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TRANSPORT PROPERTIES OF DISSOCIATING GASEOUS MIXTURES

Charles S. Shoup, Jr.

ABSTRACT

The effects of various parameters on the transport properties of dissociating gaseous mixtures were studied. In order to take advantage of the increase in thermal conductivity and specific heat due to the dissociation, the heat of dissociation must be "large", the molecular weight and molecular volume must be small, and both associated and dissociated molecules must be present in appreciable amounts at reasonable temperatures. Very few dissociation reactions meet all of these requirements.

In order to illustrate the effects of dissociation on many properties, estimates were made for the thermal conductivity, specific heat, specific volume, and viscosity of helium-aluminum chloride and helium-fluorine mixtures as a function of temperature at various pressures and compositions. The maxima in the thermal conductivity and specific heat curves, which are due to the heat of dissociation, can be varied over a wide range of temperatures by controlling the pressure and helium concentration. The dissociation produces a greater than linear increase in specific volume with increasing temperature. According to the present calculations, a helium-fluorine mixture has a thermal conductivity and specific heat which can be as much as a factor of two greater than the corresponding values for pure helium, while the viscosity of the mixture is approximately 10% greater than that of helium and is only slightly dependent on composition. The thermal properties and viscosity of helium-aluminum chloride mixtures are considerably less than those of pure helium.

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Introduction.

A chemically reacting gas may in principle be more effective as a heat transfer agent than a non-reacting gas as a consequence of the contribution of its heat of reaction to the thermal conductivity and specific heat of the gaseous mixture. For certain types of reacting gaseous mixtures, the thermal conductivity and specific heat may be enhanced several-fold at temperatures for which appreciable fractions of reactant and product are present.

As an example, consider the dissociation reaction $A \rightleftharpoons nA$. If the temperature of this mixture is increased, the system will absorb not only the heat expected if the composition were "frozen", but since the degree of dissociation increases with temperature, the system will also absorb the thermodynamic heat involved in the dissociation of some of the polymer molecules. Thus the heat of dissociation makes a significant contribution to the effective specific heat of the system. The effective thermal conductivity of the reacting mixture is likewise much greater than would be expected on the basis of the "frozen" composition alone.

A preliminary investigation of reacting mixtures was undertaken for the purpose of determining whether or not such a mixture might be feasible as a heat exchange medium in a nuclear reactor system. With this in mind, the influences of various parameters on the thermal conductivity, specific heat, viscosity, and specific volume of dissociating gases were estimated. In order to illustrate the effects of dissociation, numerical values for these properties were estimated for helium-aluminum chloride and helium-fluorine mixtures as a function of temperature at various pressures and compositions.

Theory.

The theory of thermal conductivity and heat capacity of reacting gaseous mixtures is well known¹⁻² and only the pertinent results are presented here.



The effective thermal conductivity, λ_e , and the effective specific heat, \hat{C}_{p_e} , can be expressed as the sum of two terms:

$$\lambda_e = \lambda_f + \lambda_r \quad \text{cal/cm.sec.deg.} \quad (1)$$

$$\hat{C}_{p_e} = \hat{C}_{p_f} + \hat{C}_{p_r} \quad \text{cal/deg. gram} \quad (2)$$

where the subscripts f and r refer to the contribution due to the "frozen" composition (the equilibrium composition under the existing conditions) and due to the effects of the heat of reaction respectively.

\hat{C}_{p_f} can be determined from experimental or thermodynamic data. The frozen thermal conductivity, however, is a complicated function of the thermal conductivities of the pure components. Since λ_r is usually much greater than λ_f , an error in λ_f will make only a relatively slight contribution to the error in λ_e . For this reason, an approximate relation such as the following may be used:³

$$\lambda_f = \frac{\sum_i x_i \lambda_i \sqrt[3]{M_i}}{\sum_i x_i \sqrt[3]{M_i}} \quad (3)$$

where λ_i is the thermal conductivity of the i^{th} pure component, and x_i and M_i are the mole fraction and molecular weight of that component.

If experimental values for the λ_i 's are not available, they may be calculated by means of the Eucken relation,⁴

$$\lambda_i = \frac{15}{4} \frac{R}{M_i} \left[\frac{4}{15} \frac{Cv_i}{R} + \frac{3}{5} \right] \eta_i \quad (4)$$

where Cv_i is the heat capacity (at constant volume) per mole and η_i is the viscosity of the pure component. The viscosity in turn can be determined from the relation⁴

$$\eta_i \times 10^5 = \frac{2.6693 \sqrt{M_i T}}{\sigma_i \Omega_i (2,2)^*} \quad (5)$$

where T is the absolute temperature, σ_i is the "collision diameter" of the molecule, and $\Omega_i^{(2,2)*}$, which is known as a "collision integral," is a measure of the molecule's deviation from a hard sphere model. These last two constants can be evaluated on the basis of the intermolecular potential for the molecule.

The viscosity of a gaseous mixture depends upon the binary diffusion coefficients, D_{ij} , as well as the composition of the system and the viscosities of the pure components. For a system containing three components (such as a dissociating gas in the presence of a diluent), the viscosity of the mixture, η_{mix} , can be expressed as⁽⁴⁾

$$\eta_{mix} = \sum_{i=1}^3 \frac{x_i^2}{(x_i^2/\eta_i) + 1.385 \sum_{\substack{k=1 \\ k \neq i}}^3 \frac{x_i x_k R'T}{D_{ik} P M_i}} \quad (6)$$

where x_i is the mole fraction of the i^{th} component, D_{ik} is the binary diffusion coefficient, P is the pressure in atmospheres, and R' is $82.054 \text{ cm}^3 \cdot \text{atm}/\text{deg. mole}$. The binary diffusion coefficients can be evaluated from the relation⁽⁴⁾

$$D_{ij} P \times 10^5 = \frac{262.8 \sqrt{T^3 (M_i + M_j) / 2M_i M_j}}{\sigma_{ij}^2 \Omega_{ij}^{(1,1)*}} \quad (7)$$

where $\sigma_{ij} = (1/2) (\sigma_i + \sigma_j)$ and $\Omega_{ij}^{(1,1)*}$ is a function of the intermolecular potential between unlike molecules.

The theory of the thermal conductivity and specific heat of reacting gaseous mixtures neglects any effects due to thermal diffusion, pressure gradients, and external force fields. The following discussion therefore is based upon the assumption that these effects are negligible.

The terms λ_r and \hat{C}_{p_r} in equations (1) and (2) are functions of the number and types of reactions occurring in the gas phase. For dissociation reactions of the type $A_n \rightleftharpoons n A$ in the presence of a diluent,²

$$\lambda_r = \frac{(\Delta H)^2}{RT^2} A_{11}^{-1} \quad (8)$$

$$A_{11} = \frac{\frac{R'T (nx_2 + x_1)^2}{D_{12} P} + x_3 R'T \left[\frac{n^2 x_2}{D_{13} P} + \frac{x_1}{D_{23} P} \right]}{x_1 x_2} \quad (9)$$

where R is 1.9872 cal/deg.mole, ΔH is the heat of dissociation, and the subscripts 1, 2, and 3 refer to the monomer, polymer, and diluent, respectively.

\hat{C}_{p_r} is a function of the thermal conductivity, λ_r , the binary diffusion coefficient, and the density of the mixture¹:

$$\hat{C}_{p_r} = \lambda_r / D_{12} \rho$$

where ρ is the density of the mixture.

If no diluent is present, \hat{C}_{p_r} can be expressed as

$$\hat{C}_{p_r} = \frac{(\Delta H)^2 w_1 w_2}{RT^2} \left[\frac{1 + (n-1)w_1}{n^2 M_1} \right] \quad (10)$$

where w_1 and w_2 are the mass fractions of the monomer and polymer, respectively.

