

NACA TN 3226

CASE FILE  
COPY

# NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 3226

SOME POSSIBILITIES OF USING GAS MIXTURES OTHER  
THAN AIR IN AERODYNAMIC RESEARCH

By Dean R. Chapman

Ames Aeronautical Laboratory  
Moffett Field, Calif.



WASHINGTON

August 1954

NASA FILE COPY

loan expires on last

date stamped on back cover.

PLEASE RETURN TO

DIVISION OF RESEARCH INFORMATION

NATIONAL AERONAUTICS

AND SPACE ADMINISTRATION

Washington 25, D. C.

TECHNICAL NOTE 3226

SOME POSSIBILITIES OF USING GAS MIXTURES OTHER  
THAN AIR IN AERODYNAMIC RESEARCH

By Dean R. Chapman

SUMMARY

A study is made of the advantages that can be realized in compressible-flow research by employing a substitute heavy gas in place of air. Heavy gases considered in previous investigations are either toxic, chemically active, or (as in the case of the Freons) have a ratio of specific heats greatly different from air. The present report is based on the idea that by properly mixing a heavy monatomic gas with a suitable heavy polyatomic gas, it is possible to obtain a heavy gas mixture which has the correct ratio of specific heats and which is non-toxic, nonflammable, thermally stable, chemically inert, and comprised of commercially available components.

Calculations were made of wind-tunnel characteristics for 63 gas pairs comprising 21 different polyatomic gases properly mixed with each of three monatomic gases (argon, krypton, and xenon). For a given Mach number, Reynolds number, and tunnel pressure, a gas-mixture wind tunnel having the same specific-heat ratio as air would be appreciably smaller and would require substantially less power than the corresponding air wind tunnel. Very roughly the results are as follows:

	Mixtures		
	<u>Argon</u>	<u>Krypton</u>	<u>Xenon</u>
Power required relative to air tunnel . . . . .	0.3	0.2	0.1
Characteristic dimension of test section relative to air tunnel . .	0.7	0.6	0.5

Analogous advantages can be realized in compressor research and in firing-range research. Other applications arise through the possibility of selecting and proportioning a gas mixture so as to have at wind-tunnel temperatures approximately the same dimensionless characteristics as air at flight temperatures. Characteristics which involve relaxation time and variation of specific heat with temperature fall within this category.

Most of the polyatomic gases considered are more inert and stable than Freon 12. One of the more promising gases is bromotrifluoromethane (CBrF<sub>3</sub>), commercially called Freon 13B1 or Kulene 131. Of the three

monatomic gases considered, all are completely inert, although only argon now is available in large quantities.

## INTRODUCTION

The reasons for considering gases other than air as possible test media for compressible-flow research stem primarily from the relatively low speed of sound in certain gases. In general, the heavier the gas, the lower the speed of sound at a fixed temperature. Hence, experiments conducted at a given Mach number in a heavy gas will be conducted at lower velocity than the corresponding experiment in air. Some significant advantages of conducting wind-tunnel, firing-range, and compressor experiments at a reduced velocity have been noted previously in the work of Theodorsen and Regier (ref. 1), Smelt (ref. 2), Kantrowitz (ref. 3), Huber (ref. 4), Buell (ref. 5), Donaldson (ref. 6), and von Doenhoff and Braslow (ref. 7). Some uses of gases other than air in shock tube research are discussed by Duff in reference 8. These investigations show that the substitution of a heavy gas for air offers the possibility of: (1) extending the range of existing research apparatus; (2) achieving greater economy of construction and operation of large high-speed wind tunnels; and (3) providing greater facility in obtaining data for special types of research. These advantages will be discussed briefly in the order listed.

The possibility of extending the range of existing apparatus was clearly demonstrated by the experiments of Theodorsen and Regier, which appear to be the first compressible-flow experiments in which supersonic aerodynamic data were obtained in a gas other than air. By rotating propellers in Freon 113 ( $\text{CCl}_2\text{FCClF}_2$ , having a speed of sound 0.39 times that of air, and a density 6.5 times as great) they were able to achieve tip Mach numbers of 2.7; whereas the highest tip Mach number achieved with the same apparatus using air was 1.0. Also, much higher Reynolds numbers were obtained. In a similar fashion, Buell employed the Freons, and Donaldson employed xenon as the test medium through which projectiles were fired in order to obtain Mach numbers much higher than could be obtained with the same apparatus by firing through air. An extended range of operation of a wind tunnel has been demonstrated by von Doenhoff and Braslow who report that the maximum attainable test-section Mach number of the Langley low-turbulence pressure tunnel was increased from 0.4 to 1.2 by replacing air with Freon 12.

A possibility of achieving greater economy by employing a substitute heavy gas in a wind tunnel arises because the test-section dimensions are smaller and the horsepower required is only a fraction of that required for an air wind tunnel operating at the same Mach number, Reynolds number, and pressure. Smelt has made a general study pointing out this possibility for various inert gases that have, unfortunately, a specific-heat ratio different from air. The importance of reduced power requirements, if accomplished without sacrifice in ratio of specific heats, needs no elaboration in view of the power of modern wind tunnels.

The third advantage mentioned, namely, facilitating certain types of aerodynamic research, stems directly from the lower test velocity relative to air. One consequence of reducing the velocity while maintaining physical similarity of a flow is that centrifugal stresses of rotating machinery are reduced as the square of the velocity. This can be an important advantage in the design of large wind-tunnel compressors. Also, for a given Reynolds number and Mach number, the stream dynamic pressure is significantly reduced. Consequently, it is much easier to construct certain models for testing in a heavy gas than for testing in air. Considerable compressor research has already been conducted in Freon 12 which would not have been practical if air were employed as the test medium. (See the work of Kantrowitz for example). The feature of a reduced dynamic pressure also would facilitate tests in pressurized transonic wind tunnels wherein model stresses or model-support stresses limit undesirably the useful angle-of-attack range. Firing-range research is facilitated through use of a heavy gas since a lower launching velocity results in longer time intervals for observation, as well as lower model stresses during launching. Flutter research may be facilitated because lower velocities result in lower oscillation frequencies, which, in turn, require simpler instrumentation for certain measurements. Wind-tunnel bomb-drop tests are facilitated because the lower velocity enables a smaller model to be used while simulating the required value of the Froude number ( $u_{\infty}^2/gl$ ). For example, simulation of the Froude number at a Mach number of one requires a model practically as large as the prototype if air is employed, but only about 1/4 scale if a gas four times as dense is employed.

As regards the various disadvantages involved by using substitute heavy gases in aerodynamic research, it is clear that even without detailed study these are more obvious than the advantages. The main disadvantages are: (1) The ratio of specific heat ( $\gamma$ ) differs from that of air for the heavy gases proposed thus far; (2) the use of any gas other than air results in more severe practical problems of operating a research facility; and (3) conversion of existing apparatus for operation with a heavy gas can be costly.<sup>1</sup> It is to be noted that gases with  $\gamma$  significantly different from air would not yield in a supersonic flow at a given Mach and Reynolds number, either the same skin friction or the same pressure distribution as air would yield. Further elaboration here would not be pertinent inasmuch as the present report concerns a method of eliminating the first and chief disadvantage while retaining the advantages previously discussed.

---

<sup>1</sup>An additional disadvantage sometimes expressed (e.g., ref. 9) is that the relatively long relaxation time for molecular vibrations in certain polyatomic gases would invalidate data obtained at supersonic velocities. However, in the case of most gases considered here, this is believed not to be the case. Reasons for this are based on calculations presented in an appendix and are discussed later.

There are many rather evident practical disadvantages of operating a facility with a gas other than air. Purging of the test-section region (or entire wind tunnel) before each model change handicaps the operation of any research apparatus whether it is a wind tunnel, compressor test facility, or firing range. The necessity of preventing excessive contamination by air and of minimizing leakage of the heavy gas to the atmosphere is a definite practical disadvantage. Also the operation of the necessary purification equipment, the increased pumping equipment, and the additional gas storage equipment represent such disadvantages.

As for the third disadvantage, namely, that involving the cost of converting existing equipment for operation with a gas other than air, it would appear an insurmountable one for tunnels that are not pressurized, and it would be a dominant consideration for existing large wind tunnels in which the compressor speed cannot be varied efficiently. To maintain proper matching of compressor and tunnel, the lower stream velocity of a heavy gas would require that the compressor be operated at correspondingly lower speed. Alterations to accomplish this can be costly, as can be the possible additional equipment required for pumping, purifying, and storing the heavy gas.

A general appraisalment of the various advantages relative to disadvantages cannot be made since this would depend on each particular case. The purposes of this report are to indicate a method of constructing a satisfactory heavy gas for aerodynamic testing and to evaluate the magnitude of the advantages such gases offer. Knowledge of these advantages will enable a comparison with the disadvantages to be made in a given case.

The present research was begun upon conception of the following simple idea: The proper ratio of specific heats ( $\gamma = 1.4$ ) can be achieved with a heavy gas by suitably mixing a heavy monatomic gas ( $\gamma > 1.4$ ) with a heavy polyatomic gas ( $\gamma < 1.4$ ). Exploitation of this simple idea turned out to be unexpectedly arduous because of difficulties involved in obtaining adequate chemical, physical, pharmacological, and thermodynamic data on the many polyatomic gases known to modern chemistry. Primarily as a result of recent developments in the field of fluorochemicals, it was possible to find among the known polyatomic gases over 30 which were indicated by available data to be sufficiently nontoxic, nonflammable, chemically inert, and thermally stable to justify consideration. Evaluation of the relative advantages of each polyatomic gas for aerodynamic testing requires calculating the thermodynamic properties from spectroscopic data, the proper proportions for mixing from thermodynamic properties, and then computing the density and viscosity that would result when mixed with each of three monatomic gases considered (argon, krypton, and xenon). The remainder of this report describes the detailed methods employed in the evaluation, the results obtained, and the conclusions drawn.

After completion of the main body of calculations, a short unpublished note by E. F. Relf, in England, became available in which the possibility of obtaining the proper ratio of specific heats through mixing gases also was pointed out. Relf made a rough estimation for a mixture of sulfur hexafluoride and xenon, which is one of the 63 mixtures considered in the present research.

## METHODS OF SELECTING GASES AND COMPUTING CHARACTERISTICS OF VARIOUS GAS MIXTURES

### Selection of Gases

The selection of monatomic gases for consideration is simple, since only four such gases are known - argon, krypton, xenon, and radon - that have a molecular weight greater than air. Radon, the heaviest of all, unfortunately must be excluded because of its radioactivity. The remaining three gases are completely inert. Some of their properties pertinent to the present analysis are listed in table I. Although argon is the only one now commercially available in large quantities, both krypton and xenon will be considered since they might be of use for special research in small apparatus, and since their availability undoubtedly will increase in the future.<sup>2</sup>

The selection of polyatomic gases for consideration was rather tedious. Of the approximately 13,000 polyatomic compounds listed in the 1952 Handbook of Chemistry and Physics (ref. 12), 103 were found to be gases at 0° C. Compounds that are not gaseous at 0° C were not considered. Most of the gases were not considered further because they possessed some intolerable characteristic such as being highly poisonous (e.g., COCl<sub>2</sub>, S<sub>2</sub>F<sub>10</sub>, C<sub>2</sub>N<sub>2</sub>, SO<sub>2</sub>), toxic (e.g., CH<sub>3</sub>F, CF<sub>2</sub>Br<sub>2</sub>, CH<sub>3</sub>CH<sub>2</sub>F), combustible (e.g., COS, all hydrocarbon gases), unstable (e.g., CHCl<sub>3</sub>, ClN<sub>3</sub>, PSF<sub>3</sub>), or generally active chemically (e.g., BF<sub>3</sub>, F<sub>2</sub>O, CF<sub>3</sub>SF<sub>3</sub>, CF<sub>3</sub>OF). Still others were eliminated for less obvious reasons, such as reacting with water vapor to yield corrosive products (e.g., SiF<sub>4</sub>, PF<sub>3</sub>, COF<sub>2</sub>, TeF<sub>6</sub>), or having a tendency to polymerize under pressure (e.g., CClFCF<sub>2</sub>, CH<sub>2</sub>CF<sub>2</sub>, CF<sub>2</sub>CF<sub>2</sub>), or being active when in the presence of mercury (F<sub>3</sub>CNNCF<sub>3</sub>), or imparting, upon inhalation, an offensive odor to the breath which persists long after inhalation (TeF<sub>6</sub>). This elimination process left 16 polyatomic gases for further consideration. It was noticed that all but two (CO<sub>2</sub> and N<sub>2</sub>O, the lightest two on the list) contained at least two atoms of fluorine per molecule. Because fluorine appeared to be the key to the

---

<sup>2</sup>Argon now costs about 10 cents per cubic foot of free gas in small quantities, and about 7 cents in large quantities. Because very large amounts of argon are required in the production and fabrication of titanium, the cost of argon in the near future may be greatly reduced (see e.g., ref. 10). Krypton and xenon now are produced in the United States only as by-products of air liquifaction, but recently have been produced on a more economical scale in Europe from special krypton plants (see ref. 11).

problem, recent technical publications on fluorine chemistry were scanned (especially refs. 13, 14, and 15) for further information. From this search 15 additional polyatomic gases were found which met the required conditions of being nontoxic, noncombustible, chemically inactive, and thermally stable. Among these 15 recently synthesized gases were several (e.g.,  $\text{CBrF}_3$ ) which turned out to be the most efficient for wind-tunnel use. Undoubtedly, additional new polyatomic gases will continue to be synthesized in the future inasmuch as a large industrial effort is being expended on fluorine chemistry. Quite a few apparently satisfactory gases (e.g.,  $\text{C}_3\text{ClF}_7$  and  $\text{C}_2\text{HF}_5$ ) are known to be omitted from the list. Consequently, the present report which primarily indicates current possibilities of gas mixtures in reducing wind-tunnel power is by no means exhaustive and might considerably underestimate possibilities existing several years hence.

