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AN ANALYSIS OF THE FACTORS AFFECTING THE STATE OF FUEL AND AIR MIXTURES

By Mitchell Gilbert, John N. Howard
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AN ANALYSIS OF THE FACTORS AFFECTING THE STATE OF FUEL AND AIR MIXTURES

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SUMMARY

The factors important in determining the state and the rate of change of state of mixtures of liquid fuel, fuel vapor, and dry air are discussed with reference to basic physical variables such as pressures, temperatures, and amounts present of liquid fuel, fuel vapor, and air.

Data in the form of curves and tables are given to enable estimation of temperatures and other conditions required for complete or partial vaporization of various fuels. An estimate is also made of the maximum and minimum time for evaporation of different sizes of fuel drops; the importance of knowledge of the factors affecting vaporization time is indicated from this estimate.

INTRODUCTION

Knowledge of the physical state of the fuel-air mixture (that is, the mixture quality) within the precombustion zones of a jet-propulsion burner and at the intake ports of multicylinder reciprocating engines is necessary in present aircraft-engine research. In the jet-propulsion burner research much work is being done in evaluating the performance of fuels. The variation in rate and completeness of combustion with different fuels cannot be completely understood unless the vaporization factors are given their proper emphasis in explaining the processes leading to combustion. In the reciprocating-engine field knowledge of mixture quality is needed for the correlation of fuel knock ratings between multicylinder engines and single-cyclinder laboratory engines for studying the performance of various engine components and for improving fuel distribution to cylinders. The proper evaluation of the effects of internal coolants in engines could be materially aided by mixture-quality information. Methods of description of mixture quality are therefore worth while subjects of investigation with regard to both conventional and jet-propelled power plants.

In principle, all physical properties of the mixture that influence the performance of individual engine cylinders and the character of burning in jet-propulsion units should be determined. Because of the complex, unstable, and heterogeneous nature of the fuel-air mixture usually existing between the point of fuel injection and the intake port or actual combustion zone, complete specification of these physical properties is difficult and has seldom been tried. Instead, so-called mixture temperatures and calculated equilibrium-air-distillation temperatures have been used for estimating mixture quality. Both methods are inadequate because important factors affecting mixture quality and vaporization processes are neglected. Measurements of true mixture temperatures are difficult because of wet-bulb effects on the temperature-measuring device. Equilibrium-air-distillation temperatures are inadequate because they cannot describe the dynamic process by which fuel-air mixtures are formed, but only equilibrium states.

It is the purpose of this paper to describe the physical properties that are necessary to specify mixture quality in a system containing fuel and dry air and to evaluate the theoretical relation between these properties and the physical properties of the mixture.

NOTATION

c_{pa}	specific heat of air at constant pressure, (Btu/(lb)(°R))
c_p	specific heat of fuel at constant pressure differentiated by c_{pl} and c_{pv} for liquid and vapor, respectively, (Btu/(lb)(°R))
d_o	diameter of fuel drop, (in.)
D	diffusion coefficient, (sq in./sec)
f	over-all fuel-air ratio
f_v	ratio of fuel vapor to air
g	dimensional constant, (32.2 lb(mass)-ft/lb(force)-sec^2)
L,L_1,L_2	latent heats of vaporization, (Btu/lb)
M_a	molecular weight of air, (lb/lb-molecule)
M_f	molecular weight of fuel, (lb/lb-molecule)
p	total pressure of system (sum of all partial pressures), (in. Hg absolute)

p_a partial pressure of air, (in. Hg absolute)

p_f partial pressure of fuel, (in. Hg absolute)

p_s saturation pressure of fuel corresponding to the fuel temperature, (in. Hg absolute)

R_a gas constant for air, ((0.753 in. Hg)(cu ft)/(lb)($^{\circ}$R))

r ratio of molecular weight of fuel to that of air

S_{90} slope at 90-percent-evaporated point of A.S.T.M. distillation curve, ($^{\circ}$R/percent evaporated)

X fraction of fuel evaporated

S_X slope at 100X-percent-evaporated point of A.S.T.M. distillation curve, ($^{\circ}$R/percent evaporated)

T_a air- or gas-phase temperature, ($^{\circ}$R)

T_f fuel temperature, ($^{\circ}$R)

T_{dp} dew-point temperature of fuel-air mixture, ($^{\circ}$R)

T_{90} temperature at 90-percent-evaporated point of A.S.T.M. distillation curve, ($^{\circ}$R)

T_X temperature at 100X-percent-evaporated point of A.S.T.M. distillation curve, ($^{\circ}$R)

T_{fX} equilibrium-air-distillation temperature for 100X percent evaporated, ($^{\circ}$R)

t time, (sec)

W_a weight of air, (lb)

W_f weight of fuel, (lb)

ρ_a density of air, (lb/cu ft)

ρ_f density of liquid fuel, (lb/cu ft)

DESCRIPTION OF MIXTURE QUALITY

A definitive study of the physical state of fuel-air mixtures is not possible until those properties of the mixture have been found which characterize its state and which can be specified and measured

without ambiguity. These properties can be clearly specified for a mixture formed from dry air and a pure single-component fuel. The characteristics of such a simple mixture will therefore be described and the description can be carried over to complex fuels by analogy.

Equilibrium in a fuel-air mixture may be defined as any physical state that does not change spontaneously with time. The existence of either thermal or evaporative equilibrium is sufficient to define thermodynamic equilibrium in a fuel-air mixture composed of liquid fuel, fuel vapor, and air, the condition of supersaturation excluded. When a fuel-air system is not in equilibrium, heat and material transfer between and within the gas and liquid phases will occur that will drive the system toward thermodynamic equilibrium. Further, the system, if unacted upon by external forces that may bring about pseudoequilibrium in the thermal or evaporative processes, must attain thermal and evaporative equilibrium simultaneously. Thus, liquid fuel introduced into air at the same temperature as the fuel would result in a system momentarily in thermal equilibrium. The unsaturated condition of the air with respect to the fuel vapor, however, would cause evaporation and the temperature of the system would drop (assuming adiabatic conditions). At the true equilibrium state the evaporation would have ceased and the temperature would be uniform throughout the system. The reverse situation with the system initially in evaporative equilibrium but out of thermal balance can also be visualized as being a case of pseudoequilibrium.

An appropriate idealized model of an engine intake pipe or of a jet-propulsion burner unit is a straight tube containing a nonequilibrium mixture. Although fuel-vapor and liquid concentrations, air velocities, temperatures, etc. may vary within the cross section of the flow, a description of the mixture quality can be based for present purposes on the assumption that the system is uniform. Consequently, it will be assumed that in any cross section of the flowing charge (1) all liquid is present in the form of drops uniformly distributed, (2) the fuel temperature T_f and the size of all drops is the same, (3) the temperature of the gas phase T_a is the same throughout, and (4) the fuel vapor in the gas phase is uniformly distributed (the fuel-air ratio f in the gas phase is constant). If X is the fraction evaporated, the masses of liquid and gaseous fuel per unit mass of air are $f(1 - X)$ and fX, respectively. For a given single-component fuel, knowledge of f, X, T_f, T_a, and the total pressure p completely defines the state of the mixture under the stated assumptions. These five properties of the mixture, which will be called mixture parameters, are therefore those that should be employed in studying either the physical equilibrium or nonequilibrium of a mixture of fuel and air and in determining the relation between engine performance and mixture quality.

The mixture can be said to be in equilibrium during a given interval of time, in view of the assumed uniformity, if $T_a = T_f$ during this time or if the partial pressure of the fuel p_f satisfies the equilibrium vapor-pressure-temperature relation for the fuel, which can be symbolized by $p_s = p_f = F(T_f) = F(T_a)$. The simplest criterion of equilibrium is obviously the thermal one. The complete description of the equilibrium state requires four of the five mixture parameters (X, f, p, and $T_a = T_f$).

When the mixture is not in equilibrium, the complete description requires all five parameters and, in addition, knowledge of the intrinsic properties of the system to determine the rate of approach to equilibrium, such as (1) the latent heat of vaporization of the fuel L, (2) the specific heat of the air c_{pa} and of the fuel c_{pl} and c_{pv}, (3) the molecular weights of the fuel and air M_f and M_a, (4) the vapor-pressure—temperature relation for the fuel, and (5) the heat- and material-transfer coefficients throughout the mixture as determined by the mechanical state of the fluid (that is, the drop size of the fuel and the turbulence and velocity of the air and fuel). It is important to note that knowledge of these intrinsic properties and an adequate measurement of the state of the mixture will permit determination of the rate of approach to equilibrium (at a given instant) only if the equilibrium states are also known. The conditions describing equilibrium and nonequilibrium mixtures are assumed to be applicable to the description of both single-component and multicomponent fuel-air mixtures.

PREDICTION OF MIXTURE QUALITY

Equilibrium-Air-Distillation Temperature

Dew-point temperature. - One step toward the prediction of mixture quality involves a determination of the combinations of fuel properties and engine conditions that will insure complete vaporization of the fuel ($X = 1$). The four other mixture parameters (f, T_a, T_f, and p) will be assumed to be determined by the operating conditions. The value of each parameter will vary if distribution of fuel and air is not uniform among the intake parts of a multicylinder engine or to each part of a jet-propulsion burner assembly. On the other hand, the properties of the fuel distributed to each intake port or to each part of the jet-propulsion combustion chamber fix its distillation curve, latent heat of evaporation, and specific heat.

Complete vaporization of the fuel in the mixture at the equilibrium state can be conveniently specified by reference to the dew-point temperature T_{dp}, which is the lowest temperature at which wholly

vaporized fuel can exist in an equilibrium fuel-air mixture. For a given fuel, initial fuel and air temperatures, and total pressure, the maximum fuel-air ratio that permits complete vaporization is the fuel-air ratio for the dew-point condition.

