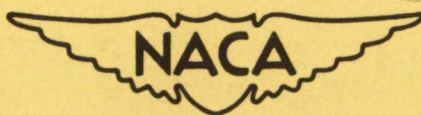# NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

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.

NACA

WASHINGTON

August 1954

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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 | | |
	Argon	Krypton	Xenon
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 $(CBrF_3)$, 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 (CCl_2FCClF_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_∞^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 (γ) 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.[1] It is to be noted that gases with γ 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.

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[1]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 appraisement 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.[2]

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., $COCl_2$, S_2F_{10}, C_2N_2, SO_2), toxic (e.g., CH_3F, CF_2Br_2, CH_3CH_2F), combustible (e.g., COS, all hydrocarbon gases), unstable (e.g., CHCCl, ClN_3, PSF_3), or generally active chemically (e.g., BF_3, F_2O, CF_3SF_3, CF_3OF). Still others were eliminated for less obvious reasons, such as reacting with water vapor to yield corrosive products (e.g., SiF_4, PF_3, COF_2, TeF_6), or having a tendency to polymerize under pressure (e.g., $CClFCF_2$, CH_2CF_2, CF_2CF_2), or being active when in the presence of mercury (F_3CNNCF_3), or imparting, upon inhalation, an offensive odor to the breath which persists long after inhalation (TeF_6). This elimination process left 16 polyatomic gases for further consideration. It was noticed that all but two (CO_2 and N_2O, the lightest two on the list) contained at least two atoms of fluorine per molecule. Because fluorine appeared to be the key to the

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[2]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., $CBrF_3$) 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., C_3ClF_7 and C_2HF_5) are known to be omitted from the list. Conse-
quently, the present report which primarily indicates current possibil-
ities 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 analo-
gous 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 cer-
tain fluorochemicals are extremely high. Most of these extreme properties
can be illustrated by a few examples. First consider the following two
gases: chloroform, $CHCl_3$, and fluoroform, CHF_3. The toxicity of chloro-
form 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, 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, $(SF_5)_2$, is extremely poisonous, since, for concen-
trations as low as one part per million - in which concentration phosgene
is harmless - sulfur pentafluoride is lethal (ref. 18). Further illustra-
tion of the extreme properties of fluorochemicals is provided by carbon
tetrafluoride, CF_4. The thermal decomposition temperature of 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 inac-
tivity 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:

molecular weight $\qquad$ $m = x_1 m_1 + x_2 m_2$ $\qquad$ (1)

equation of state $\qquad$ $p = \rho R T / m$ $\qquad$ (2)

specific heat $\qquad$ $C_v + R = C_p = x_1 C_{p_1} + x_2 C_{p_2}$ $\qquad$ (3)

ratio of specific heats $\qquad$ $\gamma = \dfrac{x_1 C_{p_1} + x_2 C_{p_2}}{x_1 (C_{p_1} - R) + x_2 (C_{p_2} - R)}$ $\qquad$ (4)

enthalpy $\qquad$ $H = x_1 H_1 + x_2 H_2$ $\qquad$ (5)

where R is the universal gas constant (1.987 cal. $^\circ K^{-1}$ 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,

$$C_{p_1} = \frac{H_1}{T} = \frac{5}{2} R = 4.97 \text{ cal.}^\circ K^{-1} \text{ mole}^{-1}$$

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

$$1 - x_1 = x_2 = \left(\frac{C_{p_2}}{R} - \frac{5}{2} \right)^{-1}$$ $\qquad$ (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., CO_2 and N_2O), wherein the atoms are arranged in a straight line,

$$\frac{C_{p2}}{R} = \frac{7}{2} + \sum_{1}^{3n-5} \frac{\left(\frac{hc\omega_i}{2kT}\right)^2}{\sinh^2\left(\frac{hc\omega_i}{2kT}\right)} \tag{7}$$

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

The various wave numbers ω_i determined from spectroscopic data for each gas are listed in table III. The constant hc/k is equal to 1.4385 °K cm For nonlinear molecules not subject to internal rotation (e.g., CF_4, CHF_3, SF_6, etc.)

$$\frac{C_{p2}}{R} = 4 + \sum_{1}^{3n-6} \frac{\left(\frac{hc\omega_i}{2kT}\right)^2}{\sinh^2\left(\frac{hc\omega_i}{2kT}\right)} \tag{9}$$

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

For nonlinear molecules subject to a torsional mode of oscillation (e.g., CF_3CF_3, CHF_2CClF_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 γ. 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 calorimetic 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 calorimetric measurements)	
CO_2	-75	7.71	7.78	
	20	8.82	8.80	ref. 57
	220	10.62	10.63	
CCl_2F_2	-30	15.6	15.7	
	0	16.6	16.7	ref. 51
	45	17.8	18.0	
	90	18.9	19.1	
CF_3CF_3	-50	21.1	21.0	
	10	24.7	24.4	ref. 22
	90	28.7	28.2	

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 μ 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 μ_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

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

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:

$$F\left(\frac{T}{T_c}\right) = \begin{cases} 27.1 \; T/T_c & \text{for } T < 1.6 \; T_c \\[4mm] \dfrac{27.1 \; T/T_c}{1 + 0.0952\left(\dfrac{T}{T_c} - 1.6\right)} & \text{for } T > 1.6 \; T_c \end{cases} \tag{12a}$$

where T is in $^{\circ}K$, m is in gm./mole, V_c is in cc/gm. mole, and μ 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:

Viscosity at 0° C in micropoises

Gas	Calculated	Experimental
Ar	210	210
Kr	229	230
Xe	211	210
SF_6	146	142
CCl_2F_2	114	118
$CHClF_2$	119	120
CO_2	134	137
N_2O	132	135
Air	170	172

This agreement is satisfactory. Consequently, in the calculations of wind-tunnel power requirements, experimental values of μ 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.

