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RESEARCH MEMORANDUM

EFFECT OF RADIANT ENERGY ON VAPORIZATION AND COMBUSTION OF LIQUID FUELS

By A. L. Berlad and R. R. Hibbard

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

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RESEARCH MEMORANDUM

EFFECT OF RADIANT ENERGY ON VAPORIZATION AND COMBUSTION OF LIQUID FUELS

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SUMMARY

The radiative processes involved in combustion were investigated to determine the present role of radiant energy transfer in combustors. It was shown that, at present, the amount of radiant energy transfer from flame to fuel is quite small in a turbojet combustor. In order to find techniques for making this radiant energy transfer from flame to fuel significant, methods of increasing the equivalent gray-body emissivities of the fuel drops and the flame, as well as the efficiency of the energy transfer itself, were examined.

The equivalent gray-body emissivity of a hydrocarbon fuel may be increased by the use of liquid or solid, soluble or nonsoluble, additives. It was found that the nonsoluble solid additive was the most desirable one. In addition to the fact that a slurry-type drop may have a greater emissivity, the suspended solid additive may also greatly contribute to the emissivity of the flame.

An approximate equation was derived from which the equivalent gray-body emissivities of such slurry-type drops may be calculated. Data necessary for these calculations were obtained by spectrophotometric analysis of thin slurry films. In addition to the fuel additive, the use of radiation-reflecting walls in a combustor was considered as a means of maintaining the efficiency of the radiative transfer of energy from flame to fuel drop. It was then shown that more than half the heat of evaporation of the hydrocarbon constituent of this slurry-type drop might be supplied by radiant energy transfer in such a modified turbojet combustor.

INTRODUCTION

One of the processes in a jet-engine combustor is the exchange of radiant energy among the fuel, oxidant, flame components, combustor walls, and combustion products. A better understanding of the nature of the involved radiative processes may supply information that is useful and necessary for optimum design and fuel specifications.

The rôle played by radiant energy in a given combustion process may vary considerably from that in some other combustion process. For example, the radiant transfer of energy from flame to fuel is quite significant in the case of a powdered-coal furnace (reference 1). On the other hand, the behavior of a combustor which encloses a weakly radiating flame and a weakly absorbing fuel-oxidant mixture may be adequately described while totally neglecting the radiant transfer of energy. The importance of radiative processes in a given combustor will depend upon a wide variety of parameters. The energy radiated by the flame per unit time per unit wavelength interval, the geometry of the combustor, the reflectivity of the combustor walls, the aerodynamics of the fuel-oxidant flow pattern, the absorption spectrum of the fuel, and other physical and chemical properties of the fuel-oxidant mixture will determine the nature and magnitude of the radiative effects taking place in the combustion process.

In this work, the similarities between black-body and molecular emission and absorption of radiant energy were employed in the consideration of the relative emission characteristics of luminous and nonluminous flames as well as the absorption characteristics of hydrocarbon fuels. The relative emissivities of luminous and nonluminous flames were examined in the infrared region with a spectrophotometer. The spectral absorption characteristics of thin films of unenhanced hydrocarbon fuels, as well as those of fuels enhanced with soluble or suspended solid additives, were measured with an infrared spectrophotometer and spectral absorptivities were deduced from these data. A formula which relates the gray-body emissivity of a slurry-type spherical drop to the absorption characteristics of a thin film of the same material and thickness is derived. These considerations for an idealized turbojet combustor are then utilized to calculate the radiant energy transfer from flame to fuel presently being obtained and to indicate techniques which will permit this radiant energy transfer from flame to fuel to be significantly large. For these calculations, a cylindrical combustion chamber, 6 inches in diameter and 18 inches in length, is chosen as a model.

The advantages to be gained by the utilization of the radiant energy medium are suggested by the fact that radiant energy transfer is almost instantaneous as well as the fact that the rate determining factors are not the same as those which control the rate of convective and conductive heat transfer in a combustor. Consequently, it is possible to have excellent radiant-energy-transfer characteristics associated with a given system under conditions which render other heat-transfer processes relatively poor. An example of such a system is an evaporating slurry-type fuel drop of high gray-body emissivity which is surrounded by high-emissivity hot gases flowing at low speeds. It has been shown for nonradiative heat-transfer conditions that the evaporation rate of a liquid drop in a flowing hot gas stream is a function of the gas-stream speed and is relatively poor at low speeds (reference 2). Under similar flow

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conditions for which the radiative transfer of energy from a high-emissivity flame to a high-emissivity slurry-type drop is considered, the optically transparent gases surrounding the drop present no obstacle to the transfer of radiation from the flame to the slurry-type drop. In such a case, then, radiant energy transfer may be a very significant factor in the vaporization rate of the drop.

The effects of radiant heat transfer in a given combustor have been investigated by many authors. In reference 3, the role of radiant heat transfer in oil burners was investigated, and it was found that for a given oil burner the heat necessary to vaporize the oil is supplied, predominantly, by radiation. In reference 4, the effect of radiation on the performance of a liquid-fuel rocket was investigated, and here the upper limit for the temperature rise of the moving gases, or drops, due to the absorption of radiant energy was found to be about 100° K for the chosen operating conditions.

The purpose of the present research at the NACA Lewis laboratory is to examine the background, basic considerations, and techniques that are useful and necessary for the proper evaluation of radiative-heat-transfer processes in a turbojet combustor, and to evaluate the possibilities for improving the combustion behavior of jet engines through the controlled use of radiant energy transfer.

BASIC CONSIDERATIONS

The energy radiated per unit area per unit time (hereinafter called emissive power) by a hot molecular aggregate may be described in one of several ways. A perfect radiator, or black body, may be characterized by the Stefan-Boltzmann law

$$W_B = \sigma T^4 \tag{1}$$

where

T absolute temperature

W_B emissive power of black body

σ Stefan-Boltzmann constant

(A complete list of the symbols used in this report appears in appendix A.) A plot of the spectral distribution of the emissive power of a black body at two temperatures is given in figure 1. Most solids emit some constant fraction of this power over the range of wavelengths and are consequently known as "gray bodies." For a gray body, the emissive power W is given by the equation

$$W = \epsilon\sigma T^4 \tag{2}$$

where

W emissive power of a gray body

ϵ emissivity of a radiating surface $(0 \leq \epsilon \leq 1)$

The radiation curve for such a hot surface is very similar to that for a black body (fig. 1) and differs only in that the corresponding ordinates are some constant fraction (equal to ϵ) of the ordinates given for a black body. Thus, black bodies and gray bodies may be very simply characterized. 2693

The emission (and absorption) characteristics of liquids and gases cannot be given in any such simple manner. It is found that for such substances, the energy emitted (or absorbed) per unit area per unit time is a complicated function of wavelength, temperature, pressure, geometry, and chemical composition of the emitting (or absorbing) molecular aggregate. Thus, the average energy emitted (or absorbed) per unit time per unit area will be obtained by graphical integration of this emitted (or absorbed) energy over the effective wavelength interval and then by division by the difference in wavelength. The spectral distribution of the molecular energy is shown for several typical cases of emission and absorption in figures 2 to 4.

As a result of the foregoing considerations, the gray-body emissivity ϵ of such a radiating substance will have meaning only as the ratio of the graphically computed average value of its emissive power, at a given temperature, to the emissive power of a black body σT^4 at the same temperature. Similarly, the gray-body emissivity ϵ of such an absorbing substance will have meaning only as the ratio of the graphically computed average value of its percent-absorption curve to the corresponding value for a black body.

In the case of heat transfer between two fluid aggregates (for example, from fluid 2 to fluid 1) where the product term $\epsilon_1\epsilon_2$ may occur, it is first necessary to obtain the product of the emissive power of fluid 2 and the percent absorption of fluid 1 at each small wavelength interval and graphically integrate the resulting product in the manner described for a single fluid. By the division of this integrated-product curve by the value that would have been obtained if these two aggregates had been black bodies, $\epsilon_1\epsilon_2$ is then obtained.

In a combustor, where a liquid-fuel spray is vaporized prior to its burning, the transfer of radiant energy from flame to liquid-fuel drop may play a significant part in the fuel evaporation process. Ideally, for an optimum radiation effect in a combustor, the product term $\epsilon_1\epsilon_2$ (as defined previously) should be as large as possible. This means that in addition to having a strong radiator and strong absorber, the fuel drops must absorb in the same spectral region in which emission from the flame occurs.

EXPERIMENTAL RESULTS AND DISCUSSION

Experimental Apparatus and Methods

Three types of experimental data are reported herein. Measurements were made, at atmospheric pressure, on the emissive characteristics of a luminous and a nonluminous Bunsen-type flame, on the absorptive characteristics of liquid hydrocarbons and solutions of potential additives, and on the absorption characteristics of a few slurries containing suspended solids.

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The emissive characteristics of the flames were determined over the wavelength range of from 0.5 to 5.5 microns using a Perkin-Elmer Model 12A infrared spectrometer (reference 5) with a lithium fluoride prism. The globar source and housing normally used with this instrument was replaced by a Bunsen burner with approximately a one-half-inch throat, and the conventional source-unit mirrors were used to image the flame on the slit. The slits were set to give near full-scale deflection at the wavelength of maximum energy emission, and the same slit setting was used to cover the range of wavelength. Emission spectra were obtained manually using a shutter just ahead of the entrance slit. The fuel used was propane and the admission of air was regulated to give a nonluminous flame which was just slightly richer than stoichiometric and a luminous flame which was sufficiently rich to yield a yellow image on the slit.

The absorption spectra of the hydrocarbons and of solutions of potential additives were obtained over the wavelength range from 2 to 6 microns with a Baird Twin Beam recording infrared spectrophotometer (reference 6) with a sodium chloride prism. The sample cell had an effective thickness of 113 microns (0.113 mm) which was determined by the interference-band technique reported in reference 7. Soluble additives were examined in carbon tetrachloride solutions and the same solvent was used in the reference beam.

Absorption by the slurries was measured at 0.5 and 1.0 micron with a Beckman DU quartz prism spectrophotometer (reference 8). Variable-thickness, quartz-windowed cells made by Adam Hilger, Limited, of London, England, were used with this instrument. These cells are of the micrometer type and have scales graduated to 10 microns (0.010 mm). The slurry absorptivities were determined on suspensions made by mulling a colloidal graphite concentrate containing about 50-percent solids with varying amounts of heavy white paraffin oil. The concentrations of graphite in the final blends were determined by filtering the sample through weighed 5-micron porous glass filters, washing the residue with pentane, drying, and reweighing. Absorption by the slurries at wavelengths between 2 and 6 microns was measured using the 113-micron cell in the previously described Baird instrument.