The condition $T_a = T_{dp}$ at any time is sufficient to specify complete vaporization in a true equilibrium mixture. For a given fuel the dew-point temperature is a function of the total pressure p, the fuel-air ratio f, and the vaporization characteristics of the fuel. Because the partial pressure of the fuel p_f at the dew point is determined by the value of the temperature, the partial pressure of the air p_a at the dew point is fixed for a given value of p. Thus, specification of the fuel, and of p and f, determines T_{dp}, p_f, p_a, and the molar concentration of fuel and air present in a dew-point mixture.

The relations among T_a, T_f, p, T_{dp}, and the fuel properties can be exhibited in the form of graphs. In figures 1 to 5 the dew-point temperature is plotted as a function of f with p as parameter for several pure fuels covering a range of volatility. The curves are based on the vapor-pressure-temperature characteristics of the fuels as given in references 1 and 2 and the equations derived in appendix A. Figure 6 gives similar information for two gasolines whose A.S.T.M. distillations have 90-percent points of 710° R and 760° R (250° F and 300° F) and equal slopes at the 90-percent points. Figure 7 shows the dew-point curves for a typical kerosene that might be used as a jet-propulsion fuel (T_{90} = 922° R). Figures 6 and 7 are based on equations derived from reference 3 and described in appendix B.

It is evident in figure 6 that the dew-point temperature for T_{90} = 710° R fuel at a total pressure p of 90 inches of mercury absolute are substantially the same as the dew-point temperatures for T_{90} = 760° R fuel at a total pressure of 30 inches for all fuel-air ratios. The form of the equations from which these curves are derived indicates that linear interpolation between the curves for two fuels as in figure 6 is permissible when the S_{90} slopes are equal. Thus from figure 6 the dew-point temperature of an AN-F-28 fuel (T_{90} = 737° R) for p = 60 inches and f = 0.10 is 545 + (582 - 545) 27/50 = 565° R. This fuel therefore cannot be completely vaporized at 565° R and a manifold pressure of 60 inches if the fuel-air ratio exceeds 0.10; also at that temperature, a less volatile fuel could not be completely vaporized at the given pressure and fuel-air ratio.

Figures 1 to 7 cannot be used directly to find what initial temperatures of the liquid fuel and of the air are necessary in order that the given fuel-air mixture will just reach the dew-point condition

at equilibrium. In order to determine these temperatures, it will be assumed that all the heat necessary to evaporate the fuel and change its temperature from T_f to the final dew-point temperature T_{dp} is abstracted from the air in the fuel-air mixture and that no heat is lost to or gained from the surroundings. The initial air temperature T_a will therefore exceed the final or dew-point temperature of the mixture and this excess will be larger, the larger the excess of T_a over T_f. The relation between $T_a - T_{dp}$ and fuel-air ratio is presented in figures 8 and 9, which are based on calculations discussed in appendix A. It will be noted that the total-pressure and the vapor-pressure characteristics of the fuel do not enter into figures 8 and 9 except insofar as these variables affect T_{dp}. Figure 8 is valid under all conditions for all types of fuel whose average $L = 144$ Btu/(lb) and whose average $c_{pl} = 0.58$ Btu/(lb)(°R), values assumed to be representative of current aviation fuels. Figure 9 is based on a kerosene whose average $L = 108$ Btu/(lb) and whose average $c_{pl} = 0.61$ Btu/(lb)(°R).

Numerical examples. - The solution of a few typical problems will indicate how figure 8 or 9 is to be used.

(1) What is the dew point of the fuel of lowest volatility that can be completely evaporated adiabatically for initial air and fuel temperatures of 500° R and a fuel-air ratio of 0.10?

In the case of equal initial fuel and air temperatures, the process of vaporization is accompanied by self-cooling of the fuel through vaporization and cooling of the air by the fuel until the system reaches the dew-point temperature at equilibrium. From figure 8 at $f = 0.10$, $T_a - T_f = 0$, $T_a - T_{dp}$ is found to be 48°; therefore, $T_{dp} = 452°$ R (-8° F) and no fuel with a higher dew-point temperature would be completely vaporized at a fuel-air ratio of 0.10. If $T_a = 600°$ R and $T_f = 500°$ R, the limiting $T_{dp} = 532°$ R (72° F)

(2) Suppose a fuel whose dew-point temperature T_{dp} at a fuel-air ratio of 0.08 is 510° R must be evaporated adiabatically by air with initial temperature of 560° R. What is the minimum initial liquid fuel temperature for complete vaporization?

$T_a - T_{dp} = 50°$, $f = 0.08$. Therefore, from figure 8, $T_a - T_f \cong 60°$ and $T_f = 560 - 60 = 500°$ R (40° F). If the fuel were initially colder, it would not evaporate completely.

Dew-point temperatures used in connection with figure 8 can, of course, be evaluated from figure 6 or its equivalent. It should be noted that the direction of change of T_a, for fixed f and T_{dp}, is always opposite to that for T_f.

Partial vaporization. - A second stage in the prediction of mixture quality is reached when calculations of equilibrium fuel-air mixtures that contain liquid fuel $(X < 1)$ are required. The correlation made by Bridgeman (reference 3) gives an equation for computing temperatures of partly vaporized equilibrium fuel-air mixtures of multicomponent fuels. This equation is given in appendix B and is similar to that used for computing dew points. A graphical equivalent of the method used in developing figures 8 and 9 can then be used for the calculation of initial air temperatures necessary to evaporate fraction X of the fuel.

Rate of Vaporization

A more complete and general prediction of mixture quality is possible if the rate of vaporization of the mixture can be specified at any instant in the vaporization process in addition to the equilibrium conditions. The initial state of the mixture can be described by specifying the fuel and the values of T_a, T_f, f, p, and that $X = 0$. The rate of change of the parameters T_a, T_f, f, and p_f with time is determined by the volatility of the fuel and other properties of the fuel-air mixture and by the values of these parameters and of p during evaporation. The total pressure p will not be affected appreciably by the vaporization for the fuel-air ratios and the air-flow velocities ordinarily encountered in jet-propulsion and reciprocating-engine power plants. If the vaporization and heat- and material-transfer processes are sufficiently rapid, the mixture will reach equilibrium before passing into the intake ports of an engine or before appreciable travel in the combustion chamber of a jet-propulsion unit. If the rates are too small, equilibrium will not be attained. In either case, prediction of mixture quality at a given point will depend upon knowledge of the rates of vaporization and of heat and material transfer in the mixture during its passage from the point of fuel injection to the point of interest.

At present it is impossible to compute rates of vaporization for mixtures of air and a fuel that contains many constituents. It is possible, however, to compute the evaporation rate for a mixture of air and a pure fuel such as that described in a previous section DESCRIPTION OF MIXTURE QUALITY.

The minimum time for complete evaporation (that is, that corresponding to isothermal evaporation into a maintained vacuum) can be estimated by an integration (see appendix C) using the evaporation rate given in reference 4, which sets a useful lower limit to the total evaporation time required. This minimum time for evaporation is given by the expression

$$t_{min} = 0.0099 \frac{\rho_f d_o}{p_s} \sqrt{\frac{\pi R_a T_f}{2rg}} \qquad \text{(sec)} \qquad (1)$$

where T_f is the temperature of the fuel drop. Actually T_f will drop somewhat during evaporation but it is assumed to be constant at the initial value because then equation (1) gives the lowest value for t_{min}.

The maximum times for complete evaporation of drops of a given size (that is, that corresponding to diffusion through still air) can be estimated approximately for a given final fuel-air ratio from the equation (derived from references 5 and 6)

$$t_{max} = 0.125 \frac{\rho_f d_o^2 p}{r\rho_a(p_s - p_f)D} \qquad \text{(sec)} \qquad (2)$$

where p_s is the saturation pressure of the fuel and p_f the partial pressure of fuel vapor near the end of vaporization. Various refinements in conditions are made by Fuchs (reference 7), such as limited space for evaporation, motion of the drop relative to the gas atmosphere, the nonstationary nature of the vaporization process, the lowering of the drop temperature due to evaporation, and variations in vapor pressure at the drop surface due to curvature and size. The net effect of these refinements will not significantly change the maximum given by equation (2).

As an illustration of the results obtained from equations (1) and (2), the times of evaporation of isooctane in air are calculated for various conditions. From the empirical relation for the diffusion coefficient D given in reference 8 for isooctane

$$D = \frac{22.1 \times 10^{-6}\ T_a^{3/2}}{p} \qquad \text{(sq in./sec)} \qquad (3)$$

Equation (2) then becomes for an r of 3.941 and an air temperature of 610° R (150° F)

$$t_{max} = 0.0951 \frac{\rho_f\ p^2}{\rho_a(p_s - p_f)}\ d_o^2 \qquad \text{(sec)} \qquad (4)$$

The maximum and minimum times of evaporation of isooctane are tabulated in table I for various conditions. The minimum time t_{min} is calculated for drops of 80° F and 100° F evaporating into a maintained vacuum. The maximum time t_{max} is calculated for evaporation controlled by diffusion through air at 150° F. The drop sizes d_o and the initial fuel temperatures t_f are assumed the same as in the vacuum case, but the final fuel-air ratios are taken to be 0.10 and 0.01. The value of p_f in equation (4) is then taken to be equal to $\left(\frac{f}{r + f}\right) p$ (see appendix A) thus assuring that the value of t_{max} obtained is an upper limit.