<center>Wind-Tunnel Power</center>

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

$$HP = J \frac{wc_pT_t}{\eta} \left[(CR)^{(\gamma-1)/\gamma} - 1 \right] \tag{13}$$

where J is a numerical constant depending only on the units employed, η 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

$$mc_p = C_p = \frac{\gamma}{\gamma - 1} R \tag{14}$$

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

$$\overline{HP} = \frac{\bar{w}}{\bar{m}} \bar{T}_t \bar{Y}(\gamma, CR) = \frac{\bar{\rho}_\infty \bar{u}_\infty \bar{L}^2}{\bar{m}} \bar{T}_t \bar{Y}(\gamma, CR) \tag{15}$$

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

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

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 $\overline{p}_t$

$$\overline{Re} = \frac{\overline{\rho_\infty u_\infty L}}{\overline{\mu}} = \left[\overline{\left(\frac{\rho_\infty}{\rho_t}\right)} \frac{\overline{p}_t \overline{m}}{\overline{T}_t} \right] \left[\overline{\left(\frac{u_\infty}{a_t}\right)} \sqrt{\frac{\overline{\gamma} \, \overline{T}_t}{\overline{m}}} \right] \frac{\overline{L}}{\overline{\mu}}$$

$$= \overline{p}_t \sqrt{\frac{\overline{m}}{\overline{T}_t}} \frac{\overline{L}}{\overline{\mu}} \overline{\left(\frac{\sqrt{\gamma} \rho_\infty u_\infty}{\rho_t a_t}\right)}$$

or, finally,

$$\overline{L} = \frac{\overline{Re}\,\overline{\mu}\sqrt{\overline{T}_t}}{\overline{p}_t \sqrt{\overline{m}} \, \overline{f}(\gamma, M_\infty)} \tag{17}$$

where

$$\overline{f}(\gamma, M_\infty) \equiv \overline{\left(\frac{\sqrt{\gamma} \rho_\infty u_\infty}{\rho_t a_t}\right)}$$

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

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

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_∞. (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 $0.97 < \overline{Y}(\gamma, 1.3) < 1$ for any γ between 1.1 and 1.4. Hence, $\overline{Y} = 1$ is a good approximation for transonic wind tunnels irrespective of γ. For the case of supersonic wind tunnels, only gas mixtures having $\gamma \approx 1.4$ are considered, for which $\overline{Y}(1.4, CR) = 1$. Consequently, in all cases of concern here, $\overline{Y} = 1$ is an adequate approximation. A similar argument shows that the ratio $\overline{Y}(\gamma, CR) / \overline{f}(\gamma, M_\infty)$ is approximately unity for the range of γ and M_∞ considered here. Inasmuch as all calculations will be made on the basis that $\overline{T}_t = 1$, the above equations simplify to

$$\overline{HP} = \frac{\overline{Re} \overline{\mu} \overline{L}}{\overline{m}} \tag{16a}$$

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

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

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

Case (1): Given M_∞, Re, and L.- This case corresponds to operating a given wind tunnel ($\overline{L} = 1$) with a gas other than air at the same values of M_∞ 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 $\overline{q} = \overline{p}_t = \overline{\mu}/\sqrt{\overline{m}}$.

Case (2): Given M_∞, 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_∞, 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 $\overline{Re} = \overline{m}/\overline{\mu}$. 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_∞, 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_∞ 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

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

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

$$\overline{L} = \overline{\mu}/\sqrt{\overline{m}} \tag{20}$$

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
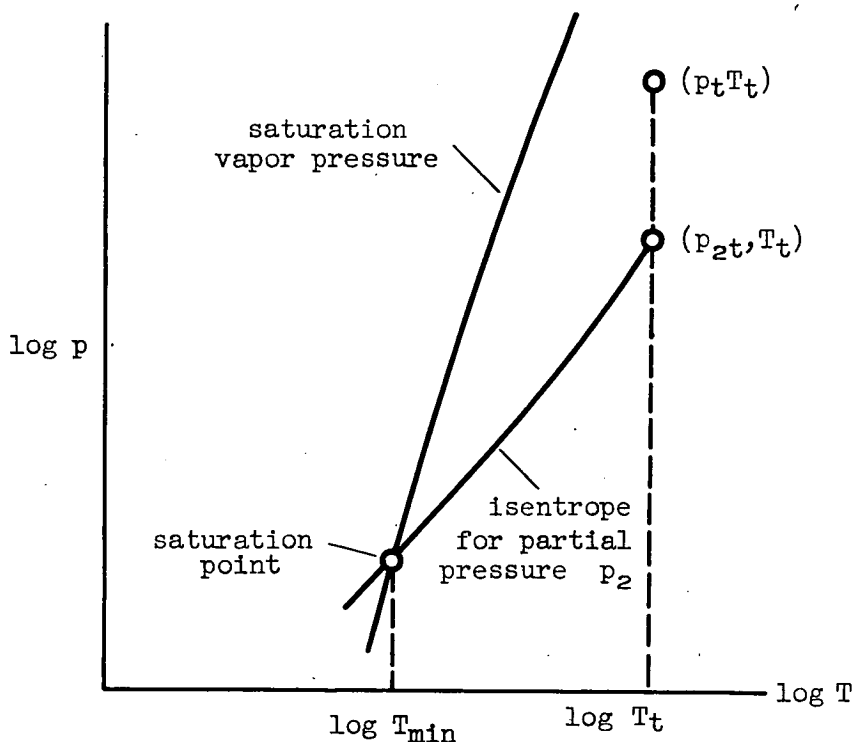
number can be calculated from the relation

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

where γ 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 $40°$ C ($100°$ 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° C total temperature. Operation at Mach numbers above about 3.5 would require total temperatures higher than the value of 40° 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_∞, 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 $\overline{\rho}_\infty$, 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 γ 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_∞, 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 γ 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 γ, perhaps between 1.3 and 1.2, might yield transonic data directly applicable to air for practical purposes. If a considerably reduced value of γ 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:

	Case (4): given Re, p_t, and M_∞		Case (3): given HP, M_∞, and L	
γ	$\overline{HP}$	$\bar{L}$	$\overline{Re}$	
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 γ 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 γ 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 γ to the lowest practical value are apparent from the table. For xenon mixtures, however, there is less to gain by

reducing γ 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 γ 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 ($pm = \rho RT$) and calorically perfect (γ = 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 γ 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, γ will vary with temperature. Under wind-tunnel conditions, γ 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 γ 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 γ 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_∞ 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° C $\approx 100^\circ$ F) has been assumed. A single mixture of 25-percent $CBrF_3$ with 75-percent monatomic gas is considered in figure 3(a). These proportions are about right for $M_\infty = 2.0$. At $M_\infty = 2.5$, γ_∞ is 1.44 and γ_t is 1.34. This variation does not seem excessive. At $M_\infty = 1.3$, γ 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 γ, as well as the complete insensitivity of subsonic flows to variations in γ, 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 γ is not important at conditions close to free-stream conditions. For example, γ 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 γ 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 γ in an air wind tunnel (long dashed curves) with the corresponding values of γ 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 γ 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 γ 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° K) corresponding to the particular curves in figure 4, are as follows:

	Reservoir temperature $^\circ$K to prevent saturation; p_t = 100 psia		
Gas	$M_\infty = 5$	$M_\infty = 6$	$M_\infty = 7$
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° K, as tabulated above, but would require pure CF_4 (γ between 1.12 and 1.33) to be heated only to about 450° K, and pure CF_3CF_3 (γ between 1.08 and 1.19) to be heated only to about 375° K. This trend is opposite to what would be expected from consideration solely of the respective boiling points (-180° C for air, -128° C for CF_4, and -78° C for CF_3CF_3) because of the dominating effect of the reduced values of γ. Reducing γ 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 β. Measurements show that β 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 (β_a) at atmosphere conditions is known for some of the fluorochemical gases, and generally is the order of 10^{-7} second. For others, β_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, β_a for $CBrF_3$ is estimated to be in the range 10^{-8} to 10^{-7} second, and that for CF_3CF_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 βC_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, β 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 βC_i greater than for flight through air (e.g., CF_4), and the other having βC_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° C, whereas the respective individual gases boil at -38° C and -52° 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 $pm = \rho RT$ 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

$$\frac{pm}{\rho RT} = 1 + \frac{p}{RT}\ B(T) \qquad\qquad\text{(A1)}$$

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:

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

where

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

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_∞, T_∞) 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:

| | $M_\infty = 2.5$ | | $M_\infty = 3.5$ | |
Gas	$\dfrac{\|p_\infty B(T_\infty)\|}{RT_\infty}$	$\dfrac{\|p_t B(T_t)\|}{RT_t}$	$\dfrac{\|p_\infty B(T_\infty)\|}{RT_\infty}$	$\dfrac{\|p_t B(T_t)\|}{RT_t}$
$CBrF_3$	0.0017	0.0033		
SF_6	.0013	.0027		
CF_3CF_3	.0010	.0018		
$CClF_3$	.0016	.0030		
CF_4	.0012	.0019	0.0007	0.0023
NF_3	.0012	.0019	.0007	.0022
CHF_3	.0017	.0034		
Air	.0005	.0002	.0002	.0002

It may be deduced that gas mixtures at test-section conditions (p_∞, T_∞) 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 (β_a) for some of the polyatomic gases considered in this report are as follows:

Gas	Temperature, $^{\circ}K$	β_a, microseconds	Reference
CCl_2F_2	293	0.09	66,4
CF_4	373	.66	67
CHF_3	373	.42	67
$CHClF_2$	293	.10	66
CH_2F_2	373	.055	67
CO_2	293	7.0	66
N_2O	293	1.1	66
Air (dry)	300	[1]14.	68

Although measurements of β_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_3CBrF_2, CF_3CClF_2, CF_3CF_3, CH_3CClF_2, CH_3CHF_2, C_3F_8, and C_4F_{10}, but not C_4F_8) would have relaxation times (β_a) in the range 10^{-8} to 10^{-9} second, and that the methane-like gases $CBrF_3$ and $CBrFClF_2$ 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 β_a for those gases having relatively long relaxation times.

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

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[1]This value corresponds to measurements of β_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 β_ν of the lowest frequency (ν) mode

$$\frac{C_p}{C_p - C_i} \beta_\nu = \frac{Z_{10}}{Z(1 - e^{-h\nu/kT})} \tag{B1}$$

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

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

$$\beta \approx \frac{C_i \beta_\nu}{C_\nu} \qquad \text{(ref. 71)} \tag{B3}$$

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

where b is a constant for each gas evaluated from measurements of β_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 $CHClF_2$-Ar mixtures in ref. 73.)

Relaxation times β_∞ corresponding to free-stream conditions (T_∞, p_∞) in a wind tunnel have been calculated for assumed reservoir conditions of one atmosphere total pressure and 40° 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	$M_\infty=1.3$, $T_\infty=230^\circ$ K, $p_\infty=0.36$ atm		M_∞ 2.5, $T_\infty=140^\circ$ K, $p_\infty=0.059$ atm		M_∞ 3.5, $T_\infty=105^\circ$ K, $p_\infty=0.013$ atm	
	β_∞, sec	d, in.	β_∞, sec	d, in.	β_∞, sec	d, in.
CCl_2F_2	2×10^{-7}	0.002				
CF_4	3×10^{-6}	.03	5×10^{-5}	0.8	3×10^{-4}	6
CHF_3	2×10^{-6}	.02	3×10^{-5}	.5		
$CHClF_2$	2×10^{-7}	.003				
CH_2F_2	1×10^{-7}	.001	7×10^{-7}	.01		
CO_2	4×10^{-5}	.5				
N_2O	6×10^{-6}	.06				
Air (dry)	7×10^{-5}	1.	3×10^{-3}	60.	4×10^{-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 β.

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_∞ 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.

$$p_{ij} = (p_{ij})_{\substack{\text{Navier} \\ \text{Stokes}}} + \mu_V \frac{\partial u_k}{\partial x_k} \delta_{ij} \tag{B5}$$

In this equation μ_V is the coefficient of volume viscosity, $\partial u_k/\partial x_k$ is (using summation convention) the divergence of the velocity vector, and δ_{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 μ_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 $f = C_p/(C_p-C_i)$ 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 $\mu_v = \gamma(\gamma-1)p\beta C_i/(C_p-C_i)$ 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 $\mu_v u_\infty/(pl) = \gamma(\gamma-1)(\beta u_\infty/l)C_i/(C_p-C_i)$. 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,

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

Which is seen to be the same as the similarity parameter.[2] 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 (μ_v/μ) $\gamma M_\infty^2/Re$, 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, μ_v/μ 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° K to 2000° K), however, μ_v/μ 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, μ_v/μ 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, $C_i = x_2 C_{i2}$. Computations of the resulting parameter $\mu_v u_\infty/p_\infty l = \gamma(\gamma-1)(\beta_\infty u_\infty/l)C_i/(C_p-C_i)$ for wind-tunnel flow conditions