Emission Characteristics of Luminous and Nonluminous Flames

In figure 2(a), the energy emitted by a nonluminous flame is plotted as a function of wavelength over a range from 0.5 to 5.5 microns. The energy scale is in relative units only with the peak at 4.4 microns being set equal to 100. This curve for a nonluminous flame is substantially the same as that presented in reference 9 except that the lower resolution of the present work and the use of fewer data points to construct the curve resulted in the loss of many of the smaller emission maxima shown in reference 9. The strong maxima at 2.7 and 4.4 microns are emissions arising from hot molecular carbon dioxide and the shoulder observed at 4.25 microns on the side of the 4.4 peak is caused by self-absorption by the carbon dioxide in the optical path. In reference 9 a study is made also of the emission from nonluminous flames at wavelengths greater than 5.5 microns and inspection of this data indicates that probably less than 10 percent of the total radiant energy from a hydrocarbon flame is emitted at wavelengths longer than 5.5 microns.

It was also concluded that emission in the visible and ultraviolet ranges arising from the C_2, CH, and OH radicals contributes a negligibly small fraction of the total radiant energy emitted by hydrocarbon flames. This conclusion is based on a calculation using the light-yield data found in reference 10 which show that, in a propane-oxygen flame, less than 0.001 percent of the heat of combustion is released as emission energy of the C_2 radical. The other radicals would need emission energies of higher orders of magnitude in order to make a significant contribution to the total radiant energy of a flame. Therefore, it is believed that the energy distribution shown in figure 2(a) between 0.5 and 5.5 microns represents at least 90 percent of the total radiation emitted by a nonluminous hydrocarbon flame.

A similar plot of the radiation from a luminous flame is shown in figure 2(b). The curve shows the same molecular emission of carbon dioxide as observed in the case of the nonluminous flame plus a significant amount of black-body radiation between 0.5 and 2.5 microns with a peak at about 1.3 microns. This black-body emission arises from the incandescent carbon in the overrich flame and would be expected to vary considerably in comparison with energy from other flames. The wavelength for maximum black-body emission would change very slightly with temperature and would shift to slightly shorter wavelengths with increasing temperatures.

Absorptivity of Fuels and of Solutions of Possible Additives

In figure 3 the absorption spectra for a 113-micron thickness of three pure hydrocarbons over the wavelength range of 0.5 to 5.5 microns and for two additional pure hydrocarbons and a typical turbojet fuel over

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the range of 2.0 to 5.5 microns are shown. These spectra are on a percent-transmission against wavelength scale and examples of all the principal types of hydrocarbon are given. The curves in the range from 2.0 to 5.5 microns were obtained with the Baird instrument and, where given, the 0.5 to 2.0 micron curves were plotted for a sample thickness of 113 microns. The molar absorptivity data of references 11 and 12 were employed. The absorption at wavelengths shorter than 2.0 microns is due to overtone effects and is of minor importance, while the strong band around 3.4 microns is a carbon-hydrogen fundamental. The band shown for 4-methyl-1-pentyne at 4.8 microns arises from the carbon-to-carbon triple bond of this compound.

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Also shown in dashed lines in figure 3 are the emission curves for a nonluminous flame plotted on an energy against wavelength scale. This was included to show more clearly the degree of matching (or mismatching) between the absorption frequencies of the fuel and the emission frequencies of the flame. It can be seen that, for these hydrocarbon fuels, there is a poor match between the wavelengths of strong absorption and the wavelengths of strong emission. This is shown more clearly in figure 4, where the absorption spectrum of a 113-micron film of 2,2,4-trimethylpentane is shown again at the top of the figure and the emission characteristics of both a nonluminous and a luminous flame are shown below. The shaded areas in the flame emission spectra represent the fraction of the total available radiant energy that would be absorbed from each type of flame by a 113-micron film of this fuel. This fraction is about 10 percent for the nonluminous flame and about 8 percent for the luminous flame. Only a small fraction of the radiant energy from either the nonluminous or luminous flame is absorbed by thin films of hydrocarbons since all hydrocarbons have high transmittancies or low absorptivities in the 4.4-micron region, a region where both types of flame have high emission energies. Hydrocarbons also have high transmittancies in the 1 to 2 micron range, a range in which the luminous flame radiates strongly.

A search was then made for additives which are soluble in hydrocarbons and which might increase and shift the maximum absorption regions of the fuel toward the maxima of the flame. The following three types of compound were considered: (1) highly polar compounds, since these usually have much higher absorptivities in the infrared than do the hydrocarbons, (2) compounds containing functional groups which have absorption maxima at around 4.4 microns, and (3) compounds with higher absorptivities in the range from 1.0 to 2.0 microns.

The spectra of a considerable number of alcohols, aldehydes, ketones, acids, esters, and amines were examined since these compounds are highly polar and might be expected to have high absorptivities in the infrared region. While many are strongly absorbing between 6 and 15 microns, none had generally high absorptivities between 0.5 and 5.5 microns and none

absorbed strongly near 4.4 microns. Figure 5 shows the spectrum of a 10-percent solution of ethanol, a typical polar compound, and its absorptive effect on the radiant energy from a nonluminous flame. The shaded area indicates that about a 15-percent absorption of the radiation of the flame by a 113-micron film of the ethanol solution is due largely to the strong absorption by the OH group at around 3.0 microns, but the desired large absorption effect is missing.

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Both the carbon-to-carbon triple bond ($C \equiv C$) and the carbon-to-nitrogen triple bond ($C \equiv N$) are known to have characteristic absorption maxima between 4.0 and 5.0 microns. The spectra of a considerable number of alkynes (containing $C \equiv C$) and nitriles (containing $C \equiv N$) were examined in a search for a compound with a strong absorption maxima near 4.4 microns. All the alkynes had absorption maxima at wavelengths greater than 4.6 microns and would therefore be ineffective in absorbing flame radiation. The nitriles had maxima at 4.5 microns, or slightly longer wavelengths, and the absorption spectra of two nitriles are shown in figure 6. The effect of the stronger absorber, acetonitrile, on the radiation from a nonluminous flame is shown at the bottom of this figure. The shaded area indicates that about 9 percent of the radiation of the flame would be absorbed by a 10-percent additive concentration in a 113-micron film. Again, this effect is relatively small and there appears to be little hope that an alkyne or a nitrile can be found which, when used in low concentrations, will give high absorptivities for flame radiation.

Strong absorption due to molecular effects cannot be expected in the range from 1.0 to 2.0 microns. The shortest wavelength for fundamental molecular absorption is about 2.8 microns and molecular absorptions at wavelengths below this are due to overtone effects. In general, absorption due to overtone effects is considerably weaker than that due to fundamentals and cannot be expected to make a significant contribution to the transfer of radiant energy from flame to fuel. Very high absorption due to electronic effects is found for many organic compounds in the ultraviolet and visible ranges. Organic dyes are examples of compounds which, at low concentration, are strongly absorbing in the visible range. It was thought that some dye-type compound might be found in which this electronic absorption extended sufficiently far into the infrared region to make a significant increase in the capacity of the fuel to absorb flame radiation. However, saturated solutions of several oil-soluble dyes were examined in the Baird instrument and none had measurable absorption at wavelengths longer than 2.0 microns. These solutions, even though nearly opaque in the visible range, had a long wavelength cut-off at some wavelengths shorter than 2.0 microns and did not appear to be of value in increasing the transfer of radiant energy from flame to fuel.

Absorption by Slurries

Since it appears unlikely that soluble additives can be found which will significantly increase the transfer of radiant energy from flame to fuel, a brief investigation was made of the absorption characteristics of slurries of solids suspended in hydrocarbon media. These suspensions would be expected to be gray-body-type absorbers and should be effective at all wavelengths.

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Absorption data were obtained from three concentrations of graphite at wavelengths of 0.5 and 1.0 micron and with film thicknesses from 20 to 500 microns. Data were also obtained at wavelengths from 2 to 6 microns with a 113-micron film thickness. The absorptivity coefficients for the graphite were then calculated from the Beer-Lambert equation

$$k = \frac{\ln \frac{I_0}{I}}{c\ 2r} \tag{3}$$

where

k absorption coefficient

I_0 incident radiant power

I transmitted radiant power

c instantaneous concentration of solids in slurry, weight fraction

$2r$ film thickness, microns

It was found that, at a given wavelength, the absorption coefficient of the graphite did not vary significantly with either concentration or film thickness. However, the coefficient did show some decrease with increasing wavelength, as shown in figure 7, where the absorption coefficient is plotted against wavelength. Each point on figure 7 represents an average of three or more determinations taken at a single wavelength but with concentration of solid, film thickness, or both varied.

A few slurries were prepared by mulling channel black into white mineral oil. The stability of these slurries was poor and the absorption coefficients calculated from absorption data taken at 0.5 and 1.0 micron varied widely. However, the coefficient for channel black appears to be roughly one-half that determined for graphite.

The relation between the transmission of a 50-micron-thick slurry film and the concentration and absorptivity of the solid as calculated from equation (3) is given in figure 8. Transmission is plotted against

concentration for solids of varying absorptivity. For example, a solid with an absorption coefficient of 3.0 would require a 0.0155 weight-fraction concentration to yield a 50-micron-thick film with a 10 percent transmittance. In general, it appears that slurries containing 0.01 to 0.03 weight fraction of solids can be prepared which would be highly absorptive in the same regions in which the flame radiates.

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APPLICATION OF RESULTS

Absorptivity of Spherical Drop Compared with That of Thin Film

The absorptivity of a liquid fuel drop (of radius r_d) may be calculated once the transmittance (fraction of incident light that is transmitted) of a thin film of the same composition (thickness = $2r_d$) has been experimentally determined. After allowances had been made for reflective effects at the drop surfaces as well as refractive and absorptive effects in the fuel-drop interior, the equivalent gray-body emissivity of a slurry-type drop was calculated (appendix B). Figure 9 gives the emissivity of such a slurry-type fuel drop (for refractive index = 1.4) as a function of the transmittance of a thin film of equal thickness and composition. Similar curves may be constructed for other refractive indices (appendix B).