It is pertinent to focus attention here on the extreme properties of fluorochemicals. Their chemistry often is totally unlike that of analogous halide compounds. Fluorochemicals include some of the most toxic compounds known, yet also include the most inactive and nontoxic compounds known. For a given molecular weight, they have the lowest boiling points of known compounds, being paralleled in this respect only by the inert monatomic gases. Intermolecular forces and surface tension are extremely low. The thermal stability and resistance to electric breakdown of certain fluorochemicals are extremely high. Most of these extreme properties can be illustrated by a few examples. First consider the following two gases: chloroform,  $\text{CHCl}_3$ , and fluoroform,  $\text{CHF}_3$ . The toxicity of chloroform is well known. Fluoroform, however, is indicated to be completely inert physiologically (ref. 16). Guinea pigs can live in an atmosphere of 80 percent fluoroform and 20 percent oxygen without being affected either during the test or afterward. Sulfur hexafluoride,  $\text{SF}_6$ , also is indicated to be physiologically inert on the basis of similar tests with small animals (ref. 17). On the other hand, the deceptively similar sulfur pentafluoride,  $(\text{SF}_5)_2$ , is extremely poisonous, since, for concentrations as low as one part per million - in which concentration phosgene is harmless - sulfur pentafluoride is lethal (ref. 18). Further illustration of the extreme properties of fluorochemicals is provided by carbon tetrafluoride,  $\text{CF}_4$ . The thermal decomposition temperature of  $\text{CF}_4$  has not yet accurately been determined since it is so high as to be in the vicinity of the carbon arc temperature (ref. 19). Carbon tetrafluoride has been heated in the presence of many metals, including Cu, Ag, Hg, C, Si, Ni, Sn, Pb, P, As, Sb, Cr, Mo, W, S, Se, Fe, Ru, and Pt up to the temperature at which glass softens without any reaction occurring. (See ref. 14, p. 433.) Sulfur hexafluoride is equally remarkable in its chemical inactivity at all temperatures below the softening point of glass.

The chemical symbol, molecular weight, chemical name, and trade name of 31 polyatomic gases considered as possible components for aerodynamic test media are listed in the first four columns of table II. A symbol designating the general classification of each gas is listed in the fifth column. The meaning of each symbol is explained in the footnote of the table. Listed in table III are certain data, to be utilized later,

regarding the boiling point, critical constants, viscosity coefficient, and spectroscopic frequencies of the various polyatomic gases. The sources of data for each gas are indicated by reference numbers in the last three columns of table II. These data were compiled from references 13 to 16 and 18 to 56.

### Computation of Thermodynamic Properties

The first step in evaluating aerodynamic qualities of any gas is to determine its thermodynamic properties such as specific heat and enthalpy. When two gases are mixed, the resulting thermodynamic properties can be calculated from the thermodynamic properties of the individual components. Using subscript 1 to denote the monatomic component, and subscript 2 to denote the polyatomic component, the following equations apply for binary mixtures of thermally perfect gases:

$$\text{molecular weight} \quad m = x_1 m_1 + x_2 m_2 \quad (1)$$

$$\text{equation of state} \quad p = \rho RT/m \quad (2)$$

$$\text{specific heat} \quad C_v + R = C_p = x_1 C_{p1} + x_2 C_{p2} \quad (3)$$

$$\text{ratio of specific heats} \quad \gamma = \frac{x_1 C_{p1} + x_2 C_{p2}}{x_1 (C_{p1} - R) + x_2 (C_{p2} - R)} \quad (4)$$

$$\text{enthalpy} \quad H = x_1 H_1 + x_2 H_2 \quad (5)$$

where  $R$  is the universal gas constant ( $1.987 \text{ cal. } ^\circ\text{K}^{-1} \text{ mole}^{-1}$ ), and  $x$  denotes the mole fraction of a component (equal to the fraction by volume, or the fractional partial pressure of the component) and is subject to the relation  $x_1 + x_2 = 1$ . For all monatomic gases,

$$C_{p1} = \frac{H_1}{T} = \frac{5}{2} R = 4.97 \text{ cal. } ^\circ\text{K}^{-1} \text{ mole}^{-1}$$

Hence, from equation (4), it follows that for  $\gamma = 7/5$ ,

$$1 - x_1 = x_2 = \left( \frac{C_{p2}}{R} - \frac{5}{2} \right)^{-1} \quad (6)$$



The thermodynamic properties of a polyatomic gas can be accurately computed from infrared and/or Raman spectroscopic data, using equations developed by methods of statistical mechanics (see ref. 57, for example). For linear molecules (e.g.,  $\text{CO}_2$  and  $\text{N}_2\text{O}$ ), wherein the atoms are arranged in a straight line,

$$\frac{C_{p2}}{R} = \frac{7}{2} + \sum_1^{3n-5} \frac{\left(\frac{hc\omega_i}{2kT}\right)^2}{\sinh^2\left(\frac{hc\omega_i}{2kT}\right)} \quad (7)$$

$$\frac{H_2}{RT} = \frac{7}{2} + \sum_1^{3n-5} \frac{\frac{hc\omega_i}{kT}}{\exp\left(\frac{hc\omega_i}{kT}\right) - 1} \quad (8)$$

The various wave numbers  $\omega_i$  determined from spectroscopic data for each gas are listed in table III. The constant  $hc/k$  is equal to  $1.4385^\circ\text{K cm}$ . For nonlinear molecules not subject to internal rotation (e.g.,  $\text{CF}_4$ ,  $\text{CHF}_3$ ,  $\text{SF}_6$ , etc.)

$$\frac{C_{p2}}{R} = 4 + \sum_1^{3n-6} \frac{\left(\frac{hc\omega_i}{2kT}\right)^2}{\sinh^2\left(\frac{hc\omega_i}{2kT}\right)} \quad (9)$$

$$\frac{H_2}{RT} = 4 + \sum_1^{3n-6} \frac{\frac{hc\omega_i}{kT}}{\exp\left(\frac{hc\omega_i}{kT}\right) - 1} \quad (10)$$

For nonlinear molecules subject to a torsional mode of oscillation (e.g.,  $\text{CF}_3\text{CF}_3$ ,  $\text{CHF}_2\text{CClF}_2$ , and all other ethane-like molecules) the above summations were employed only for the  $3n-5$  normal modes, and the torsional contribution was computed from the Pitzer-Gwinn tables (reproduced in ref. 58) using values for the potential barrier estimated from spectroscopic data. Computations were greatly facilitated through use of the tables of reference 58. Typical curves showing the molar specific heat as a function of temperature for several of the various gases considered are presented in figure 1. Curves of this type, together with equation (4), were used for each gas to determine the mixture proportions necessary

to obtain a value of 1.4 for  $\gamma$ . Similar data for the enthalpy were used to compute Mach number, pressure ratio, etc., for the different flow conditions considered.

It is noted that the thermodynamic properties calculated from spectroscopic data agree well with direct calorimetric measurements. This is illustrated in the following table:

Gas	T, °C	Calculated $C_p$ (from spectroscopic data of table III)	Experimental $C_p$ (from direct calori- metric measurements)
CO <sub>2</sub>	-75	7.71	7.78
	20	8.82	8.80
	220	10.62	10.63
CCl <sub>2</sub> F <sub>2</sub>	-30	15.6	15.7
	0	16.6	16.7
	45	17.8	18.0
	90	18.9	19.1
CF <sub>3</sub> CF <sub>3</sub>	-50	21.1	21.0
	10	24.7	24.4
	90	28.7	28.2

} ref. 57

} ref. 51

} ref. 22

### Computations of Viscosity

It will be seen subsequently that for a given Reynolds number and Mach number, the power required by a wind tunnel is directly dependent on the gas viscosity coefficient. The viscosity of a mixture of two gases can be approximately calculated from the equation (see ref. 59):

$$\mu = \frac{\mu_1}{1 + \frac{\frac{x_2}{x_1} \left[ 1 + \sqrt{\frac{\mu_1}{\mu_2} \left( \frac{m_2}{m_1} \right)^{1/4}} \right]^2}{\frac{4}{\sqrt{2}} \left( 1 + \frac{m_1}{m_2} \right)^{1/2}}} + \frac{\mu_2}{1 + \frac{\frac{x_1}{x_2} \left[ 1 + \sqrt{\frac{\mu_2}{\mu_1} \left( \frac{m_1}{m_2} \right)^{1/4}} \right]^2}{\frac{4}{\sqrt{2}} \left( 1 + \frac{m_2}{m_1} \right)^{1/2}}} \quad (11)$$

It is noted that a simple linear interpolation between the values of  $\mu$  for each component is not an adequate method of estimating the viscosity of the mixture. This is illustrated by several examples in figure 2. Curves of this type were constructed for all gas mixtures considered.

Experimental data are available for the viscosity  $\mu_1$  of the three monatomic gases, but very little data are available for the various polyatomic gases. Fortunately, the coefficient of viscosity can be estimated

quite satisfactorily from a knowledge of the critical temperature  $T_c$ , critical volume  $V_c$ , and molecular weight by the equation

$$\mu = \frac{\sqrt{mT_c}}{(V_c)^{2/3}} F\left(\frac{T}{T_c}\right) \quad (12)$$

This equation may be deduced from the general Chapman-Cowling equations for gases having intermolecular forces dependent only on powers of the distance between molecules. (See refs. 59 and 60.) Rather than to use the elaborate theoretical evaluation of the function  $F(T/T_c)$ , the more simple empirical evaluation of reference 61 is used:

$$F\left(\frac{T}{T_c}\right) = \begin{cases} 27.1 T/T_c & \text{for } T < 1.6 T_c \\ \frac{27.1 T/T_c}{1 + 0.0952 \left(\frac{T}{T_c} - 1.6\right)} & \text{for } T > 1.6 T_c \end{cases} \quad (12a)$$

where  $T$  is in  $^{\circ}\text{K}$ ,  $m$  is in gm./mole,  $V_c$  is in cc/gm. mole, and  $\mu$  is in micropoise. A comparison of the calculated and experimental viscosity coefficients of all gases considered for which experimental data could be found is given in the following table:

<u>Viscosity at 0<math>^{\circ}</math> C in micropoises</u>		
<u>Gas</u>	<u>Calculated</u>	<u>Experimental</u>
Ar	210	210
Kr	229	230
Xe	211	210
SF <sub>6</sub>	146	142
CCl <sub>2</sub> F <sub>2</sub>	114	118
CHClF <sub>2</sub>	119	120
CO <sub>2</sub>	134	137
N <sub>2</sub> O	132	135
Air	170	172

This agreement is satisfactory. Consequently, in the calculations of wind-tunnel power requirements, experimental values of  $\mu$  are employed for the 9 gases listed above, but values computed from equation (12) are

employed for the remaining gases for which experimental data are not available. Since molecules of the above 9 gases are either simple or approximately spherical in structure, the accuracy of calculations from equation (12) is expected to be less for greatly different molecular structures, such as that of  $C_4F_{10}$ , but probably is sufficient for present purposes.

#### Wind-Tunnel Power

The general equation for compressor power required to maintain a steady rate of mass flow  $w$  of a perfect gas through a compression ratio  $CR$  starting with an initial temperature  $T_t$  is given by the equation

$$HP = J \frac{w c_p T_t}{\eta} \left[ (CR)^{(\gamma-1)/\gamma} - 1 \right] \quad (13)$$

where  $J$  is a numerical constant depending only on the units employed,  $\eta$  is the combined adiabatic and mechanical efficiency (assumed to be independent of the gas), and  $c_p$  is the specific heat per unit mass. It is noted that  $c_p$  in equation (13) is related to the molar specific heat  $C_p$  and the molar universal gas constant  $R$  through the equation

$$m c_p = C_p = \frac{\gamma}{\gamma - 1} R \quad (14)$$

By using a bar to denote a quantity divided by the corresponding quantity for air (e.g.,  $\bar{m} \equiv m/(m)_{air}$ ,  $\bar{w} \equiv w/(w)_{air}$ ,  $\bar{HP} \equiv HP/(HP)_{air}$ , etc.), there results

$$\bar{HP} = \frac{\bar{w}}{\bar{m}} \bar{T}_t \bar{Y}(\gamma, CR) = \frac{\bar{p}_{\infty} \bar{U}_{\infty} \bar{L}^2}{\bar{m}} \bar{T}_t \bar{Y}(\gamma, CR) \quad (15)$$

where  $Y(\gamma, CR) \equiv \frac{\gamma}{\gamma - 1} \left[ (CR)^{(\gamma-1)/\gamma} - 1 \right]$ , and  $L$  is a characteristic dimension of the test section. A more convenient equation is obtained by introducing the Reynolds number

$$\overline{HP} = \frac{\overline{Re} \overline{\mu} \overline{L}}{\overline{m}} \overline{T}_t \overline{Y}(\gamma, CR) \quad (16)$$

from which it is apparent that, as Smelt (ref. 2) has pointed out, power economy can be achieved by employing a gas with low viscosity and high molecular weight, or by testing at the lowest temperature possible, or by testing in the smallest facility (highest operating pressure) that will yield the given Reynolds number. The quantities  $\overline{Re}$  and  $\overline{L}$  are related to the relative operating tunnel pressure  $\overline{P}_t$

$$\begin{aligned} \overline{Re} &= \frac{\overline{\rho}_{\infty} \overline{u}_{\infty} \overline{L}}{\overline{\mu}} = \left[ \left( \frac{\overline{\rho}_{\infty}}{\overline{\rho}_t} \right) \frac{\overline{P}_t \overline{m}}{\overline{T}_t} \right] \left[ \left( \frac{\overline{u}_{\infty}}{\overline{a}_t} \right) \sqrt{\frac{\overline{\gamma} \overline{T}_t}{\overline{m}}} \right] \frac{\overline{L}}{\overline{\mu}} \\ &= \overline{P}_t \sqrt{\frac{\overline{m}}{\overline{T}_t}} \frac{\overline{L}}{\overline{\mu}} \left( \frac{\sqrt{\overline{\gamma} \overline{\rho}_{\infty} \overline{u}_{\infty}}}{\overline{\rho}_t \overline{a}_t} \right) \end{aligned}$$

or, finally,

$$\overline{L} = \frac{\overline{Re} \overline{\mu} \sqrt{\overline{T}_t}}{\overline{P}_t \sqrt{\overline{m}} \overline{F}(\gamma, M_{\infty})} \quad (17)$$

where

$$\overline{F}(\gamma, M_{\infty}) \equiv \left( \frac{\sqrt{\overline{\gamma} \overline{\rho}_{\infty} \overline{u}_{\infty}}}{\overline{\rho}_t \overline{a}_t} \right)$$

Equation (17) shows that by increasing the molecular weight, or decreasing the viscosity, the size of wind tunnel required to obtain a given Reynolds number can be reduced. Hence, an alternate equation for relative wind-tunnel power is

$$\overline{HP} = \frac{(\overline{Re})^2 \overline{\mu}^2 (\overline{T}_t)^{3/2}}{\overline{P}_t (\overline{m})^{3/2}} \frac{\overline{Y}(\gamma, CR)}{\overline{F}(\gamma, M_{\infty})} \quad (18)$$

Equations (16), (17) and (18) are a generalization of similar equations developed by Smelt.