Discussion.

From the above considerations, it can be seen that the effective thermal conductivity and specific heat of a reacting gas increase according to the square of the reaction heat. Thus, a primary consideration in the choice of a reacting gas for use as a heat exchange medium is its heat of reaction. For a reaction of the type $A_n \rightleftharpoons nA$, a low value

of n (all else being equal) leads to a higher effective thermal conductivity and specific heat. When $n = 1$, however, the heat of reaction (in this case, rearrangement) is usually small. The most effective type of dissociation reaction for the purpose of increasing the efficiency of a gaseous heat exchange medium is therefore the dissociation of a dimer ($A_2 \rightleftharpoons 2A$).

In order for the effective thermal conductivity of a dissociating gas to be of the same order of magnitude as that for helium, however, the molecular weight of the monomer must be relatively small. This is illustrated by an examination of equations (7), (8), and (9) in the absence of a diluent gas. The maximum effect on λ_r occurs when $x_1 = 2/3$; i.e., when the degree of dissociation of the gaseous dimer is 50%. [$(\partial\lambda_r/\partial x_1)_T = 0$ when $x_1 = 2/3$.] Under these conditions,

$$\lambda_r = \frac{1.747 \times 10^{-6} (\Delta H)^2}{\sigma_{12}^2 \Omega_{12}^{(1,1)*} \sqrt{M_1} T^{3/2}} \quad (11)$$

The collision diameter (and to a lesser extent the collision integral) increases with increasing molecular size. From the above, it is apparent that a dissociating gas with a high heat of dissociation, low molecular weight and small molecular size should be best from the standpoint of increasing the effective thermal conductivity. By similar arguments, it can be seen that such a gas would also have a large effective specific heat.

It is apparent that the most important of these factors is the heat of dissociation. Most molecules which have a very high heat of dissociation, however, require extremely high temperatures before an appreciable concentration of monomer is achieved. (An extreme case is the dissociation of H_2 , which yields a maximum effective thermal conductivity of about 0.02 - 0.04 cal/cm.deg.sec. around 3550°C, at which temperature it is 50% dissociated.) There are very few dissociation reactions, however, in which the molecular weight of the monomer is low enough and the heat of dissociation high enough to compete with helium on the basis of thermal conductivity at reasonable temperatures. The beryllium halides, for

example, are nearly completely dissociated above 300°C. (Furthermore, the heat of dissociation of the beryllium chloride dimer is only about 13 Kcal./mole of dimer.), while the dissociation of a diatomic gas generally requires a temperature too high for consideration in a closed cycle.

Two dissociating gases are available which show some promise as heat exchange media, but both pose serious corrosion problems. The most promising dissociating gas, fluorine, presents virtually insurmountable corrosion difficulties at the present time. Although present technology is not sufficiently advanced to make its application practical in a closed cycle, because of its high heat of dissociation and low molecular weight fluorine serves as an excellent example of the effects of dissociation on the transport properties and specific heat of a gaseous mixture. On the other hand, aluminum chloride has been shown to offer some slight advantages over helium under certain conditions,⁵ despite its high molecular weight. These advantages are primarily lower viscosity and a greater than linear increase in specific volume with temperature due to the increased degree of dissociation of the dimer at high temperatures. However, the effective thermal conductivity of dissociating aluminum chloride vapor is an order of magnitude less than that of helium, and the effective specific heat is also considerably less than that of pure helium.

In order to illustrate these effects, estimates have been made for the thermal conductivity, specific heat, viscosity, and specific volume of aluminum chloride vapor and fluorine as a function of temperature at various pressures and concentrations of helium diluent. The calculations were carried out by means of an IBM 7090 digital computer, and were spot-checked by hand. No claim is made as to the accuracy of these calculations due to the approximations that were necessarily required. Although relatively large errors may be associated with the numbers which were obtained from these calculations, the trends should be reasonably accurate. In order to illustrate the trends which were obtained, the pertinent results are presented in graphical form. The actual numerical values which

were calculated are on file and are available.

Table I consists of a tabulation of intermolecular potential constants and collision integrals for selected molecules at 1000° K.⁶ The effects of the intermolecular potential constants, the heat of dissociation, and the molecular weight on the maximum thermal conductivity due to dissociation of a gaseous dimer are illustrated in Figure 1. In this figure, λ_r^{\max} is presented as a function of the molecular weight of the monomer for hypothetical gases at 1000° K., at which temperature the degree of dissociation is assumed to be 50%. The effects of the intermolecular potential constants are illustrated in a different manner in Figure 2, in which λ_r^{\max} is presented as a function of temperature for the dissociation of Be_2Cl_4 . For the purposes of this illustration, the dimer is assumed to be 50% dissociated at each temperature (thus ignoring the thermodynamically calculated equilibrium constant).⁷

The properties of the gaseous $\text{Al}_2\text{Cl}_6 \rightleftharpoons 2 \text{AlCl}_3$ system are presented as a function of temperature in Figures 3 to 8, while those of the $\text{F}_2 \rightleftharpoons 2 \text{F}$ system are presented in Figures 9 to 13. In both systems, the effects of helium in the mixtures are illustrated. It can be seen from the figures that the thermal properties of aluminum chloride vapor are considerably less than those of helium, while those of fluorine are considerably greater. Because the viscosities of helium-fluorine mixtures are roughly 10% greater than that of pure helium and are only slightly dependent on the helium concentration, a graph of the calculated viscosities of such mixtures was not considered to be of sufficient interest to include in this report.

Calculations.

The greatest uncertainty in the parameters used in the calculations is that associated with the collision integrals. The collision integrals are complicated functions of the intermolecular potential, but have been tabulated for various values of the reduced temperature $T^* = kT/\epsilon$,⁶ where k is Boltzmann's constant and T is the absolute temperature. The inter-

molecular constants ϵ/k and σ have been tabulated on the basis of the Lennard-Jones 6-12 potential, $V = 4\epsilon [(\sigma/r)^{12} - (\sigma/r)^6]$, for a variety of molecules,⁶ including fluorine. Here ϵ is the depth of the potential well and σ is the distance of approach for which the intermolecular potential energy vanishes. Although Blander et al⁵ estimated both collision integrals to be about 2.0 for aluminum chloride, in the present calculations it seemed more realistic to use values of 1.3 and 1.5 for $\Omega^{(1,1)*}$ and $\Omega^{(2,2)*}$, respectively. Values of 0.74 and 0.82 were chosen for these collision integrals for fluorine.⁶ In all cases, it was rather arbitrarily assumed that ϵ/k was identical for the monomer and dimer. Although the values of the collision integrals tend to decrease with increasing temperature, the error introduced by assuming a constant value is less than that introduced in the choice of the particular value for each collision integral. (If the collision integrals for aluminum chloride were assumed to have values of 2.0, the calculated thermal conductivity would be reduced by approximately 2×10^{-5} cal/cm.sec.deg. and the calculated viscosities would be reduced by approximately $4 - 5 \times 10^{-5}$ g/cm.sec.) The collision diameters were assumed to be the same as those given previously for fluorine⁶ and aluminum chloride,⁵ while the volume of the dimer was assumed to be twice that of the monomer.

For the dissociation of a dimer, $K_p = x_1^2 P/x_2$. Because of the dissociation, however, the diluent concentration cannot be maintained at a constant mole percent, but only at a constant weight per cent. Relations between mass fraction and mole fraction can be simply derived and are found to be

$$x_j = \frac{w_j/M_j}{\sum_i w_i/M_i} \quad w_j = \frac{x_j M_j}{\sum_i x_i M_i} \quad (12)$$

where x_j and w_j represent mole and mass fraction respectively of the j^{th} component. The mass fraction of the monomer present at any temperature can be found from the following relation, provided that the equilibrium

constant is known as a function of temperature:

$$w_1 = \frac{-B + \sqrt{B^2 - 4AC}}{2A} \quad (13)$$

where $A = 4P + K_p$, $B = (2 w_3 M_1/M_3) K_p$, and

$$C = (2 w_3 - w_3^2 - 1) K_p - (1 - w_3) B. \quad (14)$$

Thermodynamic data were taken from the JANAF tables⁷ in the present calculations.