It can also be shown (appendix B) that the concentration of a nonvolatile additive in an evaporating slurry-type drop is given by the equation

$$c = \left[1 + \left(\frac{1-c_0}{c_0}\right) - \left(\frac{r_{d,0}^3 - r_d^3}{c_0 r_{d,0}^3}\right)\left(\frac{\rho_f}{\rho_0}\right)\right]^{-1} \tag{4}$$

where

c_0 initial value of concentration of additive in the slurry-type drop, weight fraction

$r_{d,0}$ initial radius of drop

r_d radius of drop

ρ_f density of the liquid fuel

ρ_0 initial density of slurry

Thus, a knowledge of both the absorption coefficient k associated with a slurry film and the instantaneous value of the concentration of solid additive in an evaporating slurry-type drop yields an instantaneous value of the emissivity of an evaporating slurry-type drop (from equation (4) and figs. 8 and 9).

Combustor Calculations

The forementioned considerations have been utilized to calculate radiation effects in a cylindrical combustion chamber, 6 inches in diameter and 18 inches in length. Figure 10 shows the classification of the combustor regions as well as the choice of gas velocity and temperature profiles. The assumptions made were that region I was a precombustion region, that region II was continuously filled with flame, and that region III was a postcombustion region.

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When photochemical effects are neglected, the fuel drops will absorb, in transit through region I, some of the radiant energy emanating from region II and will convert this energy to sensible heat. When a set of typical operating conditions is used and the problem is treated as one in which a "disk of flame" located at the interface between regions I and II (see fig. 10) radiates energy to a homogeneous cloud of gray-body particles which fill region I, the following results are obtained (see appendix C):

(1) For the emissivity of a nonluminous flame ϵ_f of 0.05 and the emissivity of a fuel drop ϵ_d of 0.05,

$$Q_I = 0.0032\ Q_V$$

where

Q_I radiant energy absorbed by cloud of fuel drops in passage through region I

Q_V heat necessary to vaporize fuel (n-octane) drop originally at 0° C

(2) For the emissivity of a nonluminous flame ϵ_f of 0.05 and the emissivity of a fuel drop ϵ_d of 1.0,

$$Q_I = 0.053\ Q_V$$

This value is still quite negligible.

(3) In order to optimize the transfer of radiant energy from the flame to an evaporating fuel drop in region I, it was supposed that a small amount of optically opaque solid additive had been suspended in the fuel and that the effect of using this slurry-type fuel was to increase the flame emissivity to $\epsilon_f \approx 0.30$ and to increase the drop emissivity to $\epsilon_d \approx 0.80$. Such assumptions lead to a value of

$$Q_I = 0.258\ Q_V$$

(4) If, in addition to the changes introduced in case (3), the combustor walls are coated with a radiation reflector, for example, a ceramic, then

$$Q_I = 0.410\ Q_V$$

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The given values of Q_I may be further increased if smaller drops are employed. The use of smaller drops would, of course, slightly decrease the emissivity of any given drop. This, however, would be more than compensated for by the decreased probability of radiation getting through the cloud without impinging on any of the drops in it.

The Q_I values obtained in cases (3) and (4) represent significant fractions of Q_V.

An estimate of the optimum radiant energy transfer that may occur in region II can be obtained by the extrapolation of some of the calculations presented in reference 4. Such calculations yield (appendix C)

$$Q_{II} \approx 0.50\ Q_V$$

where Q_{II} is the radiant energy absorbed by a highly absorbent fuel drop in its passage through the flame-filled region II. If, further, the combustor walls are coated with a ceramic radiation reflector, then

$$Q_{II} = 0.73\ Q_V$$

It can therefore be concluded that

(1) The present role of radiant energy transfer in a combustor employing conventional aviation fuels is quite negligible.

(2) Slurry-type fuels (to enhance the radiant emissivity of both flame and fuel) and ceramic liners (to increase the reflectivity of the combustor wall) may be employed to substantially increase the role of radiant energy transfer in a combustor. These results are summarized in table I.

It is interesting to note that the innovation of an item such as a ceramic combustor liner may also affect the conductive and convective heat-transfer processes. Thus, for example, a ceramic liner that is a good thermal insulator (as well as radiation reflector) may

(1) Raise the average temperature of the primary gases inside the combustor

(2) Raise the average inside wall temperature of the combustor

(3) Increase, as a result of the porous nature of the ceramic, the amount of fuel in transit from the fuel nozzle (in region I) to region II at any given time. This may be particularly true in cases where wall-wetting spray nozzles are employed which would, in effect, increase the fuel residence time, that is, the average length of time spent by a unit mass of fuel in transit through region I.

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(4) Increase, as a result of its rough surface, the degree of turbulence in the immediate neighborhood of the wall

(5) Increase, as a result of the preceding, the heat-transfer rate to the evaporating fuel

SUMMARY OF RESULTS

1. An equation relating the gray-body emissivity of a spherical slurry-type drop to the absorption characteristics of a thin film (of the same thickness and material) was derived.

2. The equivalent gray-body emissivity of a spherical hydrocarbon jet-fuel drop (of 50-micron diameter) is almost vanishingly small ($0 < \epsilon < 0.05$). This is true of hydrocarbons in general.

3. An equivalent gray-body emissivity, for a spherical slurry-type drop with a 50-micron diameter, of 0.90 was obtained for a slurry of less than 1.5-weight percent carbon in oil.

4. These results were employed to show that (a) the transfer of radiant energy from a nonluminous flame to an unenhanced fuel drop (in a turbojet-like combustor) is negligibly small and (b) the transfer of radiant energy from a luminous flame to a slurry-type fuel drop (in a turbojet-like combustor) could supply a major portion of the heat of vaporization of the liquid fuel.

CONCLUSIONS

1. The radiant transfer of energy from flame to liquid fuel is not significant in present-day turbojet combustors.

2. The radiant transfer of energy from flame to liquid fuel can be made significant in a turbojet combustor through the use of slurry-type fuels and radiation-reflecting walls.

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APPENDIX A

SYMBOLS

The following symbols are used in this report:

A_c combustor area, πR_c^2

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A_n cross-sectional area of nth cylindrical section of spherical drop

A_1 cross-sectional area of first cylindrical section of spherical drop

a subtended area

b constant

C specific heat

c instantaneous concentration of additive in slurry-type drop, weight fraction

c_1 numerical concentration of drops

d average diameter of drop

E_a energy absorbed by fuel drop in region II

F transmission coefficient of slurry-type drop

F' transmission coefficient of slurry-type film

f_n fraction of cross-sectional area of combustor A_c covered by opaque drops

g mass absorption coefficient associated with fuel

I transmitted radiation intensity associated with incident cylindrical light beam

I_D transmitted radiation intensity of absorbing slurry-type disk

I_S transmitted radiation intensity of absorbing slurry-type sphere, $\sum_n I_n$

I_T sum of radiant energies incident on fuel drop during residence in region II of combustor

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I_0 incident radiation intensity associated with incident cylindrical light beam of radius r

K constant

k absorption coefficient

k' I_D/I_0, $e^{-2\alpha r_d}$

L $r_d\sqrt{2\left[1-\cos(\pi-2\gamma)\right]}$, equivalent path length of cylindrical light beam in refracting slurry-type drop

l $2r_d \cos \theta$, equivalent path length of cylindrical light beam in nonrefracting slurry-type drop

l_d drop mist depth

M mass in evaporating slurry-type drop

$\overline{M}$ average mass of fuel in transit through region I

m mass flow rate of fuel in region I

N_d average number of drops suspended in region I

p_c pressure in combustion chamber

Q radiant energy absorbed by cloud of fuel drops

Q_V heat of vaporization of n-octane from 0° C

q radiant energy exchange between two coaxial disks of separation S

$\overline{q}$ average radiant energy exchange between two coaxial disks of separation S

R I_S/I_D for nonreflecting, nonrefracting, absorbing medium

R' I_S/I_D for nonreflecting, refracting, absorbing medium

R'' I_S/I_D for reflecting, refracting, absorbing medium

R_c radius of combustor

r radius

$\overline{r}$ average radius

r_n $\frac{r_{n,1} + r_{n,2}}{2}$

$r_{n,1}$ inner radius of nth cylindrical section of spherical drop

$r_{n,2}$ outer radius of nth cylindrical section of spherical drop

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S separation of disks associated with flame and fuel

$\overline{S}$ average separation of disks associated with flame and fuel

T absolute temperature

ΔT change in temperature

V volume

ΔV change in volume

$\overline{v}$ average speed of fuel drop

W emissive power of gray body

W_B emissive power of black body

x length

α kc

γ angle of refraction of light ray

ϵ emissivity of a radiating surface

θ angle of incidence of light ray

μ average index of refraction, $\sin \theta / \sin \gamma$ for $\theta \neq 0$

λ wavelength of light

ρ density

$\overline{\rho}$ average density

σ Stefan-Boltzmann constant

Subscripts:

a additive

d	drop
f	liquid fuel
fl	flame
n	n^{th} cylindrical section
s	slurry
0	initial
I	region I (precombustion region)
II	region II (flame-filled region)

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APPENDIX B

DROP EMISSIVITY CALCULATIONS

Absorptivity of Sphere Compared with That of Disk of Equal Diameter and Thickness

The absorptivity of a sphere of radius r_d as compared with that of a disk of radius r_d and of length $2r_d$ may be calculated in the following manner. These calculations are applicable for cases where the wave interaction between the light and the drops is small, that is, where the particle diameters are several times the wavelength of the light. 2693

The incident radiation is considered to be a cylindrical beam of radius r which is made up of a group of concentric cylindrical sections, where the annular thickness of each section is a constant. Figure 11 is a cross-sectional view of a nonrefracting spherical drop through which such a cylindrical light beam has been passed. The axis of the cylindrical beam is in the plane of the paper.