For subsequent computations, the above equations can be simplified. It will be assumed that CR depends only on  $M_\infty$ . (To achieve this in an air tunnel, the compressor speed would have to be reduced for a heavy gas, thereby introducing the practical problem mentioned earlier.) For the case of transonic wind tunnels CR is the order of 1.3 or less, and direct numerical calculations show that  $0.97 < \bar{Y}(\gamma, 1.3) < 1$  for any  $\gamma$  between 1.1 and 1.4. Hence,  $\bar{Y} = 1$  is a good approximation for transonic wind tunnels irrespective of  $\gamma$ . For the case of supersonic wind tunnels, only gas mixtures having  $\gamma \approx 1.4$  are considered, for which  $\bar{Y}(1.4, CR) = 1$ . Consequently, in all cases of concern here,  $\bar{Y} = 1$  is an adequate approximation. A similar argument shows that the ratio  $\bar{Y}(\gamma, CR) / \bar{F}(\gamma, M_\infty)$  is approximately unity for the range of  $\gamma$  and  $M_\infty$  considered here. Inasmuch as all calculations will be made on the basis that  $\bar{T}_t = 1$ , the above equations simplify to

$$\overline{HP} = \frac{\overline{Re} \overline{\mu} \overline{L}}{\overline{m}} \quad (16a)$$

$$\overline{L} = \frac{\overline{Re} \overline{\mu}}{\overline{p}_t \sqrt{\overline{m}}} \quad (17a)$$

$$\overline{HP} = \frac{(\overline{Re})^2 (\overline{\mu})^2}{\overline{p}_t (\overline{m})^{3/2}} \quad (18a)$$

Four illustrative cases will be considered: (1) given  $M_\infty$ , Re, and L; (2) given  $M_\infty$ , L, and  $p_t$ ; (3) given  $M_\infty$ , L, and HP; and (4) given  $M_\infty$ , Re, and  $p_t$ . Since for all cases  $\bar{T}_t = \bar{M}_\infty = 1$ , the reduction in velocity is always  $\bar{u}_\infty = (\bar{m})^{-1/2}$ .

Case (1): Given  $M_\infty$ , Re, and L.— This case corresponds to operating a given wind tunnel ( $\bar{L} = 1$ ) with a gas other than air at the same values of  $M_\infty$  and Re as for air. The horsepower required for the gas mixture relative to that for air is  $\overline{HP} = \overline{\mu} / \overline{m}$ . However, from equation (17a), it is seen that  $\overline{p}_t = \overline{\mu} / \sqrt{\overline{m}}$  for given values of Re and L. Hence, in order to achieve the same Re with a heavy gas as with air, the given tunnel would be operated at a lower pressure, resulting in model loads that are proportionately lower, since  $\bar{q} = \overline{p}_t = \overline{\mu} / \sqrt{\overline{m}}$ .

Case (2): Given  $M_\infty$ , L, and  $p_t$ .— This case corresponds to substituting a gas other than air in a given wind tunnel and operating at the same pressure and Mach number as for air. From equation (17a) it follows that  $\overline{Re} = \sqrt{\overline{m}} / \overline{\mu}$ . This indicates that higher Reynolds numbers would be achieved with a heavy gas than with air, while (according to eq. (16a))

simultaneously drawing less power by the ratio  $\overline{HP} = (\overline{m})^{-1/2}$ . Since  $\overline{p}_t = 1$ , model stresses are unchanged for this case.

Case (3): Given  $M_\infty$ ,  $L$ , and  $HP$ .- This case corresponds to replacing air in a given tunnel by a gas mixture and drawing the same power for a fixed Mach number. The Reynolds number, from equation (16a), would be increased by the factor  $Re = \overline{m}/\overline{\mu}$ . In order to draw the same power as with air, the pressure and, hence, model loads would have to be increased by the factor  $\overline{p}_t = \sqrt{\overline{m}}$ .

Case (4): Given  $M_\infty$ ,  $Re$ , and  $p_t$ .- This case corresponds to conditions that might be prescribed in the initial design of a new wind tunnel whose size is to be determined by the required values of  $M_\infty$  and  $Re$ , by the selected value of  $p_t$ , and by the gas employed. From equation (18a) it is evident that in this case, the horsepower required for a heavy gas mixture is less than for air by the factor

$$\overline{HP} = \frac{(\overline{\mu})^2}{(\overline{m})^{3/2}} \quad (19)$$

This represents a greater power reduction than in the cases above because the gas-mixture wind tunnel, according to equation (17b), would be smaller than the corresponding air tunnel by the factor

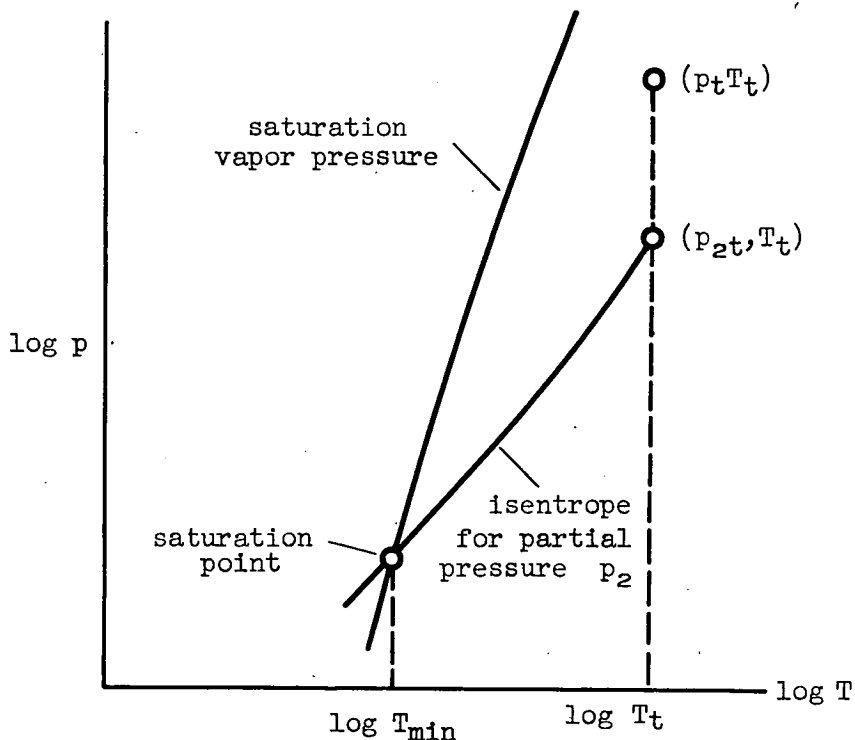
$$\overline{L} = \overline{\mu}/\sqrt{\overline{m}} \quad (20)$$

The gas-mixture wind tunnel would produce the same aerodynamic data as the larger air tunnel with the same model stresses. Computations based on these latter two equations are presented later.

#### Mach Number Limit for Condensation

Although any of the polyatomic gases would be usable in apparatus where low temperatures are not involved, such as in a subsonic wind tunnel, a firing range, or a compressor research apparatus, only a limited number would be useful in a supersonic wind tunnel where the static temperatures encountered are low and can result in condensation. An essential step in evaluating various polyatomic gases, therefore, is to determine the approximate useful Mach number range for each gas. The method of determining this was to draw the isentropic expansion curve for the partial pressure of each polyatomic gas on log-log paper together with the curve for saturation vapor pressure of that gas. As indicated in the following

sketch, the intersection point yields  $T_{\min}$ , from which the maximum Mach



number can be calculated from the relation

$$M^2 = \frac{2}{\gamma} \left( \frac{H_t}{RT} - \frac{H}{RT} \right) \quad (21)$$

where  $\gamma$  and  $H/T$  are determined from spectroscopic data by equations (4) through (10). Graphical solutions of this type were made for operating conditions of approximately  $40^\circ\text{C}$  ( $100^\circ\text{F}$ ) total temperature and several atmospheres total pressure. These solutions enabled the appropriate polyatomic gases to be selected for each of several design Mach numbers considered in the evaluation. It is emphasized that the graphical method included consideration of the variation of specific heat with temperature. As will be seen subsequently, such variation is of dominant importance in determining the limiting Mach number to which certain gases can be expanded without reaching saturation. Simplified criteria, such as boiling temperature, are quite inadequate for determining the saturation limit.



## RESULTS AND DISCUSSION

## Wind-Tunnel Power and Size

Complete computations could not be made for 10 of the 31 polyatomic gases listed in table II, since the necessary spectroscopic data and critical constants were not available for these 10 gases. Calculations have been made, however, of the relative wind-tunnel power requirements for 63 gas pairs comprising mixtures of the 21 polyatomic gases for which data are available with each of the 3 monatomic gases. Mixture proportions were determined from equation (4) using the requirement that  $\gamma_{\infty} = 1.4$  for flow in the test section. The calculations were made for three design Mach numbers, 1.3, 2.5, and 3.5. Results are tabulated in table IV(a), IV(b), and IV(c), respectively. It should be noted that all 21 polyatomic gases are included in table IV(a), since all are free from condensation at  $M_{\infty} = 1.3$ . Only 7 gases for  $M_{\infty} = 2.5$  (table IV(b)) and 2 gases for  $M_{\infty} = 3.5$  (table IV(c)) have sufficiently low boiling points to avoid saturation for the assumed condition of  $40^{\circ}$  C total temperature. Operation at Mach numbers above about 3.5 would require total temperatures higher than the value of  $40^{\circ}$  C arbitrarily assumed.

The values of relative horsepower  $\overline{HP}$  given in table IV represent case (4) mentioned previously. This case corresponds to a comparison with an air wind tunnel for the same  $M_{\infty}$ ,  $Re$ , and  $p_t$ . If desired, any of the other three cases mentioned, or any of the individual relative quantities such as  $\overline{u}_{\infty}$  or  $\overline{p}_{\infty}$ , can be readily calculated from the values of  $\overline{m}$  and  $\overline{\mu}$  listed in the tables and from the appropriate equations developed earlier.

The tabulated results show that there is no single polyatomic gas which is best for all Mach numbers or for use with all monatomic gases. For each monatomic gas, though, there are several polyatomic gases which appear roughly equal in their ability to require low wind-tunnel power. Of the gases that now are commercially available and not classified questionable in table II, the most efficient ones for use with argon are:  $CH_2F_2$ ,  $CBrF_3$ , and  $CCl_2F_2$  for  $M_{\infty} = 1.3$ ;  $CBrF_3$  and  $SF_6$  for  $M_{\infty} = 2.5$ ; and  $CF_4$  for  $M_{\infty} = 3.5$ . In general, the horsepower and size of gas-mixture wind tunnels relative to equivalent air wind tunnels are very approximately as follows:

	Mixtures		
	Argon	Krypton	Xenon
Power relative to air, $\overline{HP}$ . . .	0.3	0.2	0.1
Test-section dimension relative to air, $\overline{L}$ . . . . .	0.7	0.6	0.5

These figures imply significant advantages of gas mixtures as wind-tunnel test media.

It is interesting to note that the heaviest polyatomic gas -  $C_4F_{10}$ , having  $\bar{m}_2 = 8.2$  - does not result in either the heaviest mixture or the best mixture. This is due to the high molar specific heat of  $C_4F_{10}$  which requires that only a small amount (6.5 percent) be mixed with a monatomic gas in order to obtain  $\gamma = 1.4$ . However, for applications to low-speed subsonic research where the value of  $\gamma$  does not matter and, hence, a mixture is not needed, the heaviest gas is the best. For example, pure  $C_4F_{10}$ , having  $\gamma = 1.06$ , would require only 1.8 percent of the power, and an apparatus one-fourth the size of that required by air for a given  $M_\infty$ ,  $Re$ , and  $p_t$ . In this respect pure  $C_4F_{10}$  is several times more efficient than pure Freon 12. (See table III where corresponding values are given for all pure polyatomic gases considered.) It is evident that pure polyatomic gases having  $\gamma \approx 1.1$  are more efficient in reducing wind-tunnel power requirements than are gas mixtures having  $\gamma = 1.4$ .

A possibility that should not be overlooked is that a value of  $\gamma$  close to 1.4 may not be necessary for transonic wind tunnels or other transonic research apparatus. In view of the surprisingly small differences observed at transonic speeds by von Doenhoff and Braslow (ref. 7) between uncorrected results in Freon 12 ( $\gamma = 1.13$ ) and in air ( $\gamma = 1.4$ ), it would appear that a reduced value of  $\gamma$ , perhaps between 1.3 and 1.2, might yield transonic data directly applicable to air for practical purposes. If a considerably reduced value of  $\gamma$  is satisfactory in transonic wind tunnels (such is not anticipated in supersonic wind tunnels), then the possible advantages of gas mixtures for transonic speeds are greater than the above calculations for  $\gamma = 1.4$  would indicate. The following table for  $CBrF_3$ -Ar mixtures at  $M_\infty = 1.3$  illustrates this:

$\gamma$	Case (4): given		Case (3): given	
	$\overline{HP}$	$\overline{L}$	$\overline{Re}$	
1.4	0.37	0.74	2.0	(from table IV(a))
1.35	.30	.69	2.3	
1.3	.22	.62	2.8	
1.25	.16	.53	3.4	
1.2	.10	.44	4.5	
1.15	.06	.37	6.2	(pure $CBrF_3$ )

These figures, which are typical of many of the argon mixtures, show that by reducing  $\gamma$  to about 1.28, the power requirement for an argon gas mixture at transonic speeds would be about one-half that for the same type mixture proportioned to yield a  $\gamma$  of 1.4. This corresponds to one-fifth the power of an equivalent air wind tunnel operating at the same Reynolds number, total pressure, and Mach number (case (4)). Also, the Reynolds number of an existing transonic wind tunnel having a fixed horsepower (case (3)) would be about tripled if air were replaced by an argon gas mixture having  $\gamma = 1.28$ , but only doubled by a mixture having  $\gamma = 1.4$ . The advantages of reducing  $\gamma$  to the lowest practical value are apparent from the table. For xenon mixtures, however, there is less to gain by

reducing  $\gamma$  below 1.4. It would be desirable to conduct some experiments varying the proportions of a gas mixture in order to determine to what limit  $\gamma$  can be reduced in a transonic flow and still yield data directly applicable to air for practical purposes.