TABLE I - MAXIMUM AND MINIMUM TIMES FOR

EVAPORATION OF DROPS

d_o (in.)	T_f (°R)	t_{min} (sec)	t_{max} (sec)	
			f = 0.10	f = 0.01
0.1	540	0.048	458	296
.05	540	.024	115	74
.01	540	.0048	4.58	2.96
.005	540	.0024	1.15	.74
.001	540	.00048	.0458	.0296
.1	560	.029	216	171
.05	560	.015	53.9	42.8
.01	560	.0029	2.16	1.71
.005	560	.0015	.539	.428
.001	560	.00029	.0216	.0171

The data in table I are plotted in figure 10. The ratio t_{max}/t_{min} is proportional to d_o in accordance with equations (1) and (4). For the values of d_o plotted in figure 10 the ratio varies from 100 for $d_o \cong 0.001$ inch to 10,000 for $d_o \cong 0.1$ inch. The vaporization time of a drop will probably lie somewhere between the limits shown in figure 10 and can be theoretically predicted with greater accuracy only if the mechanisms controlling material and heat transfer in the fuel-air mixture, such as the intensity and scale of turbulence, are represented in the theory.

With the time for complete vaporization probably lying between wide limits, the time for the formation of mixtures of a given value of X is equally difficult to estimate. The vaporization process will generally take place in a limited space with varying boundary

conditions both at the drop surface and at some distance from the drop depending on the geometry of the system. The complexity of the mathematical solution of this problem is indicated in reference 7. Furthermore, the application of rate of vaporization theory to complex fuels involves the effects of multicomponent distillation and the values of T_f, p_s, p_f, D, and r become all the more difficult to determine. The complete solution of mixture-quality problems can, therefore, be seen to require experimental methods.

CONCLUSIONS

Based on this analysis, the following conclusions were drawn:

1. Mixture quality for a simple fuel can be specified by five mixture parameters; (a) the temperature of the air, (b) the temperature of the liquid fuel, (c) the fuel-air ratio, (d) the fraction vaporized, and (e) the total pressure.

2. The changes in quality of the mixture as it passes through a duct are a function of the five mixture parameters, of the intensity and scale of turbulence of the air flow, and of the physical properties of the fuel and air; that is, the latent heat of vaporization, the liquid and vapor specific heats, the vapor-pressure-temperature relation and molecular weight of the fuel, the specific heat of air, and the heat- and material-transfer coefficients throughout the mixture.

3. At the present time, mixture quality cannot be determined by theoretical prediction. Semitheoretical calculations of dew-point temperatures, of the latent heat effect and of vaporization rates can, however, be of assistance in designing and interpreting experiments.

Aircraft Engine Research Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio, January 28, 1946.

APPENDIX A

DEW-POINT TEMPERATURES

Bridgeman (reference 3) has reported a method of determining the dew-point temperatures of multicomponent fuels at atmospheric or lower pressures from data obtained from the standard A.S.T.M. evaporation curve of automotive fuels. For the calculations in the present report, his equations were assumed to hold for an AN-F-28 fuel and a kerosene fuel for a range of fuel-air ratios from 0.01 to 0.11 and for a range of pressures from 30 to 90 inches of mercury absolute.

From Bridgeman (reference 3) the following equation has been derived

$$T_{dp} = 2/3\ T_{90} - 8.95\sqrt{S_{90}} + 46.8 + \left[0.132 + 0.109\ \log_{10}(0.0348p - 0.04)f\right]T_{90} \tag{5}$$

The average error in calculated T_{dp} by equation (5) is about $\pm 2^{\circ}$ R. About one case in ten may lead to an error of $\pm 7^{\circ}$ R. The data for figure 6 were obtained by assuming $S_{90} = 3.0$ and computing T_{dp} for a range of values of p and f and for two values of T_{90}, namely 710° and 760° R. For figure 7 S_{90} is 1.67 and T_{90} is 922° R. Equation (5) and subsequent equation (11) can be used for gasolines and kerosenes.

For a pure (single-component) fuel the partial pressure of the fuel is obtained from Dalton's law. Thus

$$p_f = \left(\frac{\dfrac{W_f X}{M_f}}{\dfrac{W_a}{M_a} + \dfrac{W_f X}{M_f}}\right) p = \frac{\dfrac{W_f X}{M_f}}{\dfrac{W_a}{M_a}}\, p_a \tag{6}$$

where $p = p_a + p_f$. The term in parentheses represents the mol fraction of fuel vapor. In equation (6), $\frac{M_f}{M_a} = r$ and $\frac{W_f}{W_a} = f$ may be substituted, giving

$$p_f = \frac{fX}{r + fX}\, p = \frac{fXp_a}{r} \tag{7}$$

At the dew point $X = 1$,

$$p_f = p_s$$

thus:

$$p_s = \frac{fp_a}{r} = \left(\frac{f}{r + f}\right) p \tag{8}$$

The value of p_s for a given pure fuel is calculated from equation (8) as a function of f and p and the dew-point temperature is the temperature that corresponds to p_s in the vapor pressure-temperature relation for the fuel.

The initial air temperature necessary for complete adiabatic vaporization of the liquid fuel in an air-fuel mixture can be computed from a heat balance. Assuming that no fuel is evaporated at the start, all the heat used in evaporating the fuel and bringing it to the equilibrium dew-point temperature must be supplied by the air. Therefore

$$c_{pa} (T_a - T_{dp}) = Lf + c_p (T_{dp} - T_f) f \tag{9}$$

with the heat balance written for unit mass of air. In order that this equation be exact, it is necessary that the values of L and c_p be properly chosen. Either L is the latent heat of evaporation of the fuel at its initial temperature T_f and c_p is its mean specific heat c_{pv} at constant pressure in the gas phase between temperatures T_{dp} and T_f or L is the latent heat at the final temperature T_{dp} and c_p is the mean specific heat c_{pl} of the liquid fuel over the same temperature range.

Equation (9) may be solved for $T_a - T_{dp}$:

$$(T_a - T_{dp}) = \left[L + c_{pl} (T_a - T_f)\right] f/(c_{pa} + c_{pl}) \tag{10}$$

Figure 8 has been computed from this equation with $c_{pa} = 0.24$ Btu/(lb)(°R), $c_{pl} = 0.58$ Btu/(lb)(°R) and $L = 144$ Btu/(lb) for a series of values of f and $T_a - T_f$. Figure 9 for kerosene has been computed for values of c_{pl} and L of 0.61 and 108, respectively. It must be remembered that the value of L for a multicomponent fuel at a given temperature is the value corresponding to the average composition of the vaporizing liquid.

APPENDIX B

PARTIAL VAPORIZATION TEMPERATURES

For the equilibrium partial vaporization of a fuel-air mixture, equations given in Bridgoman (reference 3) when combined and expressed in units of degrees Rankine and inches of mercury absolute become

$$T_{fX} = 2/3\ T_X + 19.2\ \sqrt{S_X}\ \log_{10} 2(1-X) + 46.8 + T_X \left[0.132 + 0.109 \log_{10} (0.0348p - 0.04)\ fX\right] \qquad (11)$$

in which f is the initial liquid fuel-air ratio and fX (or f_v) is the vapor fuel-air ratio. No data are available on the equilibrium partial vaporization temperatures of fuel-air mixtures at pressures greater than 1 atmosphere. The validity of equation (11) is thus not established for pressures that involve significant changes in the solubility of air in gasoline such that the vapor-liquid equilibria are appreciably altered. A convenient aid to the use of equations (5) and (11) is given in table II. The bracketed right-hand term of equation (5) or (11)

$$\left[0.132 + 0.109 \log_{10} (0.0348p - 0.04)\ f_v\right]$$

is tabulated as a function $F\ (p,\ f_v)$ where f_v may be taken as f for the dew-point condition and as fX for the case of partial vaporization. Calculations involving the use of equation (5) or (11) are greatly simplified by the use of table II. Table II must be used with caution for pressures greater than 30 inches of mercury absolute when calculating T_{fX} because the errors due to shifts in vapor-liquid equilibria with pressure will be mainly in the values tabulated in table II.

In the case of equilibrium partial vaporization, the heat-balance equation analogous to equation (9) is

$$c_{pa}\ (T_a - T_{fX}) = L_1\ fX + c_{pl}\ f\ (T_{fX} - T_f) \qquad (12)$$

In equation (12) L_1 must be chosen at the final fuel temperature T_{fX} and c_{pl} must be the mean liquid specific heat at constant pressure between temperatures T_f and T_{fX}. An equivalent form of equation (12) is

$$c_{pa}\ (T_a - T_{fX}) = L_2\ fX + f(T_{fX} - T_f)\ (c_{pl} + \Delta cX) \qquad (13)$$

where L_2 is the latent heat of evaporation at the initial fuel temperature, c_{pl} the mean liquid specific heat, and the term Δc represents the mean difference in the specific heats of the fuel vapor and liquid $(c_{pv} - c_{pl})$ over the temperature range. The term Δc is also equal to the mean value, over the temperature range, of the rate of change in latent heat of evaporation of the fuel with respect to temperature.

Data on the latent heats and specific heats of the gas and liquid phases of petroleum fractions may be obtained from references 9 and 10.

APPENDIX C

EVAPORATION OF A DROP INTO VACUUM

For a drop of diameter d the evaporation rate is

$$\frac{dm}{dt} = -\pi d^2 G \qquad \text{(grams/sec)} \qquad (14)$$

where

m mass of drop, grams

G evaporation rate, grams/sec cm^2

πd^2 surface area of drop, cm^2

The mass of a drop is the volume times density:

$$m = \frac{\pi d^3 \rho_f'}{6}$$

where primed symbols represent quantities with cgs units corresponding to similar unprimed symbols used in the body of the paper with English units.

