac{\rho D \pi Z}{2} \left[\frac{\Delta M \ V^2}{2RT} \right]^2 . \qquad (1)$$

For the case in which the centrifuge is used to separate the isotopes of uranium, U-235 and U-238, the following units are commonly used:

δU = separative capacity of the centrifuge (kg U/yr),

ρ = density of the process gas (kg U/cm^3),

D = coefficient of self-diffusion of the process gas (cm^2/yr),

π = 3.1416

Z = length of the centrifuge bowl (cm),

ΔM = mass difference between species being separated by the centrifuge (3 g/g-mole),

V = peripheral velocity of the centrifuge (cm/sec),

R = gas constant (8.3147 x 10^7 ergs/g-mole/$^\circ$K), and

T = operating temperature of the centrifuge ($^\circ$K).

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For the convenience of those engaged in the development of the gas centrifuge for uranium isotope separation, a tabulation of values of $\delta U(max)$ as a function of the peripheral speed and operating temperature of the centrifuge is presented in Table I of this memo. This dependence of the separative capacity on V and T is also shown graphically in Figure 1. The values in the table were computed for a centrifuge one meter in length ($Z = 100$). Since, as indicated by equation (1), the separative capacity varies directly as the length of the centrifuge bowl, the value of the maximum separative capacity of a machine of any length is readily obtained by multiplying the tabulated value by the length (expressed in meters) of the centrifuge bowl under consideration. The actual separative capacity of a gas centrifuge will, of course, be less than the maximum value given in Table I. The problem of evaluating the efficiency of a centrifuge will be considered in forthcoming memoranda.

It is hoped that this paper will aid in clearing up the confusion which exists with regard to the dependence on temperature of the separative capacity of a gas centrifuge. Several investigators, ignoring the temperature dependence of the ρD product, have erroneously stated that the separative capacity of a centrifuge varies inversely as the square of the absolute temperature. In reality, it varies more closely as the inverse first power of the temperature. This follows from the results presented in Appendix I where values for the ρD product for UF_6 are calculated from viscosity data on the basis of the Lennard-Jones 6:12 potential model for the intermolecular forces. The derivation of equation (1) is presented in Appendix II.

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TABLE I

THE MAXIMUM THEORETICAL SEPARATIVE CAPACITY OF A GAS CENTRIFUGE 1.0 METERS IN LENGTH SEPARATING A BINARY MIXTURE OF THE ISOTOPES OF URANIUM, U-235 AND U-238, WITH UF_6 AS THE PROCESS GAS

Peripheral Velocity (meters/sec.)	Separative Capacity (Kg U Per Yr.)								
	273° K	283° K	293° K	303° K	313° K	323° K	333° K	343° K	353° K
200	0.4816	0.4641	0.4478	0.4328	0.4185	0.4049	0.3919	0.3801	0.3685
210	0.5854	0.5641	0.5443	0.5260	0.5087	0.4921	0.4764	0.4620	0.4479
220	0.7051	0.6794	0.6556	0.6336	0.6128	0.5928	0.5939	0.5565	0.5396
230	0.8423	0.8117	0.7831	0.7569	0.7320	0.7082	0.6855	0.6648	0.6446
240	0.9987	0.9623	0.9285	0.8974	0.8679	0.8396	0.8127	0.7882	0.7642
250	1.1758	1.1330	1.0932	1.0565	1.0218	0.9885	0.9569	0.9280	0.8997
260	1.3755	1.3254	1.2788	1.2360	1.1854	1.1564	1.1194	1.0856	1.0525
270	1.5997	1.5414	1.4872	1.4374	1.3902	1.3448	1.3019	1.2625	1.2241
280	1.8501	1.7828	1.7201	1.6625	1.6078	1.5554	1.5057	1.4602	1.4157
290	2.1289	2.0514	1.9793	1.9130	1.8501	1.7898	1.7326	1.6802	1.6291
300	2.4381	2.3494	2.2668	2.1908	2.1188	2.0497	1.9842	1.9243	1.8657
310	2.7798	2.6786	2.5845	2.4978	2.4158	2.3370	2.2623	2.1939	2.1271
320	3.1562	3.0413	2.9344	2.8361	2.7429	2.6535	2.5687	2.4910	2.4152
330	3.5697	3.4397	3.3188	3.2076	3.1022	3.0010	2.9051	2.8173	2.7315
340	4.-224	3.8760	3.7397	3.6144	3.4956	3.3817	3.2736	3.1746	3.0780
350	4.5169	4.3525	4.1995	4.0587	3.9254	3.7974	3.6761	3.5649	3.4564
360	5.0557	4.8716	4.7004	4.5429	4.3936	4.2504	4.1145	3.9901	3.8686
370	5.6413	5.4359	5.2448	5.0690	4.9025	4.7427	4.5911	4.4523	4.3167
380	6.2763	6.0478	5.8353	5.6397	5.4544	5.2765	5.1079	4.9535	4.8027
390	6.9635	6.7100	6.4742	6.2572	6.0516	5.8543	5.6672	5.4959	5.3285