The specific volume was calculated from the relation

$$V = 1.3334 \frac{T}{P} \left[\frac{1 + w_1 - w_3}{2 M_1} + \frac{w_3}{M_3} \right] \frac{\text{ft.}^3}{\text{lb.}} \quad (15)$$

The specific heat of reaction, \hat{C}_{p_r} , in the presence of a diluent cannot be determined as accurately as before, due to the difficulty in determining a "binary diffusion coefficient" in the expression $\hat{C}_{p_r} = \lambda_r/D_{12}\rho$. However, a very close approximation to \hat{C}_{p_r} can be found merely from a consideration of the heat of dissociation per gram of monomer and the change in the mass fraction of the monomer as the temperature is changed. Thus,

$$\hat{C}_{p_r} = \frac{\Delta H \Delta w_1}{(n M_1 \Delta T)} \quad (16)$$

where $n = 2$ for dissociation of a dimer, ΔT is the increment in temperature over which the mass fraction of the monomer increases by an amount Δw_1 . If ΔT is reasonably small, ΔH can be considered to be a constant. Use of equation (16) gives results in good agreement with equation (10) when no diluent is present.

Conclusions.

From these studies it appears that the use of dissociating gases in heat transfer applications has no practical advantage over the use of helium at the present time. Those gases which dissociate within a

practical range of temperatures generally have heats of dissociation which are too low or molecular weights which are too high to yield thermal properties comparable to helium. Although dissociating gases may produce low specific volumes and/or low viscosities, more conventional gases also exhibit these properties. It is possible, of course, that some gaseous mixture undergoing a complex reaction rather than simple dissociation may have the thermal properties necessary for a good heat transfer medium.

REFERENCES

1. J. N. Butler and R. S. Brokaw, J. Chem. Phys., 26, 1636 (1957).
2. R. S. Brokaw, J. Chem. Phys., 32, 1005 (1960).
3. L. Friend and S. B. Adler, "Transport Properties in Gases," (A. B. Cambel and J. B. Fenn, Ed.), Northwestern University Press, Evanston, Ill., 1958, p. 124.
4. J. O. Hirschfelder, C. F. Curtiss, and R. B. Bird, "Molecular Theory of Gases and Liquids," John Wiley and Sons, Inc., N. Y., 1954, p 528 ff.
5. M. Blander, L. G. Epel, A. P. Fraas, and R. F. Newton, "Aluminum Chloride as a Thermodynamic Working Fluid and Heat Transfer Medium," ORNL-2677, 1959.
6. J. O. Hirschfelder et al., op. cit., p 1110, 1126.
7. "JANAF Thermochemical Data," Dow Chemical Co., Midland, Michigan, 1961.

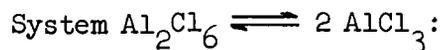
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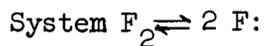
Figures:

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9. Thermal Conductivity of the Pure Mixture at Various Pressures.
10. Specific Heat of the Pure Mixture at Various Pressures.
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TABLE I

Intermolecular Potential Constants and Collision Integrals for
Selected Molecules⁽⁶⁾ at 1000°K.

Molecule	ϵ/k	σ	T^{*a}	$\Omega(1,1)^*$	$\Omega(2,2)^*$
He	10.22	2.576	97.8	0.5158	0.5902
HI	324	4.123	3.09	0.9414	1.031
F ₂	112	3.653	8.94	0.7565	0.8387
Cl ₂	357	4.115	2.80	0.9672	1.058
Br ₂	520	4.268	1.925	1.089	1.191
AsH ₃	281	4.06	3.56	0.9082	0.9959
HgI ₂	698	5.625	1.43	1.221	1.341
HgBr ₂	530	5.414	1.89	1.521	1.680
SnBr ₄	465	6.666	2.15	1.049	1.147
SnCl ₄	1550	4.540	0.645	1.806	1.990
Hg	851	2.898	1.175	1.333	1.467
C ₂ H ₂	185	4.221	5.40	0.8304	0.9147
C ₂ H ₄	205	4.232	4.89	0.8459	0.9309
C ₂ H ₆	230	4.418	4.35	0.8673	0.9530
C ₃ H ₈	254	5.061	3.94	0.8867	0.9733
n-C ₆ H ₁₄	413	5.909	2.42	1.0096	1.1052
Benzene	440	5.270	2.28	1.029	1.125
CH ₃ Cl	855	3.375	1.17	1.335	1.470
CHCl ₃	327	5.430	3.06	0.9440	1.034
CS ₂	488	4.438	2.05	1.066	1.064