The change in mass upon evaporation during an infinitesimal length of time,

$$dm = -\frac{1}{2}\pi \rho_f' d^2 d(d) \qquad (15)$$

If equation (15) is substituted in equation (14) and the resulting equation integrated between the limits $t = 0$, $d = d_o'$ and $t = t$, $d = 0$, then

$$t = \frac{\rho_f' d_o'}{2G} \qquad (16)$$

Kennard (reference 4, p. 69) derives from the kinetic theory of gases

$$G = \frac{\alpha\, p_s'}{\sqrt{2\pi RT}} \qquad \text{(grams/sec cm}^2\text{)} \qquad (17)$$

where

R gas constant/gram

T absolute temperature, $^\circ$K

p_s' saturation pressure of fuel vapor, dynes/cm^2

In the case of evaporation into a maintained vacuum, such that all the vapor molecules are removed from the vicinity of the drop as soon as they leave the surface, the value of $\alpha = 1.0$. Then, remembering that

$$RM_f = R_a' \, M_a$$

or

$$R = \frac{R_a'}{r}$$

where R_a' is the gas constant/gram for air, equation (16) becomes

$$t = \frac{\rho_f' d_o'}{p_s'} \sqrt{\frac{\pi R_a' T}{2r}} \tag{18}$$

which, upon substitution of unprimed symbols representing English units, gives equation (1)

$$t_{min} = \frac{0.0099 \, \rho_f d_o}{p_s} \sqrt{\frac{\pi R_a T_f}{2rg}} \qquad \text{(sec)}$$

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TABLE II - TABULATED VALUES OF THE FUNCTION $\left[0.132 + 0.109 \log_{10} (0.0348p - 0.04) f_v\right]$

Fuel vapor-air ratio f_v	Total pressure, p (in. Hg absolute)														
	5	10	15	20	25	30	35	40	45	50	60	70	80	90	100
0.005	-0.21396	-0.17456	-0.15336	-0.13677	-0.12763	-0.11862	-0.11106	-0.10454	-0.09881	-0.09369	-0.08488	-0.07745	-0.07105	-0.06536	-0.06053
.010	-.18115	-.14175	-.12055	-.10396	-.09482	-.08581	-.07824	-.07172	-.06599	-.06088	-.05207	-.04464	-.03822	-.03256	-.02751
.015	-.16195	-.12255	-.10135	-.08476	-.07563	-.06662	-.05905	-.05253	-.04680	-.04169	-.03287	-.02544	-.01902	-.01337	-.00832
.020	-.14833	-.10894	-.08774	-.07115	-.06201	-.05300	-.04543	-.03891	-.03318	-.02807	-.01926	-.01182	-.00540	.00025	.00530
.025	-.13777	-.09837	-.07717	-.06058	-.05144	-.04244	-.03487	-.02835	-.02262	-.01751	-.00869	-.00126	.00516	.01081	.01586
.030	-.12914	-.08974	-.06854	-.05395	-.04481	-.03581	-.02824	-.01972	-.01399	-.00887	-.00006	.00737	.01379	.01944	.02449
.035	-.12184	-.08244	-.06124	-.04665	-.03752	-.02851	-.01894	-.01242	-.00669	-.00158	.00724	.01467	.02109	.02674	.03179
.040	-.11552	-.07612	-.05492	-.04033	-.02920	-.02019	-.01262	-.00610	-.00037	.00474	.01356	.02099	.02741	.03306	.03811
.045	-.10995	-.07055	-.04935	-.03476	-.02362	-.01461	-.00704	-.00052	.00621	.01032	.01913	.02556	.03198	.03864	.04368
.050	-.10496	-.06556	-.04436	-.02977	-.01863	-.00962	-.00206	.00446	.01319	.01531	.02412	.03155	.03797	.04362	.04867
.055	-.10045	-.06105	-.03985	-.02526	-.01412	-.00511	.00245	.00898	.01471	.01982	.02863	.03606	.04248	.04814	.05318
.060	-.09633	-.05693	-.03573	-.02114	-.01000	-.00099	.00657	.01310	.01883	.02394	.03275	.04018	.04660	.05225	.05730
.065	-.09254	-.05314	-.03194	-.01735	-.00621	.00280	.01036	.01688	.02261	.02773	.03654	.04397	.05039	.05604	.06109
.070	-.08905	-.04963	-.02843	-.01384	-.00270	.00630	.01387	.02039	.02612	.03123	.04005	.04748	.05390	.05955	.06460
.075	-.08576	-.04637	-.02517	-.01058	.00056	.00957	.01714	.02366	.02939	.03450	.04332	.05075	.05716	.06282	.06787
.080	-.08271	-.04331	-.02211	-.00752	.00362	.01263	.02019	.02671	.03244	.03756	.04637	.05380	.06022	.06587	.07092
.085	-.07984	-.04044	-.01924	-.00465	.00649	.01550	.02306	.02958	.03531	.04043	.04924	.05667	.06309	.06874	.07379
.090	-.07713	-.03774	-.01654	-.00195	.00919	.01820	.02577	.03229	.03802	.04313	.05195	.05938	.06580	.07145	.07650
.095	-.07457	-.03518	-.01398	.00061	.01175	.02076	.02833	.03485	.04058	.04569	.05451	.06194	.06835	.07401	.07906
.100	-.07215	-.03275	-.01155	.00304	.01418	.02319	.03076	.03728	.04301	.04812	.05693	.06436	.07078	.07644	.08149
.105	-.06984	-.03044	-.00924	.00536	.01649	.02550	.03307	.03959	.04532	.05043	.05924	.06667	.07309	.07875	.08379
.110	-.06763	-.02824	-.00704	.00755	.01869	.02770	.03527	.04179	.04752	.05263	.06145	.06888	.07529	.08095	.08600
.115	-.06553	-.02613	-.00493	.00966	.02080	.02980	.03737	.04389	.04962	.05474	.06355	.07098	.07740	.08305	.08810
.120	-.06352	-.02412	-.00292	.01167	.02281	.03182	.03938	.04591	.05164	.05675	.06557	.07300	.07941	.08507	.09012
.125	-.06158	-.02218	-.00098	.01361	.02474	.03375	.04132	.04784	.05357	.05868	.06750	.07493	.08135	.08700	.09205
.130	-.05973	-.02033	.00087	.01546	.02660	.03561	.04317	.04970	.05543	.06054	.06935	.07678	.08320	.08886	.09390
.135	-.05794	-.01854	.00266	.01725	.02839	.03739	.04496	.05148	.05721	.06233	.07114	.07857	.08499	.09064	.09569
.140	-.05622	-.01682	.00438	.01897	.03011	.03912	.04668	.05320	.05894	.06406	.07286	.08029	.08671	.09236	.09741
.145	-.05456	-.01516	.00604	.02063	.03177	.04078	.04834	.05487	.06060	.06571	.07452	.08195	.08837	.09403	.09907
.150	-.05295	-.01355	.00765	.02224	.03337	.04238	.04995	.05647	.06220	.06731	.07613	.08356	.08998	.09563	.10068
.155	-.05140	-.01200	.00920	.02379	.03493	.04393	.05150	.05802	.06374	.06886	.07767	.08510	.09152	.09717	.10222
.160	-.04990	-.01050	.01070	.02529	.03643	.04544	.05300	.05953	.06526	.07037	.07918	.08661	.09303	.09869	.10373
.165	-.04844	-.00904	.01216	.02675	.03789	.04689	.05446	.06098	.06671	.07182	.08064	.08807	.09449	.10014	.10519
.170	-.04703	-.00763	.01357	.02816	.03930	.04831	.05587	.06240	.06813	.07324	.08205	.08948	.09590	.10156	.10660
.175	-.04565	-.00626	.01494	.02953	.04067	.04968	.05725	.06377	.06950	.07461	.08343	.09086	.09727	.10293	.10798
.180	-.04432	-.00492	.01628	.03087	.04200	.05101	.05858	.06510	.07083	.07594	.08476	.09219	.09861	.10426	.10931
.185	-.04302	-.00363	.01757	.03216	.04330	.05231	.05988	.06640	.07213	.07724	.08606	.09349	.09990	.10556	.11061
.190	-.04176	-.00236	.01884	.03343	.04456	.05357	.06114	.06766	.07339	.07850	.08732	.09475	.10117	.10682	.11187
.195	-.04053	-.00113	.02007	.03466	.04579	.05480	.06237	.06889	.07462	.07973	.08855	.09598	.10240	.10806	.11310
.200	-.03933	.00006	.02126	.03585	.04699	.05600	.06357	.07009	.07582	.08093	.08975	.09718	.10360	.10925	.11430