TABLE I (CONTINUED)

Peripheral Velocity (meters/sec.)	Separative Capacity (Kg U Per Yr.)								
	273° K	283° K	293° K	303° K	313° K	323° K	333° K	343° K	353° K
400	7.7057	7.4251	7.1642	6.9240	6.4665	6.4782	6.2712	6.0816	5.8964
410	8.5056	8.1960	7.9079	7.6428	7.3917	7.1507	6.9222	6.7129	6.5085
420	9.3663	9.0253	8.7081	8.4162	8.1397	7.8743	7.6227	7.3922	7.1671
430	10.291	9.9161	9.5675	9.2468	8.9430	8.6515	8.3750	8.1218	7.8745
440	11.282	10.871	10.137	10.137	9.8044	9.4848	9.1816	8.9041	8.6329
450	12.343	11.894	11.476	11.091	10.727	10.377	10.045	9.7415	9.4449
460	13.477	12.987	12.530	12.110	11.712	11.330	10.968	10.637	10.313
470	14.688	14.153	13.656	13.198	12.764	12.348	11.954	11.592	11.239
480	15.978	15.397	14.856	14.358	13.886	13.433	13.004	12.611	12.227
490	17.352	16.721	16.133	15.592	15.080	14.588	14.122	13.695	13.278
500	18.813	18.128	17.491	16.904	16.349	15.816	15.311	14.848	14.396
510	20.363	19.622	18.932	18.298	17.697	17.120	16.573	16.072	15.582
520	22.008	21.207	20.462	19.776	19.126	18.502	17.911	17.370	16.841
530	23.751	22.886	22.082	21.341	20.640	19.967	19.329	18.745	18.174
540	25.594	24.663	23.796	22.998	22.243	21.517	20.830	20.200	19.515
550	27.544	26.541	25.608	24.750	23.936	23.156	22.416	21.738	21.076
560	29.602	28.524	27.522	26.599	25.725	24.887	24.091	23.363	22.652
570	31.774	30.617	29.541	28.551	27.613	26.713	25.859	25.077	24.313
580	34.063	32.823	31.669	30.608	29.602	28.637	27.722	26.884	26.065
590	36.474	25.146	33.910	32.774	31.697	30.664	29.684	28.786	27.910
600	39.010	37.590	36.269	35.053	33.901	32.796	31.748	30.788	29.851
610	41.676	40.159	38.748	37.449	36.218	35.038	33.918	32.893	31.891
620	44.477	42.858	41.352	39.966	38.652	37.392	36.197	35.103	34.034
630	47.417	45.691	44.085	42.607	41.207	39.864	38.590	37.423	36.284
640	50.500	48.661	46.951	45.377	43.886	42.456	41.099	39.856	38.643