^a $T^* = kT/\epsilon$

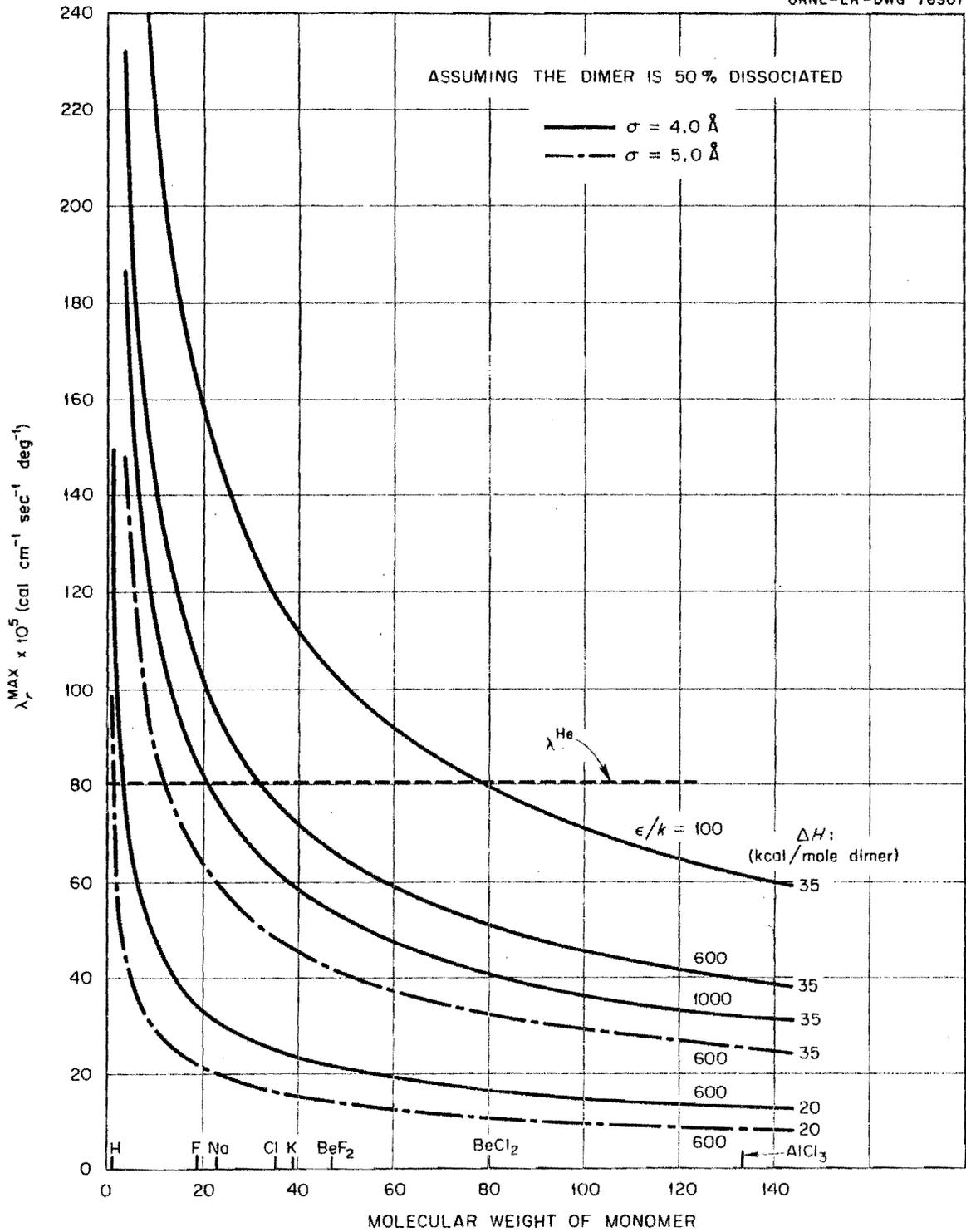


Fig. 1. Maximum Thermal Conductivity of Reaction, λ_r^{max} , Due to the Dissociation of a Hypothetical Dimer at 1000°K vs Molecular Weight of Monomer.

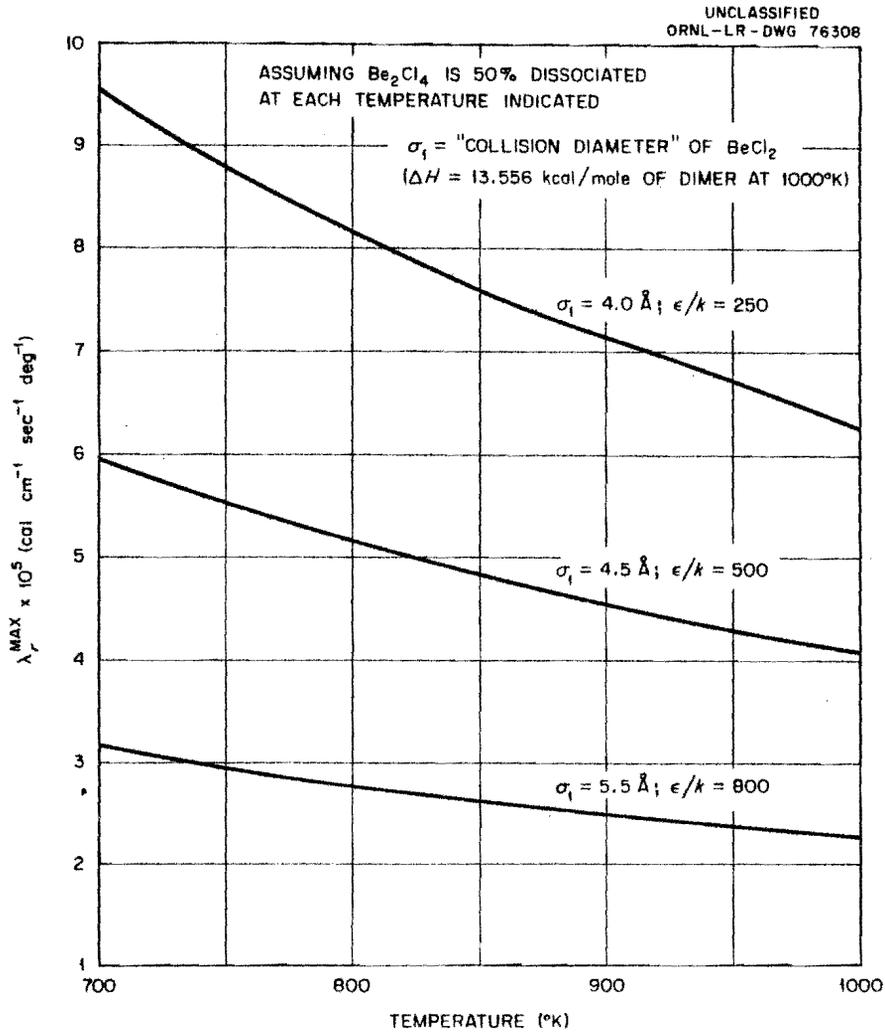


Fig. 2. Maximum Thermal Conductivity of Reaction, λ_r^{max} , for the System $\text{Be}_2\text{Cl}_4 \rightleftharpoons 2 \text{BeCl}_2$ vs Temperature.