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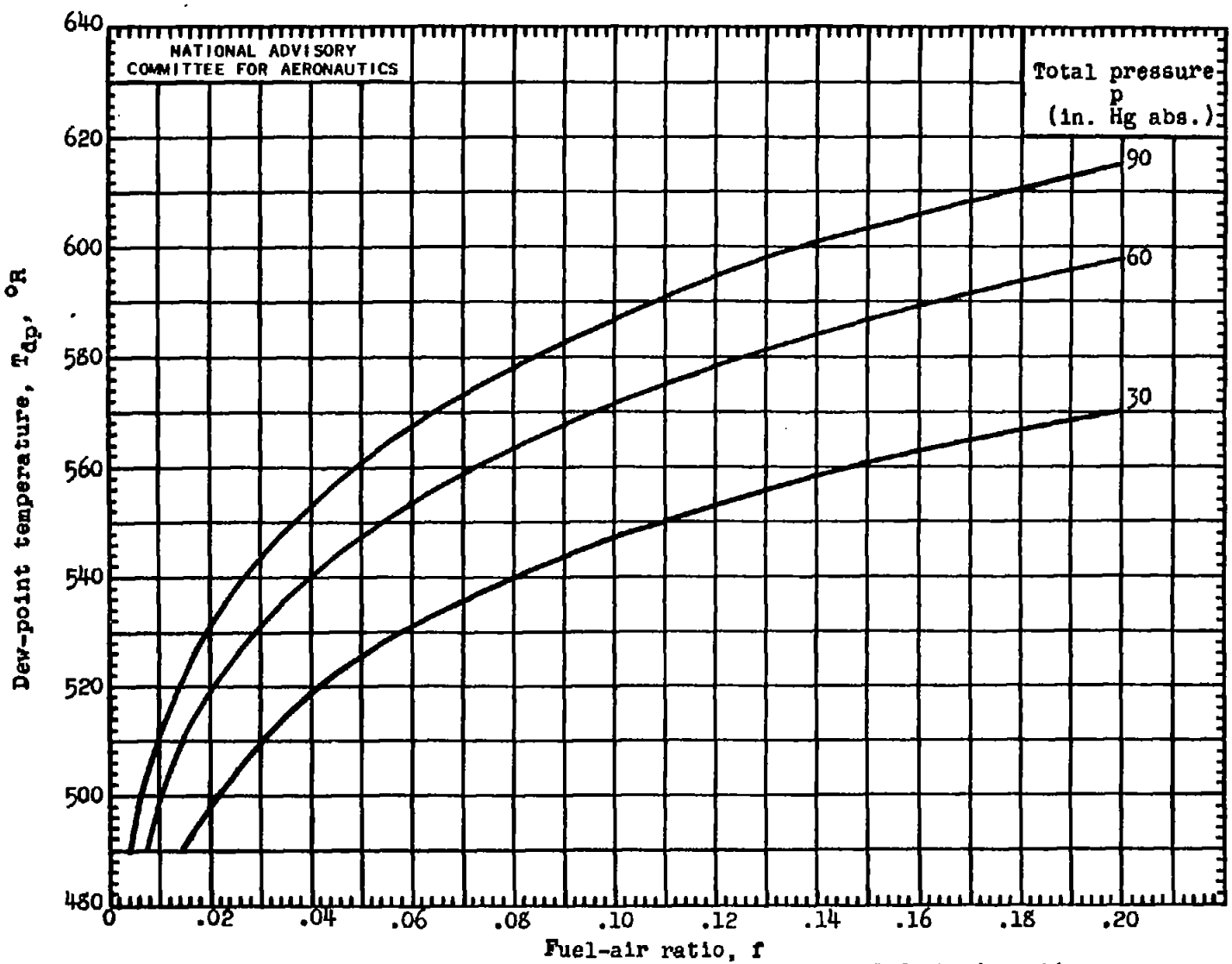

Figure 1.- Dew-point temperature as a function of total pressure and fuel-air ratio for n-octane.

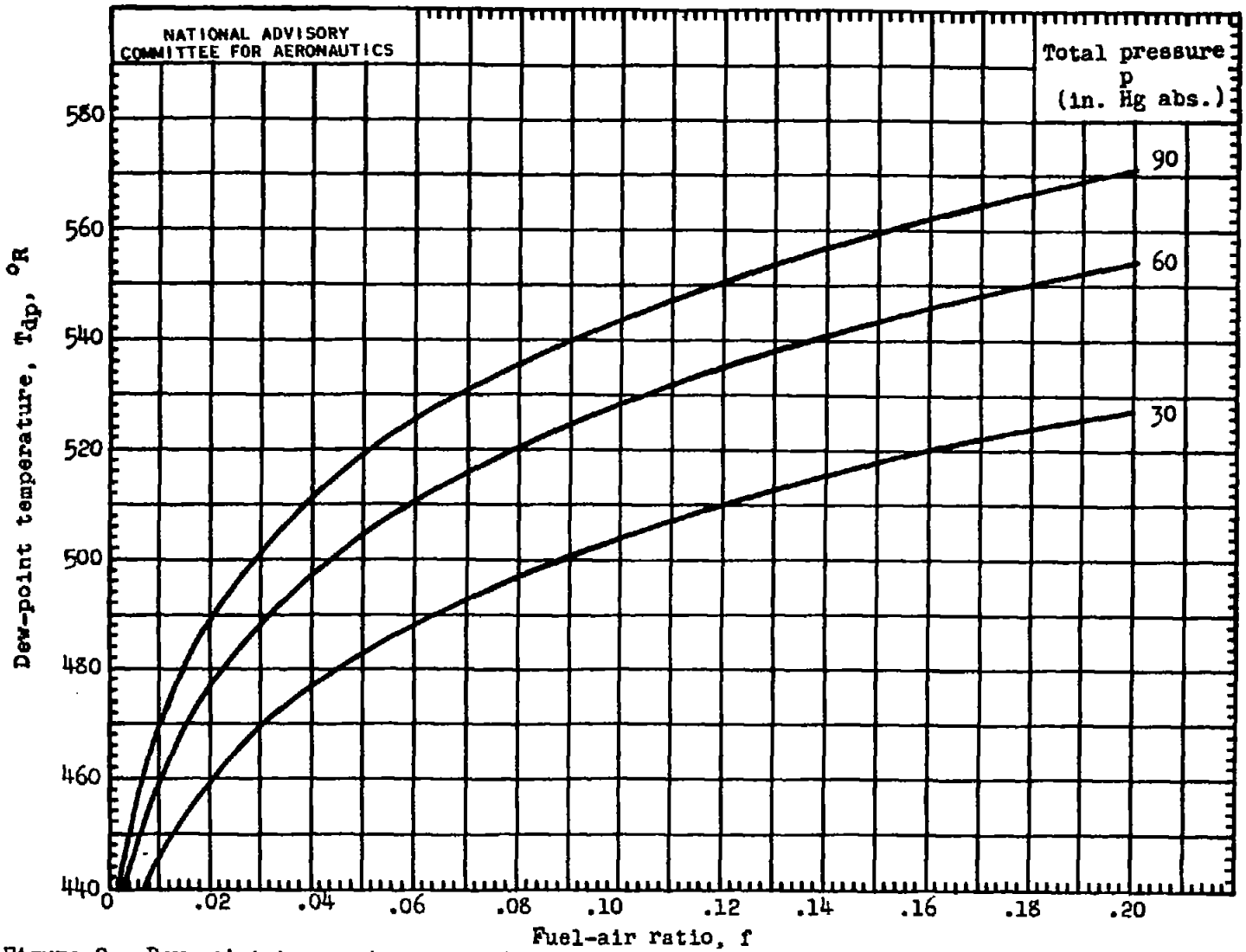

Figure 2.- Dew-point temperature as a function of total pressure and fuel-air ratio for isooctane.

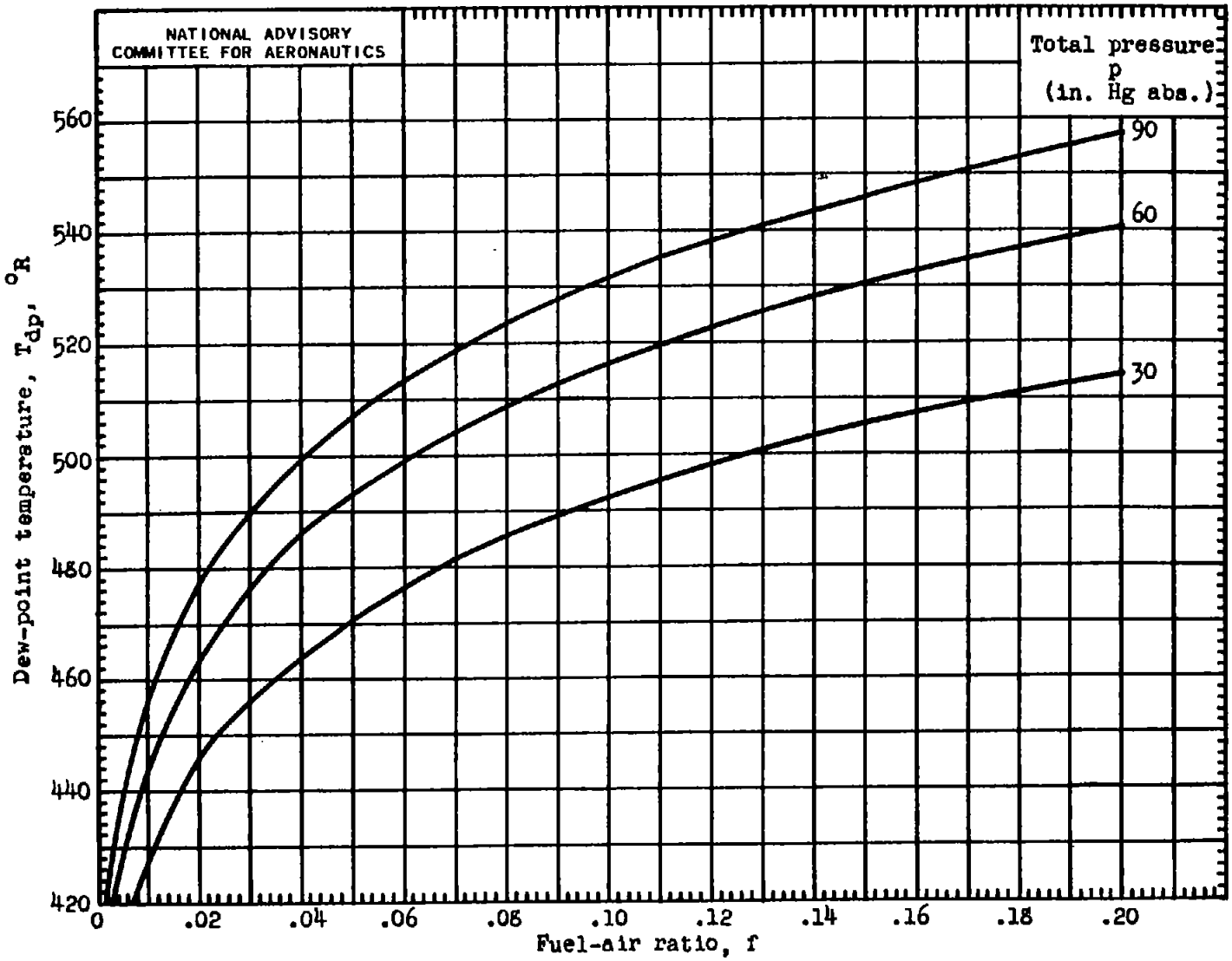

Figure 3.- Dew-point temperature as a function of total pressure and fuel-air ratio for benzene.