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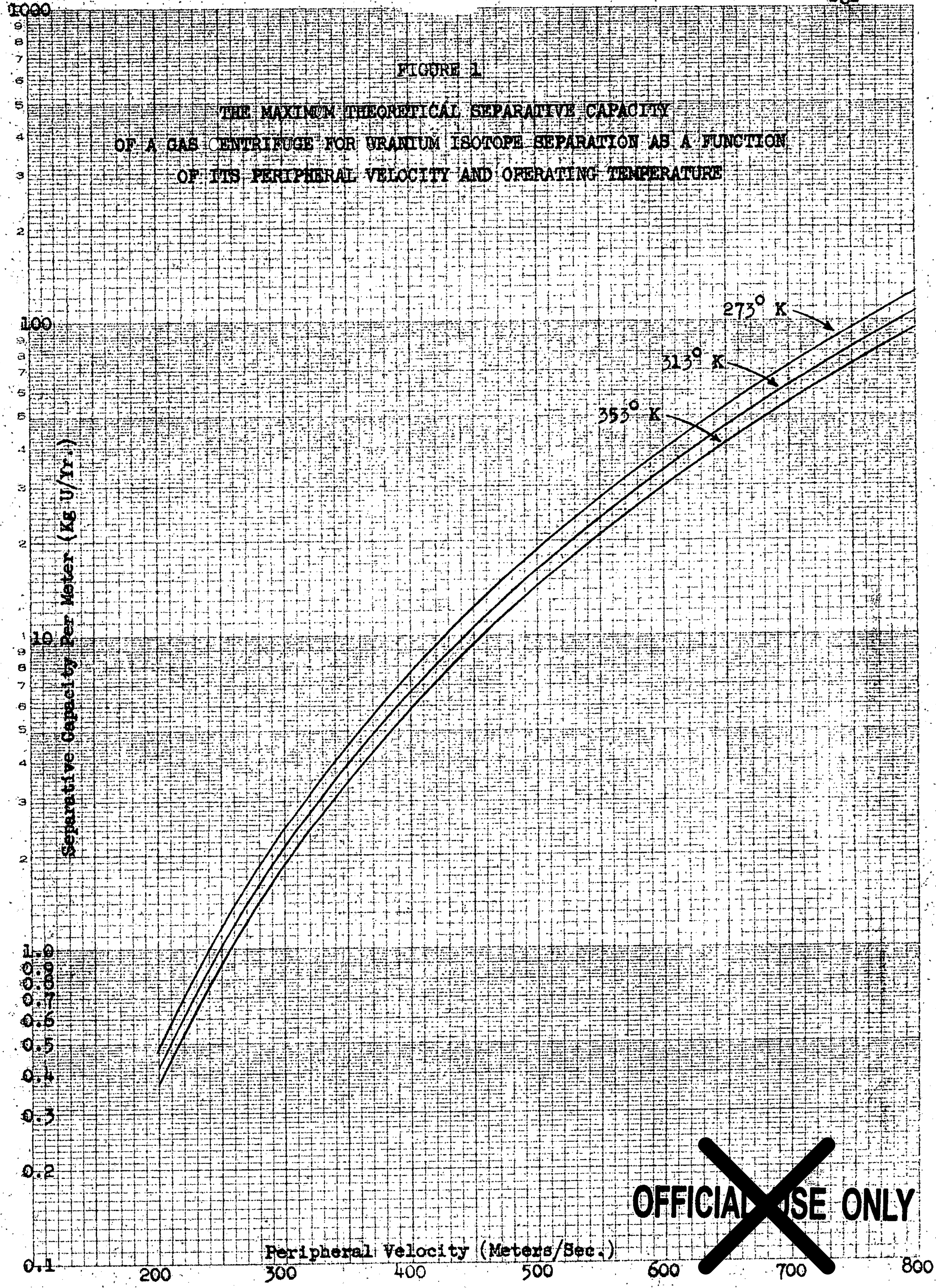
TABLE I (CONTINUED)

