024

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE

No. 1024

USE OF FREON-12 AS A FLUID FOR AERODYNAMIC TESTING

By Paul W. Huber

Langley Memorial Aeronautical Laboratory
Langley Field, Va.

Washington
April 1946

5/6/46

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE NO. 1024

USE OF FREON-12 AS A FLUID FOR AERODYNAMIC TESTING

By Paul W. Huber

SUMMARY

The thermodynamic properties of Freon-12 have been investigated to determine the possibilities of the use of this gas as a fluid for aerodynamic testing. The values of velocity of sound in Freon-12, which are less than one-half those in air, are presented as functions of temperatures and pressure, including measurements at room temperature. The density of Freon-12 is about four times that of air. Changes in state of Freon-12 may be predicted by means of the ideal gas law with an accuracy of better than 1 percent at pressures below 1 atmosphere at room temperature. Freon-12 is shown not to condense during an adiabatic expansion from normal conditions up to a Mach number of 3. The values of the ratio of specific heats γ for Freon-12 are lower than that for air, and therefore an additional parameter is introduced, which must be considered when comparisons are made of aerodynamic tests using Freon-12 with those using air.

The time lag of the vibrational heat capacity of Freon-12 to a change in temperature has been measured and found to be of the order of 2×10^{-8} second at atmospheric temperature and pressure. This time is so short that no important energy dissipations should result in most engineering applications.

INTRODUCTION

Some types of aerodynamic testing can be made more convenient by the use of a testing fluid having a lower velocity of sound than air. By the use of such a testing fluid aerodynamic tests of rotating machinery at high Mach numbers can be made at lower rotational speeds, at which structural problems are less serious, and also less power is required to obtain the same Mach number and Reynolds number as in air.

In order to become a suitable substitute for air, the fluid should have certain thermodynamic properties as well as the necessary chemical inertness. If the fluid has a substantially lower velocity of sound than air, it will be more dense. This dense gas should not depart greatly from a perfect gas because such a departure would necessitate the introduction of complicated correction factors.

The time lag of the vibrational heat capacity of the gas to a change in temperature must be short to avoid important energy dissipations as a result of this lag. At room temperature, air has very little vibrational heat capacity so that even though its time lag is long, resulting energy defects are negligible. Also, the gas must not condense over a sufficient range of pressure and temperature above and below atmospheric.

Freon-12 (CCl_2F_2) has been proposed as a possible fluid for aerodynamic testing. Some thermodynamic properties of this gas, including the time lag of its vibrational heat capacity and the velocity of sound, are presented and discussed herein.

SYMBOLS AND UNITS

T_{cr} critical temperature, $^{\circ}K$

P_{cr} critical pressure, atmosphere

R gas constant, cubic centimeter atmosphere per gram mole per $^{\circ}K$ or foot-pounds per slug per $^{\circ}F$

a' Van der Waals' constant, atmosphere (cubic centimeter per gram mole)^2

b' Van der Waals' constant, cubic centimeter per gram mole

c_v specific heat at constant volume, units of R

c_p specific heat at constant pressure, units of R

γ ratio of specific heats, nondimensional (c_p/c_v)

p pressure

p_v vapor pressure, millimeters of mercury

V specific volume

T temperature, $^{\circ}$K or $^{\circ}$F absolute

U internal energy

a velocity of sound, feet per second

m molecular weight

s entropy

ρ density

P_r Prandtl number, nondimensional $\left(\frac{c_p\mu}{k}\right)$

k thermal conductivity, Btu per second per square foot per ($^{\circ}$F per foot)

μ viscosity, slugs per foot per second

M local Mach number, nondimensional

M_1 Mach number of undisturbed stream when body is at critical speed, nondimensional

$$\frac{Q}{Sa_{cr}\rho_{cr}} \quad \frac{\text{Mass flow at M}}{\text{(Area at M)(Speed of sound at M=1)(Density at M=1)}}$$

u/u_1 ratio of maximum local low-speed velocity on body to velocity of undisturbed stream, nondimensional

p_2/p_1 ratio of static pressure after shock to static pressure before shock, nondimensional

T_{sat} temperature at which Freon-12 vapor becomes saturated at pressure corresponding to M

x fraction of air in mixture of Freon-12 and air, by weight

Subscripts:

s stagnation conditions

m mixture of Freon-12 and air

THERMODYNAMIC PROPERTIES OF FREON-12

Van der Waals' constants.- The values of critical temperature and pressure for Freon-12 were obtained from references 1 (p. 474) and 2, which were in good agreement. By use of these values and the equations for a' and b' from page 12 of reference 3, Van der Waals' constants were calculated as follows:

$$a' = \frac{27}{64}\frac{R^2 T_{cr}^{\ 2}}{P_{cr}} = 10.62 \times 10^6$$

$$b' = \frac{RT_{cr}}{8P_{cr}} = 99.72$$

where

$T_{cr} = 384.6^\circ$ K = 232° F

P_{cr} = 39.56 atmospheres = 581 pounds per square inch

R = 82.064 cubic centimeter atmosphere per gram mole per ^{o}K

$$\left(p + \frac{a'}{V^2}\right)(V - b') = RT \qquad (1)$$

Equation (1) is Van der Waals' equation of state.

By use of these values of a' and b' and equation (1), values of pV/RT were plotted in figure 1 to show departure of Freon-12 from a perfect gas. Van der Waals' equation of state was selected for its simplicity and indicates the order of magnitude of the departure. Since Van der Waals' equation is not accurate in the neighborhood of the condensation point, the curves are not extended to the condensation point.

Specific heats.- Measured and calculated values of c_v for Freon-12 are taken from reference 4. These values are plotted over a range of temperature in figure 2. By use of these values of c_v, c_p was calculated for the Van der Waals' gas as follows:

From page 40 of reference 3,

$$c_p - c_v = \left[\left(\frac{\partial U}{\partial V}\right)_T + p\right]\left(\frac{\partial V}{\partial T}\right)_p \qquad (2)$$

since, from page 65 of reference 3,

$$\left(\frac{\partial U}{\partial V}\right)_T = \frac{a'}{V^2}$$

and, from equation (1),

$$\left(\frac{\partial V}{\partial T}\right)_p = \frac{R}{\dfrac{2a'b'}{V^3} - \dfrac{2a'V}{V^3} + p + \dfrac{a'}{V^2}}$$

Therefore

$$c_p - c_v = \frac{Ra'V + R_p V^3}{2a'b' - a'V + pV^3} \tag{3}$$

A plot of c_p/c_v against temperature at pressures of 0.1, 1, and 10 atmospheres is shown in figure 3.

VELOCITY OF SOUND

The velocity of sound in Freon-12 as a Van der Waals' gas was calculated over a range of temperature at pressures of 0.1, 1, and 10 atmospheres as follows:

From page 318 of reference 3,

$$a^2 = \left(\frac{dp}{d\rho}\right)_s = -\frac{\left(\frac{\partial s}{\partial \rho}\right)_p}{\left(\frac{\partial s}{\partial p}\right)_\rho} \tag{4}$$

Also

$$\left(\frac{\partial s}{\partial \rho}\right)_p \left(\frac{\partial \rho}{\partial T}\right)_p = \left(\frac{\partial s}{\partial T}\right)_p = \frac{c_p}{T}$$

$$\left(\frac{\partial s}{\partial p}\right)_\rho \left(\frac{\partial p}{\partial T}\right)_\rho = \left(\frac{\partial s}{\partial T}\right)_\rho = \frac{c_v}{T}$$

and, from $\rho = \frac{m}{V}$,

$$\left(\frac{\partial \rho}{\partial T}\right)_p = -\frac{m}{V^2}\left(\frac{\partial V}{\partial T}\right)_p$$

When the foregoing equations are combined,

$$\left(\frac{\partial p}{\partial \rho}\right)_s = - \frac{\frac{c_p}{T}\left(\frac{\partial p}{\partial T}\right)_\rho}{\frac{c_v}{T}\left(\frac{\partial \rho}{\partial T}\right)_p}$$

$$= \frac{V^2 \gamma \left(\frac{\partial p}{\partial T}\right)_V}{m\left(\frac{\partial V}{\partial T}\right)_p} \tag{5}$$

Substitution in equation (5) for $\left(\frac{\partial p}{\partial T}\right)_V$ and $\left(\frac{\partial V}{\partial T}\right)_p$ from equation (1) results in

$$a^2 = \frac{V^2\gamma}{m} \; \frac{\frac{2a'b'}{V^3} - \frac{a'}{V^2} + p}{V - b'} \tag{6}$$

Values of a, calculated from equation (6), are plotted in figure 4. The velocity of sound in Freon-12 at room temperature and at pressures of 0.13 and 1 atmosphere was also measured. (See fig. 4.) The measurements were made by use of a Helmholtz resonator and were in agreement with the calculated values to better than 0.5 percent, which was the experimental accuracy of the measurements.