#### Deviations from Thermal and Caloric Perfection

Under wind-tunnel conditions air generally is considered as being both thermally perfect ( $p_m = \rho RT$ ) and calorically perfect ( $\gamma = \text{constant}$ ). Most other gases can not be so considered. Calculations of the degree of deviation from thermal perfection for the various argon gas mixtures are presented in Appendix A. It will suffice here to state that such deviations are indicated to be unimportant for normal operating conditions of wind tunnels. The smallness of these deviations is due in part to the monatomic (argon) component, which by itself is almost thermally perfect, and, in part, to the fact that the polyatomic component is a fluorochemical. The unusually low intermolecular forces in fluorochemical gases result in small deviations from thermal perfection.

Deviations from caloric perfection, on the other hand, are not small and represent an important technical consideration. The specific heat of polyatomic gases varies widely, as figure 1 clearly indicates. Thus, a gas mixture proportioned to yield  $\gamma = 1.4$  for one Mach number will not yield the same value of  $\gamma$  at other Mach numbers. This may limit the Mach number range over which a single gas mixture could be used satisfactorily. Also, at a fixed Mach number,  $\gamma$  will vary with temperature. Under wind-tunnel conditions,  $\gamma$  for air is quite constant, but varies under flight conditions where higher temperatures are encountered.

To aid in evaluating the importance of caloric imperfections, the variation of  $\gamma$  with temperature has been computed for various gas mixtures and for air under both wind-tunnel and flight conditions. In these computations the spectroscopic frequencies listed in table III were employed to determine  $\gamma$  for the gas mixtures, whereas the tables of reference 62 were employed for air. Instead of showing the computed variation as a function of some temperature parameter, an enthalpy parameter  $(H - H_\infty)/(H_t - H_\infty)$  is employed which always is zero for free-stream conditions and always is unity for reservoir conditions, regardless of the nature of the gas. Some of the results are shown in figure 3. Air under flight conditions at a given  $M_\infty$  is represented by a cross-sectioned band because ambient temperatures in the atmosphere vary considerably with altitude. Gases under wind-tunnel conditions are represented by a single curve since a fixed reservoir temperature (about  $40^\circ \text{C} \approx 100^\circ \text{F}$ ) has been assumed. A single mixture of 25-percent  $\text{CBrF}_3$  with 75-percent monatomic gas is considered in figure 3(a). These proportions are about right for  $M_\infty = 2.0$ . At  $M_\infty = 2.5$ ,  $\gamma_\infty$  is 1.44 and  $\gamma_t$  is 1.34. This variation does not seem excessive. At  $M_\infty = 1.3$ ,  $\gamma$  is uniformly less than 1.4, varying between 1.37 and 1.34. In view of

previous comments about the apparent insensitivity of transonic flows to much larger variations in  $\gamma$ , as well as the complete insensitivity of subsonic flows to variations in  $\gamma$ , it would appear that a single mixture could be used satisfactorily from low subsonic speeds to at least  $M_\infty = 2.5$ . The situation, however, is more difficult for the Mach number range between 2.5 and 3.5, as figure 3(b) illustrates. In this case the single mixture is one of 40-percent  $CF_4$  with 60-percent monatomic gas. It is to be noted that the variation of  $\gamma$  is not important at conditions close to free-stream conditions. For example,  $\gamma$  does not appear within the body of linearized subsonic or supersonic theory, but first appears in second-order terms. Hence, Busemann's second-order theory for two-dimensional flow has been used to estimate the range within which  $\gamma$  must be maintained in order to introduce less than 1-percent error in  $\Delta p/q$ . The boundaries of this range, indicated by dotted lines in figure 3(b), shrink together as  $M_\infty \rightarrow 1$  and as  $M_\infty \rightarrow \infty$ . For the moderate Mach numbers under consideration, it is seen that only the region of abscissa between about 0.2 and 1.0 is important when assessing the variations in specific-heat ratio. Consequently, it is deduced that the gas mixture approximates flight conditions at  $M_\infty = 3.5$  about as well as does air in a wind tunnel. Such is not the case, though, for  $M_\infty = 2.5$  (top portion of fig. 3(b)), and it is not known whether variations near the stagnation region of the magnitude shown are important. If they are, then the flow in an air wind tunnel also will show important differences from the flow in flight through air at Mach numbers of about 4 or greater. This may be seen from figure 4 by comparing the values of  $\gamma$  in an air wind tunnel (long dashed curves) with the corresponding values of  $\gamma$  in flight (cross-sectioned region). The observed differences are considerably greater than any of figure 3(b) between flight conditions and gas-mixture wind-tunnel conditions. It is also evident from figure 4 that the temperature dependence of  $\gamma$  for polyatomic gases may actually represent a real virtue, particularly in hypersonic research. For polyatomic gases under wind-tunnel conditions, as well as for air under flight conditions, these caloric imperfections arise from the same physical phenomenon, namely, temperature dependent energy of vibration between atoms within a molecule. Under flight conditions at Mach numbers of about 6 or greater, additional energy can be transferred through dissociation, which is responsible for values of  $\gamma$  less than 1.28 in flight.

In order to achieve hypersonic Mach numbers in a wind tunnel without supersaturating the test medium, it is necessary, of course, to heat the medium. The approximate reservoir temperatures (estimated to nearest  $25^\circ$  K) corresponding to the particular curves in figure 4, are as follows:

Gas	Reservoir temperature $^\circ$ K to prevent saturation; $p_t = 100$ psia		
	$M_\infty = 5$	$M_\infty = 6$	$M_\infty = 7$
Air	350	450	550
0.4- $CF_4$ +0.6-Ar	475	600	675
0.2- $CF_4$ +0.2-Ar+0.6 air	500	625	750

As might be expected, the gas mixtures require higher operating temperatures than does air. It is interesting, however, that this trend can be reversed if it is not required that the caloric imperfections of gas mixtures sensibly duplicate those of air under flight conditions. For example, to achieve a Mach number of 7 at 100 psia reservoir pressure would require air to be heated to about  $550^{\circ}$  K, as tabulated above, but would require pure  $\text{CF}_4$  ( $\gamma$  between 1.12 and 1.33) to be heated only to about  $450^{\circ}$  K, and pure  $\text{CF}_3\text{CF}_3$  ( $\gamma$  between 1.08 and 1.19) to be heated only to about  $375^{\circ}$  K. This trend is opposite to what would be expected from consideration solely of the respective boiling points ( $-180^{\circ}$  C for air,  $-128^{\circ}$  C for  $\text{CF}_4$ , and  $-78^{\circ}$  C for  $\text{CF}_3\text{CF}_3$ ) because of the dominating effect of the reduced values of  $\gamma$ . Reducing  $\gamma$  will reduce the rate at which temperature varies with pressure in an expansion process, since  $T \sim p^{(\gamma-1)/\gamma}$ . This results in producing lower pressures, and hence higher Mach numbers, before the temperature is reduced to a point where saturation occurs. From a physical viewpoint, this phenomenon can be traced to the conversion of internal vibrational energy of a molecule into directed kinetic energy during expansion of a polyatomic gas. Thus, for a given reduction in random kinetic energy (given temperature drop), the greater the initial internal vibration energy the greater will be the directed kinetic energy at completion of expansion. Hence, to achieve a given ratio of directed to random energy (given Mach number), the polyatomic gas need not be expanded to as low a temperature.

#### Deviations from Thermal Equilibrium (Heat Capacity Lag)

When a polyatomic molecule passes through a region of rapid change in temperature, the energy stored in vibration between atoms within the molecules does not always adjust to its environment with sufficient rapidity to maintain thermodynamic equilibrium. This leads to a time lag in the heat capacity determined by the relaxation time  $\beta$ . Measurements show that  $\beta$  increases if either pressure or temperature decreases. An excessive long relaxation time could significantly affect a high-speed flow, especially in a wind tunnel where the pressures and temperatures encountered are low, and can magnify such effects.

Detailed computations are presented in Appendix B which provide an estimate of relaxation-time effects for various gases. Here only end results are discussed. The relaxation time ( $\beta_a$ ) at atmosphere conditions is known for some of the fluorochemical gases, and generally is the order of  $10^{-7}$  second. For others,  $\beta_a$  is not known from direct measurements, but can be estimated from related measurements by using certain empirical relationships between relaxation time and molecular structure. Thus,  $\beta_a$  for  $\text{CBrF}_3$  is estimated to be in the range  $10^{-8}$  to  $10^{-7}$  second, and that for  $\text{CF}_3\text{CF}_3$  to be in the range  $10^{-9}$  to  $10^{-8}$  second. The relaxation time for dry air, on the other hand, is relatively long, being the order of  $10^{-5}$  second.

Relaxation time is not the only important quantity which must be considered. The basic parameters which measure effects of heat-capacity lag on a gas flow involve the product  $\beta C_i$ , where  $C_i$  is the heat capacity of internal vibrations within the molecules. From the estimates in Appendix B, heat-capacity lag appears of more importance in altering boundary-layer flow than in altering pressure distribution, and is of greatest importance at low Reynolds numbers. For air under wind-tunnel conditions,  $\beta$  is relatively long, but  $C_i$  is negligible, thereby rendering relaxation effects negligible even at low Reynolds numbers. For most of the gas mixtures under wind-tunnel conditions, the estimated relaxation effects are negligible at Reynolds numbers of the order of  $10^6$  or greater, but are significant at Reynolds numbers of the order of  $10^4$  or less. It should be remembered that for air under flight conditions,  $C_i$  is not negligible as it is in a wind tunnel. Thus, relaxation effects can be significant in flight, although the estimates of Appendix B suggest this may be the case only at high altitudes (low Reynolds numbers) and at high flight speeds. Heat-capacity lag is estimated to be significant at Reynolds numbers below about  $10^3$  for moderate supersonic speeds, and below about  $10^5$  for moderate hypersonic speeds. Although relaxation-time effects in flight would not be simulated in an air wind tunnel, it is possible to simulate them approximately in a gas-mixture wind tunnel by employing two polyatomic gases in the mixture - one having  $\beta C_i$  greater than for flight through air (e.g.,  $CF_4$ ), and the other having  $\beta C_i$  less than for flight through air (e.g.,  $CF_3CF_3$ ). This possibility may be of interest in low-density, high Mach number research.

It should be mentioned that the idea of employing more than one polyatomic gas in a mixture can be utilized profitably in other ways. For example, various pairs of some polyatomic gases when mixed in special proportions form an azeotropic mixture; that is, a mixture for which the boiling temperature is not intermediate between the boiling temperatures of the two constituent gases, as ordinarily is the case, but is lower than the boiling temperature of either constituent. A mixture of 32-percent  $C_3F_8$  with 68-percent  $CH_2F_2$ , for example, boils at  $-58^\circ C$ , whereas the respective individual gases boil at  $-38^\circ C$  and  $-52^\circ C$  (ref. 63). Thus, although neither  $C_3F_8$  nor  $CH_2F_2$  could individually be used at  $M_\infty = 2.5$  under normal wind-tunnel operating conditions without danger of condensation (and, hence, have not been included in table IV(b)), their azeotropic mixture would be usable under such conditions. Other gas pairs known to form azeotropic mixtures are  $CHF_3$  with  $C_2F_6$ ,  $CF_2Cl_2$  with  $CF_2CFCF_3$ ,  $CHClF_2$  with  $CF_2CFCF_3$ , and  $CF_2Cl_2$  with  $CH_3CHF_2$  (see refs. 48 and 63). A related point worth mentioning is that certain polyatomic gases which would not be usable singly because of flammability characteristics may be usable when mixed with other gases. An extreme example illustrating this point is the obviously flammable butane ( $C_4H_{10}$ ) which, when mixed with  $CF_2Cl_2$  in portions up to about 30 percent, is no longer flammable (ref. 64).

## CONCLUDING REMARKS

By employing in place of air a test medium consisting of a heavy monatomic gas mixed with a heavy polyatomic gas in proportions that yield the desired value of 1.4 for the ratio of specific heats, it appears possible in conducting aerodynamic research to realize certain significant advantages. The existence of some of these advantages has been demonstrated by previous investigations concerned with pure, heavy, polyatomic gases, especially the Freons. Because pure polyatomic gases have a specific-heat ratio much lower than that of air, they cannot be employed to yield aerodynamic data directly applicable to air for flows involving extensive supersonic regions. Aerodynamic data obtained with the gas mixtures considered herein would directly apply to air.

A salient result of this study is the observation that a gas mixture can be concocted which behaves - under low-temperature wind-tunnel conditions - dynamically similar in several respects to air under high-temperature flight conditions, whereas air under low-temperature wind-tunnel conditions behaves dissimilarly. This situation arises because the flow of two gases can be made dynamically similar on a macroscopic scale, even though they differ in microscopic structure, provided all the pertinent, dimensionless, macroscopic parameters (such as involve, for example, relaxation phenomena and temperature variation of specific heat) are duplicated between the two gases. In achieving dynamic similarity, it is not necessary to duplicate any dimensional quantity such as temperature.

Many of the fluorochemical gases studied in the present research are more inert than Freon 12. This extreme inertness is highly desirable, especially since some of these gases when mixed with the necessary small amount of oxygen can be breathed even in large quantities without observable effect by animals, and presumably also by man. Likewise, because of their inertness they could be used without undesirable effect on machinery.

Since the magnitude of the advantages that can be achieved through use of gas mixtures has been shown to be large, they may outweigh the evident operational disadvantages which result from use of any gas other than air. Whether or not the advantages surmount the disadvantages can only be ascertained by detailed study of individual cases. Clearly, though, the possible use of gas mixtures warrants consideration in the design of future research facilities. The advantages of gas mixtures also may be worth consideration in regard to certain existing facilities where the Reynolds number and/or Mach number range is now undesirably low, or

where the annual power consumption is undesirably high. In view of the magnitude of the advantages, it appears that some experimental work with gas mixtures is in order.

Ames Aeronautical Laboratory  
National Advisory Committee for Aeronautics  
Moffett Field, Calif., Mar. 12, 1954



## APPENDIX A

## ESTIMATE OF DEVIATIONS FROM THERMAL PERFECTION

By definition, a thermally perfect gas obeys the equation of state  $p_m = \rho RT$  given previously as equation (2). Real gases closely follow this equation if the density is low, or if the temperature is near the Boyle temperature (about  $2.6 T_c$ ), but deviate from it under other conditions. A more exact state equation is

$$\frac{p_m}{\rho RT} = 1 + \frac{p}{RT} B(T) \quad (A1)$$

where  $B(T)$  is the second virial coefficient having dimensions of volume. According to the law of corresponding states,  $B(T)$  is proportional to the critical volume  $V_c$ .