Peripheral Velocity (meters/sec.)	Separative Capacity (Kg U Per Yr.)								
	273° K	283° K	293° K	303° K	313° K	323° K	333° K	343° K	353° K
650	53.731	51.775	49.955	48.281	46.694	45.172	43.728	42.406	41.115
660	57.114	55.035	53.101	51.321	49.635	48.017	46.482	45.077	43.704
670	60.655	58.447	56.393	54.503	42.712	50.993	49.364	47.872	46.414
680	64.358	62.016	59.836	57.830	55.930	54.107	52.378	50.794	49.247
690	68.229	65.745	63.434	61.308	59.293	57.360	55.527	53.849	52.209
700	72.271	69.640	67.192	64.940	62.806	60.759	58.817	57.039	55.302
710	76.490	73.705	71.115	68.731	66.473	64.306	62.251	60.369	58.530
720	80.891	77.946	75.207	72.686	70.297	68.006	65.832	63.842	61.898
730	85.479	82.368	79.473	76.809	74.285	71.863	69.567	67.464	65.409
740	90.260	86.974	83.917	81.105	78.440	75.883	73.458	71.237	69.068
750	95.239	91.772	88.546	85.578	82.766	80.068	77.509	75.166	72.877
760	100.42	96.765	93.364	90.235	89.270	84.425	81.727	79.256	75.843
770	105.81	101.96	98.376	95.078	91.954	88.957	86.114	83.510	80.967
780	111.42	107.36	103.59	100.11	96.825	93.669	90.675	87.934	85.256
790	117.24	112.97	109.00	105.35	101.89	98.565	95.415	92.531	89.713
800	123.29	118.80	114.63	110.78	107.14	103.65	100.34	97.306	94.343

FIGURE 1

THE MAXIMUM THEORETICAL SEPARATIVE CAPACITY OF A GAS CENTRIFUGE FOR URANIUM ISOTOPE SEPARATION AS A FUNCTION OF ITS PERIPHERAL VELOCITY AND OPERATING TEMPERATURE



APPENDIX I

COMPUTATION OF VALUES OF THE ρD PRODUCT FOR UF_6

Hirshfelder et al. (1) present the following equations, derived on the basis of the Lennard-Jones 6:12 potential model, for the coefficient of viscosity and the coefficient of self-diffusion of a pure dilute gas:

$$\eta = 266.93 \times 10^{-7} \frac{\sqrt{MT}}{\sigma^2 \Omega^{(2,2)*}(T^*)} f_\eta \qquad (I.1)$$

and

$$D = 0.0026280 \frac{\sqrt{\frac{T^3}{M}}}{p\sigma^2 \Omega^{(1,1)*}(T^*)} f_D \qquad (I.2)$$

where

η is the viscosity in g/cm/sec,

D is the coefficient of self-diffusion in cm^2/sec,

T is the temperature in $^\circ K$,

p is the pressure in atmospheres,

$T^* = kT/\epsilon$ is the reduced temperature,

ϵ/k is a potential parameter in $^\circ K$,

M is the molecular weight,

σ is the collision diameter of the molecules in Å,

$\Omega^{(2,2)*}$ and $\Omega^{(1,1)*}$ are collision integrals whose values are tabulated as functions of the reduced temperature,

f_η and f_D are slowly varying functions of temperature which differ only slightly from unity.

Thus, it is seen that both the coefficient of viscosity and the coefficient of self-diffusion are dependent on the same two potential parameters, ϵ/k and σ. Values for these two parameters can be obtained by fitting equation (I.1) to experimentally determined values for the viscosity of UF_6 and the values thus obtained for ϵ/k and σ used in equation (I.2) to yield the coefficient of self-diffusion. This procedure was followed. The values of the ρD product were then computed assuming that the density of UF_6 was related to its pressure and temperature by the ideal gas law. This should be a satisfactory assumption for the pressure and temperature ranges under consideration. The ρD product is thus given by

$$\rho D = \frac{Mp}{RT} D = 0.0026280 \frac{\sqrt{MT}}{R\sigma^2 \Omega^{(1,1)*}(T^*)} , \qquad (I.3)$$

where

ρD is in g UF_6/cm/sec and

R is the gas constant (82.058 atm $cm^3/g\text{-}mol/^{\circ}K$).