Heat-capacity lag.- The time lag of the vibrational heat capacity of Freon-12 was determined by the methods used in references 5 and 6. The sample consisted of a 145-pound bottle of the commercial liquid, which was sufficient for all the tests. The gas analysis submitted by the manufacturer of this sample showed that impurities were present to less than 0.1 percent. After the Freon-12 gas was evaporated into the test apparatus, data were taken at various sets of conditions and the total-head defects obtained are plotted in figure 5. The defects shown are small and vary almost inversely as the diameter of the impact tube, which is the case for a gas with a very short relaxation time. (See references 5 and 6.)

In order to establish further the relaxation time as short, a nozzle $2\frac{1}{2}$ inches long was substituted for the $1\frac{1}{2}$-inch nozzle and the defects were found to remain the same. The total-head defects remained almost constant with a change in temperature. Also, the addition of 4 percent water, 5 percent air, and 1.5 percent alcohol into the gas had but little effect on the defects obtained, the effect being to slightly reduce the total-head defects. A very rapid adjustment of the vibrational heat capacity of Freon-12 with a sudden change in temperature was thus indicated. The relaxation times calculated from a few of the points in figure 5 are of the order of 2×10^{-8} second (at atmospheric pressure), if all the vibrational heat capacity is assumed to adjust with a single relaxation time.

Other properties.- Values of the vapor pressure of Freon-12 were calculated over a range of temperature from the following formula taken from reference 2:

$$\log p_v = 34.5123 - 1816.5T^{-1} - 10.859 \log T + 0.007175T \tag{7}$$

where

$$203.1 < T < 384.6^\circ \text{ K}$$

The values of p_v calculated are plotted in atmospheres in figure 6. The data in the following table of viscosity and thermal conductivity at a pressure of 1 atmosphere for Freon-12 can be obtained from reference 1, pages 790 and 959, respectively. The Prandtl number for Freon-12 is useful in problems involving heat transfer and in problems involving viscous compressible flow, such as the flow in a compressible boundary layer. The following values of the Prandtl number for Freon-12 have been calculated for a pressure of 1 atmosphere and are presented along with, viscosity and thermal conductivity in comparison with a few of those of air:

Temperature (°F abs.)	Viscosity, μ (slug/ft-sec)		Thermal conductivity, k [Btu/(sec)(sq ft)(°F/ft)]		Prandtl number $P_r = \frac{c_p\mu}{k}$ (nondimensional) (a)	
	Air	Freon-12	Air	Freon-12	Air	Freon-12
402	----------	2.13×10^{-7}	------------	----------	-----	-----
492	3.61×10^{-7}	2.44	0.389×10^{-5}	0.133×10^{-5}	0.717	0.825
582	----------	2.74	------------	.178	-----	.751
672	4.55	3.03	.508	.222	.696	.706
762	----------	----------	------------	.269	-----	-----

[a]Units of k are in ft-lb rather than in Btu in order to make P_r nondimensional.

The latent heats of vaporization of Freon-12 are given in reference 7.

DISCUSSION OF PROPERTIES OF FREON-12

The empirical constants a' and b' in Van der Waals' equation of state (equation (1)) are corrections for the attractions between molecules and for the size of the molecules, which are both zero in the equation of state for a perfect gas. These properties of Freon-12 cause it to depart from a perfect gas by only a small amount at pressures below 1 atmosphere and at ordinary temperatures. The departure from a perfect gas is of the order of 1 percent at atmospheric conditions and, for a given temperature, varies approximately as the pressure. The density of Freon-12 at pressures of 1 atmosphere and 70° F is 0.009845 slug per cubic foot where $R = 411.5$ foot-pounds per slug per °F and

$$\frac{pV}{RT} = 0.9855$$

from figure 1. This density is more than four times that of air.

The values of c_v/R for Freon-12 (fig. 2) are much higher than those for air, which results in noticeably lower values of γ. The value of γ for Freon-12, as may be seen in figure 3, at normal conditions is about 1.13 as compared with 1.4 for air. Since many of the aerodynamic relationships are functions of γ, these relationships for Freon-12 would be expected to be somewhat different from the relationships for air. In order to compare some of these aerodynamic relationships for Freon-12 with those for air, plots of p/p_s, T/T_s, and mass flow per unit area are presented in nondimensional form as functions of the local Mach number in figures 7, 8, and 9, respectively. These relations were obtained from compressible-fluid theory by use of values of γ corresponding to $\frac{T + T_s}{2}$. The results in figures 7 and 9, however, are approximately the same as the results obtained when γ is treated as constant and equal to 1.125.

The difference between T/T_s for Freon-12 and air is largely due to the difference in γ (fig. 8). Little difference can be seen between the values of p/p_s for Freon-12 and for air in figure 7 and between the values of mass flow per unit area for Freon-12 and for air in figure 9 up to a Mach number of 1.5. The large difference between the curves for air and Freon-12 in figure 8 will become noticeable in tests of rotating turbines or compressors in which simulation of the Mach numbers entering both the rotors and stators will not be possible. In aerodynamic tests of nonrotating systems, however, it can be seen from figure 9 that Mach numbers may be closely simulated at all points below Mach numbers of 1.4.

The effect of the differences shown in figure 8 on tests of rotating machinery can best be explained as follows. If the Mach numbers entering the rotor are equal in Freon-12 and air, the ratio of rotational speeds will be the ratio of the entering velocity of sound of air and Freon-12. Because of the temperature changes that take place in the rotor blades, however, the ratio of velocity of sound in air and Freon-12 leaving the rotor will then no longer be equal to the ratio of rotational speeds. The Mach numbers entering the rotor and the stator, therefore, cannot be simultaneously simulated.

$a = \sqrt{\gamma g R T}$

A plot of u^2/u_1^2 as a function of M_1 for Freon-12 is presented in figure 10. The calculations were based on the methods of reference 8. Plots of static-pressure and total-pressure ratios across a shock wave in Freon-12 as a function of Mach number are presented in figure 11. In figures 7 to 11, the departure of Freon-12 from a perfect gas is assumed to be zero.

The velocity of sound in Freon-12 can be seen in figure 4 to be less than one-half that in air at standard conditions. This low velocity of sound in Freon is largely due to the low value of R and partly due to the low value of γ. The variation of velocity of sound with pressure at pressures of 1 atmosphere or lower are not large and can be calculated with reasonable accuracy from the equation for the velocity of sound in a perfect gas, in which $R = 411.5$ foot-pounds per slug per $^{\circ}$F. In aerodynamic tests, the velocity of sound and the density will change appreciably when small amounts of air are present in the Freon-12. Probably the most convenient method of correcting for this presence of air is to measure the velocity of sound. The values of γ and R for the mixture can be found if the velocity of sound is known, for mixtures of perfect gases, as follows:

$$a_m^2 = \gamma_m R_m T$$

$$R_m = R_{air}x + R_{Freon}(1 - x)$$

$$\gamma_m = \frac{\left(\frac{c_p}{R}\right)_m}{\left(\frac{c_p}{R}\right)_m - 1}$$

where

$$c_{p_m} = c_{p_{air}}x + c_{p_{Freon}}(1 - x)$$

The short relaxation time measured in Freon-12 means that this gas will adjust its vibrational heat capacity to a change in temperature rapidly enough to allow no important dissipations to occur in most engineering applications. The relaxation time has been measured at atmospheric pressure and it will increase as the temperature and pressure are lowered. (See references 5 and 6.) If a compression takes place within a distance of 0.10 inch at a Mach number of 2 in Freon-12 at a pressure of 1 atmosphere, the compression time would be 1000 times longer than the relaxation time. Conditions inside a shock wave will be altered because of heat-capacity lag. In particular, the thickness of the shock wave will be increased (to the order of 0.001 in. at 0.1 atm. pressure). If the boundary-layer thickness were of this order, it is possible that changes in the boundary-layer separation effects due to shocks would be noticeable. A discussion of the effects of heat-capacity lag on shock waves is presented in reference 9.