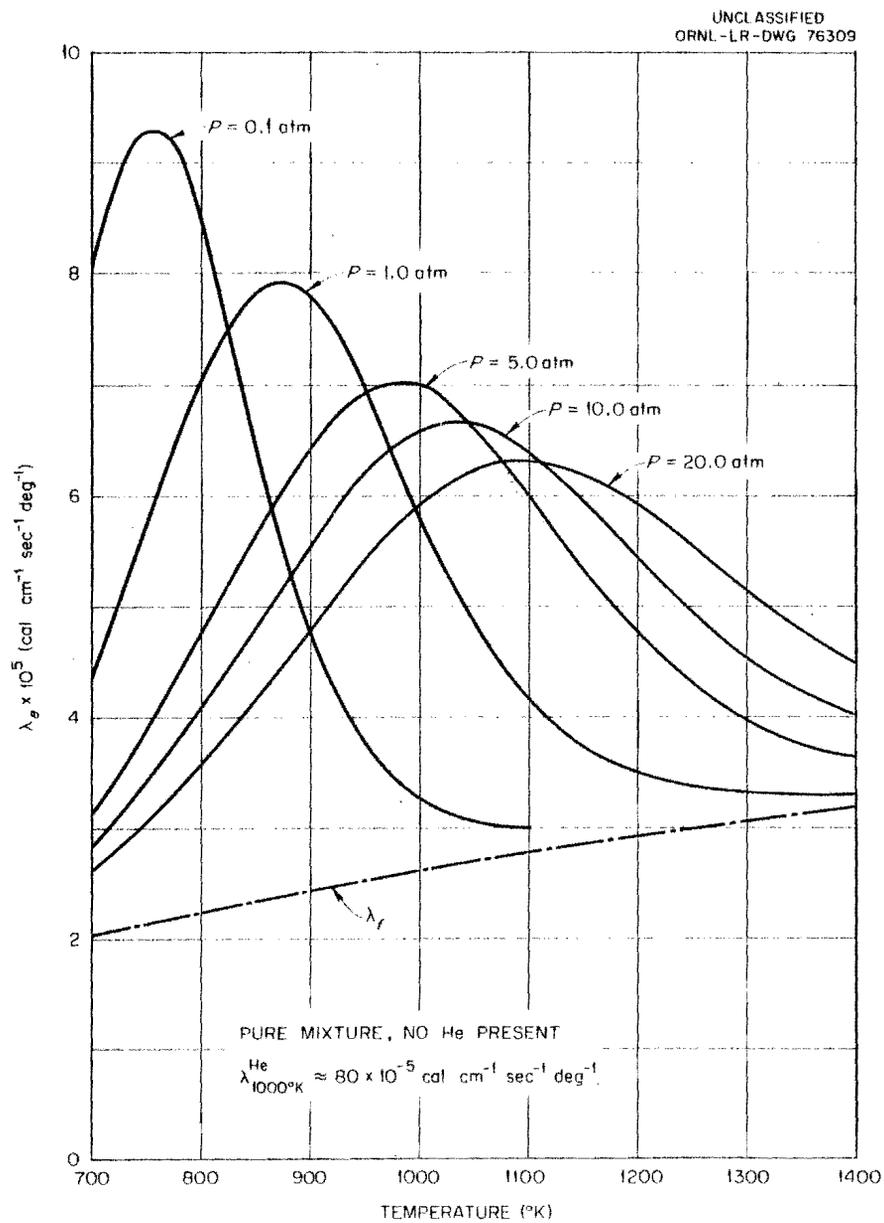


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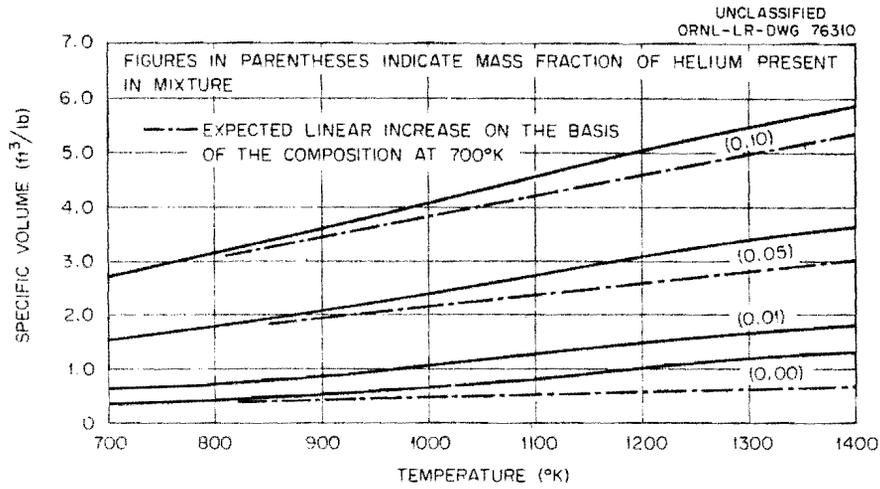


Fig. 4. $\text{Al}_2\text{Cl}_6 \rightleftharpoons 2 \text{AlCl}_3$: Specific Volume at 10 atm and Various Mass Fractions of Helium.

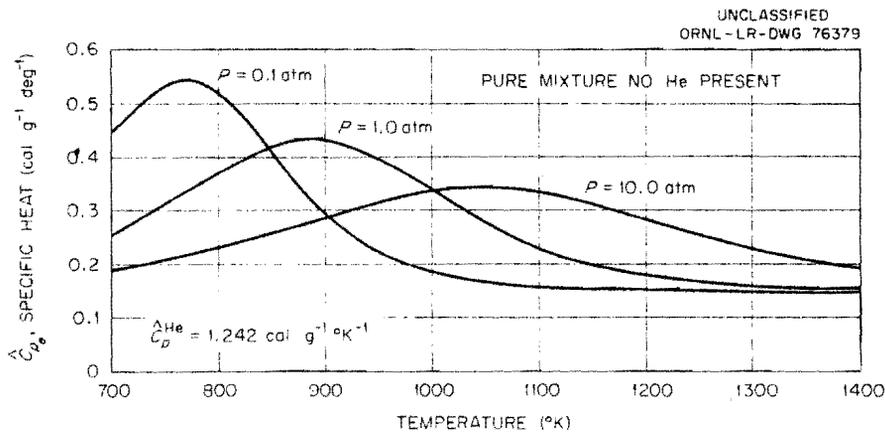


Fig. 5. $\text{Al}_2\text{Cl}_6 \rightleftharpoons 2 \text{AlCl}_3$: Specific Heat at Various Pressures.

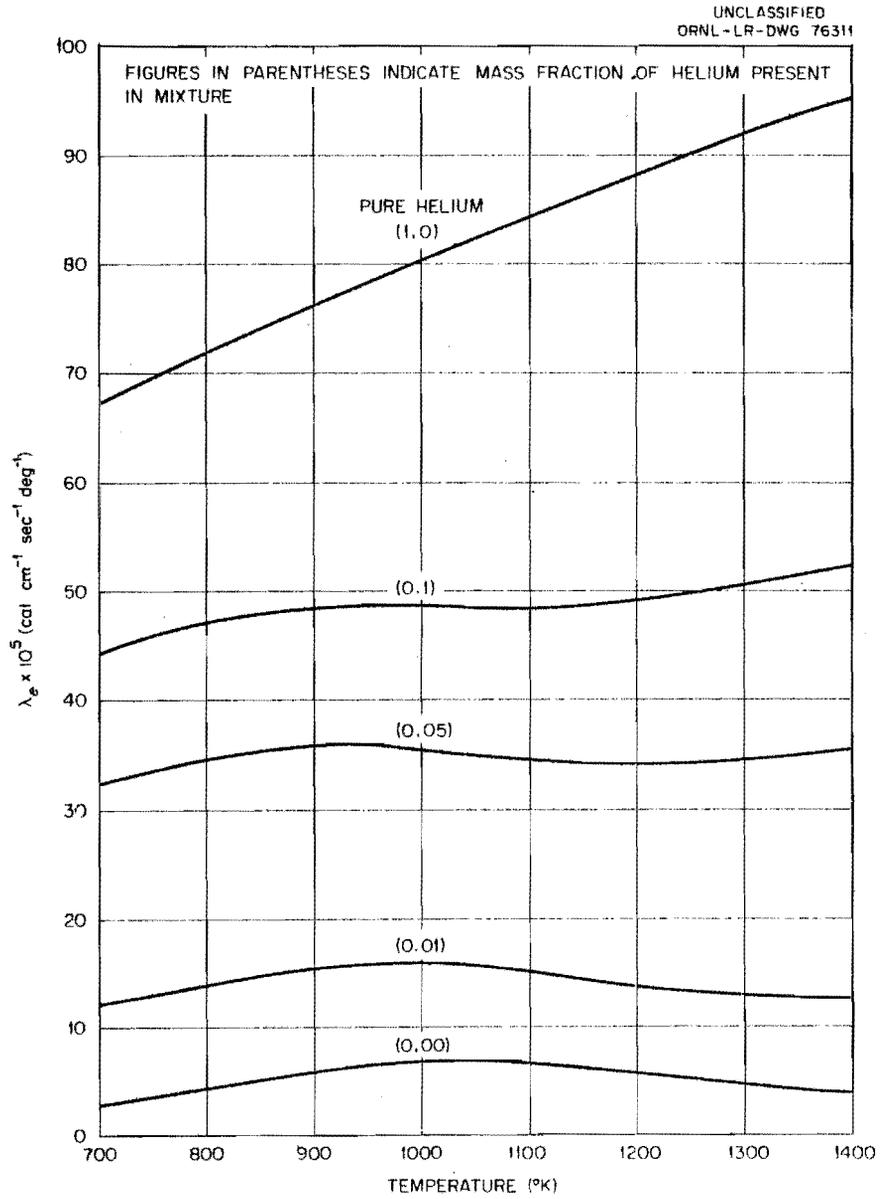


Fig. 6. $\text{Al}_2\text{Cl}_6 \rightleftharpoons 2\text{AlCl}_3$: Thermal Conductivity at 10 atm and Various Mass Fractions of Helium.