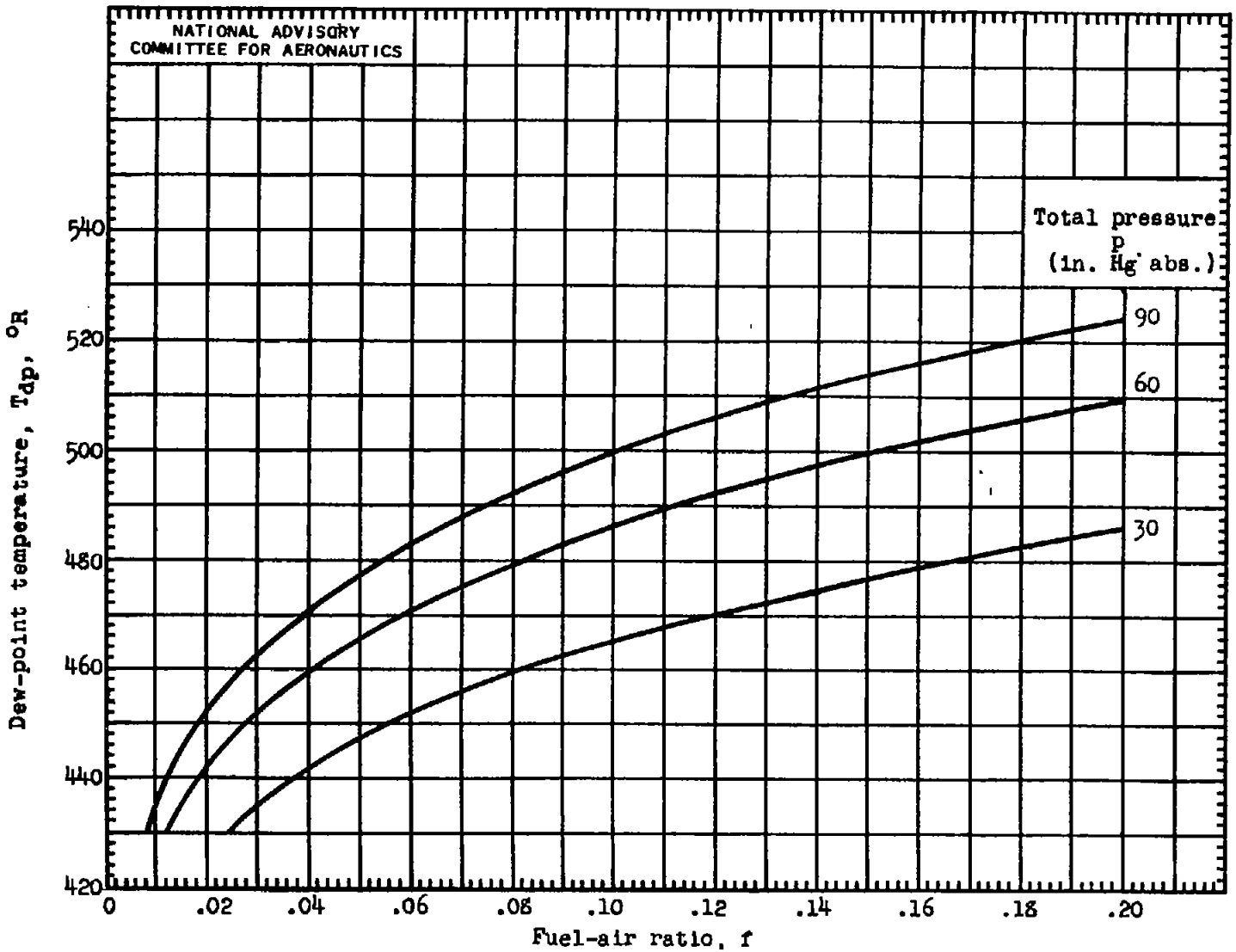

Figure 4.- Dew-point temperature as a function of total pressure and fuel-air ratio for carbon tetrachloride (CCl_4).

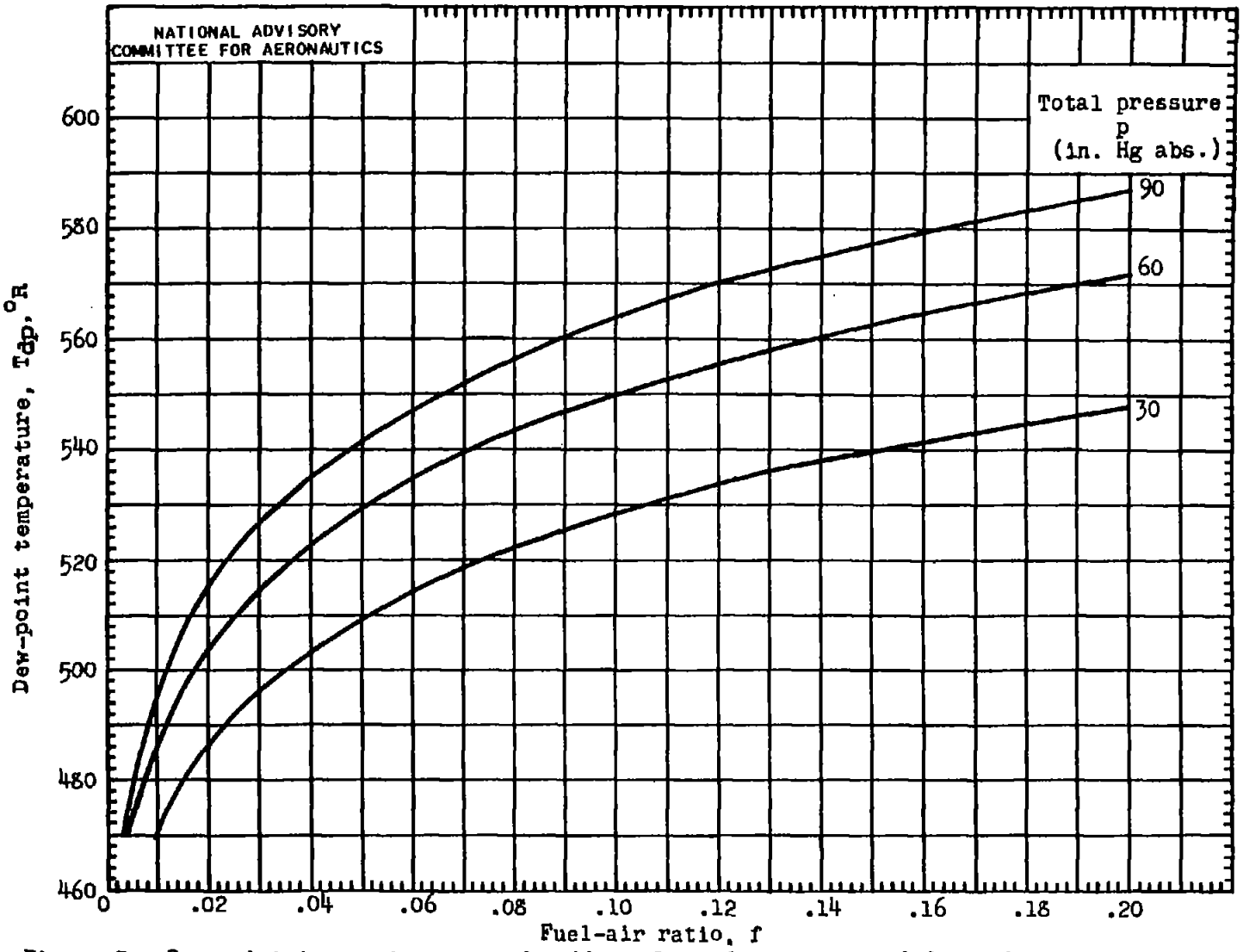

Figure 5.- Dew-point temperature as a function of total pressure and fuel-air ratio for ethyl alcohol (C_2H_5OH).