The experimental data obtained by Myerson and Eicher (2) for the viscosity of UF_6 were used to evaluate the potential parameters. DeMarcus and Starnes (3) found that, over the temperature range from 313° K to 473° K, the viscosity data could be fitted by a value of ϵ/k equal to 261° K. Using this value for ϵ/k, it was found that the corresponding value of σ which fits the viscosity data is 5.853 Å.

The values of the ρD product were then calculated for UF_6 by means of equation (I.3) with these two values for the potential parameters. The results obtained are shown by the solid curve of Figure 2. A somewhat different set of values for the ρD product for UF_6 has been published by J. A. McMillan (4) of Argentina. He employed an inverse power repulsion law for the intermolecular forces as the model for his calculations. The values which he obtained are indicated by the broken curve of Figure 2.

The only experimental value of the ρD product for UF_6 which has been reported is that obtained by Ney and Armistead (5) in 1946. They found that at 303° K

$$\rho D = 234 \pm 9 \text{ micropoises.}$$

It can be seen from Figure 2 that the value of the ρD product computed on the basis of the Lennard-Jones 6:12 potential lies within the limits of experimental error while that computed [illegible] se power repulsion law does

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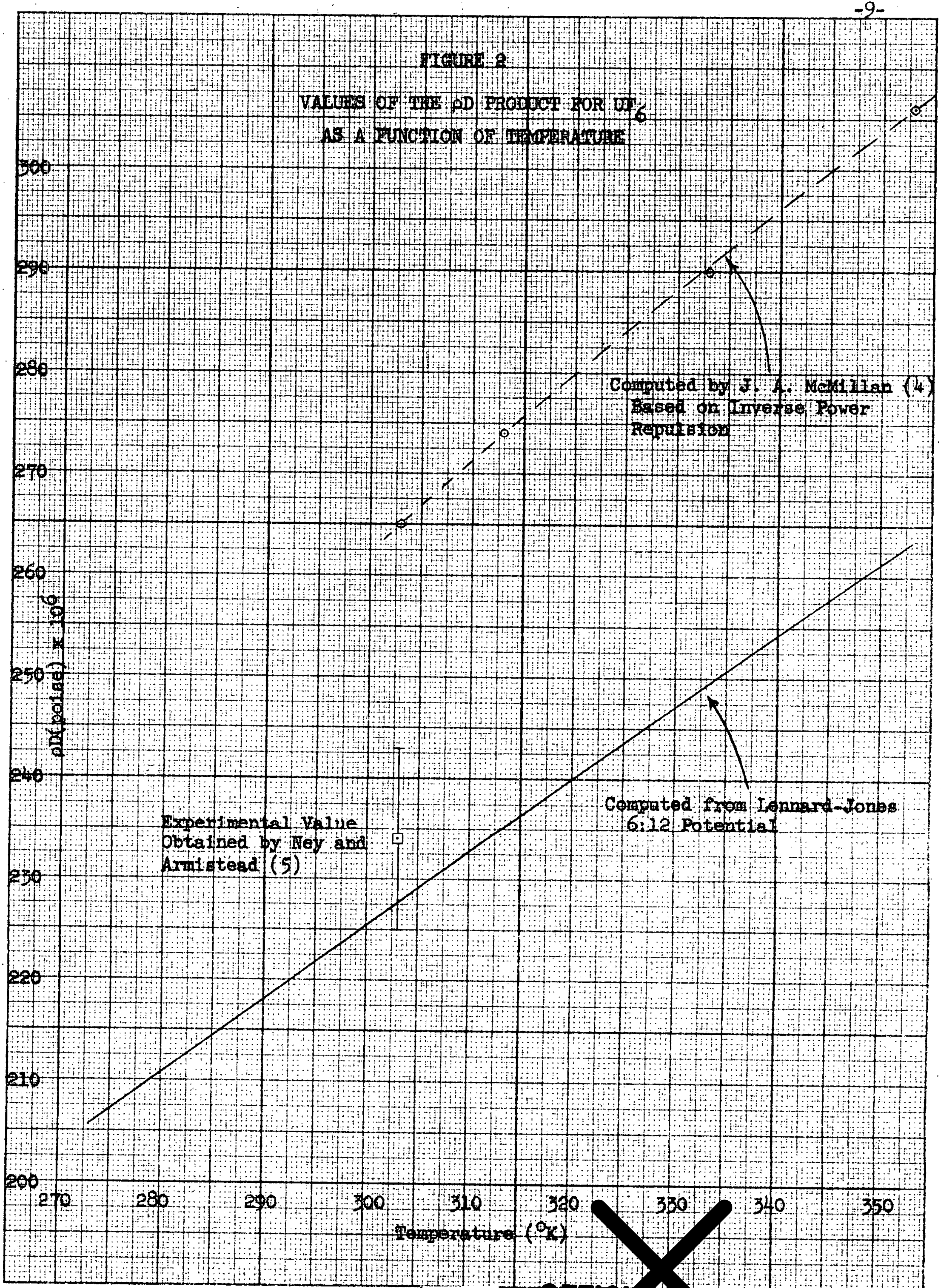
FIGURE 2