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[2]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	$\gamma(\gamma-1)\dfrac{x_2 C_{i2}}{C_p - C_i}\dfrac{\beta_\infty u_\infty}{l}$ for l = 1 in., p_t = 1 atm		
	$M_\infty = 1.3$	$M_\infty = 2.5$	$M_\infty = 3.5$
CCl_2F_2	0.0003		
CF_4	.004	0.04	0.1
CHF_3	.002	.01	
$CHClF_2$	.0003		
CH_2F_2	.00006	.0001	
CO_2	.03		
N_2O	.005		
Air (dry)	.0002	.00005	.00008

For transonic wind tunnels it is seen that only CO_2 mixtures would exhibit appreciable relaxation effects on pressure distribution. On the other hand, for $M_\infty = 3.5$, mixtures involving CF_4 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 β 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 $\mu\dfrac{\partial u}{\partial y}$. The ratio of the relaxation term to the ordinary term in the equation of motion is

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

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 δ/l to be of the order of $[6 + (\gamma-1)M_\infty^2]/\sqrt{Re}$. Hence,

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

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 μ_v/μ. However, for air under flight conditions ($\mu_v/\mu \sim 10^2$), the ratio can be significant at low Reynolds numbers (e.g., at $Re \sim 500$ for $M_\infty = 3.5$, at $Re \sim 5000$ for $M_\infty = 7$, and at $Re \sim 200,000$ 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 μ_v/μ 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 μ_v/μ 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^{-1} $^\circ$K^{-1})

Re   Reynolds number

T   temperature

u   velocity

V   volume of gas

w   mass-flow rate, (ρu) times (cross-section area)

x   . mole fraction, equal to ratio of partial pressure to mixture
       static pressure and equal to fraction by volume

β relaxation time

γ ratio of specific heats

ρ mass density

μ viscosity coefficient

μ_v volume viscosity coefficient

ω wave number (cm^{-1}, from spectroscopic data)

Subscripts

∞ 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

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

Symbol	Gas	m, $\dfrac{\text{gm.}}{\text{mole}}$	Boiling temp., $^\circ C$	Critical constants			Viscosity at 0° C μ_0, micropoise
				T_c, $^\circ K$	p_c, atm.	V_c, 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_2	nitrogen	28	-196	126	33.5	90.0	166
O_2	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_2, gm/mole	Chemical name	Common or trade name	General classification (1)	Remarks	Spectroscopic data	Toxicity data (Ref.)	Physical data (Ref.)
C_4F_{10}	238	n-perfluorobutane		S	Reported "as nontoxic as fluorocarbons." Chemistry resembles NF_3. Stable to at least 400° C.	45	14	14, 19, 15
C_3F_9N	221	perfluorotertiaryamine		S?		45	56	14, 56, 44, 46, 23
C_4F_8	200	perfluorocyclobutane	Freon C318	S	Toxicity unknown.			48, 15, 26
CF_3CBrF_2	199	bromoethforane		S?	Toxicity, liquid density unknown.			14, 56, 24
CF_3SF_5	196	trifluoromethylsulfurpentafluoride		S?				20
SeF_6	193	selenium hexafluoride		S?	Toxicity unknown.	50	14	14, 25, 42 / 14, 56, 19
C_3F_8	188	perfluoropropane		S	Musty odor. Toxicity, liquid density unknown.			44, 47
C_2F_8NF	171	perfluorodimethylamine		S?	Toxicity probably excessive. More toxic than $CHClF_2$.	49	21	26
$CBrClF_2$	165	bromochlorodifluoromethane	Freon 12B1	Q				
CF_3CClF_2	155	chloroethforane	Freon 115	S	Reported "as nontoxic as fluorocarbons." Liquid density unknown. Stable to at least 400° C.	33	56	14, 26 / 14, 56, 44, 23
CF_3OCF_3	154	perfluoroether		S?				
$CBrF_3$	149	bromotrifluoromethane	Freon 13B1, Kulene 131	S	Excellent fire extinguisher	35	21,56	14, 26, 56
SF_6	146	sulfurhexafluoride		S, I	Excellent high-voltage gaseous insulator. Extremely inert chemically. Thermally stable to about 500° C.	29	17	14, 56, 25, 27, 52 / 53
CF_3CF_3	138	ethforane		S	Thermally stable to about 700° C.	34		14, 56, 19, 39, 22 / 14, 26
$CClF_2CHF_2$	137	1-chloro-2-hydroethforane	Freon 124a	S?	Toxicity unknown			14, 26, 63 / 14, 56, 44
CCl_2F_2	121	dichlorodifluoromethane	Freon 12	S	Musty odor. Toxicity, liquid density unknown.	30, 51	18,38,63	14, 26
CF_3NF_2	121	perfluoromethylamine		S?		28, 30		14, 26
$CClF_3$	105	chlorotrifluoromethane	Freon 13	S	Toxicity, liquid density unknown.	55		14
SO_2F_2	102	sulfuryl fluoride		S?	Chemistry resembles SF_6			
CHF_2CHF_2	102	1-hydro-2-hydroethforane		S?	Toxicity, liquid density unknown.	37	18	14 / 14, 26
CH_3CClF_2	101	1-chloro-1,1-difluoroethane	Genetron 101	Q	Slightly flammable, toxicity marginal. (See remarks for Genetron 100.)			
$FCONF_2$	99	carbonylnitrogentrifluoride		S?	Toxicity, liquid density unknown. Reported as very inert.	28, 30		14
CF_4	88	carbontetrafluoride	Freon 14	S	Extreme thermal stability and chemical inertness.	30	21	14, 56, 19
$CHClF_2$	87	chlorodifluoromethane	Freon 22	Q	Toxicity marginal (classified U.A.L. group 5A).		38	14
CH_3CF_3	84	1,1,1-trifluoroethane		S?	Toxicity and flammability unknown	31, 32 / 54	43, 25	14 / 14, 43
NF_3	71	nitrogentrifluoride		S?	Toxicity uncertain since early tests (Ruff, ref. 43) are questionable.	28, 30	16	14
CHF_3	70	fluoroform	Freon 23, Genetron 100	S, I	Thermally stable to at least 1100° C.	36	10, 25	14
CH_3CHF_2	66	1,1-difluoroethane		Q	Slightly flammable, but forms nonflammable azeotropic mixture with Freon 12. Azeotropic mixture called "Carrene 7," has m = 100, T_b = -33° C.			14
CH_2F_2	52	difluoromethane	Freon 32	S?	Flammability unknown.	30	25	14
CO_2	44	carbon dioxide		Q	Toxic for prolonged exposure at concentrations above about 3 per cent.	41	25	40, 13
N_2O	44	nitrous oxide		Q	Nonflammable but acts as oxidant at high temperature. Toxic at high concentrations.	41	25	40, 13