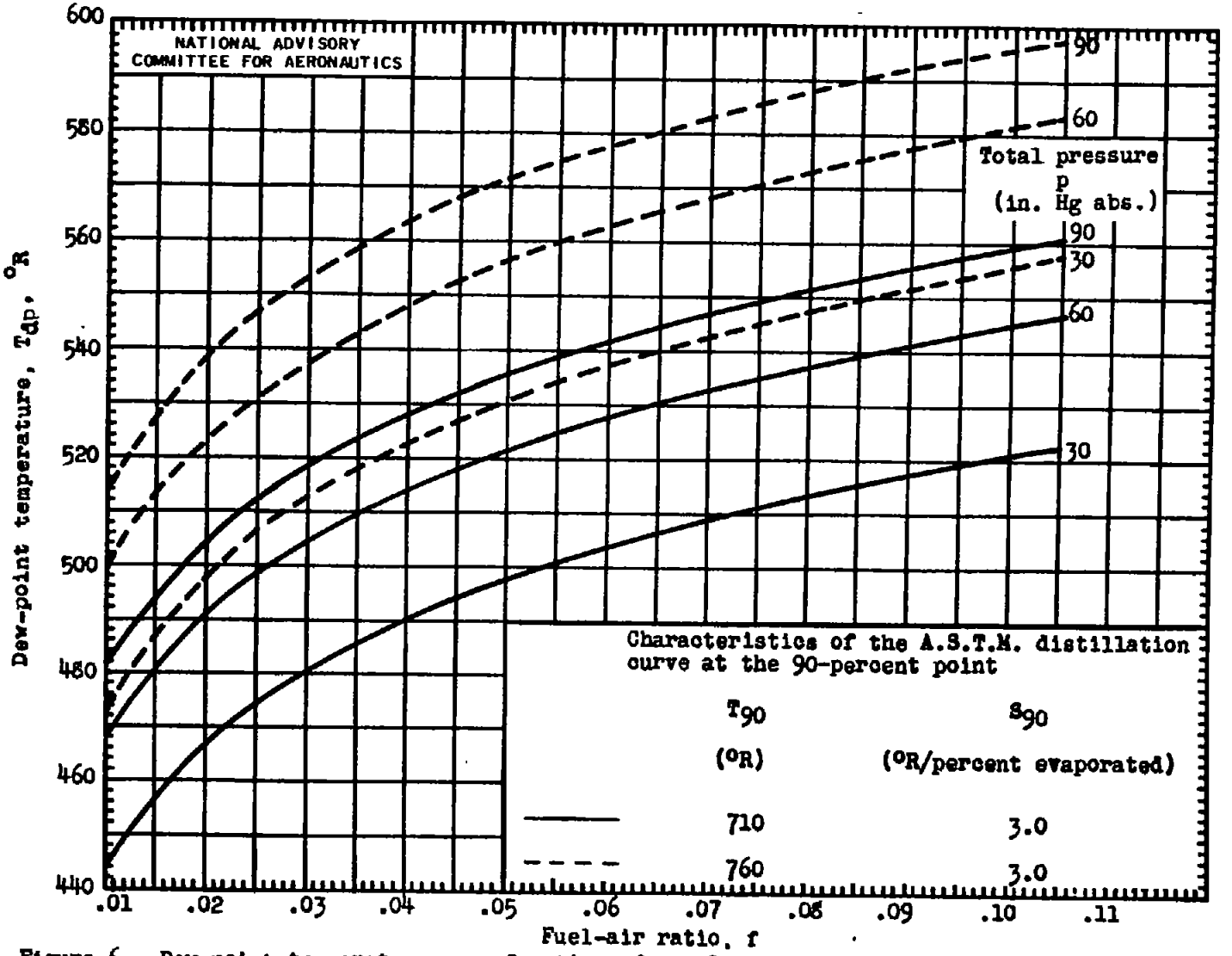

Figure 6.- Dew-point temperature as a function of total pressure and fuel-air ratio for two gasolines.

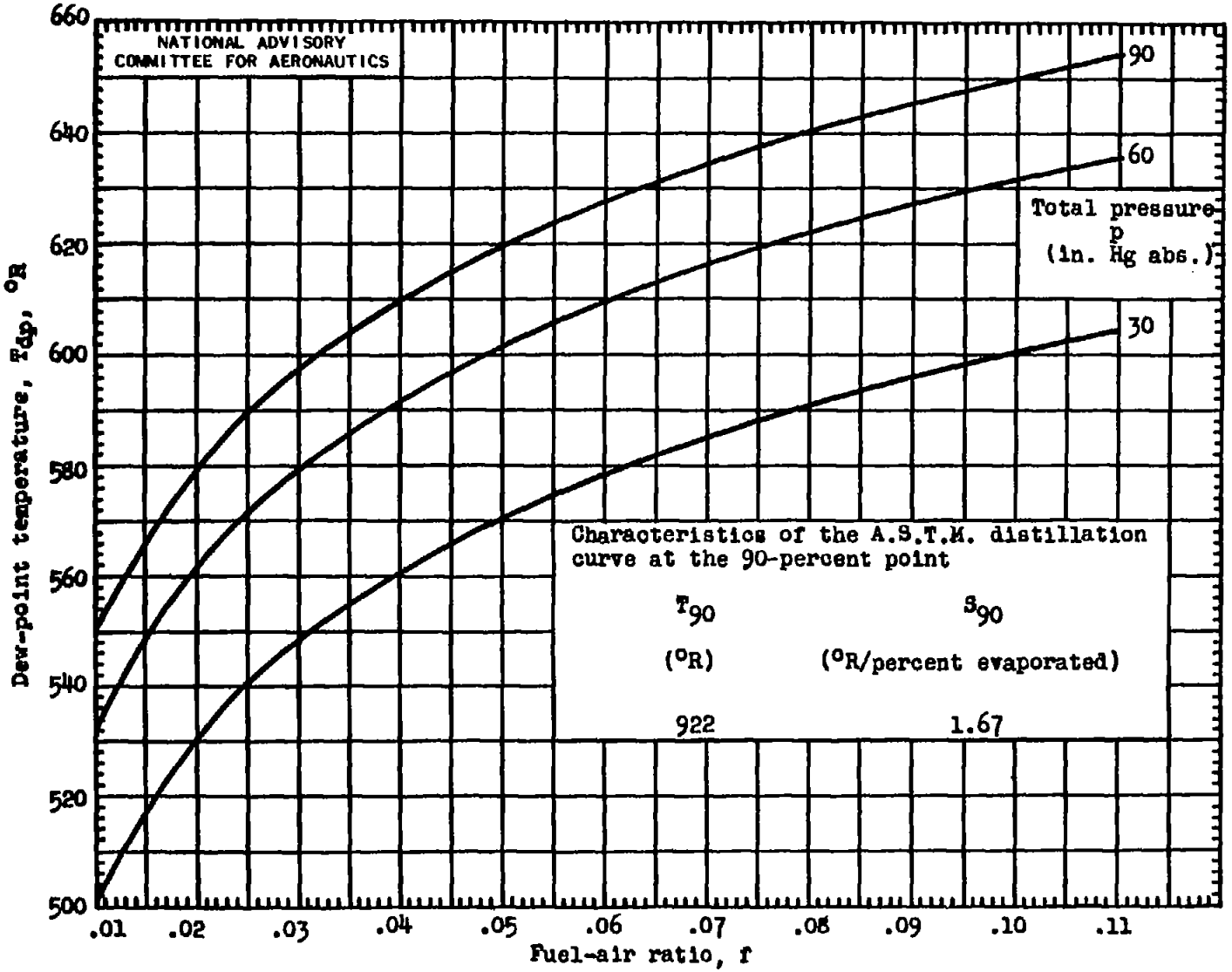

Figure 7.- Dew-point temperature as a function of total pressure and fuel-air ratio for kerosene.

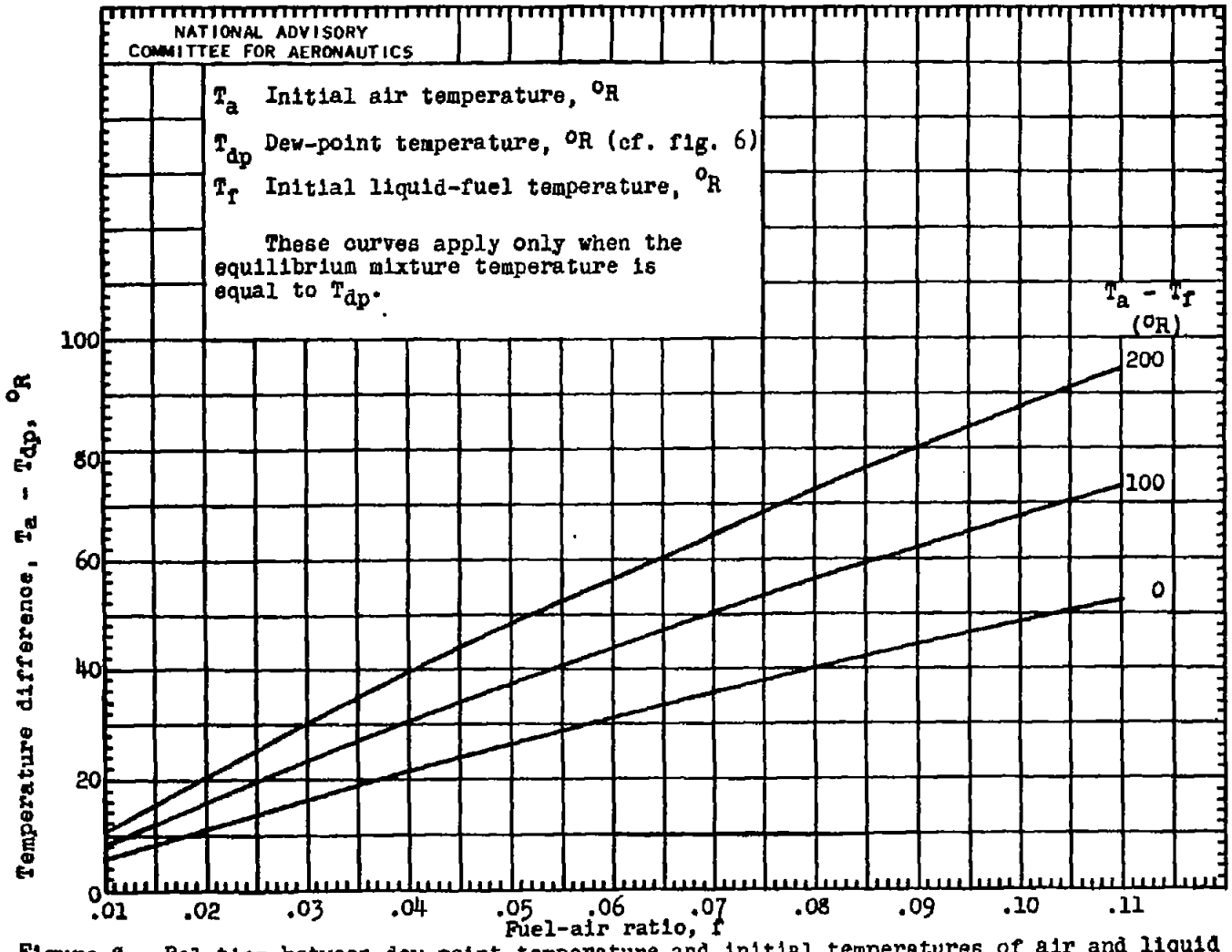

Figure 8.- Relation between dew-point temperature and initial temperatures of air and liquid fuel (gasoline) when the mixture reaches the dew-point condition through adiabatic evaporation of all the liquid fuel. Average latent heat of vaporization of fuel (gasoline), 144 Btu/(lb); specific heat of liquid fuel, 0.58 Btu/(lb)(°R); specific heat of air, 0.24 Btu/(lb)(°R).