In order to determine the possibilities that Freon-12 will condense at the low temperatures encountered from adiabatic expansion to high Mach numbers, calculations have been made and are presented in figure 12. Curves are given for a stagnation temperature of 550° F absolute and various stagnation pressures. As can be seen from figure 12, Freon-12 will remain a gas to Mach numbers of 3 or more, depending upon the stagnation pressure, for the stagnation temperature shown. In figure 12, the departure of Freon-12 from a perfect gas is assumed equal to zero.

CONCLUDING REMARKS

Various thermodynamic properties of Freon-12 have been presented, in order to determine the possibilities of Freon-12 as a fluid for aerodynamic testing. The velocity of sound in Freon-12 is less than one-half that in air and the density of Freon is approximately four times that of air. The value of the ratio of specific heats γ for Freon-12 is lower than that for air but the effect of this lower value of γ for Freon-12 is shown to be small at Mach numbers less than 1.4. In rotating machinery, however, the Mach numbers in rotating and stationary coordinates cannot be simultaneously simulated in Freon-12 and in air. Freon-12 does not depart markedly from a perfect gas at pressures of 1 atmosphere and lower and will not condense at normal conditions up to a Mach number of 3.

The time lag of the vibrational heat capacity of Freon-12 to a change in temperature is so short that no important energy dissipation should occur as a result of this lag in most engineering applications.

Freon-12 must necessarily be used in a closed system and the presence of small amounts of air will noticeably change the velocity of sound so that measurements of the velocity of sound would be necessary for a reasonably accurate knowledge of the working fluid.

In general, the properties of Freon-12 are such that interpretation of aerodynamic tests using this fluid in terms of similar tests using air seems possible. An actual comparison of aerodynamic data obtained from tests using air with data obtained from tests using Freon-12 will be necessary to establish this relationship.

Langley Memorial Aeronautical Laboratory
National Advisory Committee for Aeronautics
Langley Field, Va., December 7, 1945

REFERENCES

1. Perry, John H.: Chemical Engineers' Handbook. Second ed., McGraw-Hill Book Co., Inc., 1941.

2. Tables annuelles de constantes et données numériques. Vol. XI, secs. 13, 14, no. 6, Hermann & Cie (Paris), 1937:

   Jorissen, W. P., and van Keekem, P. C.: Tension de vapeur - températures d'ébullition. P. 13-19.

   Keesom, W. H., van Santen, J. J. M., and Haantjes, J.: Lois des gaz. P. 14-6.

3. Epstein, Paul S.: Textbook of Thermodynamics. John Wiley & Sons, Inc., 1937.

4. Eucken, A., and Bertram, A.: Die Ermittelung der Melwärme einiger Gase bei tiefen Temperaturen nach der Wärmeleitfähigkeitsmethode. Zeitschr. f. phys. Chem., Abt. B, Bd. 31, Nr. 5, Feb. 1936, p. 363.

5. Kantrowitz, Arthur: Effects of Heat-Capacity Lag in Gas Dynamics. NACA ARR No. 4A22, 1944. (Classification canceled June 1945.)

6. Kantrowitz, Arthur, and Huber, Paul W.: Heat-Capacity Lag in Turbine-Working Fluids. NACA RB No. L4E29, 1944.

7. McAdams, William H.: Heat Transmission. Second ed., McGraw-Hill Book Co., Inc., 1942, p. 398.

8. von Kármán, Th.: Compressibility Effects in Aerodynamics. Jour. Aero. Sci., vol. 8, no. 9, July 1941, pp. 337-356.

9. Bethe, H. A., and Teller, E.: Deviations from Thermal Equilibrium in Shock Waves. Rep. No. X-117, Ballistic Res. Lab., Aberdeen Proving Ground, 1945.

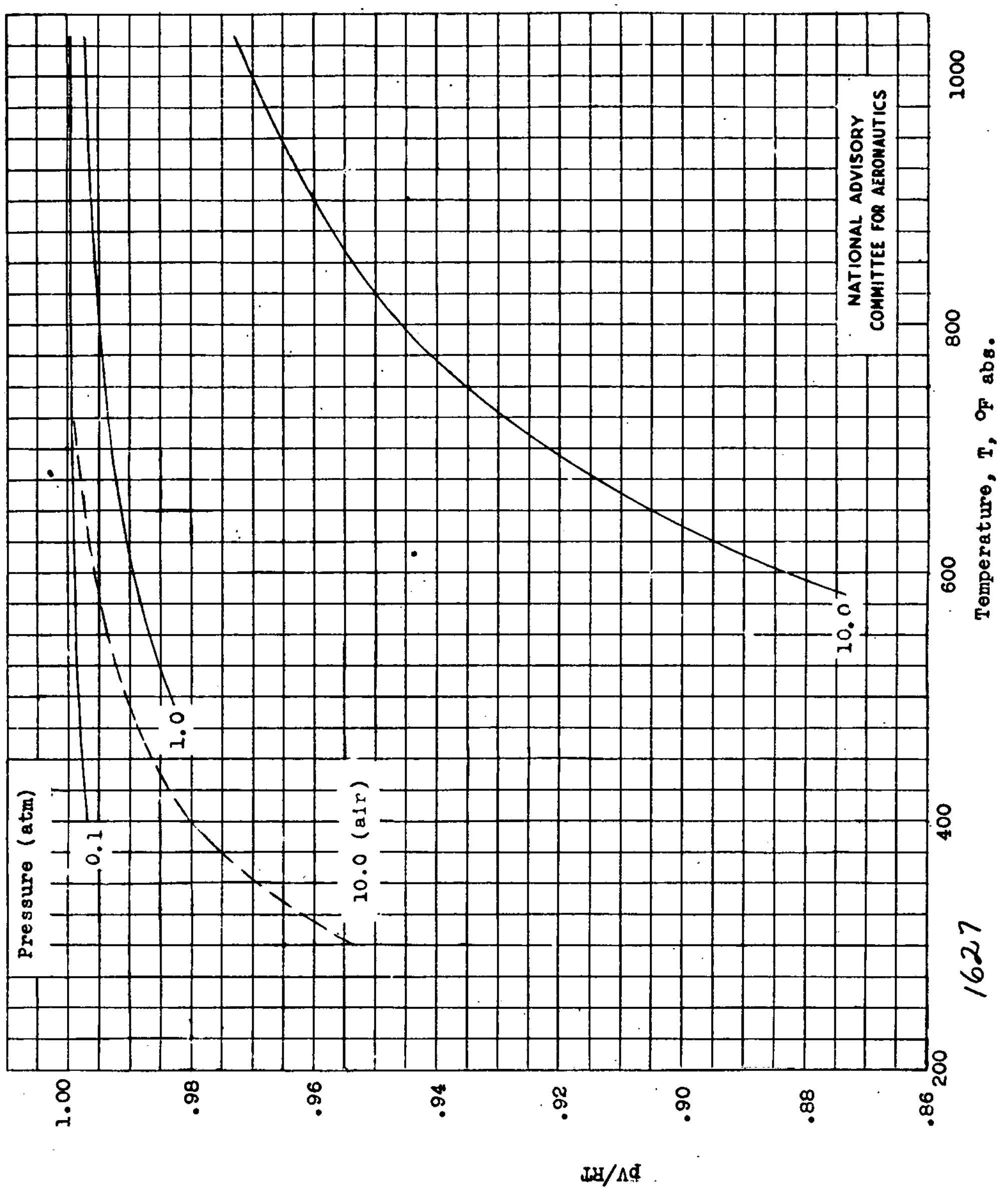


Figure 1.- Departure of Freon-12 from a perfect gas. pV/RT calculated from equation (1).