[1]S   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)	T_c, °K	P_c, atm.	V_c, cc/gm mole	Viscosity at 0°C μ_2, micropoise	$\dfrac{\bar{m}_2}{\mu_2}$	$\dfrac{(\bar{\mu}_2)^2}{(\bar{m}_2)^{3/2}}$	Spectroscopic data fundamental wave numbers, ω_1, cm^{-1} (3)
C_4F_{10}	238	-2	387	23	378	111	12.7	0.018	1431,1385,1340,1285,1239(2),1220,1008(2),963,745(2),699,660(2),613,569,439
C_3F_9N	221	-11	390e		331e				359,338(2),285,273,258,250(2),192(2),173,86
C_4F_8	200	-6	386e	32e	268e	111	10.7	.023	
CF_3CBrF_2	199	-22				128	9.2	.031	
CF_3SF_5	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	1150,1102,872,648,440,400,380,300,200
C_2F_6NF	171	-37							1350,1124,1236,1186,1132,982,763,648,595,561,454,441,366,331,315, torsion,186(2)
$CBrClF_2$	165	-4	427	41.2	232	121	8.1	.036	
CF_3CClF_2	155	-38	353	30.8	260	119	7.7	.039	
CF_3OCF_3	154	-59	341	36.8	199	143	6.2	.059	1207(2),1087,762,548(2),348,297(2)
$CBrF_3$	149	-60	319	29.9	201	142	6.1	.060	940(3),775,644(2),615(3),524(3),363(3)
SF_6	146	-64 sub.	293	36.7	220	139	5.9	.063	1420,1250(2),1235(2),1120,810,715,620(2),520(2),380(2),350,214(2),torsion
CF_3CF_3	138	-78	400		251	108	7.5	.038	
$CClF_2CHF_2$	137	-10							
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							1210(2),1102,783,560(2),478,356(2)
$CClF_3$	105	-80	302	39	180				1502,1269,885,848,553,544,539,385,300
SO_2F_2	102	-55	340e			136	4.6	.091	
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
$FCONF_2$	99	-82							1265(3),904,630(3),437(2)
CF_4	88	-128	228	36.8	139	171	3.1	.19	3023,1347,1311,1178,1116,809,595,422,365
$CHClF_2$	87	-41	370	48.5	165	120	4.3	.094	3034(2),2975,1409,1142(2),1123(2),1281,1234(2),970(2),830,606(2),541,368(2),238,torsion
CH_3CF_3	84	-47							
NF_3	71	-129	230e	47	125e	164	2.6	.24	1032,647,905(2),493(2)
CHF_3	70	-84	306	44.3	136	134	3.1	.16	1376(2),1160(2),1117,697,508(2),3062
CH_3CHF_2	66	-25	387		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		170	93	3.3	.12	3012,2949,1508,1435,1262,1176,1116,1090,529
CO_2	44	-79 sub.	304	72.9	96	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. sublimes 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.