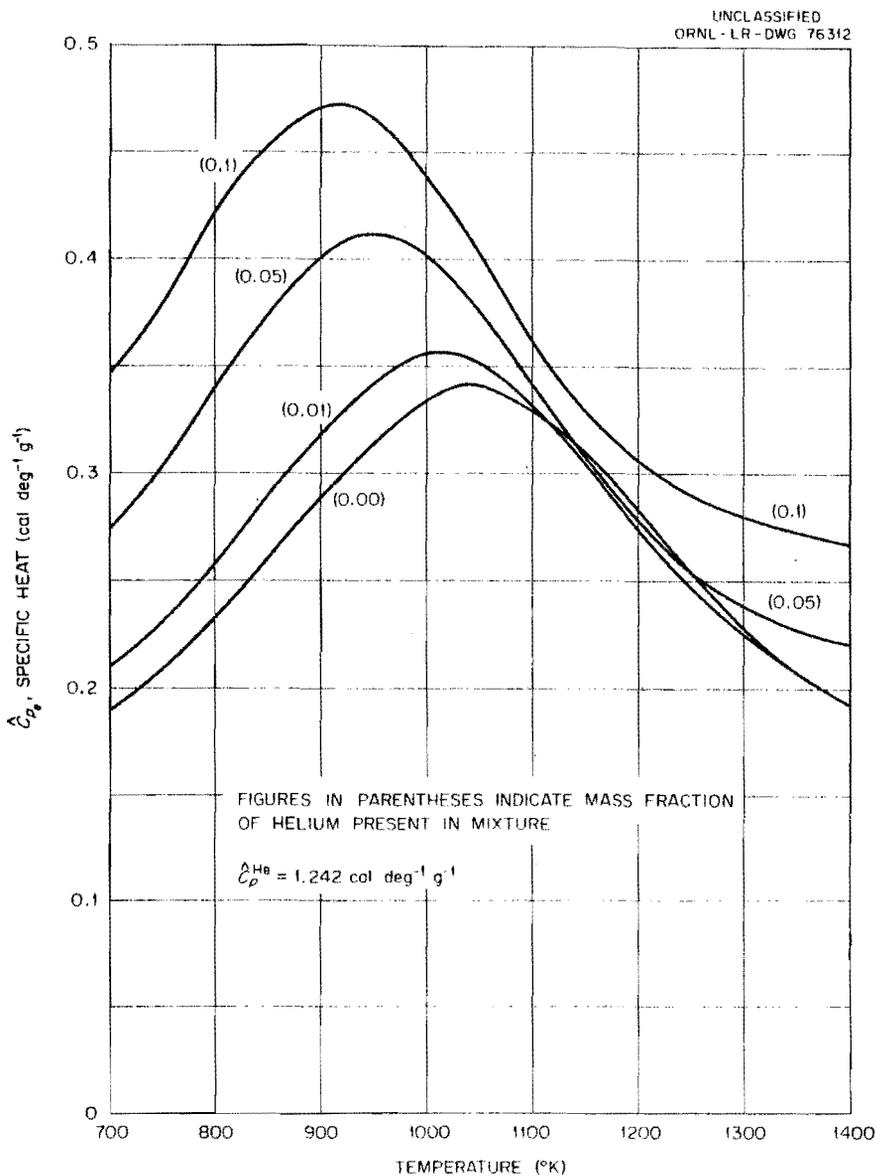


Fig. 7. $\text{Al}_2\text{Cl}_6 \rightleftharpoons 2 \text{AlCl}_3$: Specific Heat at 10 atm and Various Mass Fractions of Helium.