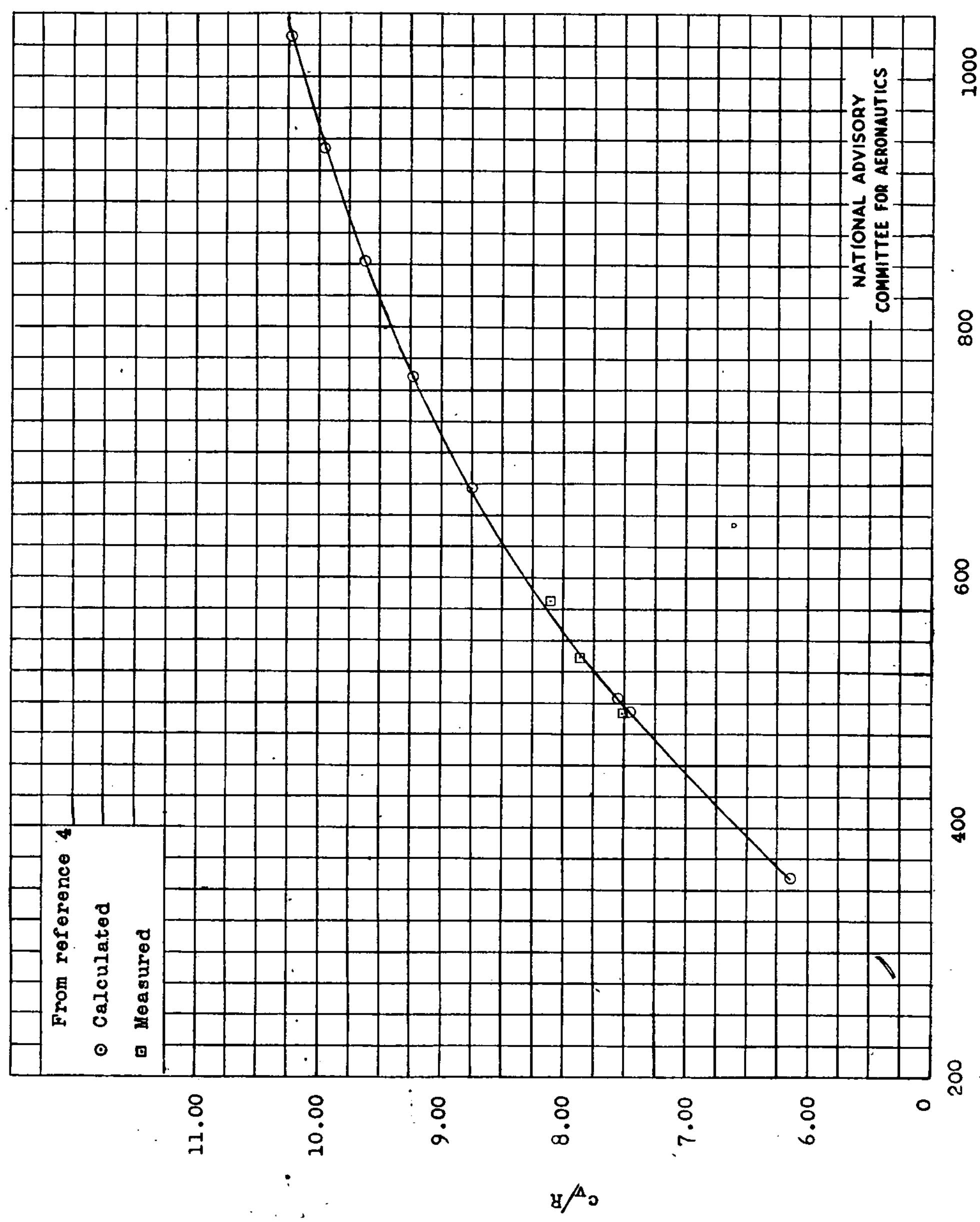


Figure 2.- Specific heat of Freon-12 at constant volume c_v/R. Obtained from reference 4.

$$\left(R = 82.064 \, \frac{\text{cc atm}}{\text{gm mole } ^\circ\text{K}} = 411.5 \, \frac{\text{ft-lbs}}{\text{slug } ^\circ\text{F}} \right)$$

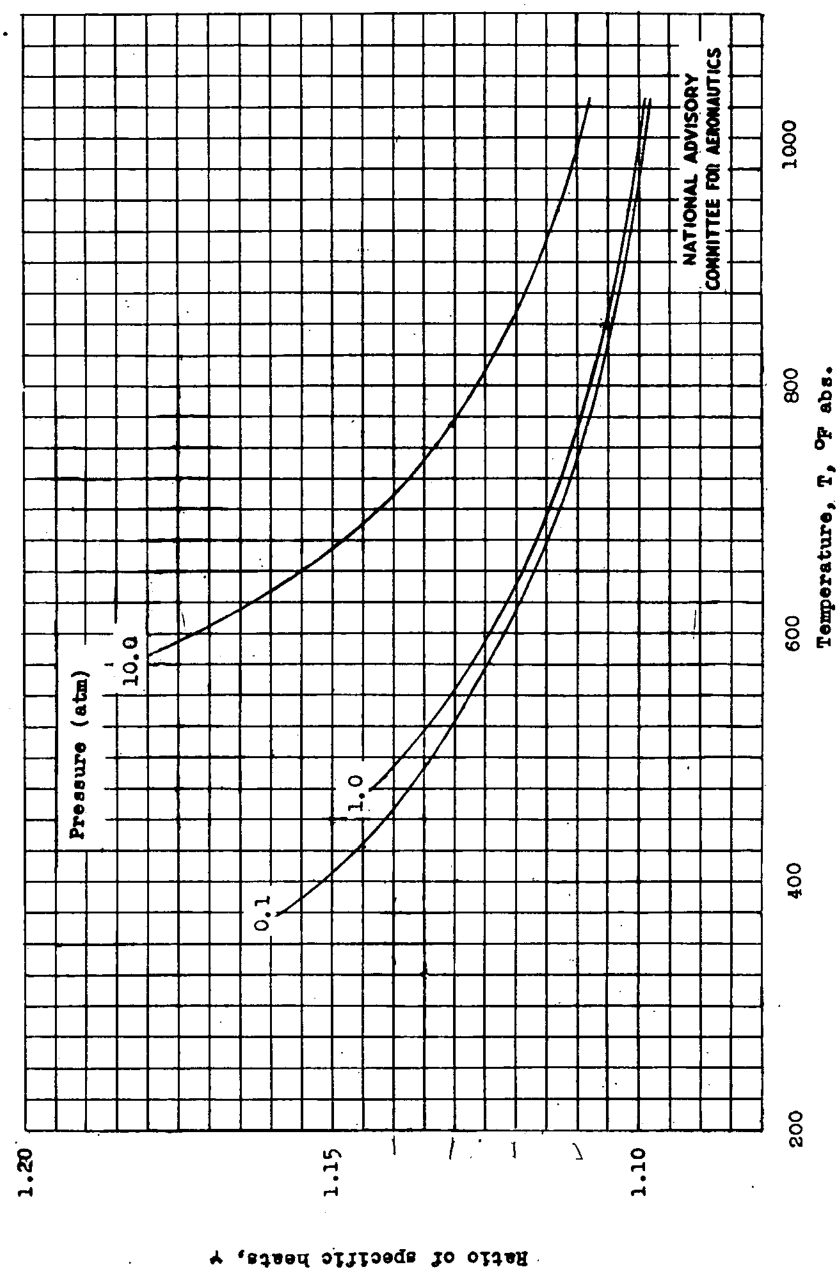


Figure 3.- Ratio of the specific heats of Freon-12 γ as a Van der Waals' gas. Calculated from equation (3).