VALUES OF THE ρD PRODUCT FOR UF_6 AS A FUNCTION OF TEMPERATURE



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not. The values of the separative capacity presented in Table I were computed, therefore, using the values of the ρD product obtained from the Lennard-Jones 6:12 potential.

References

1. Hirshfelder, J. O., Curtiss, C. F., and Bird, R. B., Molecular Theory of Gases and Liquids, John Wiley and Sons, New York (1954).

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4. McMillan, J. A., Treatment of Gaseous UF_6 by Means of an Inverse Molecular Force Model, Publication of the National Commission of Atomic Energy of Argentina (1954) U.S.A.E.C. Translation No. GAT-T-646.

5. Ney, E. P. and Armistead, F. C., Phys. Rev., 71, 14 (1947).

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APPENDIX II

DERIVATION OF THE EQUATION FOR THE MAXIMUM SEPARATIVE CAPACITY OF A GAS CENTRIFUGE

Consider a centrifuge of length Z and of radius r_2 (these are the internal dimensions of the centrifuge bowl) which rotates at a constant angular velocity of ω radius per second.

A. The Radial Density and Pressure Gradients in the Gas Centrifuge

If the centrifuge contains a single pure gas which rotates at the same angular velocity as the centrifuge bowl, each element of the gas will have a force impressed on it by virtue of its angular acceleration. This force will be directed outwards and will be equal to $(\rho\omega^2 r)(rdrd\phi dz)$. At steady state this force must be balanced by a force resulting from the pressure gradient established in the centrifuge bowl. The inward force on an element of the gas due to the pressure gradient is given by $(dp/dr)(rdrd\phi dz)$. Equating these two forces, one obtains the result,

$$\frac{dp}{dr} = \rho\omega^2 r \;, \tag{II.1}$$

where

p is the pressure (dynes/cm^2),

r is the spatial coordinate in the radial direction (cm),

ρ is the density of the gas (g/cm^3), and

ω is the angular velocity of the centrifuge (radians/sec).

The pressure and the density of a gas are related by an equation of state. If the maximum pressure permitted within the centrifuge bowl is not too high, the equation of state for an ideal gas will suffice. The relationship between the pressure and density of an ideal gas is given by the well-known equation,

$$p = \frac{\rho RT}{M} \;, \tag{II.2}$$

where

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T is the temperature of the gas (^{o}K),

M is the molecular weight of the gas, and

R is the gas constant (8.3147×10^{7} ergs/g-mole/^{o}K).