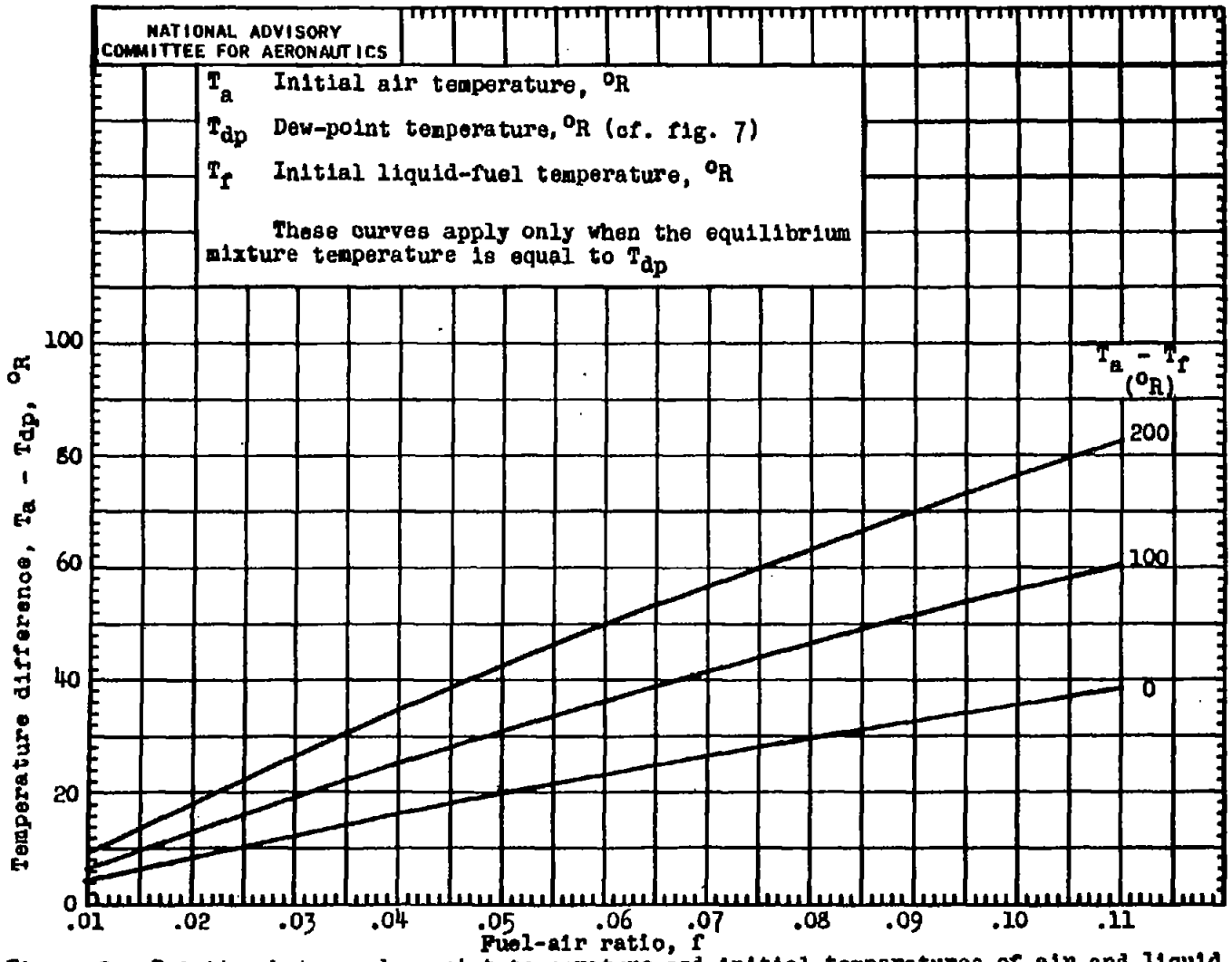

Figure 9.- Relation between dew-point temperature and initial temperatures of air and liquid fuel (kerosene) when the mixture reaches the dew-point condition through adiabatic evaporation of all the liquid fuel. Average latent heat of vaporization of fuel, 108 Btu/(lb); specific heat of liquid fuel, 0.61 Btu/(lb)(°R); specific heat of air, 0.24 Btu/(lb)(°R).

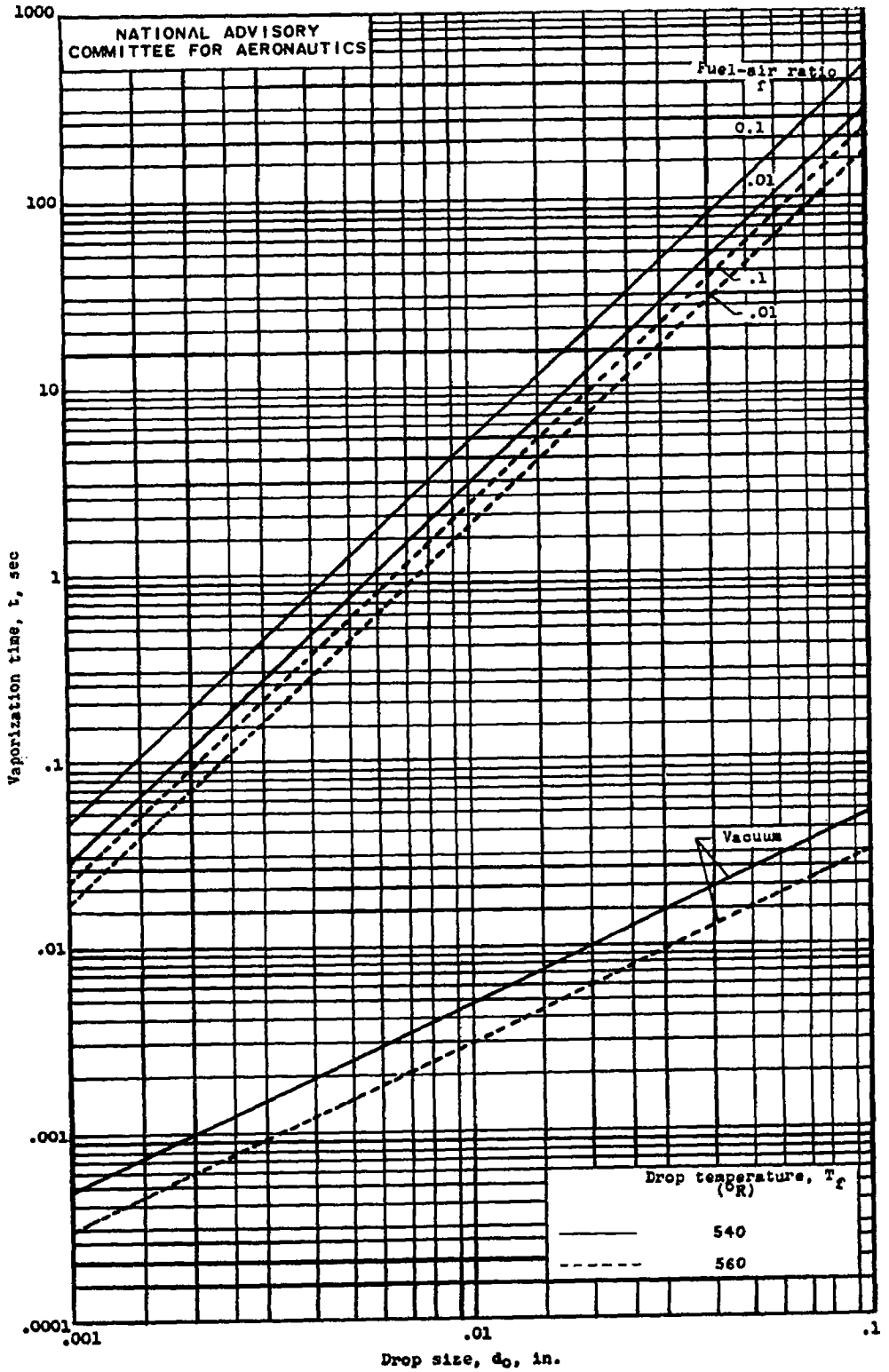

Figure 10. - Maximum and minimum (vacuum) vaporization times for fuel drops at constant temperature as functions of drop size for isooctane.