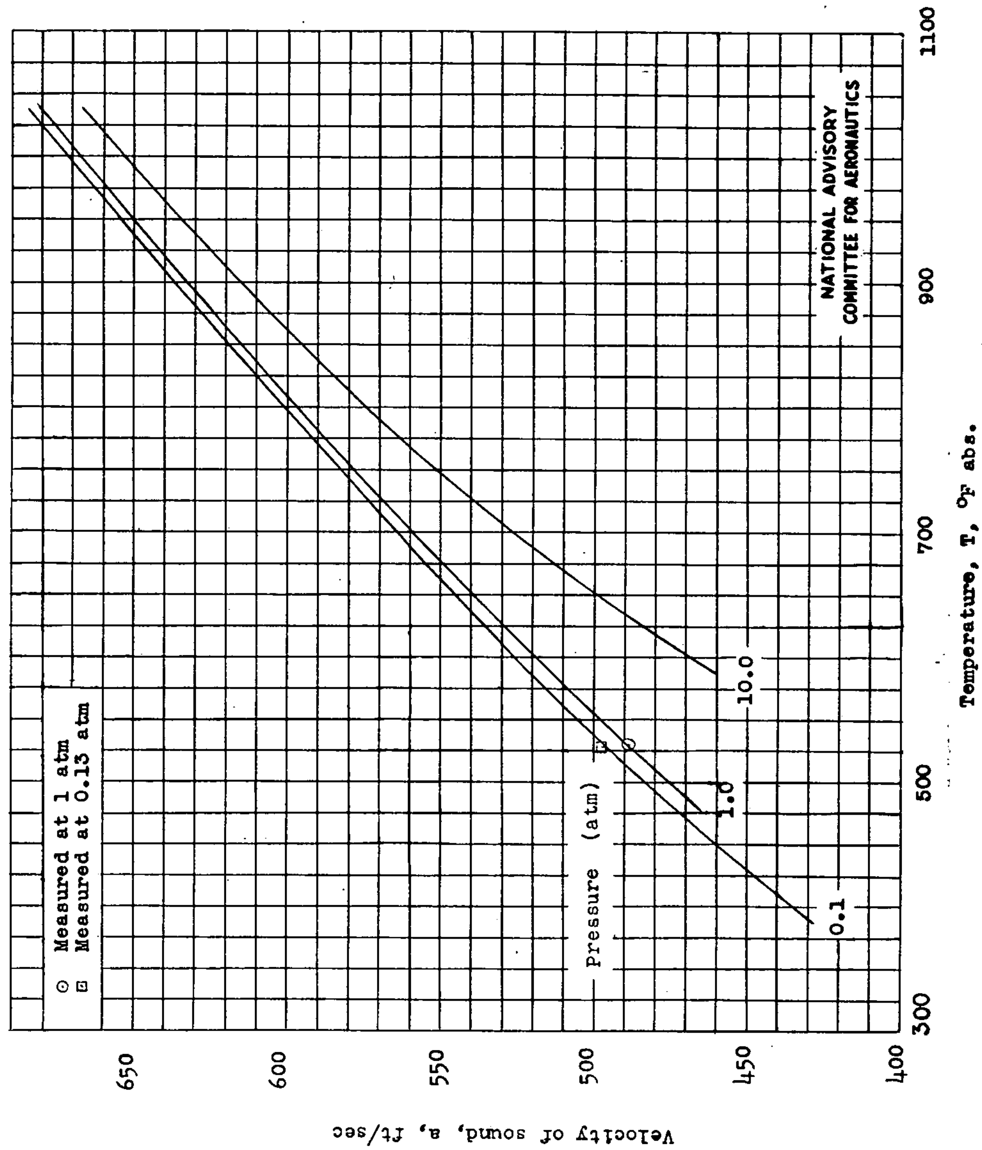


Figure 4.- Velocity of sound in Freon-12 as a Van der Waals' gas. Calculated from equation (6).

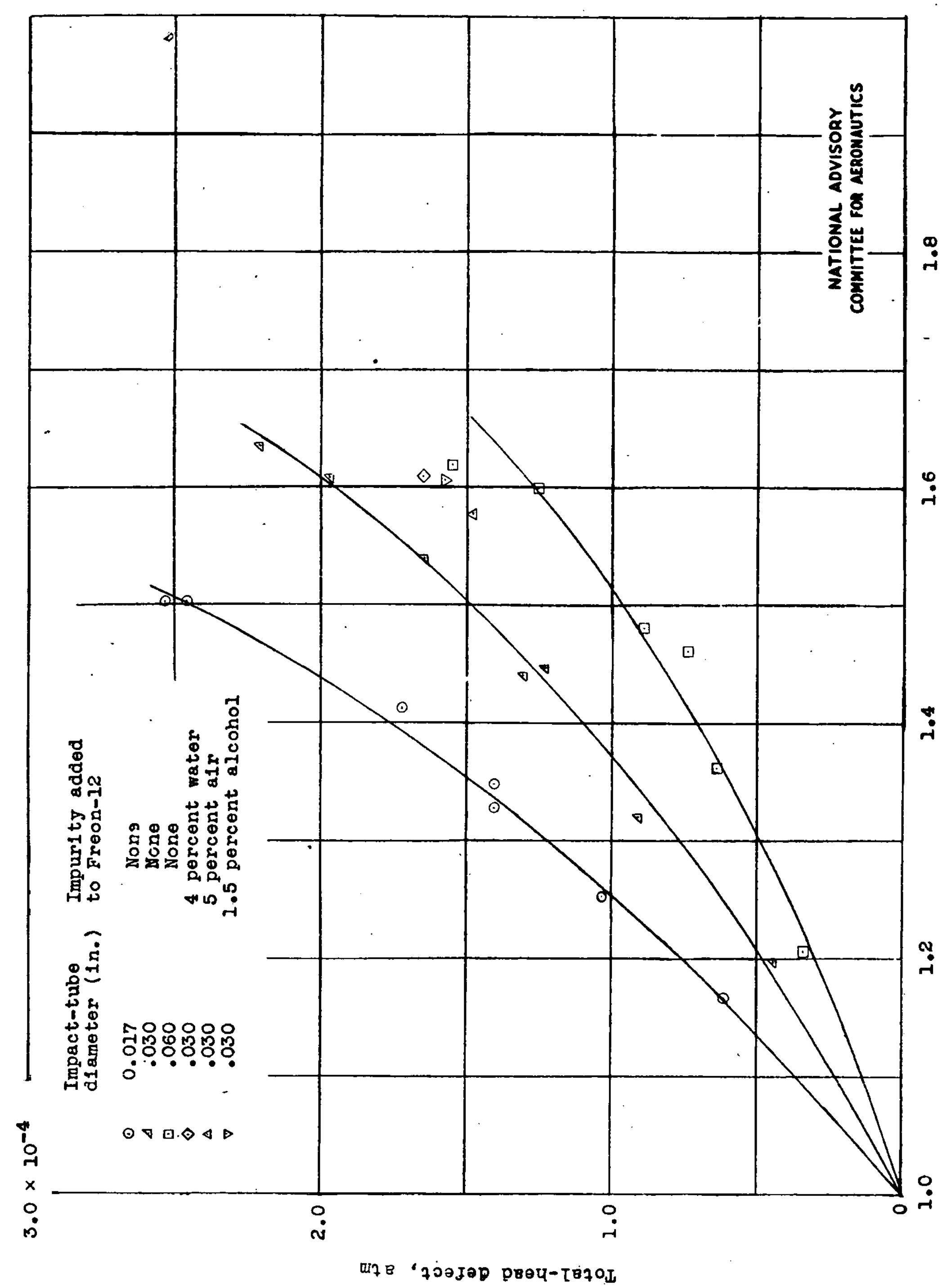


Figure 5.- Experimental total-head defect of Freon-12 for expansion from chamber pressure to 1 atmosphere. Chamber temperature, 75° F.