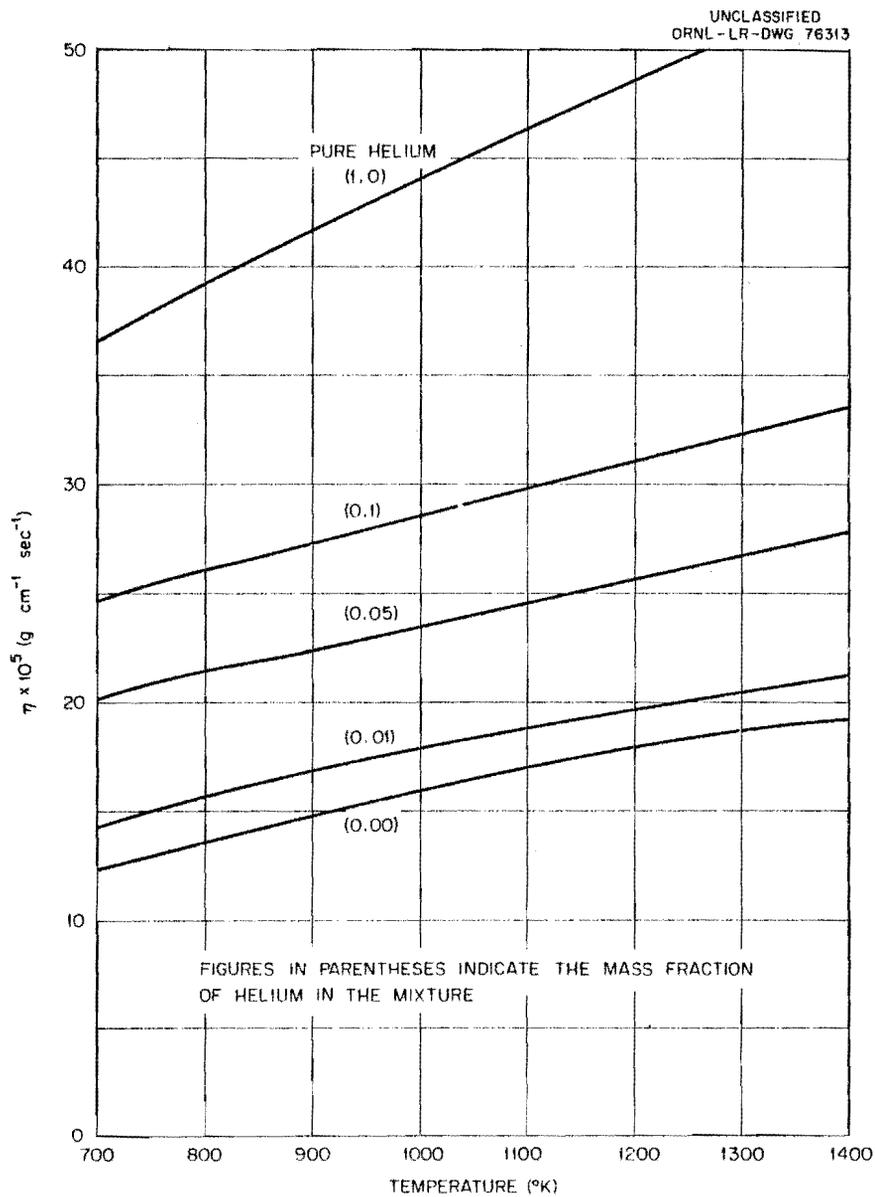


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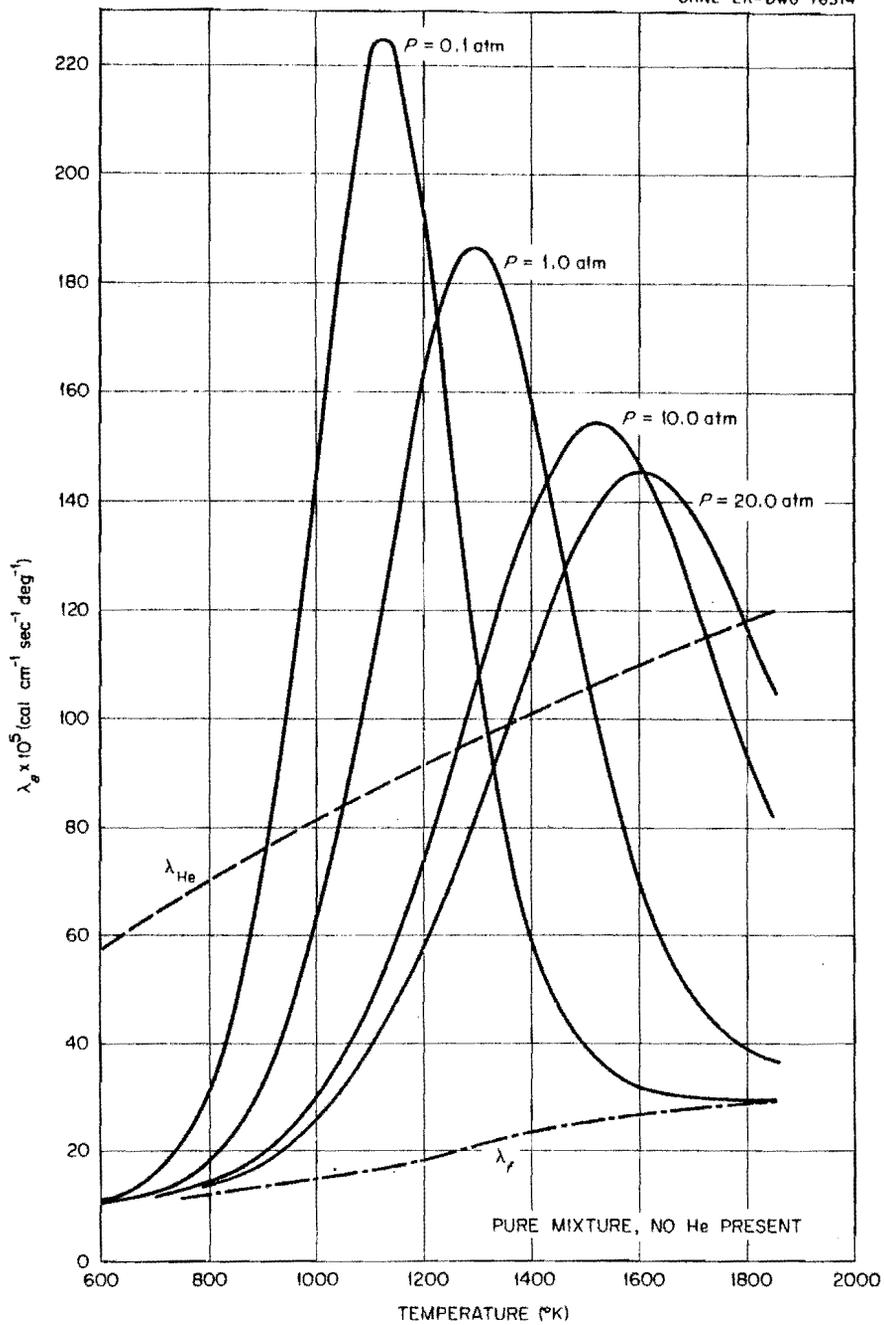


Fig. 9. $F_2 \rightleftharpoons 2 F$: Thermal Conductivity at Various Pressures.

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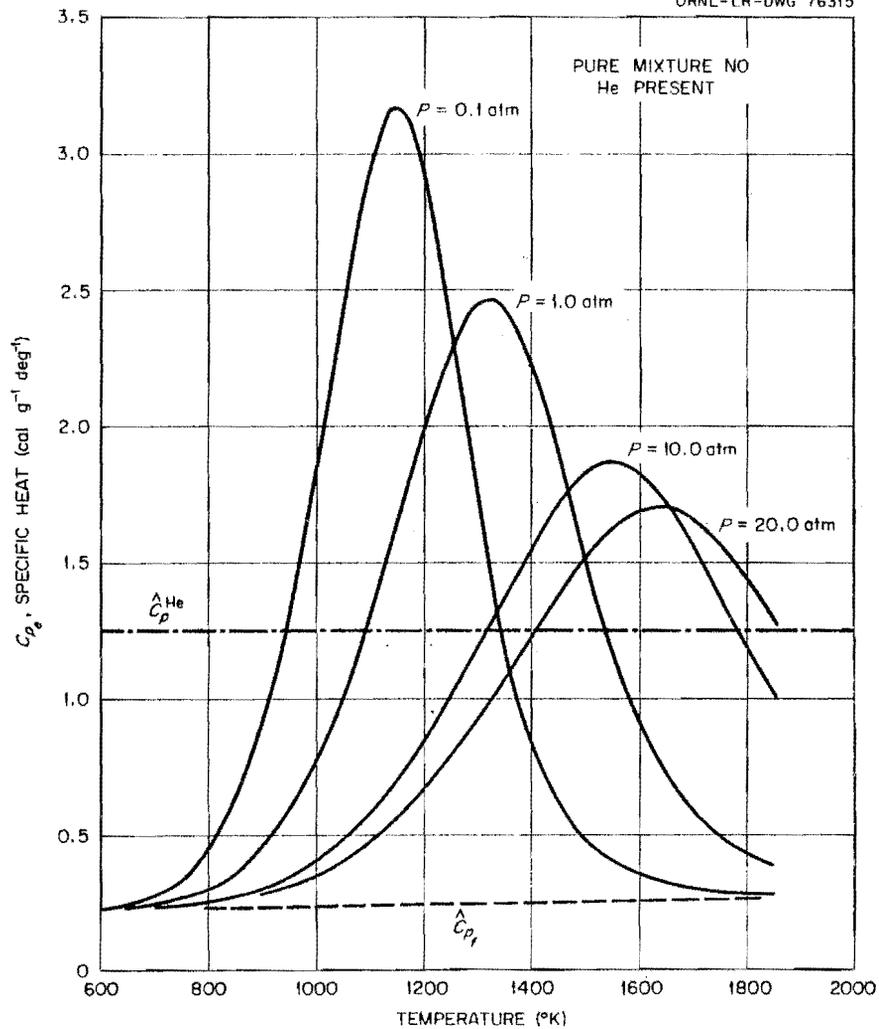


Fig. 10. $\text{F}_2 \rightleftharpoons 2 \text{F}$: Specific Heat at Various Pressures.

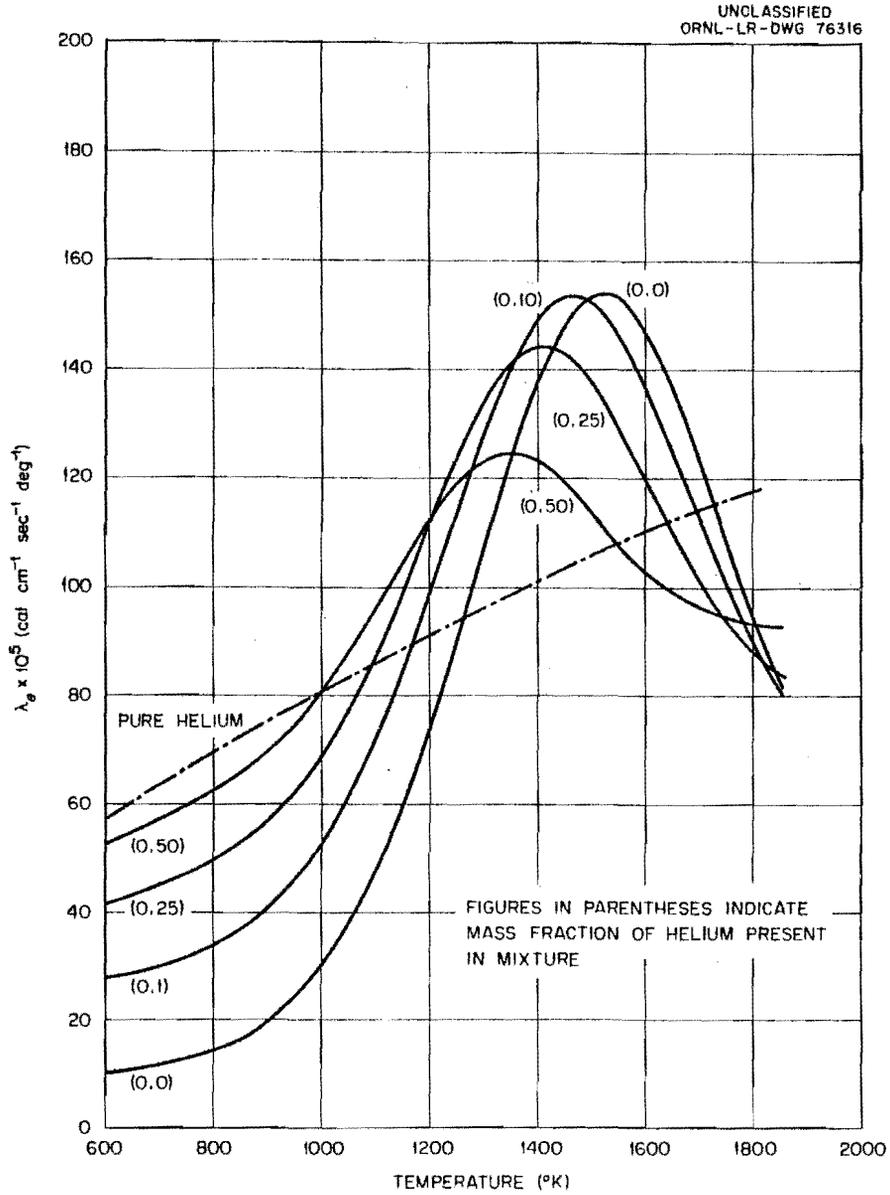


Fig. 11. $F_2 \rightleftharpoons 2F$: Thermal Conductivity at 10 atm and Various Mass Fractions of Helium.