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TABLE IV.- CHARACTERISTICS OF GAS-MIXTURE WIND TUNNELS

Polyatomic gas Formula	m_2, gm/mole	C_{p_2}, cal/mole °K (1)	x_2	x_1	$\bar{m}$ argon	$\bar{m}$ krypton	$\bar{m}$ xenon	$\bar{\mu}$ argon	$\bar{\mu}$ krypton	$\bar{\mu}$ xenon	$\bar{L}$ argon	$\bar{L}$ krypton	$\bar{L}$ xenon	$\overline{HP}$ argon	$\overline{HP}$ krypton	$\overline{HP}$ xenon
				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_∞, Re, & Pt			Horsepower of gas-mixture wind tunnel relative to air tunnel for same M_∞, Re, & Pt		
(a) Design Mach number 1.3; T_∞ = 230° K																
C_4F_{10}	238	35.8e	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_4F_8	200	33.5	.07	.93	1.77	3.17	4.69	1.12	1.23	1.15	.84	.69	.53	.53	.27	.13
CF_3CBrF_2	199	24.4e	.10	.90	1.93	3.29	4.79	1.12	1.22	1.15	.80	.67	.53	.46	.25	.13
SeF_6	193	22.5	.11	.89	1.98	3.31	4.79	1.17	1.25	1.17	.83	.69	.53	.49	.27	.13
C_3F_8	188	29.5e	.08	.92	1.80	3.18	4.69	1.13	1.24	1.16	.84	.69	.53	.53	.27	.13
$CBrClF_2$	165	15.8	.19	.81	2.18	3.41	4.76	1.03	1.13	1.08	.70	.61	.50	.34	.20	.11
CF_3CClF_2	155	23.0	.11	.89	1.82	3.16	4.62	1.10	1.20	1.13	.81	.68	.53	.49	.26	.13
$CBrF_3$	149	14.7	.21	.79	2.15	3.35	4.65	1.09	1.17	1.12	.74	.64	.52	.37	.22	.13
SF_6	146	18.9	.14	.86	1.91	3.19	4.59	1.12	1.22	1.15	.81	.68	.53	.48	.26	.13
CF_3CF_3	138	21.8	.12	.88	1.78	3.11	4.55	1.13	1.23	1.16	.85	.70	.54	.54	.28	.14
CCl_2F_2	121	15.2	.20	.80	1.93	3.14	4.45	1.02	1.13	1.09	.74	.64	.52	.39	.23	.13
$CClF_3$	105	13.8	.23	.77	1.89	3.05	4.35	1.06	1.16	1.12	.77	.67	.54	.44	.26	.14
CH_3CClF_2	101	16.8	.17	.83	1.74	2.99	4.35	.99	1.12	1.08	.75	.65	.52	.43	.24	.13
CF_4	88	12.5	.27	.73	1.82	2.93	4.14	1.15	1.23	1.17	.85	.72	.57	.53	.30	.16
$CHClF_2$	87	12.0	.29	.71	1.84	2.92	4.10	.98	1.09	1.06	.73	.63	.53	.39	.24	.14
(b) Design Mach number 2.5; T_∞ = 140° K																
NF_3	71	11.1	.33	.67	1.73	2.74	3.86	1.11	1.20	1.16	.85	.73	.59	.54	.32	.18
CHF_3	70	10.7	.35	.65	1.74	2.72	3.79	1.01	1.11	1.08	.76	.67	.56	.44	.28	.16
CH_3CHF_2	66	13.5	.24	.76	1.59	2.74	4.00	.95	1.09	1.06	.76	.66	.53	.45	.26	.14
CH_2F_2	52	9.22	.47	.53	1.57	2.37	3.24	.78	.91	.93	.63	.59	.52	.31	.23	.15
CO_2	44	8.11	.63	.37	1.47	2.03	2.63	.92	1.02	1.02	.76	.72	.63	.48	.36	.25
N_2O	44	8.45	.57	.43	1.46	2.11	2.81	.94	1.09	1.04	.78	.72	.62	.50	.35	.23
(c) Design Mach number 3.5; T_∞ = 105° K																
$CBrF_3$	149	11.0	.33	.67	2.62	3.62	4.73	1.03	1.10	1.06	.64	.58	.49	.25	.17	.11
SF_6	146	11.5	.30	.70	2.49	3.54	4.69	1.04	1.12	1.07	.66	.59	.50	.28	.19	.11
CF_3CF_3	138	15.3	.19	.81	2.03	3.25	4.57	1.09	1.17	1.12	.76	.65	.52	.41	.24	.13
$CClF_3$	105	10.2	.39	.61	2.24	3.17	4.19	.98	1.07	1.05	.66	.60	.51	.29	.20	.13
CF_4	88	9.31	.46	.54	2.14	2.95	3.90	1.10	1.16	1.13	.75	.68	.57	.39	.27	.17
NF_3	71	8.74	.53	.47	1.94	2.65	3.43	1.05	1.13	1.10	.76	.69	.60	.41	.29	.19
CHF_3	70	8.60	.55	.45	1.95	2.63	3.38	.92	1.00	1.00	.66	.62	.54	.31	.23	.16
CF_4	88	8.40	.58	.42	2.34	2.97	3.66	1.07	1.12	1.10	.70	.65	.58	.32	.25	.17
NF_3	71	8.19	.62	.38	2.04	2.62	3.24	1.03	1.09	1.07	.72	.67	.60	.36	.28	.20

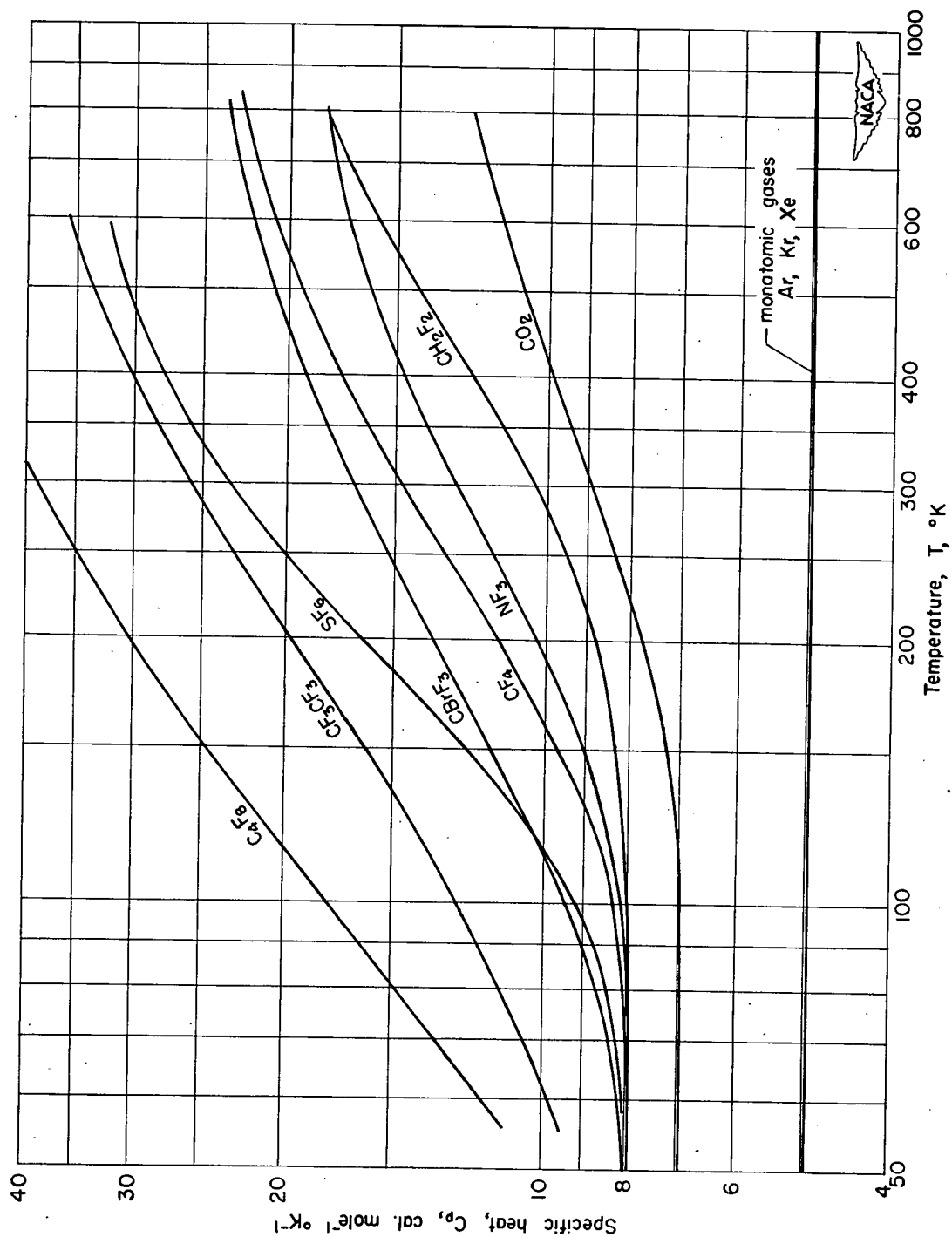1e estimated from similar gases and from average bond frequencies of ref. 58.