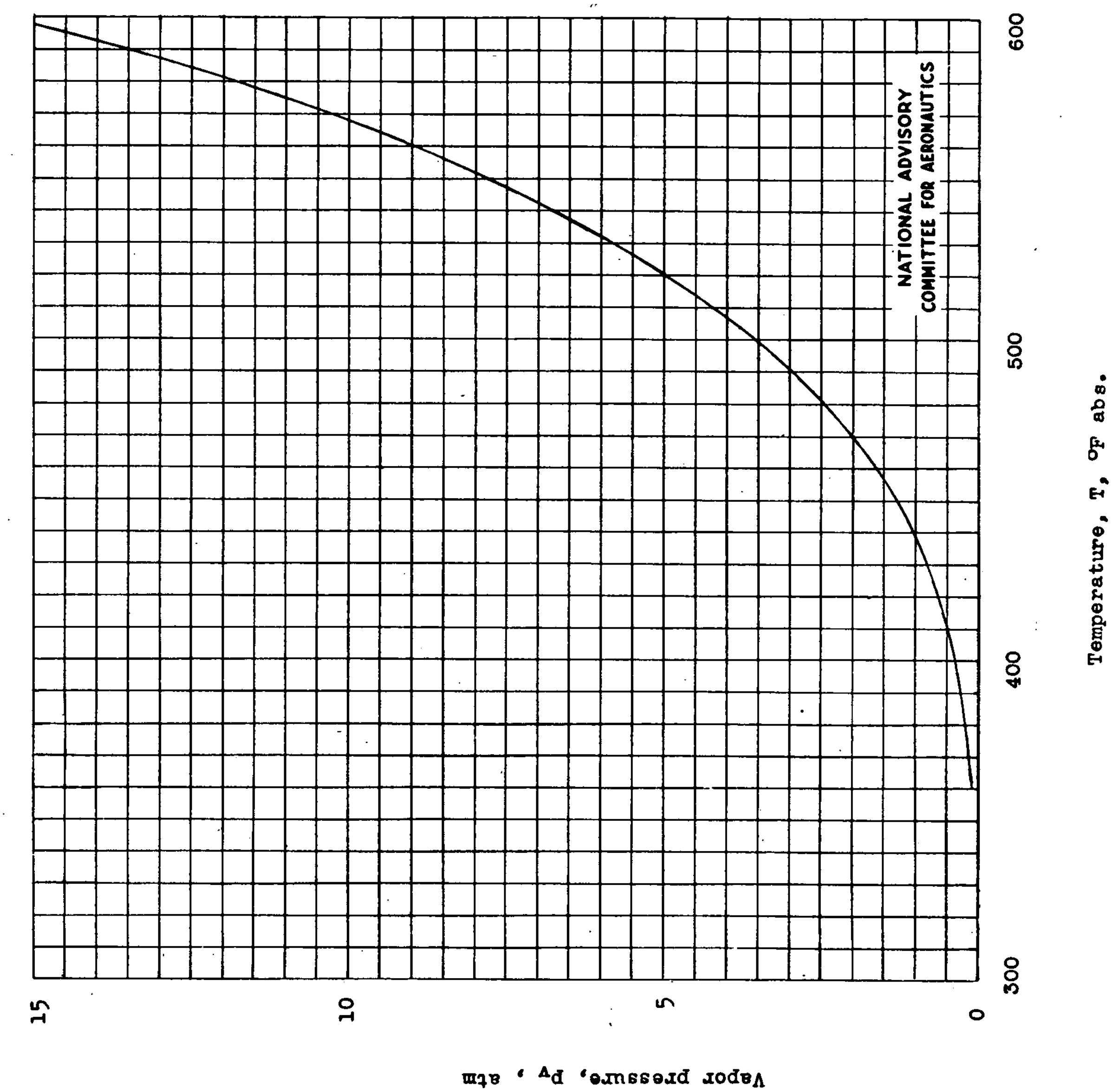
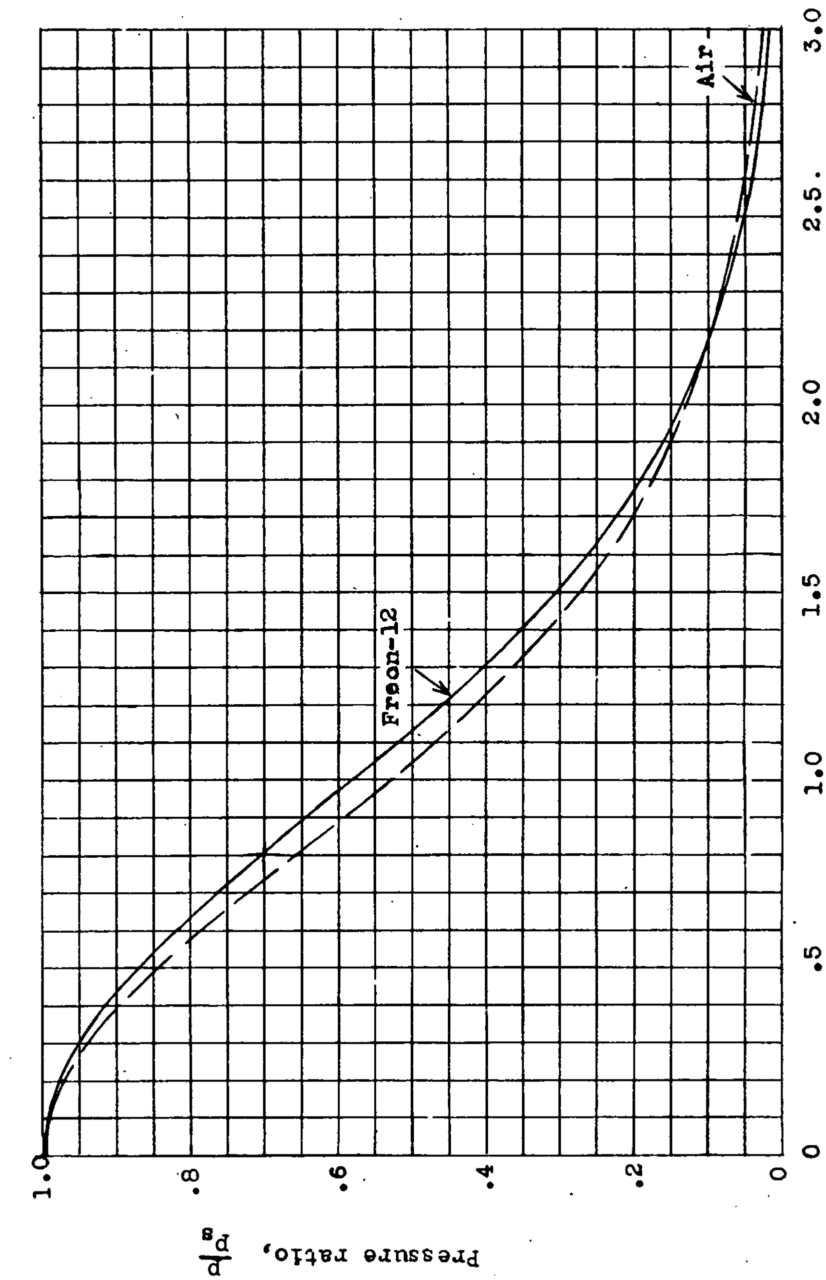


Figure 6.- Vapor pressure of Freon-12. Calculated from equation (7).



NATIONAL ADVISORY
COMMITTEE FOR AERONAUTICS

Figure 7.- Pressure ratio for Freon-12 and air as a function of Mach number for isentropic flow. Stagnation γ for Freon-12, γ_s = 1.125.