From the results of reference 65, the second virial coefficient for a pure gas is approximately  $0.75V_c B^*(T^*)$ , where  $T^* \equiv 1.3T/T_c$  and where  $B^*(T^*)$  is a fixed dimensionless function tabulated in reference 65. For a mixture of two gases the appropriate relations are:

$$B(T) = x_1^2 B_1(T) + 2x_1 x_2 B_{12}(T) + x_2^2 B_2(T) \quad (A2)$$

where

$$\left. \begin{aligned} B_1 &= 0.75 V_{c1} B^*(1.3T/T_{c1}) \\ B_2 &= 0.75 V_{c2} B^*(1.3T/T_{c2}) \\ B_{12} &= 0.75 \left( \frac{V_{c1}^{1/3} + V_{c2}^{1/3}}{2} \right)^3 B^*(1.3T/\sqrt{T_{c1}T_{c2}}) \end{aligned} \right\} \quad (A3)$$

By use of these equations, the term  $pB(T)/RT$  of equation (A1) - which represents the fractional deviation from thermal perfection - has been calculated for the gas mixtures listed in table IV. Computations were made both for reservoir conditions ( $p_t, T_t$ ) and test-section conditions ( $p_\infty, T_\infty$ ) at Mach numbers of 1.3, 2.5, and 3.5. For  $M_\infty = 1.3$  the values of  $p_t B(T_t)/RT_t$  and  $p_\infty B(T_\infty)/RT_\infty$  were about the same. The average value of  $|pB(T)/RT|$  per atmosphere of reservoir pressure varied from

about 0.0014 ( $C_4F_8$ ,  $C_3F_8$ ,  $CF_3CF_3$ ,  $CF_4$ , and  $NF_3$  mixtures) to about 0.004 ( $CH_2F_2$  mixture). Inasmuch as transonic research apparatuses commonly are limited to reservoir pressures of several atmospheres (often because of critical model loads), the resulting deviations from thermal perfection would be within about 1 percent and can be neglected. For  $M_\infty = 2.5$  and  $M_\infty = 3.5$ , the values of  $|p_\infty B(T_\infty)/RT_\infty|$  are substantially lower than  $|p_t B(T_t)/RT_t|$ . Both are tabulated as follows:

Gas	$M_\infty = 2.5$		$M_\infty = 3.5$	
	$ p_\infty B(T_\infty) $	$ p_t B(T_t) $	$ p_\infty B(T_\infty) $	$ p_t B(T_t) $
	$RT_\infty$	$RT_t$	$RT_\infty$	$RT_t$
CBrF <sub>3</sub>	0.0017	0.0033		
SF <sub>6</sub>	.0013	.0027		
CF <sub>3</sub> CF <sub>3</sub>	.0010	.0018		
CCLF <sub>3</sub>	.0016	.0030		
CF <sub>4</sub>	.0012	.0019	0.0007	0.0023
NF <sub>3</sub>	.0012	.0019	.0007	.0022
CHF <sub>3</sub>	.0017	.0034		
Air	.0005	.0002	.0002	.0002

It may be deduced that gas mixtures at test-section conditions ( $p_\infty, T_\infty$ ) would deviate 1 percent from thermal perfection at reservoir pressures between about 6 and 10 atmospheres for  $M_\infty = 2.5$ , and at about 14 atmospheres for  $M_\infty = 3.5$ . Since practical operation pressures of wind tunnels are well within these limits, the flow of these gas mixtures over a typical model can be regarded as closely approximating that of a thermally perfect gas. Deviations from thermal perfection at reservoir conditions ( $p_t, T_t$ ) are two to three times as large as at test-section conditions. Hence, when computing test-section Mach number or dynamic pressure from measured values of  $p_t$  and  $T_t$ , the deviations near reservoir conditions may have to be considered for reservoir pressures of the order of 5 to 10 atmospheres or greater.

## APPENDIX B

RELAXATION-TIME DATA AND ESTIMATE OF  
EFFECT FOR VARIOUS GAS MIXTURES

Results of measurements of relaxation time at atmospheric pressure ( $\beta_a$ ) for some of the polyatomic gases considered in this report are as follows:

Gas	Temperature, °K	$\beta_a$ , microseconds	Reference
CCl <sub>2</sub> F <sub>2</sub>	293	0.09	66,4
CF <sub>4</sub>	373	.66	67
CHF <sub>3</sub>	373	.42	67
CHClF <sub>2</sub>	293	.10	66
CH <sub>2</sub> F <sub>2</sub>	373	.055	67
CO <sub>2</sub>	293	7.0	66
N <sub>2</sub> O	293	1.1	66
Air (dry)	300	<sup>1</sup> 14.	68

Although measurements of  $\beta_a$  could be found only for those gases listed, certain known characteristics of relaxation time enable a rough estimate to be made for some of the remaining gases; for example, molecules with freedom of internal rotation invariably have very short relaxation times, generally less than  $10^{-8}$  second (see ref. 69, for example). Also the smaller the lowest fundamental vibration frequency, the shorter the relaxation time (see refs. 66 and 67). These general characteristics indicate that fluorocarbon molecules with internal rotation (e.g., CF<sub>3</sub>CBrF<sub>2</sub>, CF<sub>3</sub>CClF<sub>2</sub>, CF<sub>3</sub>CF<sub>3</sub>, CH<sub>3</sub>CClF<sub>2</sub>, CH<sub>3</sub>CHF<sub>2</sub>, C<sub>3</sub>F<sub>8</sub>, and C<sub>4</sub>F<sub>10</sub>, but not C<sub>4</sub>F<sub>8</sub>) would have relaxation times ( $\beta_a$ ) in the range  $10^{-8}$  to  $10^{-9}$  second, and that the methane-like gases CBrF<sub>3</sub> and CBrFClF<sub>2</sub> would have a relaxation time in the range of  $10^{-7}$  to  $10^{-8}$  second. It is to be noted that relaxation times listed are for pure gases, and that the presence of certain impurities can greatly reduce  $\beta_a$  for those gases having relatively long relaxation times.

Inasmuch as the relaxation time depends on temperature and pressure, some method of estimating  $\beta$  for the particular conditions encountered in wind tunnels must be employed. The analysis of Bethe and Teller

---

<sup>1</sup>This value corresponds to measurements of  $\beta_a$  for oxygen in the presence of nitrogen but in the absence of water vapor. Dry air is considered since air in supersonic wind tunnels and in the stratosphere is essentially dry.

---

(ref. 68) yields for the relaxation time  $\beta_v$  of the lowest frequency ( $v$ ) mode

$$\frac{C_p}{C_p - C_i} \beta_v = \frac{Z_{10}}{Z(1 - e^{-hv/kT})} \quad (B1)$$

where  $C_i$  is the total contribution to specific heat of internal vibration energy,  $Z$  is the total number of collisions one molecule experiences per second, and  $Z_{10}$  is the average number of collisions required to deactivate the lowest mode from the first quantum state to the zero state. Subsequent calculations are based on the additional equations

$$Z = 1.3 \frac{p}{\mu} \quad (\text{ref. 70}) \quad (B2)$$

$$\beta \approx \frac{C_i \beta_v}{C_v} \quad (\text{ref. 71}) \quad (B3)$$

$$Z_{10} \approx 25 \left( \frac{b}{T^{1/3}} \right)^{-3/2} e^{b/T^{1/3}} \quad (\text{ref. 68}) \quad (B4)$$

where  $b$  is a constant for each gas evaluated from measurements of  $\beta_a$  at the temperatures listed in the above table. These equations were developed for pure polyatomic gases. They will be used also for gas mixtures since the basic theory (especially eq. (B4)) is highly approximate, and since the effectiveness of an argon molecule in exciting vibration generally is roughly the same as that of an inert polyatomic molecule. (See the summary table in ref. 72 and the specific data for  $\text{CHClF}_2$ -Ar mixtures in ref. 73.)

Relaxation times  $\beta_\infty$  corresponding to free-stream conditions ( $T_\infty, p_\infty$ ) in a wind tunnel have been calculated for assumed reservoir conditions of one atmosphere total pressure and  $40^\circ \text{C}$  total temperature. The results, together with the "relaxation distance"  $d \equiv \beta_\infty u_\infty$ , were computed to two significant figures and are tabulated to one significant figure as follows:

Gas	$M_\infty=1.3, T_\infty=230^\circ \text{ K}, p_\infty=0.36 \text{ atm}$		$M_\infty=2.5, T_\infty=140^\circ \text{ K}, p_\infty=0.059 \text{ atm}$		$M_\infty=3.5, T_\infty=105^\circ \text{ K}, p_\infty=0.013 \text{ atm}$	
	$\beta_\infty,$ sec	$d,$ in.	$\beta_\infty,$ sec	$d,$ in.	$\beta_\infty,$ sec	$d,$ in.
$\text{CCl}_2\text{F}_2$	$2 \times 10^{-7}$	0.002				
$\text{CF}_4$	$3 \times 10^{-6}$	.03	$5 \times 10^{-5}$	0.8	$3 \times 10^{-4}$	6
$\text{CHF}_3$	$2 \times 10^{-6}$	.02	$3 \times 10^{-5}$	.5		
$\text{CHClF}_2$	$2 \times 10^{-7}$	.003				
$\text{CH}_2\text{F}_2$	$1 \times 10^{-7}$	.001	$7 \times 10^{-7}$	.01		
$\text{CO}_2$	$4 \times 10^{-5}$	.5				
$\text{N}_2\text{O}$	$6 \times 10^{-6}$	.06				
Air (dry)	$7 \times 10^{-5}$	1.	$3 \times 10^{-3}$	60.	$4 \times 10^{-2}$	1000

It is interesting that under wind-tunnel conditions, air has the longest relaxation time. For  $M_\infty \geq 2.5$  any model less than 5 feet long in an air wind tunnel would be entirely immersed within the relaxation region from the bow wave. This does not mean, however, that relaxation effects are important for air in a wind tunnel because the amount of internal vibration heat capacity ( $C_i$ ) that lags is very small. The effect of heat-capacity lag on flow conditions is influenced by both  $C_i$  and  $\beta$ .

To determine the dimensionless parameters which form a pertinent measure of relaxation effects, use is made of the theoretical equivalence between relaxation phenomena and volume-viscosity phenomena. In references 70, 74, and 75, this equivalence is shown to be valid at least under conditions where the relaxation time is small compared to the characteristic time ( $l/u_\infty$  for aerodynamic problems), and where  $C_i$  is small compared to  $C_p$ . For purposes of estimation, then, the complete, first-order stress tensor, including the volume viscosity, is used as the basis of computation.

$$P_{ij} = \underset{\text{Stokes}}{(P_{ij})_{\text{Navier}}} + \mu_v \frac{\partial u_k}{\partial x_k} \delta_{ij} \quad (\text{B5})'$$

In this equation  $\mu_v$  is the coefficient of volume viscosity,  $\partial u_k / \partial x_k$  is (using summation convention) the divergence of the velocity vector, and  $\delta_{ij}$  is unity if  $i$  is equal to  $j$ , but is zero otherwise. The ultrasonic theory of Tisza (ref. 74), the kinetic theory of Kohler (ref. 70), and the irreversible thermodynamics theory of Meixner (ref. 75) each indicate  $\mu_v$  to be proportional to  $\gamma(\gamma-1)p\beta$ , although the proportionality factor  $f \equiv \mu_v / \gamma(\gamma-1)p\beta$  differs somewhat between these analyses. The various values calculated for  $f$  are  $C_i / C_p$ ,  $C_i / (C_p - \gamma C_i)$ , and  $C_i / (C_p - \gamma C_i)$ , respectively. These values are mutually consistent in view of the common assumption made in references 74, 70, and 75, that  $C_i$  is

small compared to  $C_p$ . For present purposes an intermediate value  $f = C_p / (C_p - C_1)$  is used, since a comparison with the Kantrowitz impact-pressure theory (ref. 76) indicated this value to yield the same energy dissipation - and, hence, the same total-pressure defect - as the Kantrowitz theory for a gas flow wherein small relaxation effects occur. Consequently, the evaluation  $\mu_v = \gamma(\gamma-1)p\beta C_1 / (C_p - C_1)$  together with equation (B5) will be employed to estimate effects of heat-capacity lag both for inviscid and viscous flow.

For inviscid flow the Navier-Stokes portion of the stress tensor is simply the static pressure  $p$ . The pertinent similarity parameter involving relaxation time is  $\mu_v u_\infty / (pl) = \gamma(\gamma-1)(\beta u_\infty / l) C_1 / (C_p - C_1)$ . Since the equation of steady motion is  $\rho u_j \partial u_i / \partial x_j = -\partial p_{ij} / \partial x_j$ , the ratio of the relaxation term to the other stress term is, in order of magnitude,

$$\frac{\frac{\partial}{\partial x} \left( \mu_v \frac{\partial u_k}{\partial x_k} \right)}{\frac{\partial}{\partial x} (p)} \sim \frac{\mu_v u_\infty}{pl} \quad (B6)$$

Which is seen to be the same as the similarity parameter.<sup>2</sup> Hence,  $\mu_v u_\infty / pl$  is interpreted as a measure of the fractional effect of relaxation phenomena on pressure distribution.

Inasmuch as the parameter  $\mu_v u_\infty / pl$  can be rearranged as  $(\mu_v / \mu) \gamma M_\infty^2 / Re$ , it is clear that relaxation effects on pressure distribution generally will not be important except for low-density, high Mach number conditions where  $Re$  is small. For dry air at wind-tunnel temperatures,  $\mu_v / \mu$  is negligible compared to unity, and hence the parameter  $\mu_v u_\infty / pl$  also is negligible, even at low Reynolds numbers. For dry air at flight temperatures (say  $300^\circ K$  to  $2000^\circ K$ ), however,  $\mu_v / \mu$  varies between about 80 and 200, thereby indicating sizable relaxation effects, for example, at  $M_\infty = 3.5$  if the Reynolds number of flight is the order of several thousand or less. For gas mixtures at wind-tunnel temperatures,  $\mu_v / \mu$  varies widely depending on the polyatomic gas, and covers the range from about 20 to 1000, thus encompassing values both less than and greater than those for air under flight conditions.