By substituting for the density in equation (I.1) by means of the equation of state, a differential equation for the pressure gradient in the centrifuge is obtained,

$$\frac{dp}{dr} = \frac{Mp}{RT}\,\omega^{2}r \ , \qquad \text{(II.3)}$$

which is readily integrated to yield

$$p(r) = p(r_2)e^{-\frac{M\omega^{2}r_2^{2}}{2RT}\left[1-\left(\frac{r}{r_2}\right)^{2}\right]} \ . \qquad \text{(II.4)}$$

Equation (II.4) gives the pressure $p(r)$ at any point within the centrifuge as a function of the coordinate r, the pressure at the periphery $p(r_2)$, the peripheral velocity (ωr_2), and the temperature and molecular weight of the gas. Equations (II.3) and (II.4) could just as easily have been written in terms of the density instead of the pressure; thus, an alternate form of equation (II.3) is

$$\frac{d\rho}{dr} = \frac{M\rho}{RT}\,\omega^{2}r \ . \qquad \text{(II.3a)}$$

Should the centrifuge contain not a single pure gas, but a mixture of gases, an equation of the form of equation (II.3) could be written for each species present. In particular, for the case of a binary gas mixture consisting of species 1 and 2, one would have the equations

$$\frac{d\rho_1}{dr} = \frac{M_1\rho_1}{RT}\,\omega^{2}r \quad \text{and} \quad \frac{d\rho_2}{dr} = \frac{M_2\rho_2}{RT}\,\omega^{2}r \ . \qquad \text{(II.5)}$$

Since the total gas density, ρ, is equal to the sum of the partial densities, ρ_1 and ρ_2, it follows that

$$\frac{d\rho}{dr} = \frac{M_1\rho_1 + M_2\rho_2}{RT}\,\omega^2 r \,. \qquad \text{(II.6)}$$

B. The Transport in the Radial Direction in the Gas Centrifuge

In the case of a binary gas mixture consisting of species 1 and 2, the current of component 1 in the radial direction due to molecular diffusion, J_{1D}, is given by the familiar expression,

$$J_{1D} = -D\frac{d\rho_1}{dr} \qquad \text{(II.7)}$$

where

J_{1D} is the diffusive current of species 1 in the radial direction (g/cm^2/sec) and

D is the coefficient of diffusion (cm^2/sec).

Should species 1 and 2 be two different isotopic modifications of the same element or compound, then D would be the coefficient of self-diffusion of the gas.

Now, when a steady state condition is attained within the centrifuge, there will be a density gradient in component 1 given by equation (II.5), and yet, at the steady state, the current of component 1 must vanish. Therefore a current of component 1, J_{1C}, which, at the steady state, is equal in magnitude but opposite in direction to J_{1D} must be induced by the rotational motion of the centrifuge. It follows from equations (II.5) and (II.7) that this current of component 1 which results from the action of the centrifuge is given by

$$J_{1C} = D\frac{M_1\rho_1}{RT}\,\omega^2 r \,. \qquad \text{(II.8)}$$

This current will be present whenever the gas under consideration is rotating at the angular velocity ω; that is, the validity of equation (II.8) is not restricted to the steady state condition. The total current of component 1 in the radial direction, J_1, is the sum of the currents J_{1D} and J_{1C} and is therefore given by

$M_1\rho_1$ $d\rho_1$

$$J_1 = J_{1C} + \qquad \text{(II.9)}$$

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If one now lets the symbol x designate the mass fraction of component 1 in the gas mixture, the partial density ρ_1 can be replaced by the product $x\rho$, and equation (II.9) can be written in the form

$$J_1 = \rho D \frac{M_1}{RT} \omega^2 rx - D \frac{d\rho}{dr} x - \rho D \frac{dx}{dr} . \qquad \text{(II.10)}$$

Finally, replacing $d\rho/dr$ which appears in the preceding equation by means of equation (II.6), one obtains the desired form of the expression for the net transport of component 1 in the radial direction in the centrifuge,

$$J_1 = - \rho D \left[\frac{M_2 - M_1}{RT} x(1 - x)\omega^2 r + \frac{dx}{dr} \right] . \qquad \text{(II.11)}$$