From figure 12,

$$l = 2r_d \cos \theta \tag{B1}$$

and

$$L = r_d\sqrt{2\left[1 - \cos(\pi-2\gamma)\right]} \tag{B2}$$

This incident beam may be broken up into K sections such that

$r_{n,1}$ inner radius of nth section of cylindrical light beam

$r_{n,2}$ outer radius of nth section of cylindrical light beam

The cross-sectional area of the nth section is

$$A_n = \pi(r_{n,2}^2 - r_{n,1}^2) \tag{B3}$$

Let

$$r_n = \frac{r_{n,2} + r_{n,1}}{2} \tag{B4}$$

then

$$A_n = \pi(r_{n,2} - r_{n,1})(r_{n,2} + r_{n,1}) = 2\pi r_n(r_{n,2} - r_{n,1}) \tag{B5}$$

Let

$$(r_{n,2} - r_{n,1}) = \frac{r_d}{K} = \text{constant} \tag{B6}$$

Case I: No reflective or refractive effects are assumed to occur. From figure 12

$$I_n = (I_0)_n e^{-\alpha l_n} \tag{B7}$$

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where

I_n transmitted radiation intensity associated with n^{th} section of incident light beam

$(I_0)_n$ incident radiation intensity associated with n^{th} section of incident light beam

Since $(I_0)_n = bA_n$, where b is a constant, it follows that

$$I_n = bA_n e^{-\alpha l_n} \tag{B8}$$

From equations (B5) and (B6), it follows that r_n may assume the values

$$r_n = \frac{r_d}{2K}, \frac{3r_d}{2K}, \frac{5r_d}{2K}, \ldots, \frac{(2n-1)r_d}{2K}, \ldots$$

$$n = 1,2,3, \ldots, n, \ldots$$

Thus

$$A_n = \frac{(2n-1)\pi r_d^2}{K^2} \tag{B9}$$

It is also evident, that

$$A_n = (2n-1)A_1 \tag{B10}$$

Thus,

$$I_n = (2n-1)bA_1 e^{-\alpha l_n} \tag{B11}$$

The intensity transmitted by the absorbing sphere thus becomes

$$I_S = \sum_{n=1}^{K} I_n = \sum_{n=1}^{K} (2n-1)bA_1 e^{-\alpha l_n} \tag{B12}$$

A similar expression may be written for the intensity transmitted by the absorbing disk:

$$I_D = \sum_{n=1}^{K} (2n-1)bA_1 e^{-2\alpha r_d} \tag{B12a}$$

The value of R, which is defined as I_S/I_D, is expressed as

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$$R = \frac{I_S}{I_D} = \frac{\sum(2n-1)e^{-\alpha l_n}}{e^{-2\alpha r_d}\sum(2n-1)} = \frac{\sum(2n-1)e^{\alpha(2r_d-l_n)}}{\sum(2n-1)}$$

which yields, for example, if $K = 20$,

$$R = \frac{1}{400}\sum_{n=1}^{20}(2n-1)e^{2\alpha r_d(1 - \cos\theta_n)} \tag{B13}$$

Case II: Refractive and absorptive effects are assumed to occur. From Snell's law

$$\mu = \frac{\sin\theta}{\sin\gamma} = \text{average index of refraction of drop} \tag{B14}$$

θ angle of incidence

γ angle of refraction

Equation (B11) must be rewritten as

$$I_S = \sum_{n=1}^{K} I_n = \sum_{n=1}^{K}(2n-1)bA_1 e^{-\alpha L_n} \tag{B15}$$

as before,

$$I_D = \sum_{n=1}^{K}(2n-1)bA_1 e^{-2\alpha r_d} \tag{B15a}$$

This yields, when $K = 20$,

$$R' = \frac{I_S}{I_D} = \frac{1}{400}\sum_{n=1}^{20}(2n-1)e^{\alpha(2r_d-L_n)}$$

$$R' = \frac{1}{400}\sum_{n=1}^{20}(2n-1)e^{\alpha r_d\left\{2 - \sqrt{2[1 - \cos(\pi-2\gamma_n)]}\right\}} \tag{B16}$$

Case III: Reflective, refractive, and absorptive effects are assumed to occur. Both equations (B15) and (B15a) must now be amended.

The average reflection coefficient associated with the nth zone can be written (reference 13)

$$\frac{1}{2}\left[\frac{\sin^2(\theta_n-\gamma_n)}{\sin^2(\theta_n+\gamma_n)} + \frac{\tan^2(\theta_n-\gamma_n)}{\tan^2(\theta_n+\gamma_n)}\right]$$

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Then,

$$F_n = \left\{1 - \frac{1}{2}\left[\frac{\sin^2(\theta_n-\gamma_n)}{\sin^2(\theta_n+\gamma_n)} + \frac{\tan^2(\theta_n-\gamma_n)}{\tan^2(\theta_n+\gamma_n)}\right]\right\} \tag{B17}$$

is the transmission coefficient of the nth section (of the first air to fluid surface) of the drop. For a highly absorbing drop, the multiple internal reflections inside the liquid sphere may be neglected, to a high degree of approximation.

For this case, equation (B15) may be rewritten

$$I_S = \sum_{n=1}^{K} I_n = \sum_{n=1}^{K} (2n-1)F_n bA_1 e^{-\alpha L_n} \tag{B18}$$

It can be shown (reference 13) that the average reflection coefficient for the first surface of the disk may be written as

$$\left(\frac{\mu-1}{\mu+1}\right)^2$$

The transmissivity of the first surface of the disk F_n' may be written

$$F_n' = 1 - \left(\frac{\mu-1}{\mu+1}\right)^2 \tag{B19}$$

If $k' = \frac{I_D}{I_O} = e^{-2\alpha r_d}$ for the disk, the first internal reflection may be taken into account by the following equation:

$$F' = F_n' = 1 - \left(\frac{\mu-1}{\mu+1}\right)^2 (1+k')$$

However, for a highly absorbing disk, expression (B19) may be used. Thus, equation (B15a) becomes

$$I_D = \sum_{n=1}^{K} (2n-1)bF_n' A_1 e^{-2\alpha r_d} \tag{B18a}$$

Thus, the following expression is obtained for the ratio of the transmitted intensities:

$$R'' = \frac{I_S}{I_D} = \frac{1}{400\ F'} \sum_{n=1}^{20} F_n(2n-1)e^{\alpha r_d \left\{2 - \sqrt{2\left[1 - \cos(\pi - 2\gamma_n)\right]}\right\}} \tag{B20}$$

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The emissivity of this slurry-type drop may now be calculated in terms of the transmissivity of a thin film (disk) of the slurry. For unit incident intensity,

$$R'' = \frac{\left[\frac{1}{400} \sum_{n=1}^{20} (2n-1)F_n\right] - \epsilon}{k'} \tag{B21}$$

For the case where $\mu = 1.4$, equation (B21) becomes

$$\epsilon = 0.9289 - k'R'' \tag{B22}$$

Thus from a knowledge of αr, as found in the laboratory from thin films, the emissivity of a spherical drop can be computed. For the case where $\mu = 1.4$, a plot is made of ϵ against k' (fig. 9).

Although the curve shown in figure 9 is calculated for an average index of refraction of 1.4, similar curves for other indices of refraction may be readily constructed. This follows from the facts that (1) at $k' = 0$, $\epsilon = \frac{1}{400} \sum_{n=1}^{20} (2n-1)F_n$; (2) at $\epsilon = 0$, $k' \approx 1 - 2\left(\frac{\mu-1}{\mu+1}\right)^2$ (all but the light reflected at the two surfaces of the thin film is transmitted); and (3) the shape of this curve corresponds very closely to that shown in figure 9.

Similarly, for less accurate approximations, the emissivity will be given by the expressions $(1-Rk')$ where R is obtained from equation (B13), which neglects reflection and refraction effects, and $(1-R'k')$ where R' is obtained from equation (B16), which neglects only reflection effects. The value of R'' in equation (B20) is the most applicable value and should be used exclusively.

The values of R, R', and R'' for various values of k' (or αr) when $\mu = 1.4$ are given in table II.

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Emissivity of Evaporating Slurry-Type Drop in Terms of Initial Emissivity Assuming Unchanged Amount of Additive

Let

M_f	mass of liquid fuel in evaporating slurry-type drop
$M_{f,0}$	initial mass of liquid fuel in evaporating slurry-type drop
M_a	mass of (nonvolatile) additive in evaporating slurry-type drop
V_d	volume of drop
r_d	radius of drop
$r_{d,0}$	initial radius of drop
c	instantaneous concentration of solids in drop, weight fraction
c_0	initial concentration of solids in drop, weight fraction
ρ_f	density of fuel
ρ_a	density of additive
ρ_0	initial density of slurry
$\left[\rho_f(\Delta V_d)\right]_{r_{d,1}}^{r_{d,2}}$	mass of fuel evaporated during change in drop size from $r_{d,1}$ to $r_{d,2}$

$$V_d = \frac{4}{3}\pi(r_d)^3 = \frac{M_a}{\rho_a} + \frac{M_f}{\rho_f} \tag{B23}$$

It follows that

$$M_a = \rho_a\left(\frac{4}{3}\pi r_d^3 - \frac{M_f}{\rho_f}\right) \tag{B24}$$

At any given time

$$M_f = M_{f,0} - \left[\rho_f(\Delta V_d)\right]_{r_{d,1} = r_{d,0}}^{r_{d,2} = r_d}$$

thus

$$M_f = M_{f,0} - \frac{4}{3}\pi(r_{d,0}^3 - r_d^3)\rho_f \tag{B25}$$

The concentration of additive c is defined as

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$$c \equiv \frac{M_a}{M_a + M_f} \tag{B26}$$

thus

$$M_f = \left(\frac{1-c}{c}\right) M_a \tag{B27}$$

Equation (B25) may be rewritten with the aid of equation (B27) as

$$M_a \left(\frac{1-c}{c}\right) = M_{f,0} - \frac{4}{3}\pi(r_{d,0}^3 - r_d^3)\rho_f$$

which gives

$$1 + c\left[\frac{4\pi(r_{d,0}^3 - r_d^3)\rho_f}{3M_a} - \frac{M_{f,0}}{M_a} - 1\right] = 0 \tag{B28}$$

The relations

$$c_0 = \frac{M_a}{M_{f,0} + M_a} \tag{B26a}$$

$$\rho_0 = \frac{M_a + M_{f,0}}{\frac{4}{3}\pi r_{d,0}^3} \tag{B29}$$

may be employed to transform equation (B28) to

$$c = \left[1 + \left(\frac{1-c_0}{c_0}\right) - \left(\frac{r_{d,0}^3 - r_d^3}{c_0 r_{d,0}^3}\right)\left(\frac{\rho_f}{\rho_0}\right)\right]^{-1} \tag{B30}$$

APPENDIX C

RADIATION EFFECTS IN CYLINDRICAL COMBUSTION CHAMBER

A cylindrical combustion chamber 18 inches in length and 6 inches in diameter is considered. Further, it is considered that the chamber may be divided into three sections (I, II, and III) and that the velocity and temperature profiles shown in figure 10 are applicable. A homogeneous distribution of fuel drops in region I (precombustion region) approaching region II, which is completely filled with flame, is assumed. Region III is a postcombustion region.