In a gas mixture,  $C_1 = x_2 C_{12}$ . Computations of the resulting parameter  $\mu_v u_\infty / p_\infty l = \gamma(\gamma-1)(\beta_\infty u_\infty / l) C_1 / (C_p - C_1)$  for wind-tunnel flow conditions

---

<sup>2</sup>A more precise calculation of this ratio of stress terms can be made using the continuity equation to eliminate  $\partial u_k / \partial x_k$ . This procedure ultimately yields a value  $(\mu_v u_\infty / pl) [M^2 \partial(u/u_\infty) / \partial(x/l)]$ , from which it can be deduced that, the simple parameter  $(\mu_v u_\infty / pl)$  will underestimate relaxation effects for bluff obstacles like the sphere, but will overestimate them for slender obstacles like an airfoil.

over a 1-inch model yield the following results:

Gas	$\gamma(\gamma-1) \frac{x_2 C_{i2}}{C_p - C_i} \frac{\beta_{\infty} u_{\infty}}{l}$ for $l = 1$ in., $p_t = 1$ atm		
	$M_{\infty} = 1.3$	$M_{\infty} = 2.5$	$M_{\infty} = 3.5$
CCl <sub>2</sub> F <sub>2</sub>	0.0003		
CF <sub>4</sub>	.004	0.04	0.1
CHF <sub>3</sub>	.002	.01	
CHClF <sub>2</sub>	.0003		
CH <sub>2</sub> F <sub>2</sub>	.00006	.0001	
CO <sub>2</sub>	.03		
N <sub>2</sub> O	.005		
Air (dry)	.0002	.00005	.00008

For transonic wind tunnels it is seen that only CO<sub>2</sub> mixtures would exhibit appreciable relaxation effects on pressure distribution. On the other hand, for  $M_{\infty} = 3.5$ , mixtures involving CF<sub>4</sub> would be affected roughly by 10 percent for the assumed conditions of  $p_t = 1$  atmosphere and  $l = 1$  inch. To maintain these effects below about 1 percent would require the product  $p_t l$  to be greater than 10 atmosphere-inches (e.g., a 5-inch model in a 2-atmosphere tunnel). Such restrictions are believed not to represent serious limitations on the usefulness of gas mixtures, especially since the favorable effect of certain impurities in reducing  $\beta$  has not been included in the analysis. It is concluded, then, that insofar as pressure distribution in inviscid flow is concerned, relaxation effects need not be considered for the usual wind-tunnel operation conditions.

For viscous flow within a laminar boundary layer, the Navier-Stokes portion of the stress tensor customarily is approximated by  $\mu \frac{\partial u}{\partial y}$ . The ratio of the relaxation term to the ordinary term in the equation of motion is

$$\frac{\frac{\partial}{\partial x} \left( \mu_v \frac{\partial u_k}{\partial x_k} \right)}{\frac{\partial}{\partial y} \left( \mu \frac{\partial u}{\partial y} \right)} \sim \frac{\frac{1}{l} \left( \mu_v \frac{\partial u_k}{\partial x_k} \right)}{\frac{1}{\delta} \left( \mu \frac{\partial u}{\partial y} \right)} \sim \left( \frac{\delta}{l} \right) \frac{\mu_v}{\mu} \frac{\partial x_k}{\partial y}$$

Examination of the solution to boundary-layer equations for flow over a flat plate (e.g., ref. 77) indicates the average value of  $(\partial u_k / \partial x_k) / (\partial u / \partial y)$  to be of the order of  $(\gamma-1)M_{\infty}^2 / 10\sqrt{Re}$ , and  $\delta/l$  to be of the order of  $[6 + (\gamma-1)M_{\infty}^2] / \sqrt{Re}$ . Hence,

$$\frac{\frac{\partial}{\partial x} \left( \mu_v \frac{\partial u_k}{\partial x_k} \right)}{\frac{\partial}{\partial y} \left( \mu \frac{\partial u}{\partial y} \right)} \sim \frac{\mu_v}{\mu} \left[ \frac{(\gamma-1)M_\infty^2}{10 \text{ Re}} \right] [6 + (\gamma-1)M_\infty^2] \quad (\text{B7})$$

This ratio, which is interpreted as a measure of the fractional effect of relaxation phenomena on boundary-layer flow, is important primarily at low Reynolds numbers and high Mach numbers, just as is the effect of relaxation phenomena on inviscid flow. For air under wind-tunnel conditions, the expression (B7) is entirely negligible due to the very low values of  $\mu_v/\mu$ . However, for air under flight conditions ( $\mu_v/\mu \sim 10^2$ ), the ratio can be significant at low Reynolds numbers (e.g., at  $\text{Re} \sim 500$  for  $M_\infty = 3.5$ , at  $\text{Re} \sim 5000$  for  $M_\infty = 7$ , and at  $\text{Re} \sim 200,000$  for  $M_\infty = 10$ ). In order to simulate in a low-density gas-mixture wind tunnel the heat-capacity lag that would exist in the boundary layer during flight, the ratio  $\mu_v/\mu$  would have to be simulated. As previously noted, it is possible to simulate this ratio in a gas-mixture wind tunnel due to the wide range of values of  $\mu_v/\mu$  covered by the various polyatomic gases.



## APPENDIX C

## NOTATION

a	speed of sound
c	speed of light
$c_p$	specific heat per unit mass
$C_p$	specific heat per mole
CR	wind-tunnel compression ratio
g	acceleration of gravity
h	Plank's constant
H	molar enthalpy
HP	horsepower
k	Boltzman's constant
l	characteristic length of model
L	characteristic dimension of wind-tunnel test section
m	molecular weight (29 grams per mole for air)
M	Mach number
n	number of atoms per molecule
p	pressure
q	dynamic pressure, $\frac{1}{2}\rho u^2$
R	universal gas constant per mole (1.987 cal. mole <sup>-1</sup> °K <sup>-1</sup> )
Re	Reynolds number
T	temperature
u	velocity
V	volume of gas
w	mass-flow rate, ( $\rho u$ ) times (cross-section area)

x	mole fraction, equal to ratio of partial pressure to mixture static pressure and equal to fraction by volume
$\beta$	relaxation time
$\gamma$	ratio of specific heats
$\rho$	mass density
$\mu$	viscosity coefficient
$\mu_v$	volume viscosity coefficient
$\omega$	wave number ( $\text{cm}^{-1}$ , from spectroscopic data)

#### Subscripts

$\infty$	free-stream conditions in test section
c	critical conditions for gaseous phase of a compound
t	total conditions for gas brought isentropically to rest (wind-tunnel reservoir conditions)
o	0° centigrade
1	monatomic gas
2	polyatomic gas

#### Superscripts

-	quantity divided by corresponding quantity for air
---	--

## REFERENCES

1. Theodorsen, Theodore, and Regier, Arthur: Experiments on Drag of Revolving Disks, Cylinders, and Streamline Rods at High Speeds. NACA Rep. 793, 1944.
2. Smelt, R.: Power Economy in High-Speed Wind Tunnels by Choice of Working Fluid and Temperature. RAE Rep. No. Aero 2081, British, 1945.
3. Kantrowitz, Arthur: The Supersonic Axial-Flow Compressor. NACA Rep. 974, 1946.
4. Huber, Paul W.: Use of Freon 12 As a Fluid for Aerodynamic Testing. NACA TN 1024, 1946.
5. Buell, C. E.: Spark Photography of Projectile Flight in Special Gases. Part I. The Freons. New Mexico School of Mines, Res. and Dev. Div. Tech. Rep. 453, 1948.
6. Donaldson, Coleman DuP., and Sabol, Alexander P.: Experiments on Aerodynamic Phenomena at Mach Numbers in the Range from 10 to 20. Proc. of First U. S. Nat. Cong. Appl. Mech., 1951, pp. 757-762.
7. von Doenhoff, A. E., and Braslow, A. L.: Studies of the Use of Freon-12 as a Wind-Tunnel Testing Medium. NACA TN 3000, 1953.
8. Duff, Russell E.: The Use of Real Gases in a Shock Tube. Univ. of Mich., Engr. Res. Inst. Proj. M720-4, Rep. 51-3, 1951.
9. Gunn, J. C.: Relaxation Time Effects in Gas Dynamics. British R. & M. No. 2338, British A.R.C., 1946.
10. Smout, Arthur: Discussion of paper "Titanium-A Survey" by P. L. Teed. Jour. of R.A.S., vol. 57, no. 508, Apr. 7, 1953, pp. 207-208.
11. Ruhemann, Martin.: The Separation of Gases. Second ed., ch. IX, Oxford Univ. Press, 1949.
12. Anon: Handbook of Chemistry and Physics. 33rd edition, 1951-1952. Chemical Rubber Publishing Company, Cleveland, Ohio.
13. Anon: Fluorocarbons Issue. Ind. Engr. Chem., Mar. 1947.
14. Simons, J. H., ed.: Fluorine Chemistry. Vol. 1. Academic Press Inc., N. Y., 1950.

15. Slessor, C., and Schram, S. R., eds.: Preparation, Properties, and Technology of Fluorine and Organic Fluoro Compounds. National Nuclear Energy Series, div. VII, vol. I, McGraw-Hill Book Co., New York, 1951.
16. Henne, Albert L.: Fluoroform. Jour. Am. Chem. Soc., no. 59, 1937, p. 1200.
17. Lester, D., and Greenberg, L. A.: The Toxicity of Sulfur Hexafluoride. Archives of Industrial Hygiene and Occupational Medicine, vol. 2, 1950, p. 348.
18. Lester, D., and Greenberg, L. A.: The Toxicity of Sulfur Pentafluoride. Archives of Industrial Hygiene and Occupational Medicine, vol. 2, 1950, p. 350.
19. Steunenberg, R. K., and Cady, G. H.: Pyrolysis of Fluorocarbons. Jour. Am. Chem. Soc., vol. 74, 1950, p. 4165.
20. Silvey, G. A., and Cady, G. H.: Trifluoromethylsulfur Pentafluoride. Jour. Am. Chem. Soc., vol. 72, 1950, p. 3624.
21. Chambers, William H., et al.: An Investigation of the Toxicity of Proposed Fire Extinguishing Fluids. Medical Div. Res. Rep. no. 23, CMLEM-52. Chem. Corps, Army Chem. Center, Maryland, 1950.
22. Wicklund, John S., Flieger, Howard W., and Masi, Joseph F.: Heat Capacity of Gaseous Hexafluoroethane. Nat. Bur. of Standards Jour. Res., vol. 51, no. 2, Aug. 1953, pp. 91-92.
23. Hendricks, James O.: Industrial Fluorochemicals. Ind. Engr. Chem., vol. 45, Jan. 1953, p. 99.
24. Nodiff, E. A., Grosse, A. V., and Hauptschein, M.: Physical Properties of n-Perfluoroalkyl Halides and Dihalides and a Comparison With Corresponding Alkyl Compounds. Jour. Org. Chem., vol. 18, 1953, p. 235.
25. Sidgwick, N. V.: The Chemical Elements and Their Compounds. Vols. I and II, Oxford Univ. Press, 1950.
26. Eiseman, B. J., Jr.: Pressure-Volume-Temperature Properties of the Freon Compounds. Refrig. Engr., vol. 60, Jan. 1952, pp. 496-503.
27. Miller, H. C., Verdelli, L. S., and Gall, J. F.: Some Physical Properties of Sulfur Hexafluoride. Ind. Engr. Chem., vol. 43, 1951, p. 1126.
28. Decker, C. E., Meister, A. G., and Cleveland, F. F.: Substituted Methanes. VI. Force Constants and Calculated Thermodynamic Properties for Some Trifluoromethanes. Jour. Chem. Phys., vol. 19, 1951, p. 784.

29. Lagemann, R. T., and Jones, E. A.: The Infrared Spectrum of Sulfur Hexafluoride. *Jour. Chem. Phys.*, vol. 19, 1951, p. 534.
30. Plyler, E. K., and Benedict, W. S.: Infrared Spectra of Eighteen Halogen-Substituted Methanes. *Nat. Bur. of Standards Jour. Res.*, vol. 47, Sept. 1951, pp. 202-220.
31. Cowan, R. D., Herzberg, G., and Sinha, S. P.: Rotation-Vibration Spectra of Diatomic and Simple Polyatomic Molecules with Long Absorbing Paths. IV. The Spectrum of Methyl Fluoroform ( $\text{CH}_3\text{CF}_3$ ) from 19 to 0.7. *Jour. Chem. Phys.*, vol. 18, 1950, p. 1538.
32. Nielsen, J. R., and Claassen, H. H.: Infra-Red and Raman Spectra of Fluorinated Ethanes. II. 1,1,1-Trifluoroethane. *Jour. Chem. Phys.*, vol. 18, 1950, p. 1471.
33. Nielsen, J. R., Liang, C. Y., Smith, R. M., and Smith, D. C.: Infra-Red and Raman Spectra of Fluorinated Ethanes. V. The Series  $\text{CF}_3\text{CF}_3$ ,  $\text{CF}_3\text{CF}_2\text{Cl}$ ,  $\text{CF}_3\text{CFCl}_2$ , and  $\text{CF}_3\text{CCl}_3$ . *Jour. Chem. Phys.*, vol. 21, 1953, p. 383.
34. Nielsen, J. R., and Richards, C. M.: The Infra-Red Absorption Spectra of Hexafluoroethane Gas. *Jour. Chem. Phys.*, vol. 16, 1948, p. 67.
35. McGee, P. R., Cleveland, F. F., Meister, A. G., Decker, C. E., and Miller, S. I.: Substituted Methanes. X. Infrared Spectral Data, Assignments, Potential Constants, and Calculated Thermodynamic Properties for  $\text{CF}_3\text{Br}$  and  $\text{CF}_3\text{I}$ . *Jour. Chem. Phys.*, vol. 21, 1953, p. 242.
36. Smith, D. C., Saunders, R. A., Nielsen, J. Rud, and Ferguson, E. E.: Infrared and Raman Spectra of Fluorinated Ethanes. IV. The Series  $\text{CH}_3\text{-CH}_3$ ,  $\text{CH}_3\text{-CH}_2\text{F}$ ,  $\text{CH}_3\text{-CHF}_2$ , and  $\text{CH}_3\text{-CF}_3$ . *Jour. Chem. Phys.*, vol. 30, no. 5, May 1952, pp. 847-859.
37. Smith, D. C., Brown, G. M., Nielsen, J. R., Smith, R. M., and Liang, C. Y.: Infrared and Raman Spectra of Fluorinated Ethanes. III. The Series  $\text{CH}_3\text{CF}_3$ ,  $\text{CH}_3\text{CF}_2\text{Cl}$ ,  $\text{CH}_3\text{CFCl}_2$ , and  $\text{CH}_3\text{CCl}_3$ . *Jour. Chem. Phys.*, vol. 20, 1952, p. 473.
38. Nuckolls, A. H.: The Comparative Life, Fire, and Explosion Hazards of of Common Refrigerants. Underwriters Laboratories Repts. Misc. Hazard no. 2375, 1933; and, Nuckolls, Asa Hopkins: The Comparative Life, Fire, and Explosion Hazards of Difluoromonochloromethane ("Freon-22"). Underwriters Labs., Inc., Chicago, Misc. Hazard no. 3134, 1940.
39. White, Locke Jr., and Rice, O. K.: The Thermal Reaction of Hexafluoroethane with Quartz. *Jour. Am. Chem. Soc.*, vol. 69, 1947, p. 267.