C. The Maximum Separative Capacity of the Gas Centrifuge

Consider now an element of volume within the centrifuge bowl consisting of a ring of radius r, of width dr, and of height dz. The amount of component 1 transferred across this volume element per unit time, τ, is

$$\tau = 2\pi r J_1 dz . \qquad \text{(II.12)}$$

The maximum separative capacity of this volume element can be computed as follows. Suppose that two large reservoirs are separated from each other by the volume element under consideration. One reservoir can be assumed to contain an amount of gas A initially at concentration x_A in component 1, the other an amount of gas B initially at concentration x_B. If no net transfer of material takes place through the separating element, the total amount of material in each reservoir at the end of a unit of time will be the same as the initial quantity. The concentrations, however, will be altered due to the transfer, τ of component 1 from the B-reservoir to the A-reservoir and the simultaneous transfer of the same amount of the other component in the opposite direction. Thus, at the end of a unit of time the concentration of component 1 in the A-reservoir will be

$$x_A + \frac{\tau}{A}$$

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and in the B-reservoir the concentration will be

$$x_B - \frac{\tau}{B} .$$

The separative capacity of the element is equal to the separative work produced per unit time which in turn is equal to the increase in the "value" of the material in the reservoirs per unit time. The increase in the "value" of the material in the A-reservoir is given by

$$AV(x_A + \frac{\tau}{A}) - AV(x_A)$$

where V(x) is the value function. Expanding the first term in Taylor series about x_A, the increase in "value" of the material in the A-reservoir can be seen to be approximated by

$$\tau V'(x_A) .$$

Similarly, the increase in "value" of the material in the B-reservoir is approximated by

$$BV(x_B - \frac{\tau}{B}) - BV(x_B) \simeq \tau V'(x_B) .$$

The separative capacity of the element, $d(\delta U)$, is equal to the sum of the changes per unit time in the "value" of the material in the two reservoirs and can be written

$$d(\delta U) = \tau\Big[V'(x_A) - V'(x_B)\Big] \simeq \tau(x_A - x_B)V''(x_B) . \qquad \text{(II.13)}$$

From equations (II.13), (II.12), and (II.11) the separative capacity of the element can be written in the form

$$d(\delta U) = - 2\pi\rho D r dz\left[\frac{M_2 - M_1}{RT} x(1 - x)\omega^2 r + \frac{dx}{dr}\right] \frac{dx}{x^2(1 - x)^2} , \qquad \text{(II.14)}$$

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where $V''(x)$ has been replaced by

$$V''(x) = \frac{1}{x^2(1 - x)^2} \qquad \text{(II.15)}$$

which follows from the definition of the value function, and the concentration difference $(x_A - x_B)$ which is just the concentration difference across the element has been replaced by dx.

From an inspection of equation (II.14), treating dx as a variable, it can be seen that the separative capacity of the element will be a maximum when

$$\frac{dx}{dr} = -\frac{1}{2}\,\frac{M_2 - M_1}{RT}\,x(1 - x)\omega^2 r\ . \qquad \text{(II.16)}$$

Substituting this condition into equation (II.14), one obtains the expression for the maximum separative capacity of a volume element in a gas centrifuge:

$$d(\delta U)_{max} = \frac{\pi\rho D r}{2}\left[\frac{M_2 - M_1}{RT}\,\omega^2 r\right]^2 drdz\ . \qquad \text{(II.17)}$$

The separative capacity of the centrifuge as a whole is obtained by integrating the above expression for $d(\delta U)_{max}$ over the volume of the centrifuge, $0 \leq z \leq Z$ and $0 \leq r \leq r_2$. Thus, the maximum separative capacity of a gas centrifuge is given by

$$\delta U_{max} = \frac{\pi Z\rho D}{2}\left[\frac{(M_2 - M_1)\omega^2 r_2^2}{2RT}\right] \qquad \text{(II.18)}$$

which is often written

$$\delta U_{max} = \frac{\rho D\pi Z}{2}\left[\frac{\Delta M V^2}{2RT}\right]^2 , \qquad \text{(II.19)}$$

where V is the peripheral velocity, ([illegible]), and ΔM is the mass difference between the components, $M_2 - M_1$.

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