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Region I - Precombustion Zone

The fuel drops in region I will absorb some of the radiant energy emanating from region II and will convert this energy to sensible heat. Photochemical effects are herein neglected.

The following typical data will be considered:

Combustion-chamber pressure, p_c, lb/sq in. abs	15
Length of precombustion zone, x_I, in.	3
cm	7.62
Average drop diameter, d, microns	50
Average drop radius, $\overline{r}_d$, microns	25
Average density of drop, ρ_d, gm/cu cm	0.7
Fuel mass flow, m, lb/sec	0.015
Average speed of drop in region I, $\overline{v}_I$, ft/sec	10
Radius of combustor, R_c, in.	3
cm	7.62
Cross-sectional area of combustor, A_c, sq cm	182
Average mass of fuel found in transit in region I, $\overline{M}$, lb	3.75×10^{-4}
Subtended drop area, a_d, sq cm	1.965×10^{-5}
Average number of drops suspended in region I, N_d	3.765×10^{6}

An estimate of the sensible heat transfer from the flame of region II to the drops in region I may be made in the following manner. It has been shown (reference 14) that, for a cloud of optically opaque particles,

$$f_n = 1 - \left(1 - \frac{a_d}{A_c}\right)^{c_1 l_d A_c} = 1 - \left(1 - \frac{a_d}{A_c}\right)^{N_d} \tag{C1}$$

where

f_n fraction of cross-sectional area of combustor A_c covered by opaque drops (drop stopping power)

N_d average number of drops suspended in region I

c_1 numerical concentration of drops

l_d depth of mist of drops

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It is found that for these conditions

$$f_n = 0.334$$

Thus, for a cloud of opaque drops, the effective absorbing area is equal to 0.334 A_c. The drops in region I may be considered as a disk (about two-thirds porous) which is absorbing energy transmitted through the circular face of a cylindrical volume of flame that exists in region II. The problem therefore becomes one involving the radiant energy exchange between a disk (flame) of some equivalent gray-body emissivity and another disk of a given gray-body emissivity and porosity.

The maximum stopping power of this cloud of drops is 0.406. Since $f_n = 0.334$ for $\epsilon = 1.0$ and $f_n \rightarrow 0.406$ for $\epsilon \rightarrow 0$, then

$$f_n = 0.406(1-\epsilon_d) + 0.334\epsilon_d \tag{C1a}$$

for all values of ϵ_d.

It can be shown (reference 15) that for such a system, the radiant energy exchange q_I is

$$q_I = \epsilon_{fl}\epsilon_d\sigma f_n T^4 \left\{\frac{\pi}{2}\left[2R_c^{\,2} + S^2 - \sqrt{(2R_c^{\,2} + S^2)^2 - 4R_c^{\,4}}\right]\right\} \tag{C2}$$

where

q_I energy transferred per unit time from disk associated with flame to disk associated with fuel drops

ϵ_{fl} equivalent gray-body emissivity of flame

ϵ_d equivalent gray-body emissivity of fuel drop

σ Stefan-Boltzmann constant, 4.92×10^{-8}, kg-cal/(sq m)(hr)($^{\circ}K^4$)

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

S separation of two coaxial disks

The expression

$$\bar{q}_I = \frac{\int_{S=0}^{S=3''} q_I \, dS}{\int_{S=0}^{S=3''} dS} \tag{C3}$$

may be evaluated for this geometry and yields an average value of $S = 1.35$ in. (see fig. 13) = 0.0342 m.

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Radiant energy transfer in region I under typical conditions: $(\epsilon_d)(\epsilon_{fl}) = (0.05)(0.05)$. - When $(\epsilon_d)(\epsilon_{fl}) = (0.05)(0.05)$ and the following values are used

T 2000° K

f_n $0.406(1 - \epsilon_d) + 0.334\,\epsilon_d = 0.402$

R_c 3 in. or 0.0762 m

S 1.35 in. or 0.0342 m

σ 4.92×10^{-8} kg-cal/(sq m)(hr)(°K^4)

it is found that the sensible heat absorbed by the fuel drops in region I $\bar{q}_I$ is 9.16 kg-cal/hr or, when a residence time for these drops of 6.95×10^{-6} hr is used, the heat absorbed is

$$Q_I = 0.374 \text{ cal} = 3.20 \times 10^{-3}\, Q_V$$

where Q_V is the heat necessary to vaporize a fuel drop which has originally been at 0° C (117 cal/gm). This represents the radiant energy transfer in region I under typical conditions.

Radiant energy transfer in region I under conditions: $(\epsilon_d)(\epsilon_{fl}) = (1.0)(0.05)$. - The change of ϵ_d from 0.05 to 1.0 then gives

$$f_n = 0.334$$

and

$$Q_I = 0.053\, Q_V$$

This value is still quite small.

Radiant energy transfer in region I when flame and drop emissivities are increased and combustor walls are radiation reflectors. - If a solid additive should be mixed with the fuel (carbon perhaps) which (1) increases the flame emissivity to $\epsilon_{fl} \approx 0.30$ and (2) increases the drop emissivity to $\epsilon_d \approx 0.80$ and radiation-reflection walls are introduced to effectively make $S = 0$, then 2693

$$Q_I = 0.410\ Q_V$$

Radiant energy transfer in region I when combustor walls are total absorbers (rather than reflectors). - When the combustor walls are total absorbers, the data for the preceding case yield

$$Q_I = 0.258\ Q_V$$

It should be noted that the value of Q_I may be further increased in the given cases if the drop size is decreased, thus increasing the value of f_n while only slightly decreasing the value of ϵ_d.

Region II - Combustion Zone

In order to estimate the radiant energy transfer that may occur in region II, a set of conditions similar to those employed in reference 4 may be assumed.

It was shown (reference 4) that the energy absorbed by fuel drops moving axially through a flame-filled cylindrical section may be calculated from the expression

$$E_a = 8\pi g \rho \bar{r}_d^{\,3} I_T \tag{C4}$$

where

E_a energy absorbed by fuel drop, cal

g mass absorption coefficient associated with fuel drop, sq cm/gm

ρ density of absorbing fuel, gm/cu cm

$\bar{r}_d$ average radius of drop, cm

I_T sum of radiant energies incident on drop during residence time in region II

The calculation of I_T is quite involved and the values of I_T found in reference 4 may be used to calculate a suitable I_T for the conditions present in this combustor. This calculation yields

$$E_a = 1.92 \times 10^{-6} \text{ cal/drop}$$

It is also shown in reference 4 that

$$\Delta T = \frac{6gI_T}{C} \tag{C5}$$

where

ΔT temperature rise of fuel in region II caused by radiation absorption

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C specific heat of fuel, 0.58 cal/gm °C

This yields $\Delta T \approx 100^\circ$ C, the same value obtained in reference 4 for a rocket calculation. This coincidence results, in the main part, from the fact that the higher rocket temperatures are balanced by the lower flow rates existing in a turbojet combustor. This temperature rise in region II corresponds to a sensible heat increase of about half the heat of evaporation. Thus

$$Q_{II} \approx 0.5\ Q_V$$

The value of g employed here (and in reference 4) is actually quite high (40 sq cm/gm) compared with that which may be expected in the case of a typical hydrocarbon fuel. However, it is somewhat smaller than that value of g which might be expected for a slurry-type fuel drop and corresponds to an emissivity of about 0.5 for a 50-micron-diameter drop.

It is also estimated (reference 4) that the neglect of radiation reflection from the walls will lead to the value of Q_{II} which is too small by a factor of 10 percent. When a value of 0.2 for the reflectivity of the Inconel walls is used, it follows that the introduction of radiation-reflecting walls will yield

$$Q_{II} \approx 0.73\ Q_V$$

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TABLE I - RADIATION EFFECTS IN 6-INCH DIAMETER

TURBOJET-TYPE COMBUSTOR

[Flow, 1 lb air/sec (f/a = 0.015); temperature in region II, 2000° K; pressure, 15 lb/sq in. abs.]

Combustor region I - radiation effects	
Effect	Q_I/Q_V
Maximum present effect	0.0032
Maximum effect that may be achieved by changing only the fuel-drop emissivity	.053
Maximum effect that may be achieved by changing the character of the flame, fuel, and walls	.410
Maximum effect that may be achieved by changing the character of the flame and fuel (walls remain highly emissive)	.258
Maximum effect that may be achieved by changing the character of the walls alone	.0052
Combustor region II - radiation effects	
Effect	Q_{II}/Q_V
Maximum effect for the given flame and fuel considerations	0.50
Maximum effect for the given flame and fuel conditions with reflecting walls	.73
Maximum effect for the given flame and fuel conditions and emitting (extremely hot, insulated) walls (T_{wall} = 2500° R)	.69

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TABLE II - VALUES OF R, R', AND R" (I_S/I_D) RATIOS FOR ABSORBING MEDIA HAVING VARIOUS REFLECTION AND REFRACTION PROPERTIES

[μ = 1.4.]