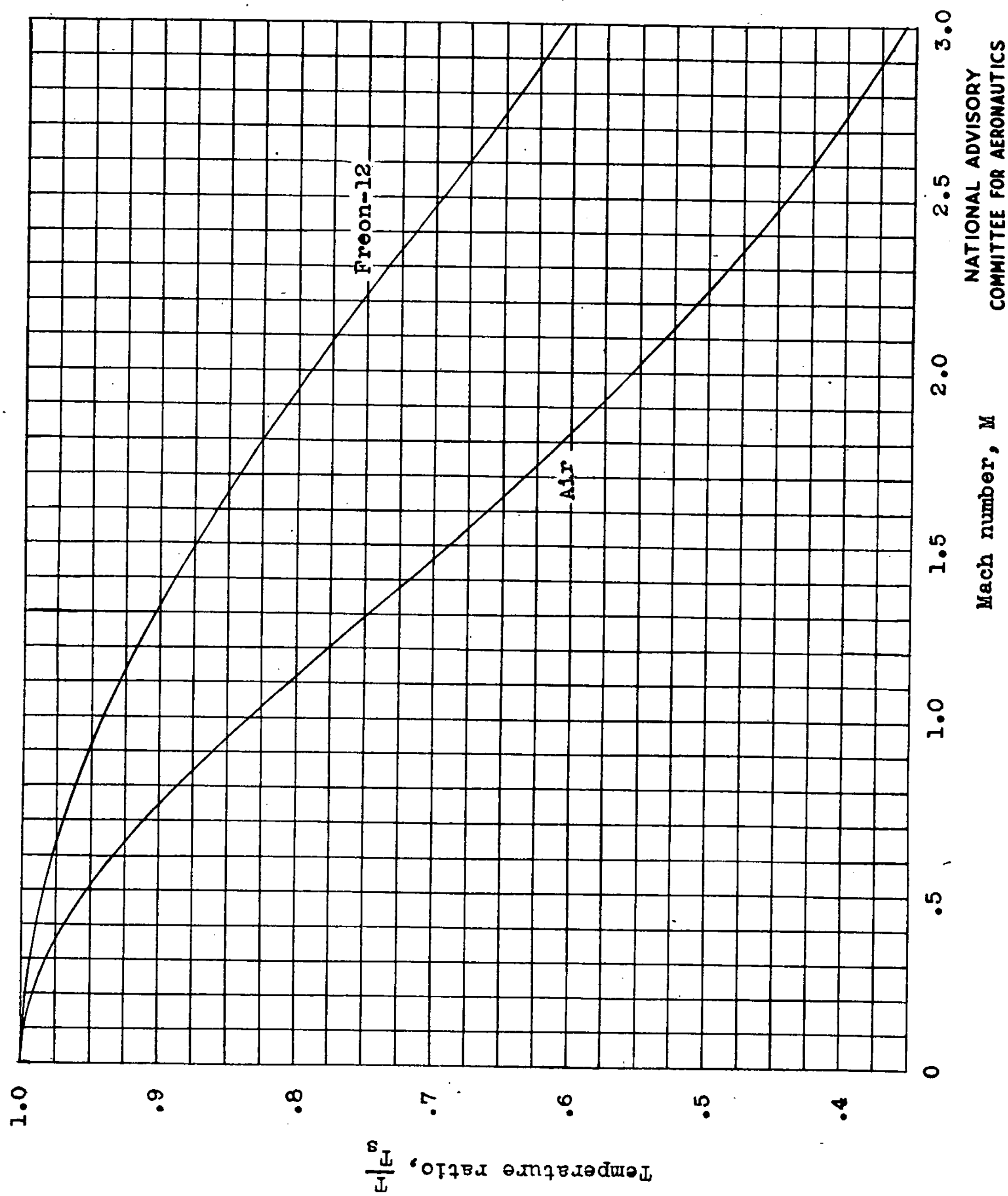
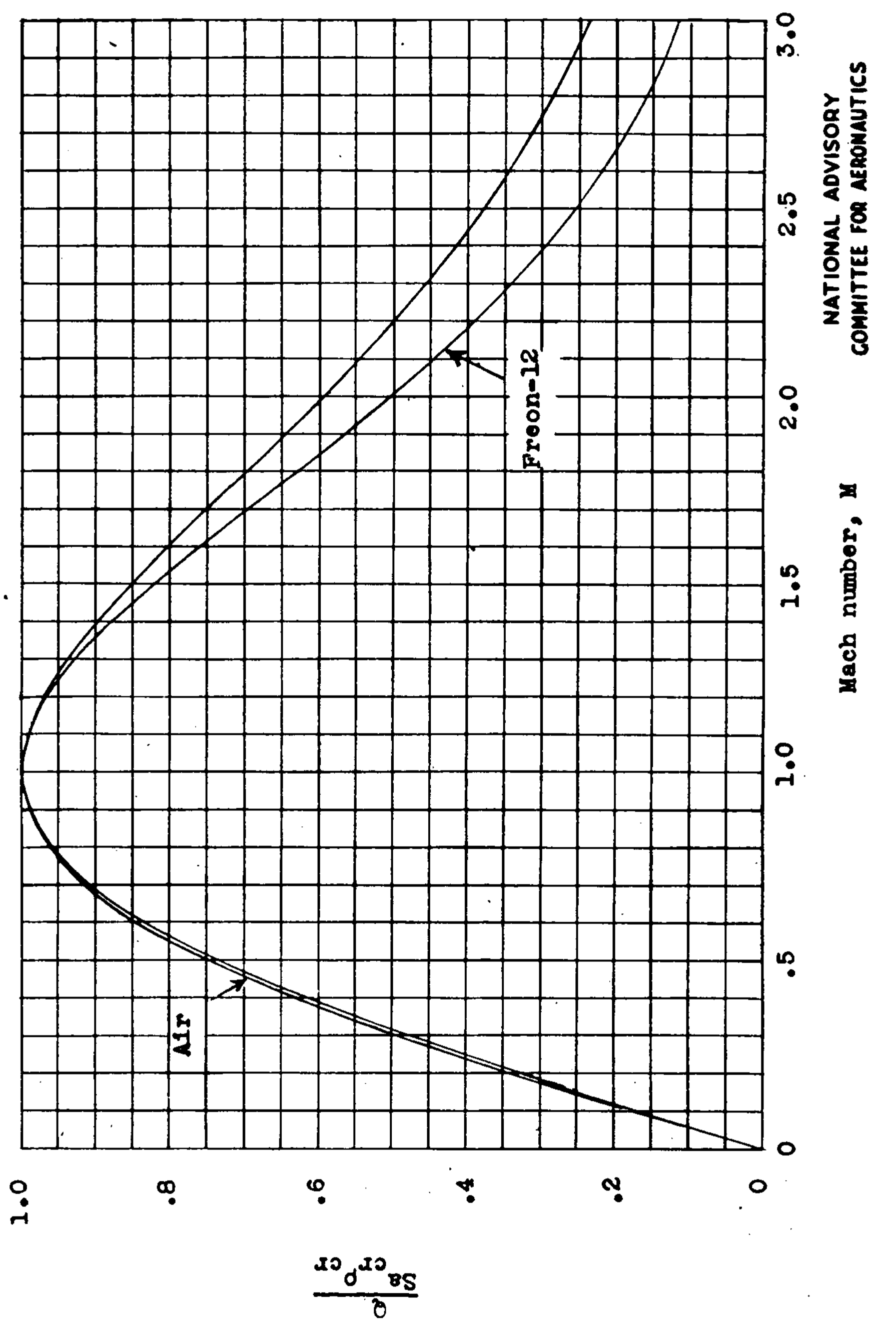


Figure 8.- Temperature ratio for Freon-12 and air as a function of Mach number for isentropic flow. Stagnation γ for Freon-12, $\gamma_s = 1.125$.



NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

Figure 9.- Mass flow per unit area for Freon-12 and air as a function of Mach number for isentropic flow. Stagnation γ for Freon-12, γ_s = 1.125.

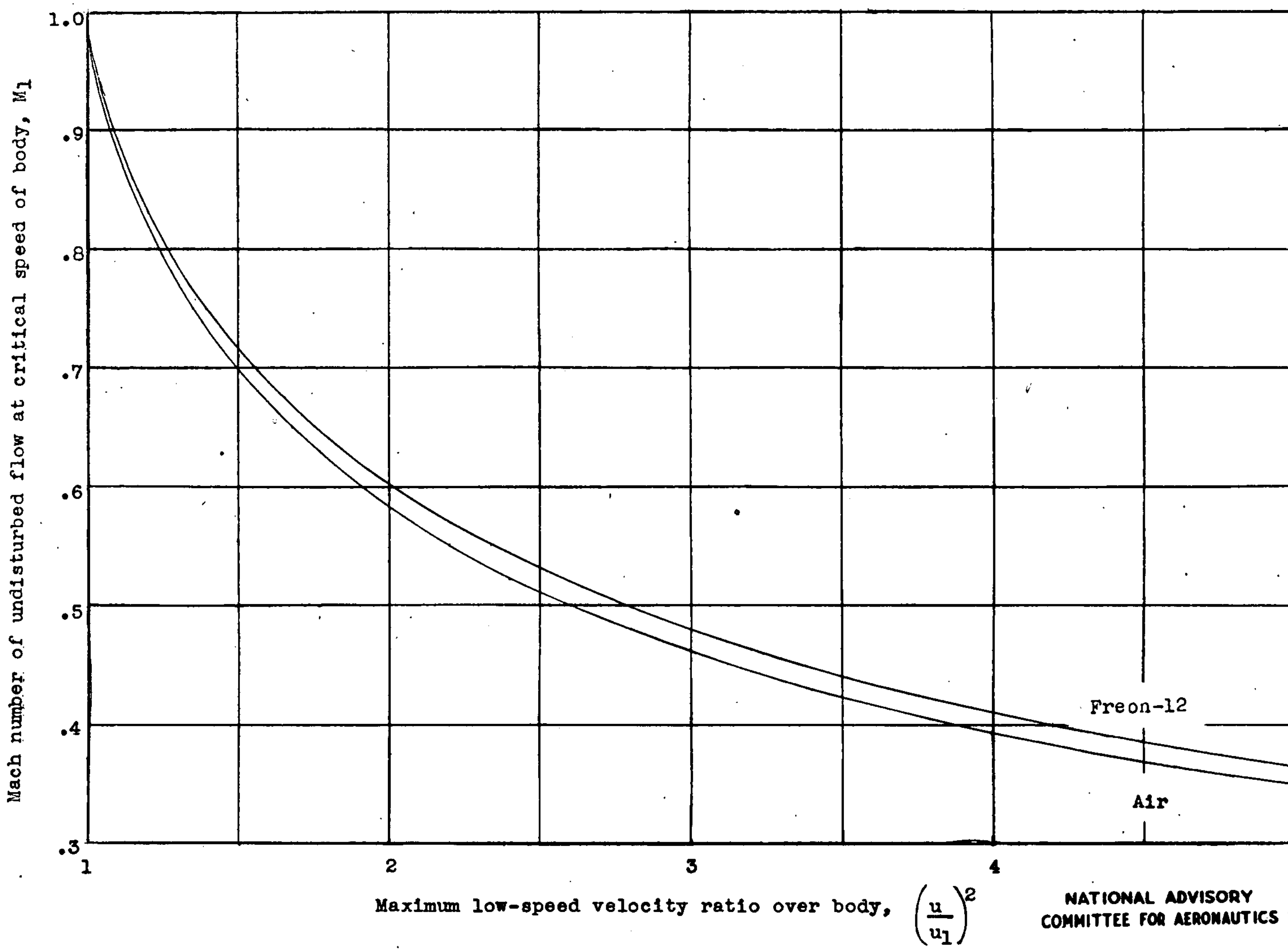


Figure 10.- Critical Mach number plotted against maximum low-speed velocity ratio for Freon-12 and air. For Freon-12, $\gamma = 1.125$.