40. Kobe, K. A.: The Critical Properties of Elements and Compounds. Chem. Rev., vol. 52, 1953, p. 117.
41. Herzberg, Gerhard: Molecular Spectra and Molecular Structure. Vol. II. Infrared and Raman Spectra of Polyatomic Molecules. Van Nostrand, Inc., New York, 1945.
42. Yost, D. M., and Claussen, W. H.: The Thermochemical Constants of the Hexafluorides of Sulfur, Selenium and Tellurium. Jour. Am. Chem. Soc., vol. 55, 1933, p. 885.
43. Ruff, O.: Zur Kenntnis des Stickstoff-3-fluorids. Zeitschrift für anorganische und allgemeine chemiel., vol. 197, 1933, p. 273.
44. Haszeldine, R. S., and Sharpe, R. G.: Fluorine and its Compounds. Methuen's Monographs on Chemical Subjects. John Wiley and Sons, New York, 1951.
45. Claassen, H. H.: Vibration Spectra and Normal Coordinate Treatment of Perfluorocyclobutane. Jour. Chem. Phys., vol. 18, 1950, p. 543.
46. Haszeldine, R. S.: Perfluoro-tert.-amines. Chem. Soc. Jour. I, 1951, p. 102.
47. Thompson, J., and Emeleus, H. J.: The Fluorination of Trimethylamine. Chem. Soc. Jour. 4, 1949, p. 3080.
48. Whipple, G. H.: Vapor-Liquid Equilibria of Some Fluorinated Hydrocarbon Systems. Ind. Engr. Chem., vol. 44, 1952, p. 1664.
49. Plyler, E. K., and Acquista, N.: Infrared Absorption Spectra of Five Halomethanes. Nat. Bur. of Standards Jour. Res., vol. 48, no. 1, Jan. 1952, pp. 92-97.
50. Yost, D. M.: The Raman Spectra of Volatile Fluorides. Applications of Raman Spectra to Chemical Problems. Proc. Indian Acad. Sci., vol. 8A, 1948, p. 33.
51. Masi, J. F.: Thermodynamic Properties of Gaseous Difluorodichloromethane. Jour. Amer. Chem. Soc., vol. 74, 1952, p. 4738.
52. Schumb, W. C.: Preparation and Properties of Sulfur Hexafluoride. Ind. Engr. Chem., vol. 39, no. 3, Mar. 1947, pp. 421-423.
53. Anon: Sulfur Hexafluoride. General Chem. Co. Tech. Service Bull. SF<sub>6</sub>-A, 1952.
54. Wilson, M. K., and Polo, S. R.: The Infrared Spectra of NF<sub>3</sub> and PF<sub>3</sub>. Jour. Chem. Phys., vol. 20, 1952, p. 1716.

55. Perkins, W. D., and Wilson, M. K.: The Infrared Spectrum of  $\text{SO}_2\text{F}_2$ . Jour. Chem. Phys., vol. 20, 1952, p. 1791.
56. Kirk, Raymond E., and Othmer F., eds.: Encyclopedia of Chemical Technology. Interscience Pub., Inc., N. Y., vol. 6, 1951, pp. 667-771.
57. Fowler, Ralph H., and Guggenheim, E. A.: Statistical Thermodynamics. Ch. III, Cambridge Univ. Press, 1952.
58. Hougen, Olaf A., and Watson, Kenneth M.: Chemical Process Principles. Vol. II of Thermodynamics. John Wiley and Sons, N. Y., 1947.
59. Wilke, C. R.: A Viscosity Equation for Gas Mixtures. Jour. Chem. Phys., vol. 18, 1950, p. 517.
60. Hirschfelder, Joseph O., Bird, R. Byron, and Spotz, Ellen L.: The Transport Properties of Gases and Gaseous Mixtures. II. Chemical Reviews., vol. 44, no. 1, 1949, pp. 205-231.
61. Sabatier, Germain: Viscosity des Gaz et Donnees Critques. J. Chim. Phys., vol. 48, 1951, p. 113.
62. Staff of The Johns Hopkins University, Applied Physics Laboratory: Handbook of Supersonic Aerodynamics. Vol. V of Properties of Gases, sec. 15. Bur. of Ordnance, Navy Dept. NAVORD Rep. 1488, Aug. 1953.
63. Hadley, E. H., and Bigelow, L. A.: The Action of Elementary Fluorine Upon Organic Compounds. IX. The Vapor Phase Fluorination of Methane. Jour. Am. Chem. Soc. 62, 1940, p. 3302.
64. Midgley, T., Jr., and Henne, A. L.: Organic Fluorides as Refrigerants. Ind. Engr. Chem. 22, no. 5, 1931, p. 542.
65. Bird, R. B., Hirschfelder, J. O., and Curtis, C. F.: Survey of the Equation of State and Transport Properties of Gases and Liquids. Proc. of Third Midwestern Conference on Fluid Mech., Univ. of Minn., Inst. of Tech., Minneapolis, Minn., Mar. 23-25, 1953.
66. Griffith, Wayland: Vibrational Relaxation Times in Gases. Jour. Appl. Phys., vol. 21, no. 12, Dec. 1950, pp. 1319-1325.
67. Fogg, P. G. T., Hanks, P. A., and Lambert, J. D.: Ultrasonic Dispersion in Halo-Methane Vapors. Proc. Roy. Soc. (London). Series A, vol. 219, no. 1139, pp. 490-499, Oct. 7, 1953.
68. Bethe, Hans Albrecht and Teller, E.: Deviations from Thermal Equilibrium in Shock Waves. Aberdeen Proving Ground, Aberdeen, Md., Ballistic Research Laboratory. Rep. X-117, 1945.

69. Lambert, J. D., and Rowlinson, J. S.: Ultrasonic Dispersion in Organic Vapours. Proc. Roy. Soc. (London). Series A. no. 1078, Dec. 22, 1950, vol. 204, pp. 424-434.
70. Kohler, Max: Reibung in massig verdunnten Gasen als Folge Verzogerter einstellung der Energie. Zeit. f. Physik. 125, 715-732 (1949).
71. Schafer, Klaus: Die stossanregung intramolekularer schwingungen in gasen und gasmischungen. VII Theorie der schalldispersion bei vorhandensien mehrer normal-schwingungen. Zeit. f. Physilcalische Chemie B 46, 212-228 (1940).
72. Walker, Richard: Heat Capacity Lag in Gases. NACA TN 2537, 1951.
73. Rossing, Thomas D. and Legvold, Sam: Heat Capacity Lag of Gas Mixtures. Iowa Engineering Experiment Station, Iowa State College, Ames, Iowa. Final Report, Contract NAW-6219, Aug. 17, 1952 to Aug. 17, 1953.
74. Tisza, L.: Supersonic Absorption and Stokes' Viscosity Relation. Phys. Rev., vol. 61, no. 7-8, Apr. 1-15, 1942, pp. 531-536.
75. Meixner, J.: Allgemeine Theorie der Schallabsorption in Gasen und Flussigkeiten unter Berucksichtigung der Transporterscheinungen. Acoustica, vol. 2, pp. 101-109, 1952.
76. Kantrowitz, Arthur R.: Heat-Capacity Lag in Gas Dynamics. Jour. Chem. Phys., vol. 14, no. 3, Mar. 1946, pp. 150-164.
77. Chapman, Dean R., and Rubesin, Morris W.: Temperature and Velocity Profiles in the Compressible Laminar Boundary Layer with Arbitrary Distribution of Surface Temperature. Jour. Aero. Sci., vol. 16, no. 9, Sept. 1949, pp. 547-565.



TABLE I.- PROPERTIES OF HEAVY MONATOMIC GASES AND AIR CONSTITUENTS

Symbol	Gas	m, gm. mole	Boiling temp., °C	Critical constants			Viscosity at 0° C $\mu_0$ , micropoise
				T <sub>c</sub> , °K	P <sub>c</sub> , atm.	V <sub>c</sub> , cc/gm. mole	
Ar	argon	40	-186	151	48	75.3	210
Kr	krypton	84	-153	210	54	92.1	230
Xe	xenon	131	-107	290	58.2	114	210
N <sub>2</sub>	nitrogen	28	-196	126	33.5	90.0	166
O <sub>2</sub>	oxygen	32	-183	154	49.7	74.4	189
	air	29		132	37.2	83	172



TABLE II.- GENERAL CHARACTERISTICS OF POLYATOMIC GASES

Formula	M <sub>w</sub> , gm. mole	Chemical name	Common or trade name	General classifi- cation .. (1)	Remarks	References	
						Spectro- scopic data	Toxicity data
C <sub>4</sub> F <sub>10</sub> C <sub>2</sub> F <sub>6</sub> N <sub>2</sub>	238 221	n-perfluorobutane perfluorotertiaryamine		S S?	Reported "as nontoxic as fluorocarbons." Chemistry resembles NF <sub>3</sub> . Stable to at least 400° C.	14 56	14, 19, 15 14, 56, 44, 46, 23
C <sub>4</sub> F <sub>8</sub> CF <sub>3</sub> CF <sub>2</sub> CF <sub>3</sub> CF <sub>2</sub> F	200 199 196	perfluorocyclobutane bromoethorane trifluoromethylsulfur-	Freon C318	S S? S? S?	Toxicity unknown. Toxicity, liquid density unknown.	45	48, 15, 26 20
SeF <sub>6</sub> C <sub>6</sub> F <sub>6</sub> C <sub>6</sub> F <sub>8</sub> C <sub>6</sub> F <sub>8</sub> N <sub>2</sub>	193 186 171	pentafluoride selenium hexafluoride perfluoropropane perfluorodimethylamine		S? S? S? S?	Toxicity unknown. Musty odor. Toxicity, liquid density unknown. Toxicity probably excessive. More toxic than CHCl <sub>3</sub> .	50	14, 25, 42 14, 56, 19 44, 47
CH <sub>2</sub> ClCF <sub>2</sub> CF <sub>3</sub> OCF <sub>3</sub>	165 155 154	bromochlorodifluoromethane chloroethorane perfluoroether	Freon 12B1 Freon 115	Q S S?	Reported "as nontoxic as fluorocarbons." Liquid density unknown. Stable to at least 400° C. Excellent fire extinguisher	49	26
CBr <sub>2</sub> F <sub>2</sub> CF <sub>3</sub> SFe <sub>6</sub>	149 146	bromotrifluoromethane sulfurhexafluoride	Freon 12B1 Kulene 131	S S, I	Excellent high-voltage gaseous insulator. Extremely inert chemically. Thermally stable to about 500° C. Thermally stable to about 700° C.	33 35	14, 26 14, 56, 44, 23 14, 26, 56
CF <sub>3</sub> CF <sub>2</sub> CCL <sub>2</sub> CF <sub>2</sub> CCL <sub>2</sub> F <sub>2</sub> CF <sub>3</sub> NF <sub>2</sub>	138 137 121 121	ethorane 1-chloro-2-hydroethorane dichlorodifluoromethane perfluoromethylamine	Freon 12Ha Freon 12	S S? S? S?	Musty odor. Toxicity, liquid density unknown.	29	14, 56, 25, 27, 52, 53
CCl <sub>3</sub> F SO <sub>2</sub> F <sub>2</sub>	105 102	chlorotrifluoromethane sulfuryl fluoride	Freon 13	S	Toxicity, liquid density unknown. Chemistry resembles SF <sub>6</sub> .	34	14, 56, 19, 39, 22 14, 26
CHF <sub>2</sub> CHF <sub>2</sub> CF <sub>3</sub> CClF <sub>2</sub>	102 101	1-hydro-2-hydroethorane 1-chloro-1, 1-difluoro- ethane	Genetron 101	S? Q	Slightly flammable, toxicity marginal. (See remarks for Genetron 100.)	30, 51	14, 26, 63 14, 56, 44
FCNF <sub>2</sub> CF <sub>4</sub> CHClF <sub>2</sub>	99 88 87	carbonylnitrogen-tri- fluoride carbon tetrafluoride chlorodifluoromethane	Freon 14 Freon 22	S? S Q	Toxicity, liquid density unknown. Reported as very inert. Extreme thermal stability and chemical inertness. Toxicity marginal (classified U.A.L. Group 5A).	28, 30 30	14 14, 56, 19 14
CH <sub>3</sub> CF <sub>3</sub> NF <sub>3</sub> CHF <sub>3</sub> CH <sub>3</sub> CHF <sub>2</sub>	84 71 70 66	1,1,1-trifluoroethane nitrogen trifluoride fluoroform 1,1-difluoroethane	Freon 23 Genetron 100	S? S? S, I Q	Toxicity and flammability unknown Toxicity uncertain since early tests (Ruff, ref. 43) are questionable. Thermally stable to at least 1100° C. Slightly flammable, but forms nonflammable azeotropic mixture with Freon 12. Azeotropic mixture called "carrene 7," has m = 100, T <sub>0</sub> = -33° C.	31, 32 54 28, 30 36	14 43, 25 14, 43 14 18, 25
CH <sub>2</sub> F <sub>2</sub> CO <sub>2</sub> N <sub>2</sub> O	52 44 44	difluoromethane carbon dioxide nitrous oxide	Freon 32	S? Q Q	Flammability unknown. Toxic for prolonged exposure at concentrations above about 3 per cent. Nonflammable but acts as oxidant at high temperature. Toxic at high concentrations.	30 41 41	14 25 40, 13 25 40, 13

15 satisfactory, in that sufficient information is available to regard the gas as nontoxic, noncorrosive, nonflammable, thermally stable at at least about 200° C, and inert chemically.  
 S? may be satisfactory, but available information is insufficient to judge it so. (See remarks for each gas thus classified.)  
 Q questionable because of possessing at least one undesirable characteristic (see remarks) which, however, may not be totally disqualifying.  
 I inert physiologically, as determined by tests with small animals living in atmosphere of 20-percent oxygen, 80-percent gas in question, and showing no observable effects either during the duration of tests (usually several hours) or afterwards.