(k')	(αr)	R"	R'	R
0.001	3.454	2.884	3.152	47.947
.002	3.107	2.543	2.766	28.931
.004	2.761	2.507	2.438	17.798
.006	2.558	2.098	2.265	13.514
.008	2.414	1.998	2.153	11.170
.010	2.303	1.924	2.070	9.674
.015	2.101	1.799	1.930	7.497
.020	1.956	1.716	1.837	6.280
.030	1.753	1.607	1.716	4.944
.040	1.609	1.535	1.635	4.199
.050	1.498	1.483	1.577	3.717
.060	1.407	1.442	1.531	3.372
.070	1.330	1.408	1.494	3.110
.080	1.263	1.380	1.462	2.903
.090	1.204	1.355	1.434	2.735
.100	1.151	1.334	1.411	2.595
.150	.949	1.257	1.324	2.138
.200	.805	1.206	1.267	1.875
.250	.693	1.169	1.225	1.700
.300	.602	1.140	1.191	1.574
.350	.525	1.117	1.164	1.478
.400	.458	1.097	1.141	1.400
.450	.399	1.081	1.121	1.337
.500	.347	1.067	1.048	1.284
.550	.299	1.054	1.089	1.238
.600	.255	1.043	1.076	1.198
.650	.215	1.032	1.063	1.163
.700	.178	1.023	1.052	1.132
.750	.144	1.015	1.042	1.105
.800	.112	1.008	1.032	1.080
.850	.0813	1.001	1.023	1.057
.900	.0527	.995	1.015	1.037

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5X

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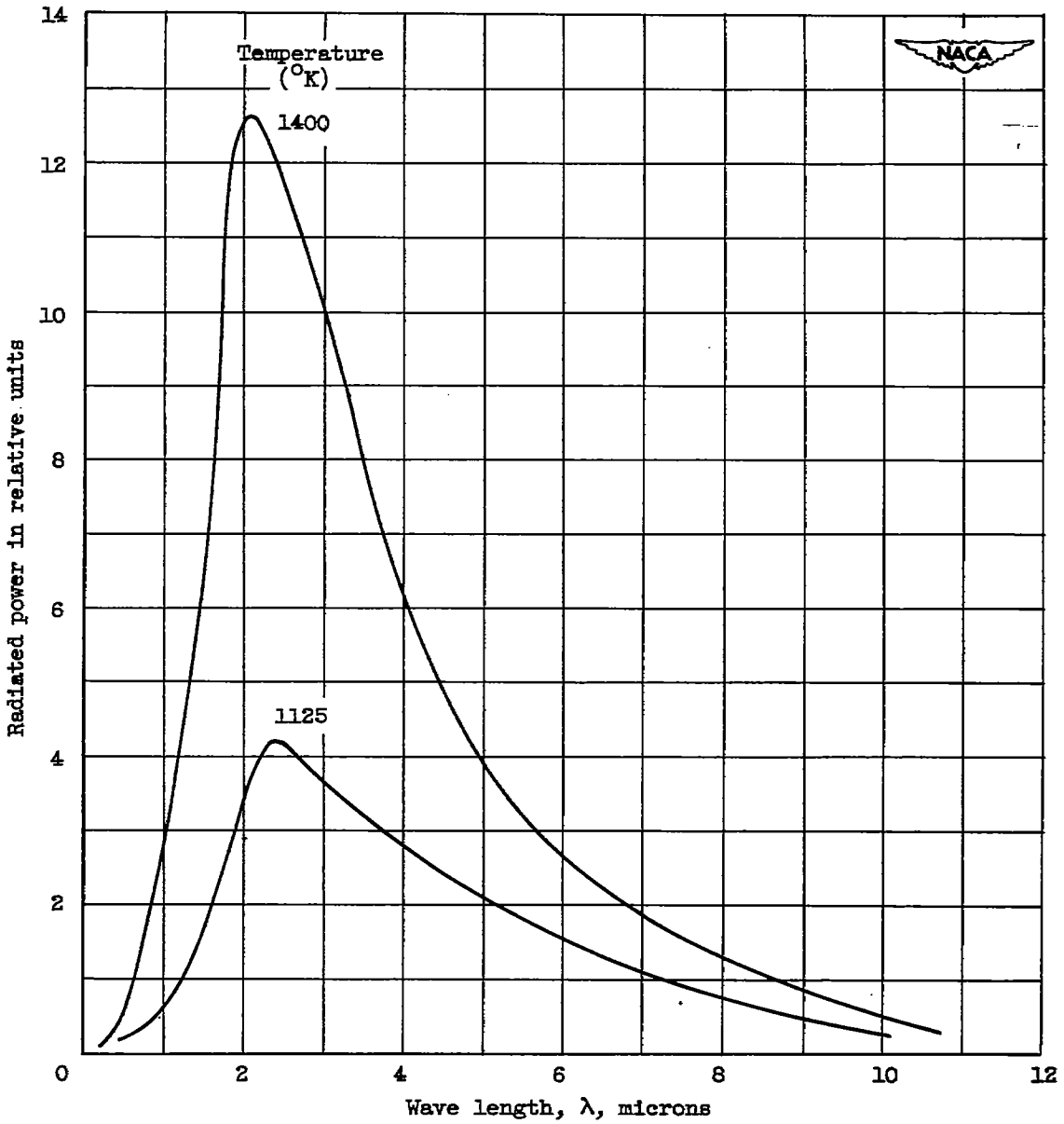

Figure 1. - Spectral distribution in terms of indicated power for black-body radiation at 1125° and 1400° K.

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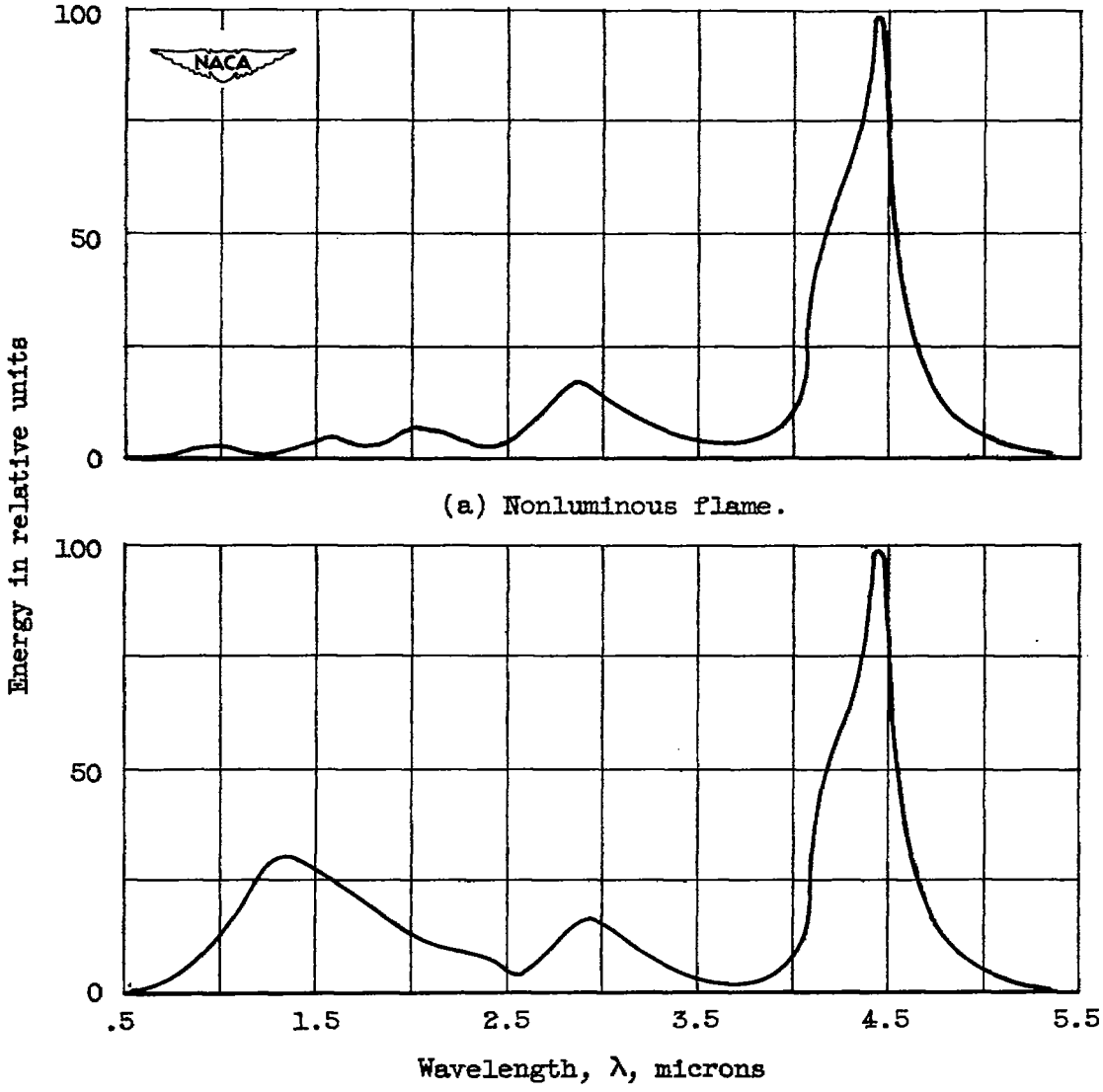

(a) Nonluminous flame.

(b) Luminous flame.

Figure 2. - Energy emitted as function of wavelength for propane-air flames.