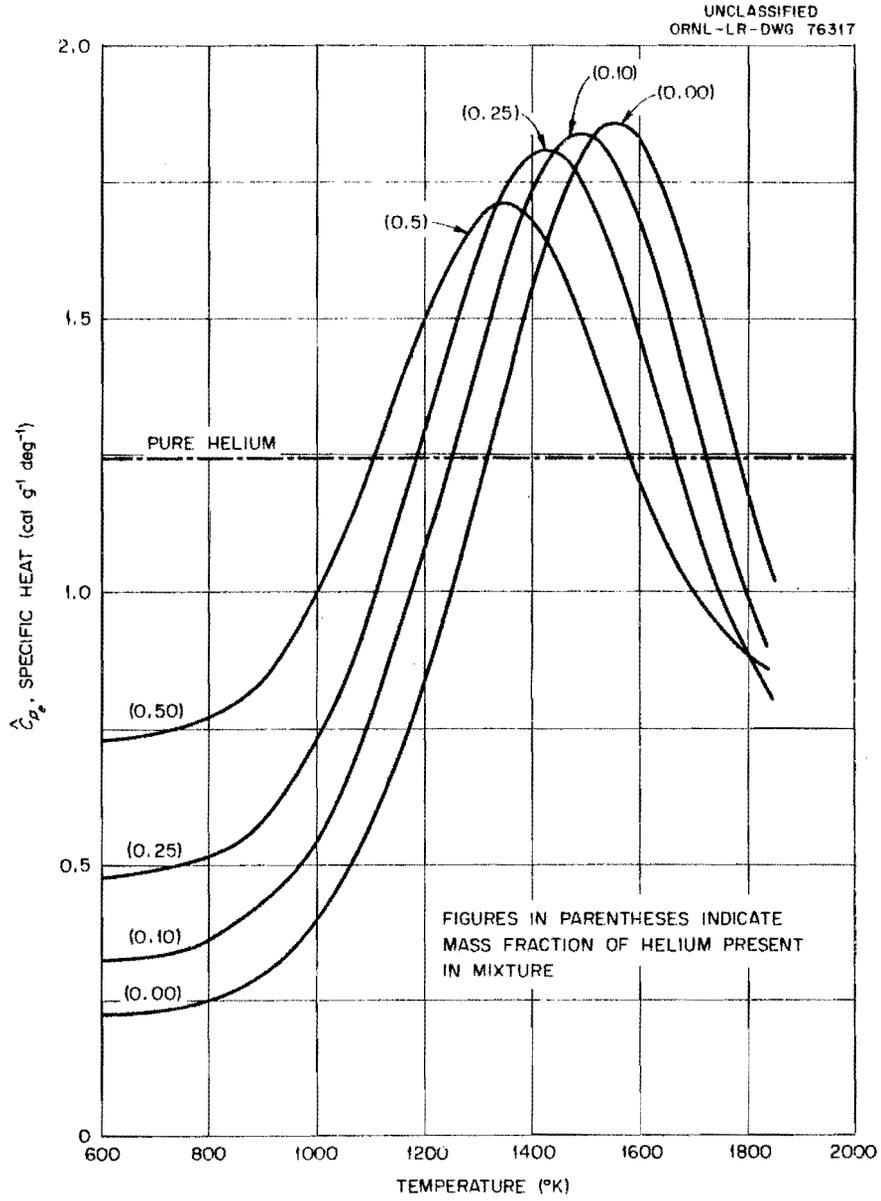


Fig. 12. $F_2 \rightleftharpoons 2 F$: Specific Heat at 10 atm and Various Mass Fractions of Helium.

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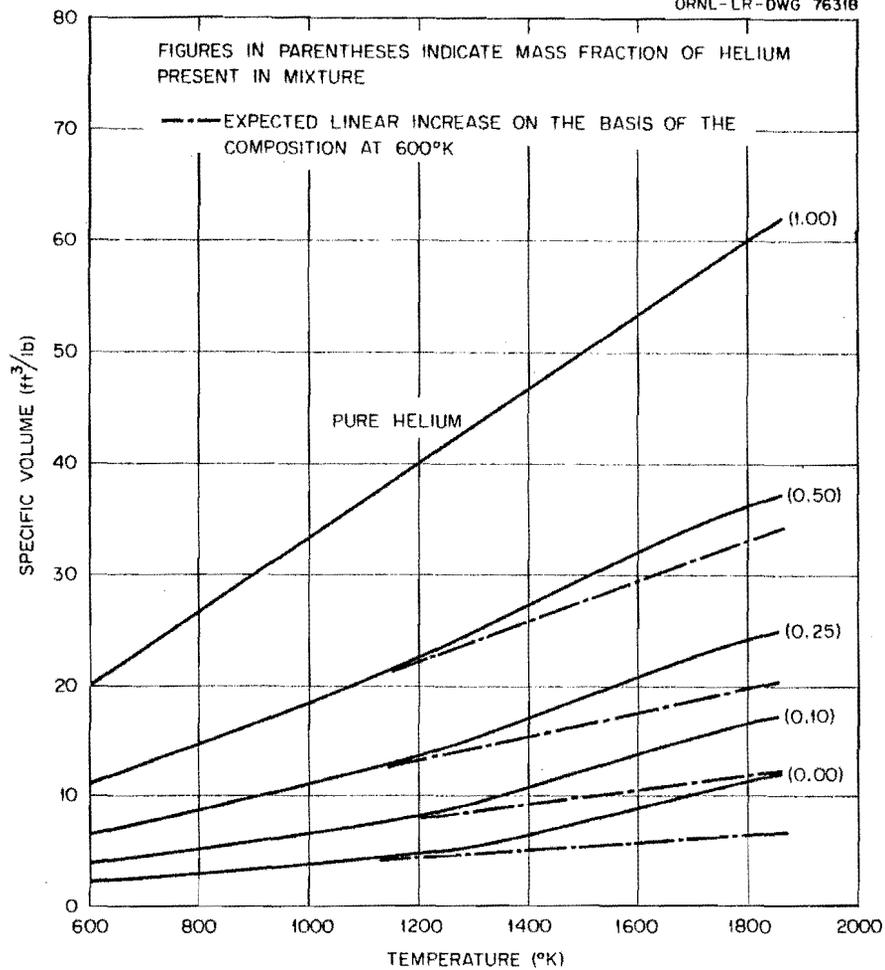


Fig. 13. $F_2 \rightleftharpoons 2 F$: Specific Volume at 10 atm and Various Mass Fractions of Helium.

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42. Laboratory Records, ORNL RC
- 43-57. DTIC, AEC
58. Division of Research and Development, ORO