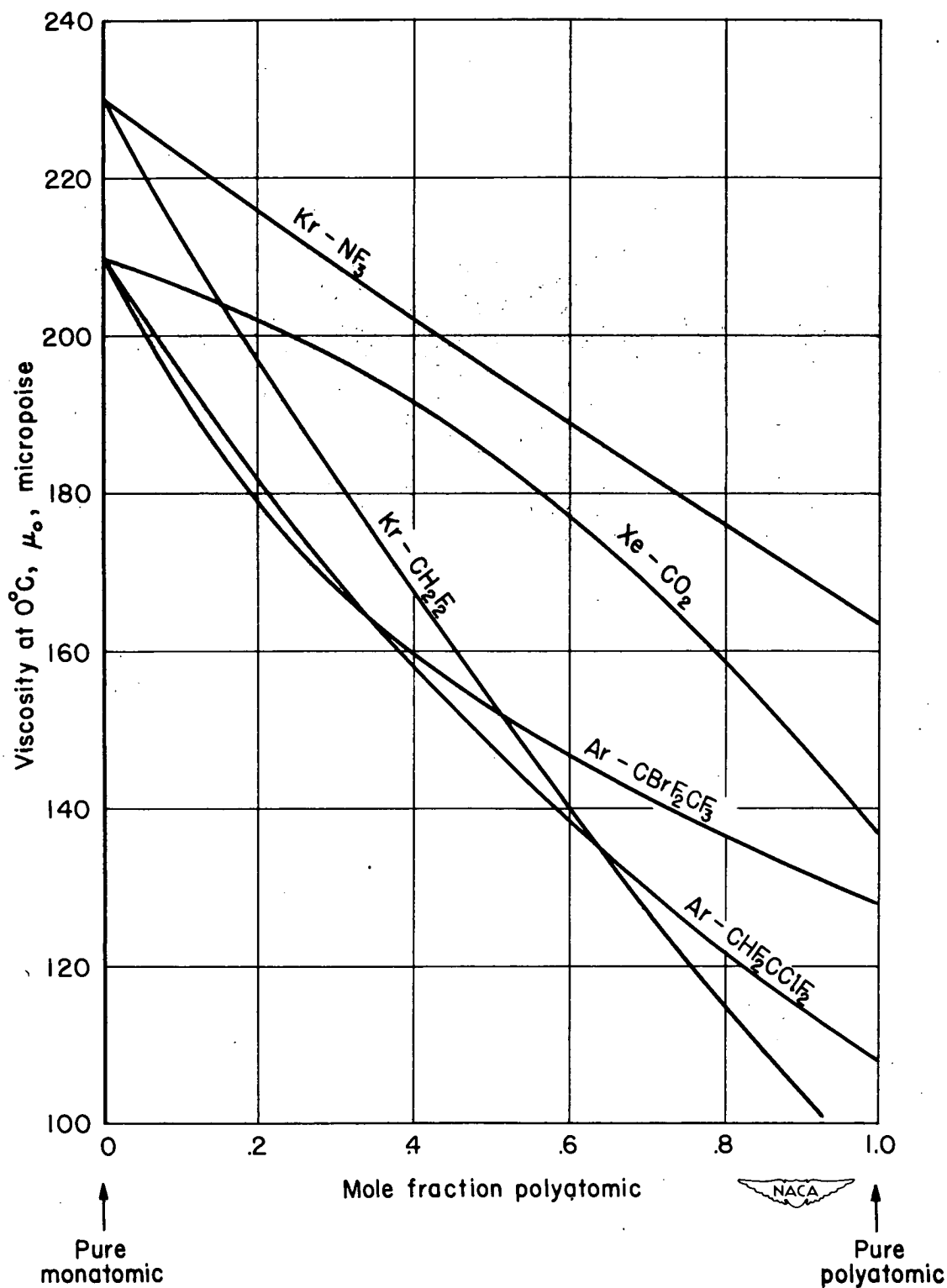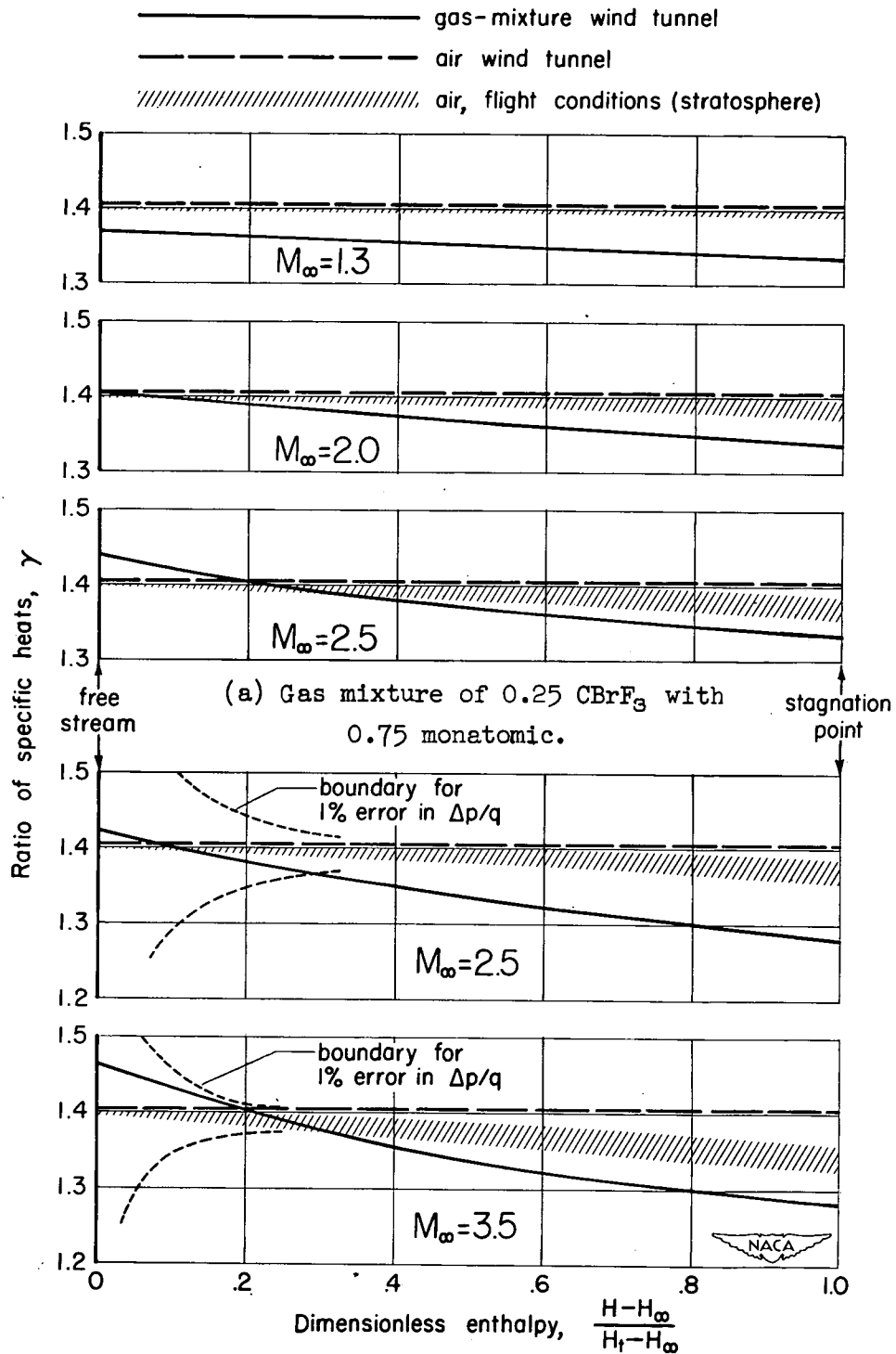Figure 1.- Some typical examples of specific heat computed from spectroscopic data.