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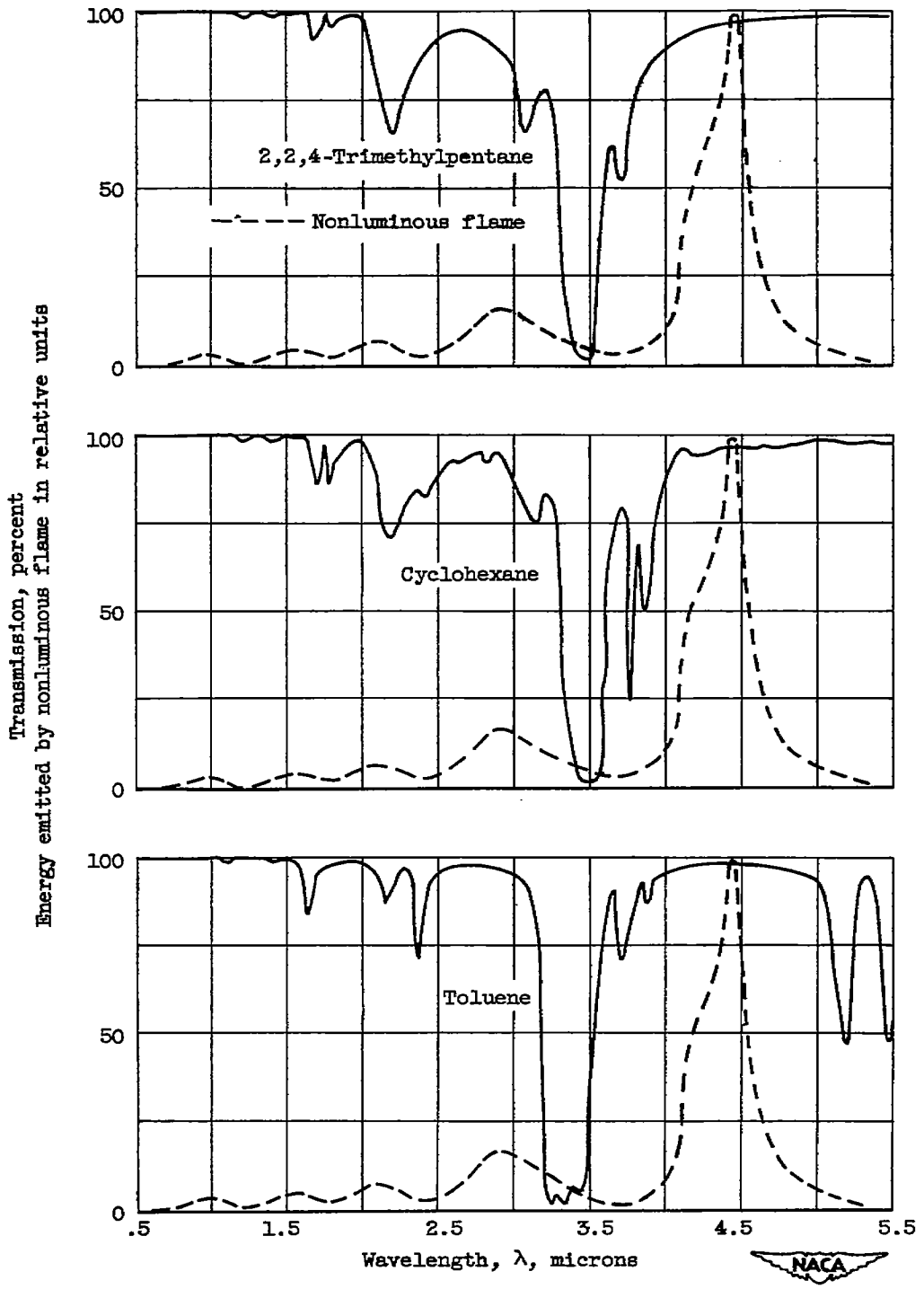

Figure 3. - Transmission of six hydrocarbon fuels and emission of nonluminous propane-air flame as function of wavelength.

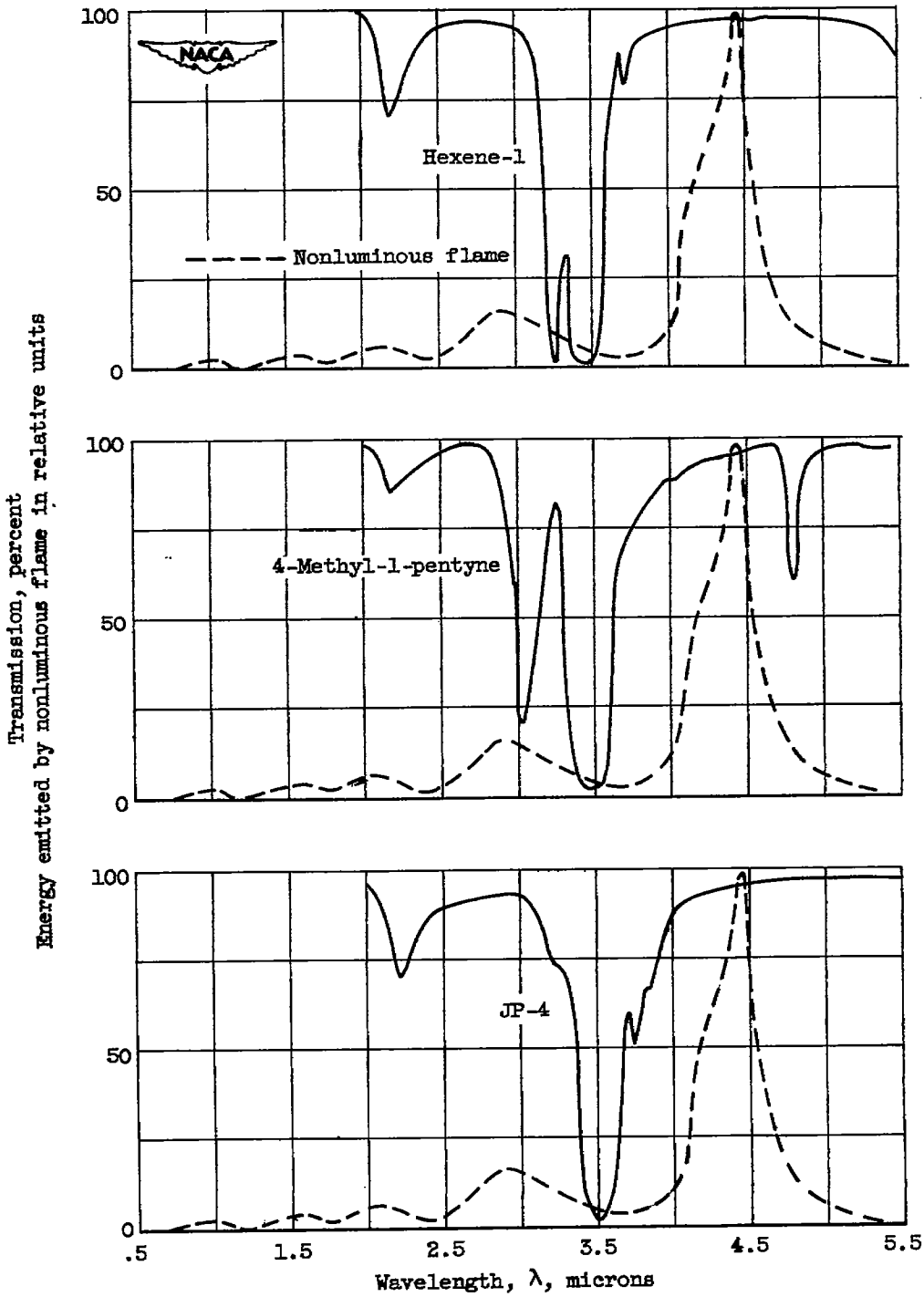

Figure 3. - Concluded. Transmission of six hydrocarbon fuels and emission of nonluminous propane-air flame as function of wavelength.

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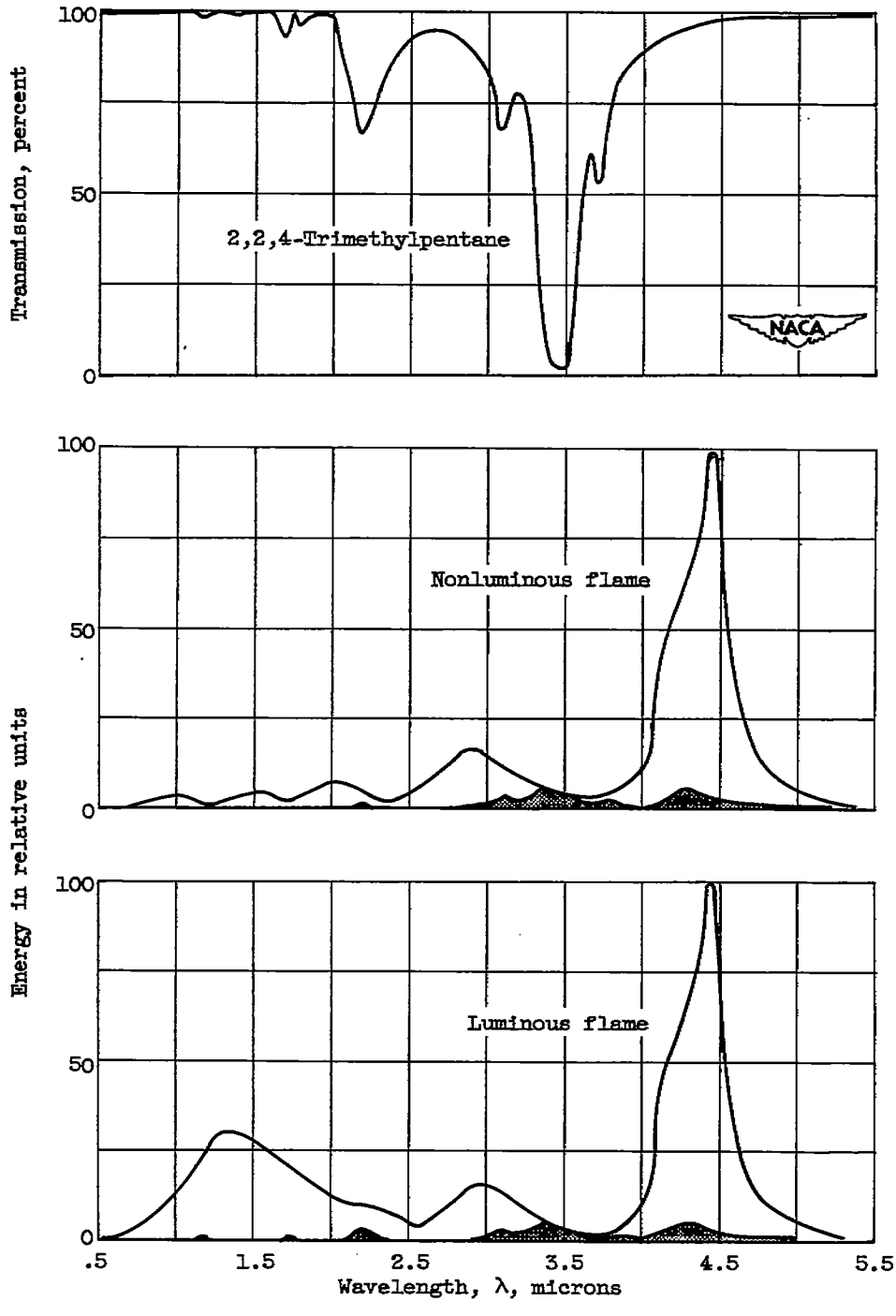

Figure 4. - Transmission of 2,2,4-trimethylpentane and its absorptive effect on emission of nonluminous and luminous flames. (Shaded areas represent fraction of total available radiant energy absorbed by 2,2,4-trimethylpentane.)