TABLE III.- PHYSICAL CHARACTERISTICS OF POLYATOMIC GASES

Formula	$m_2$ , gm mole	Boiling temp., $T_b$ , °C (1)	Critical constants			Viscosity at 0° C $\mu_2$ , micropoise	$\frac{\bar{m}_2}{P_2}$	$\frac{(\bar{V}_2)^2}{(\bar{m}_2)^{3/2}}$	Spectroscopic data fundamental wave numbers, $\omega_1$ , $\text{cm}^{-1}$ (a)
			$T_c$ , °K	$P_c$ , atm.	$V_c$ , cc/gm. mole				
$C_4F_{10}$	238	-2	387	23	378	111	12.7	0.018	
$C_3F_8$	221	-11	390e		331e	111	10.7	.023	1431, 1385, 1340, 1285, 1239(2), 1280, 1008(2), 963, 745(2), 699, 660(2), 613, 569, 439 359, 338(2), 285, 273, 258, 250(2), 192(2), 173, 86
$C_4F_8$	200	-6	386e	32e	268e	128	9.2	.031	
$CF_3CF_2F_2$	199	-22							
$CF_3CF_2F_2$	196	-20							
$SeF_6$	193	-47 sub.	340e	26e	219e	154	7.4	.047	787(3), 708, 662(2), 461(3), 405(3), 245(3)
$C_3F_8$	188	-38	344e		298e	122	9.1	.030	
$C_2F_6NF$	171	-37							
$CF_3CF_2F_2$	165	-4	427	41.2	232	121	8.1	.036	1150, 1102, 872, 648, 440, 400, 380, 300, 200
$CF_3CClF_2$	155	-38	353	30.8	260	119	7.7	.039	1350, 1241, 1236, 1186, 1132, 982, 763, 648, 595, 561, 454, 441, 366, 331, 315, torsion, 186(2)
$CF_3OCF_3$	154	-59							
$CF_3F_3$	149	-60	341		199	143	6.2	.059	1207(2), 1087, 762, 548(2), 348, 297(2)
$SF_6$	146	-64 sub.	319	36.8	201	142	6.1	.060	940(3), 775, 644(2), 615(3), 524(3), 363(3)
$CF_3CF_3$	138	-78	293	29.9	220	139	5.9	.063	1420, 1250(2), 1235(2), 1120, 810, 715, 620(2), 520(2), 380(2), 350, 214(2), torsion
$CClF_2CHF_2$	137	-10	400	36.7	251	108	7.5	.038	
$CCl_2F_2$	121	-30	385	39.6	218	118	6.1	.055	1159, 1101, 906, 667, 473, 455, 437, 318, 261
$CF_3NF_2$	121	-78							
$CClF_3$	105	-80	302	39	180	136	4.6	.091	1210(2), 1102, 783, 560(2), 478, 356(2)
$SO_2F_2$	102	-55	340e						1502, 1269, 885, 848, 553, 544, 539, 385, 300
$CHF_2CHF_2$	102	-23							
$CH_3CClF_2$	101	-9	411	40.7	232	97	6.2	.049	3035, 2965, 1447, 1395, 1231, 1202, 1127, 1103, 967, 904, 683, 544, 526, 435, 429, 334, 305, torsion
$FCO NF_2$	99	-82							
$CF_4$	88	-128	228	36.8	139	171	3.1	.19	1265(3), 904, 630(3), 437(2)
$CHClF_2$	87	-41	370	48.5	165	120	4.3	.094	3023, 1347, 1311, 1178, 1116, 809, 595, 422, 365 3034(2), 2975, 1409, 1442(2), 1281, 1234(2), 970(2), 830, 606(2), 541, 368(2), 238, torsion
$CH_3CF_3$	84	-47							
$NF_3$	71	-129	230e		125e	164	2.6	.24	1032, 647, 905(2), 493(2)
$CH_3F$	70	-84	306	47	136	134	3.1	.16	1376(2), 1160(2), 1117, 697, 508(2), 3062
$CH_3CHF_2$	66	-25	387	44.3	181	96	4.1	.091	3018, 3001, 2979, 2963, 1460, 1452, 1414, 1372, 1360, 1171, 1145, 1120, 925, 868, 570, 472, 392, torsion
$CH_2F_2$	52	-52	351	72.9	96	93	3.3	.12	3012, 2949, 1508, 1435, 1262, 1176, 1116, 1090, 529
$CO_2$	44	-79 sub.	304			137	1.9	.34	2349, 1340, 667(2)
$N_2O$	44	-88	310	71.7	98	135	1.9	.33	2237, 1288, 588(2)

1sub. sublimates at atmospheric pressure.

2e estimated from similar gases, or from liquid density and reduced orthobaric density of similar gases.

3 number in parentheses denotes degree of degeneracy of wave number it follows.



TABLE IV.- CHARACTERISTICS OF GAS-MIXTURE WIND TUNNELS

Polyatomic gas		Mixture proportions		Mixture molecular weight relative to air		Mixture viscosity at 0° C relative to air		Size of gas-mixture wind tunnel relative to air wind tunnel for same $M_w$ , Re, & pt		Horsepower of gas-mixture wind tunnel relative to air tunnel for same $M_w$ , Re, & pt					
Formula	$m_2$ , gm./mole	$x_2$	$x_1$	argon $\bar{m}$	krypton $\bar{m}$	xenon $\bar{m}$	argon $\bar{\mu}$	krypton $\bar{\mu}$	xenon $\bar{\mu}$	argon $\bar{I}$	krypton $\bar{I}$	xenon $\bar{I}$	argon $\bar{HP}$	krypton $\bar{HP}$	xenon $\bar{HP}$
(a) Design Mach number 1.3; $T_w = 230^\circ K$															
C <sub>4</sub> F <sub>10</sub>	238	0.07	0.93	1.82	3.23	4.76	1.13	1.24	1.16	0.84	0.69	0.53	0.52	0.27	0.13
C <sub>4</sub> F <sub>8</sub>	200	.07	.93	1.77	3.17	4.69	1.12	1.23	1.15	.84	.69	.53	.53	.27	.13
CF <sub>3</sub> CF <sub>2</sub> F <sub>2</sub>	199	.10	.90	1.93	3.29	4.79	1.12	1.22	1.15	.80	.67	.53	.46	.27	.13
SeF <sub>6</sub>	193	.11	.89	1.98	3.31	4.79	1.17	1.25	1.17	.83	.69	.53	.49	.27	.13
C <sub>3</sub> F <sub>8</sub>	188	.08	.92	1.80	3.18	4.69	1.13	1.24	1.16	.84	.69	.53	.53	.27	.13
CB <sub>2</sub> ClF <sub>2</sub>	165	.19	.81	2.18	3.41	4.76	1.03	1.13	1.08	.70	.61	.50	.34	.20	.11
CF <sub>3</sub> CClF <sub>2</sub>	155	.11	.89	1.82	3.16	4.62	1.10	1.20	1.13	.81	.68	.53	.49	.26	.13
CF <sub>3</sub> CF <sub>3</sub>	149	.21	.79	2.15	3.35	4.65	1.09	1.17	1.12	.74	.64	.52	.37	.22	.13
SF <sub>6</sub>	146	.14	.86	1.91	3.19	4.59	1.12	1.22	1.15	.81	.68	.53	.48	.26	.13
CF <sub>3</sub> CF <sub>3</sub>	138	.12	.88	1.78	3.11	4.55	1.13	1.23	1.16	.85	.70	.54	.54	.28	.14
CCl <sub>2</sub> F <sub>2</sub>	121	.20	.80	1.93	3.14	4.45	1.02	1.13	1.09	.74	.64	.52	.39	.23	.13
CClF <sub>3</sub>	105	.23	.77	1.89	3.05	4.35	1.06	1.16	1.12	.77	.67	.54	.44	.26	.14
CH <sub>3</sub> CClF <sub>2</sub>	101	.17	.83	1.74	2.99	4.35	.99	1.12	1.08	.75	.65	.52	.43	.24	.13
CF <sub>4</sub>	88	.27	.73	1.82	2.93	4.14	1.15	1.23	1.17	.85	.72	.57	.53	.30	.16
CHClF <sub>2</sub>	87	.29	.71	1.84	2.92	4.10	.98	1.09	1.06	.73	.63	.53	.39	.24	.14
NF <sub>3</sub>	71	.33	.67	1.73	2.74	3.86	1.11	1.20	1.16	.85	.73	.59	.54	.32	.18
CHF <sub>3</sub>	70	.35	.65	1.74	2.72	3.79	1.01	1.11	1.08	.76	.67	.56	.44	.28	.16
CH <sub>3</sub> CHF <sub>2</sub>	66	.24	.76	1.59	2.74	4.00	.95	1.09	1.06	.76	.66	.53	.45	.26	.14
CH <sub>2</sub> F <sub>2</sub>	52	.47	.53	1.57	2.37	3.24	.78	.91	.93	.63	.59	.52	.31	.23	.15
CO <sub>2</sub>	44	.63	.37	1.47	2.03	2.63	.92	1.02	1.02	.76	.72	.63	.48	.36	.25
N <sub>2</sub> O	44	.57	.43	1.46	2.11	2.81	.94	1.04	1.04	.78	.72	.62	.50	.35	.23
(b) Design Mach number 2.5; $T_w = 140^\circ K$															
CB <sub>2</sub> F <sub>3</sub>	149	.33	.67	2.62	3.62	4.73	1.03	1.10	1.06	.64	.58	.49	.25	.17	.11
SF <sub>6</sub>	146	.30	.70	2.49	3.54	4.69	1.04	1.12	1.07	.66	.66	.50	.28	.19	.11
CF <sub>3</sub> CF <sub>3</sub>	138	.19	.81	2.03	3.25	4.57	1.09	1.17	1.12	.76	.65	.52	.41	.24	.13
CClF <sub>3</sub>	105	.39	.61	2.24	3.17	4.98	.98	1.07	1.05	.66	.66	.51	.29	.20	.13
CF <sub>4</sub>	88	.46	.54	2.14	2.95	3.90	1.10	1.16	1.13	.75	.68	.57	.27	.20	.13
NF <sub>3</sub>	71	.53	.47	1.94	2.65	3.43	1.05	1.13	1.10	.76	.69	.60	.41	.29	.19
CHF <sub>3</sub>	70	.55	.45	1.95	2.63	3.38	.92	1.00	1.00	.66	.62	.54	.31	.23	.16
(c) Design Mach number 3.5; $T_w = 105^\circ K$															
CF <sub>4</sub>	88	.58	.42	2.34	2.97	3.66	1.07	1.12	1.10	.70	.65	.58	.32	.25	.17
NF <sub>3</sub>	71	.62	.38	2.04	2.62	3.24	1.03	1.09	1.07	.72	.67	.60	.36	.28	.20

ie estimated from similar gases and from average bond frequencies of ref. 58.





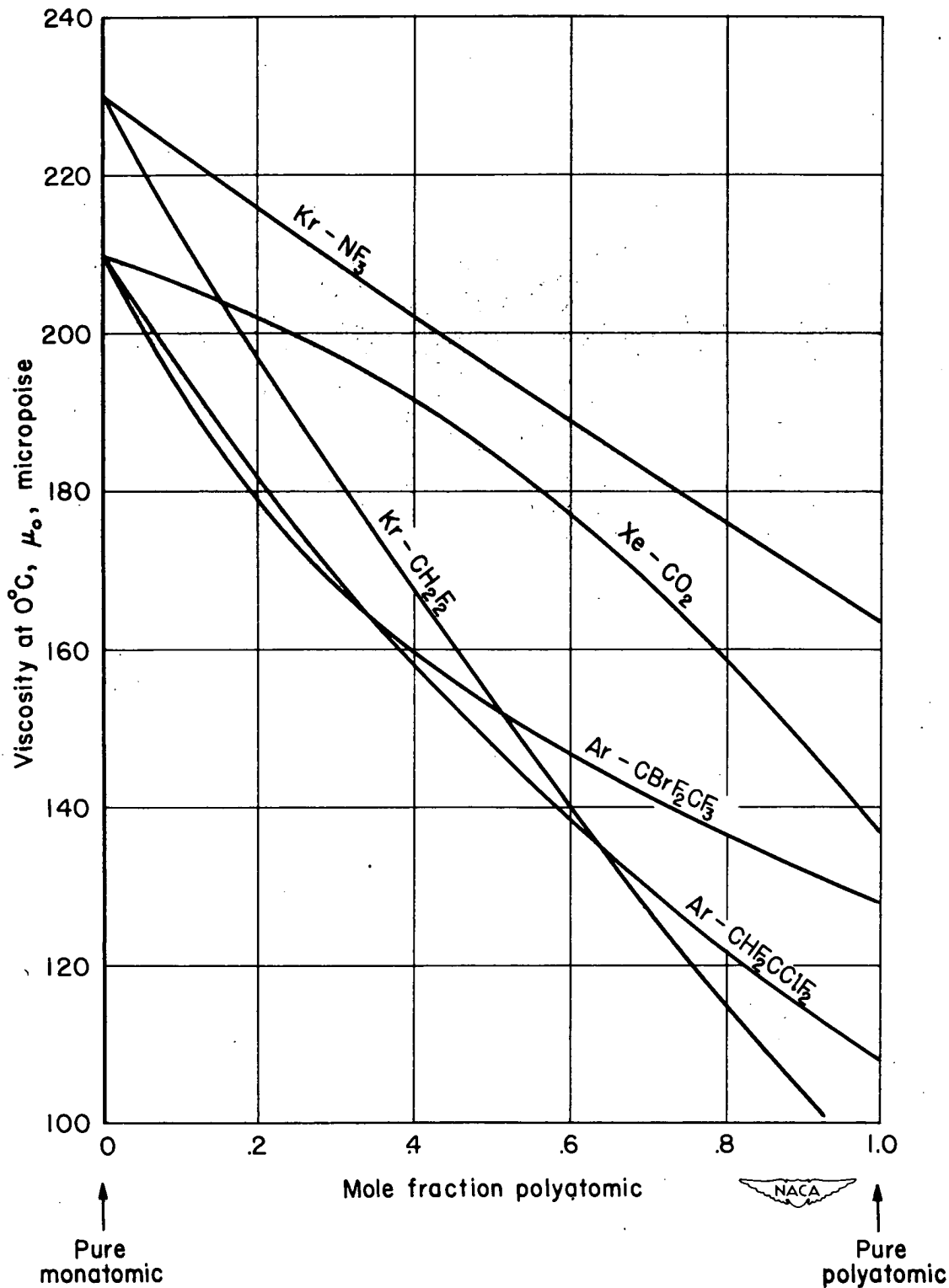


Figure 2.- Some typical examples of viscosity coefficient for gas mixtures.