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

(a) Gas mixture of 0.25 CBrF$_3$ with 0.75 monatomic.

(b) Gas mixture of 0.4 CF$_4$ with 0.6 monatomic.

Figure 3.- Variation of specific-heat ratio between free-stream and
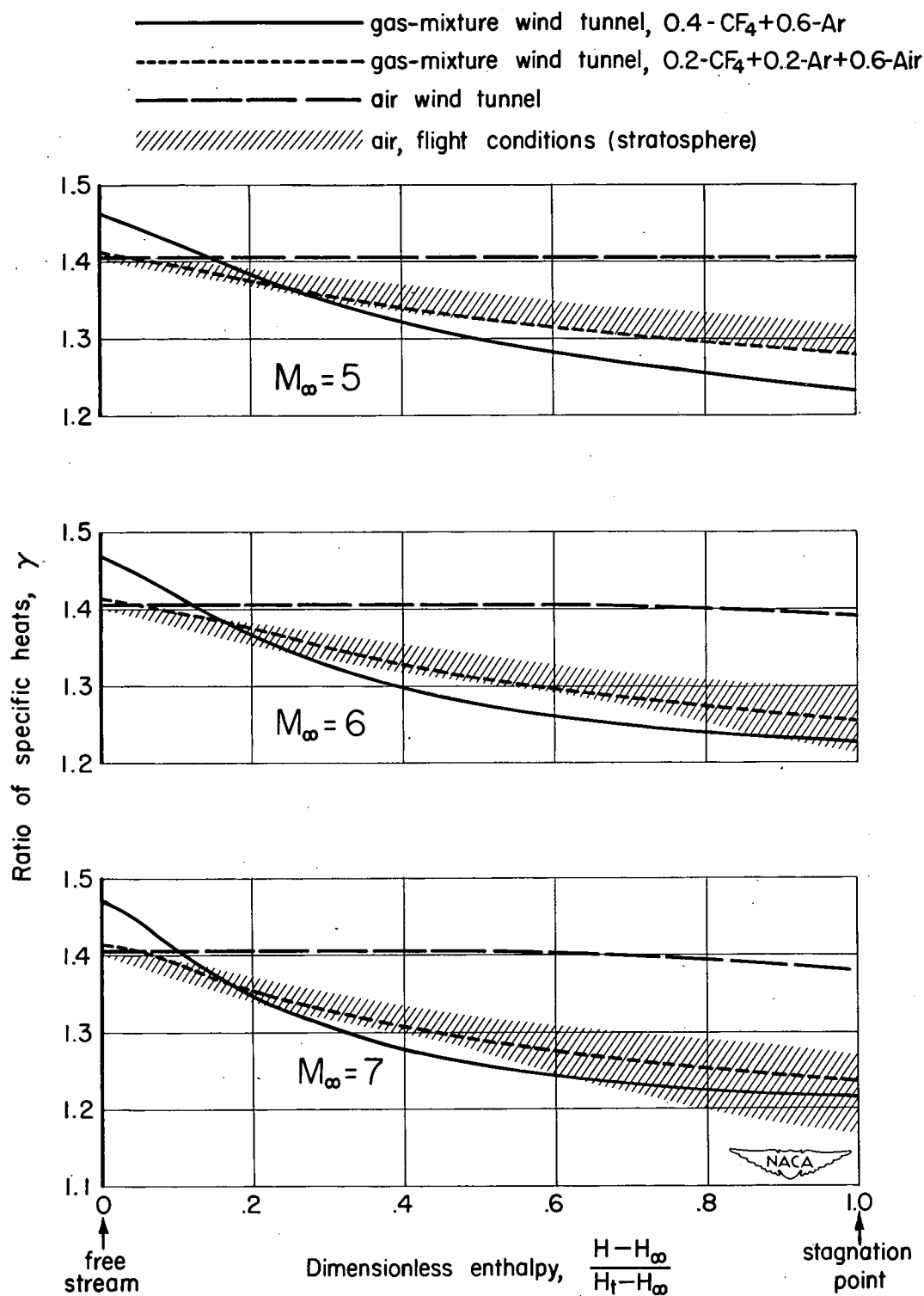stagnation conditions for various gas mixtures.

Figure 4.- Variation of specific-heat ratio between free-stream and stagnation conditions at hypersonic speeds.