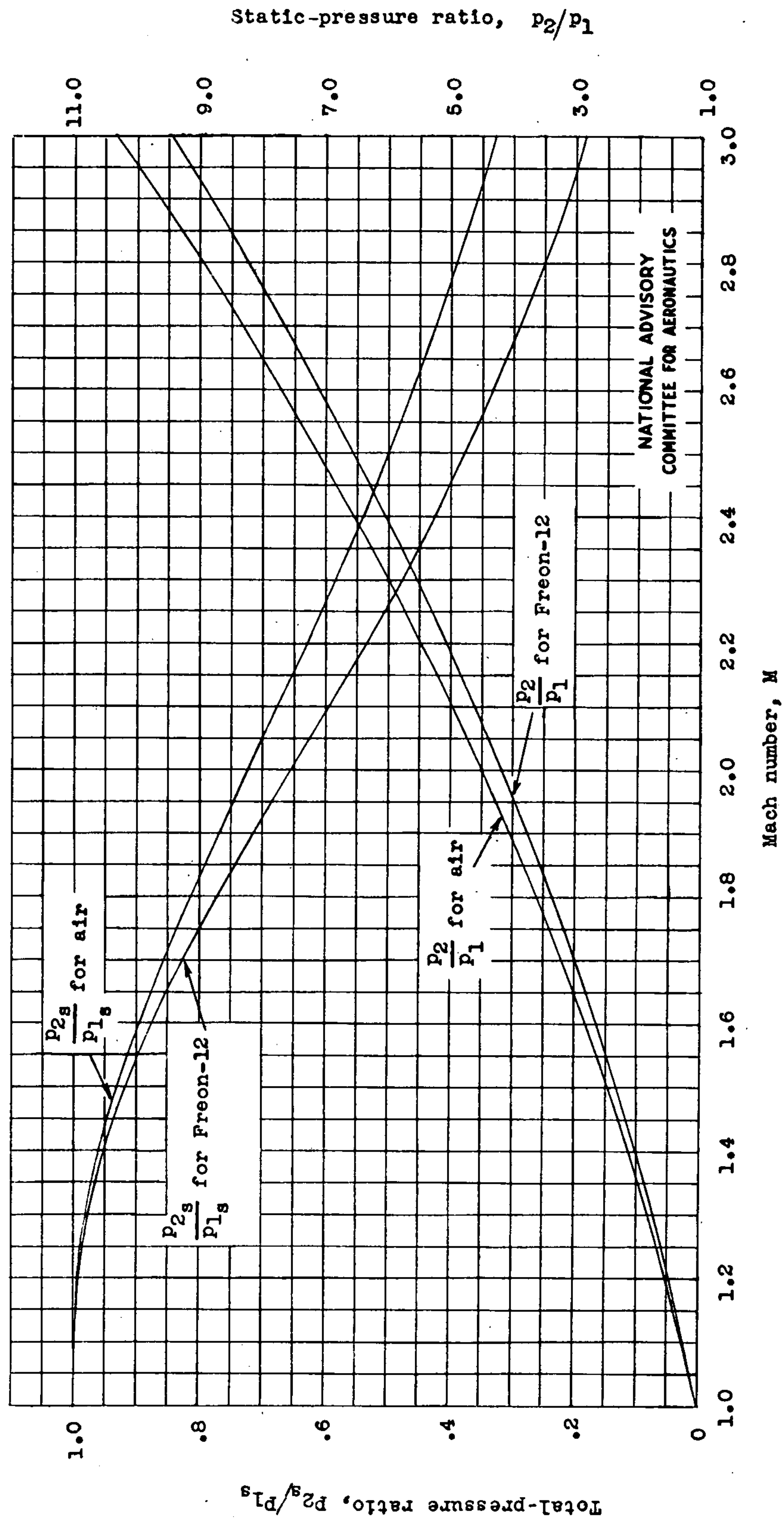


Figure 11.- Static- and total-pressure ratios across a shock wave in Freon-12 and air. For Freon-12, γ = 1.125.

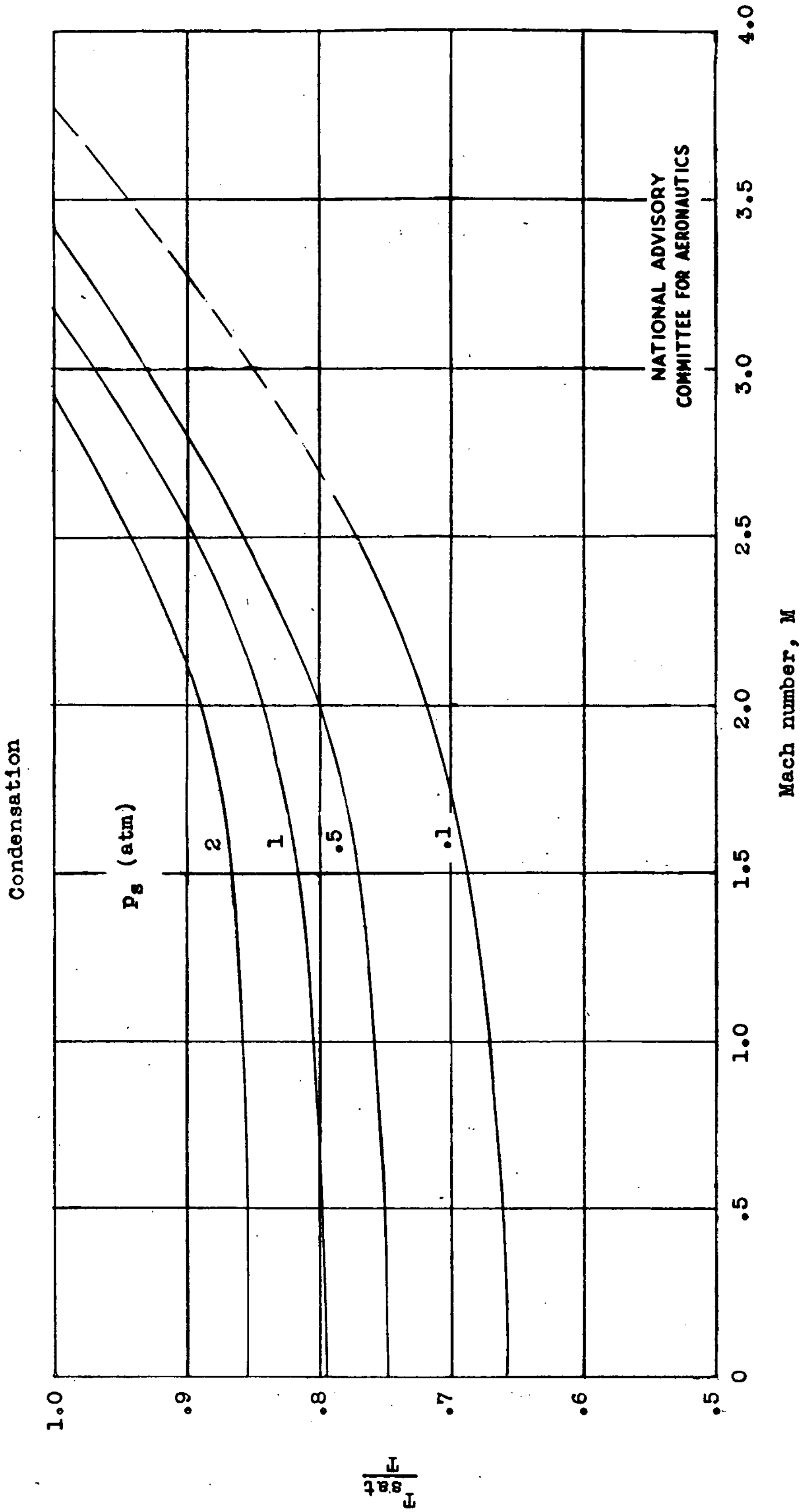


Figure 12.- Condensation limits for adiabatic expansion from stagnation temperature 550° F absolute.