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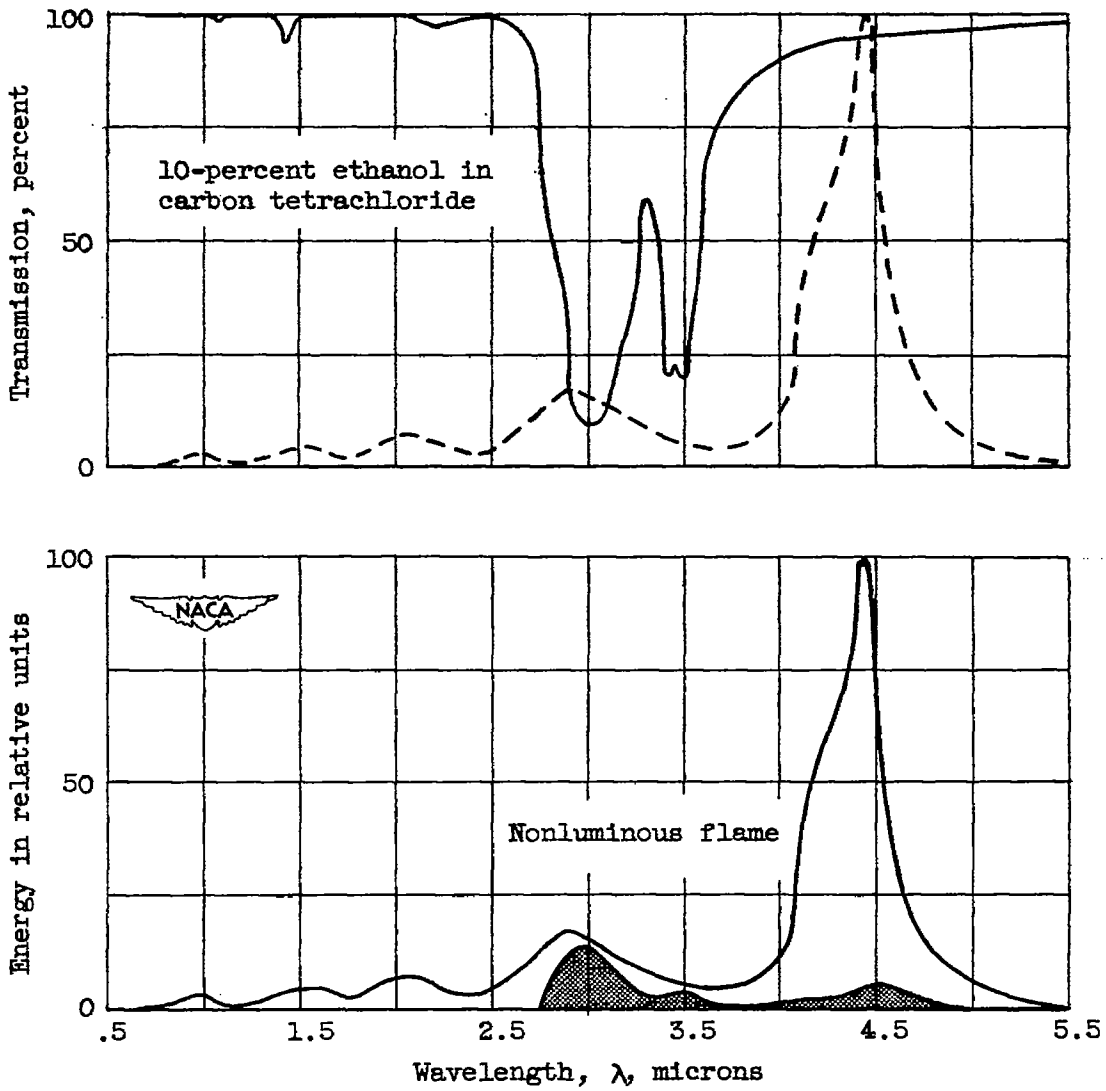

Figure 5. - Transmission of 10-percent solution of ethanol as function of wavelength and its absorptive effect on emission of nonluminous flame. (Shaded areas represent fraction of total available radiant energy absorbed by ethanol solution.)

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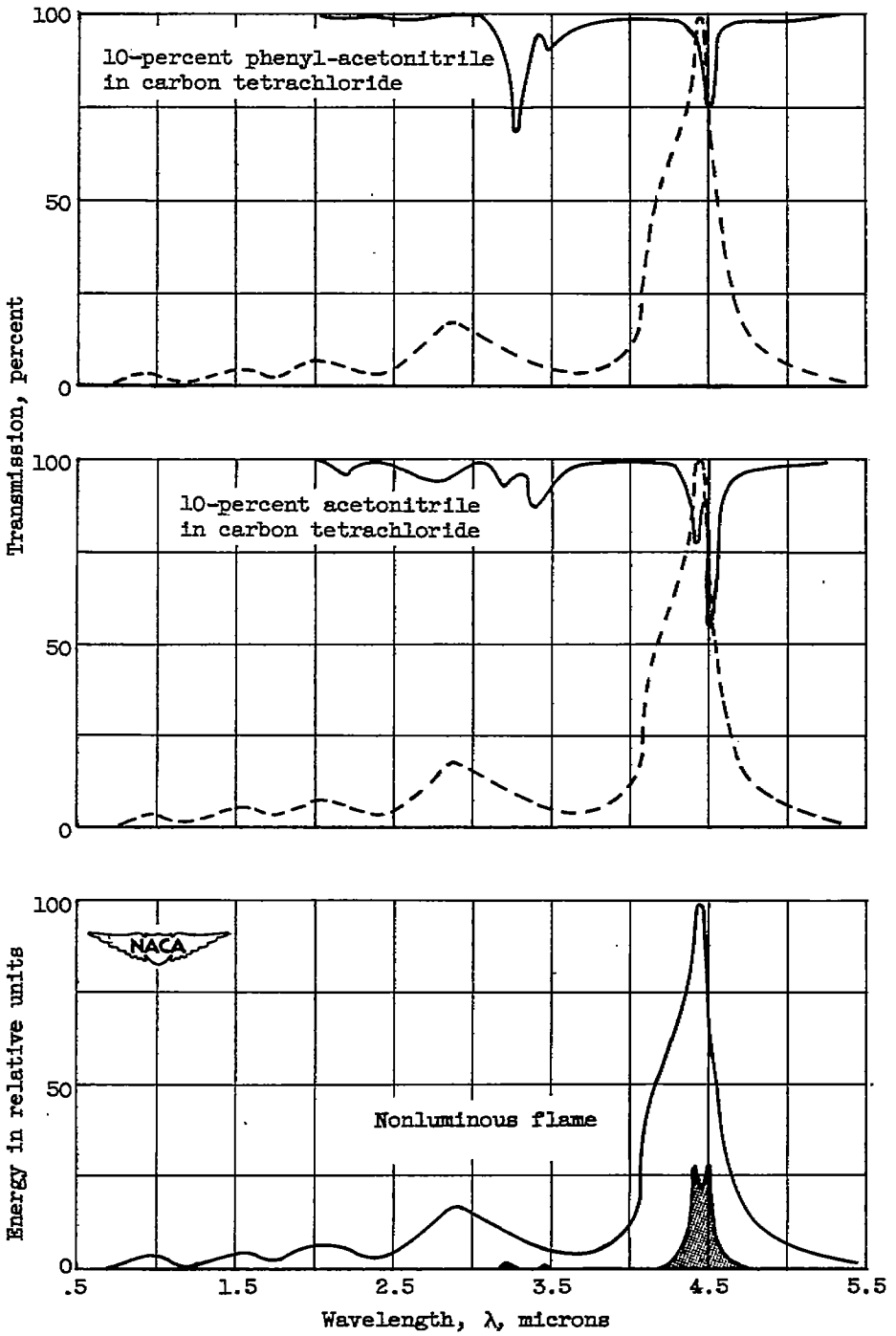

Figure 6. - Transmission of solutions of two nitriles and absorptive effect of acetonitrile on the energy radiated from a nonluminous flame. (Shaded areas represent fraction of total available radiant energy absorbed by acetonitrile.)

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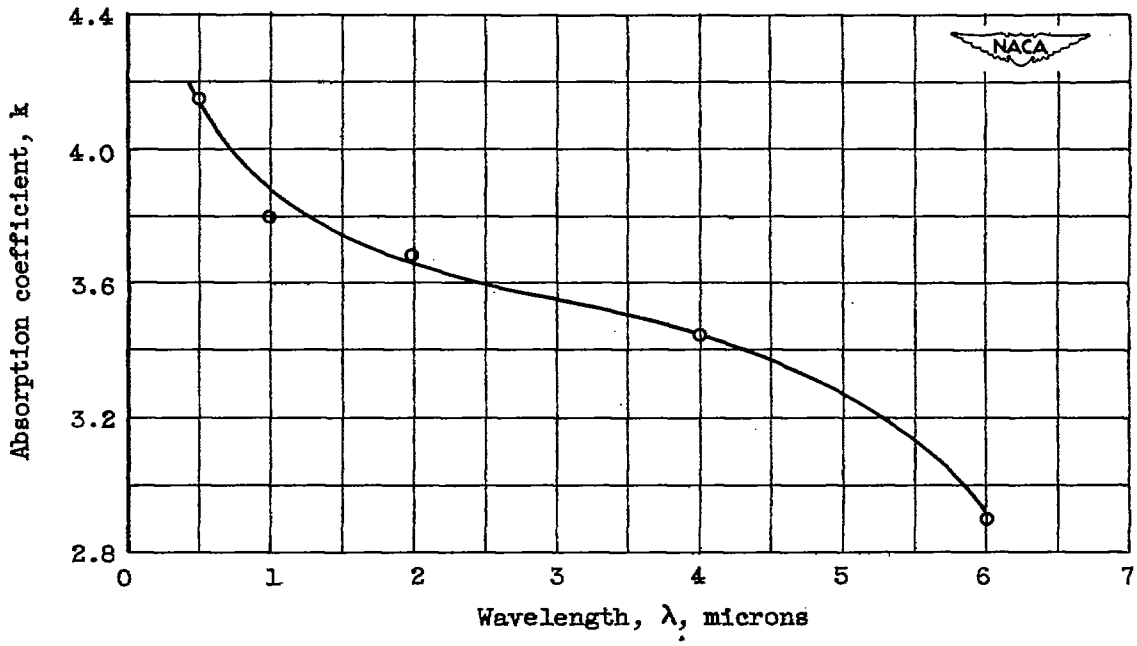

Figure 7. - Absorption coefficient of graphite in slurries as function of wavelength.

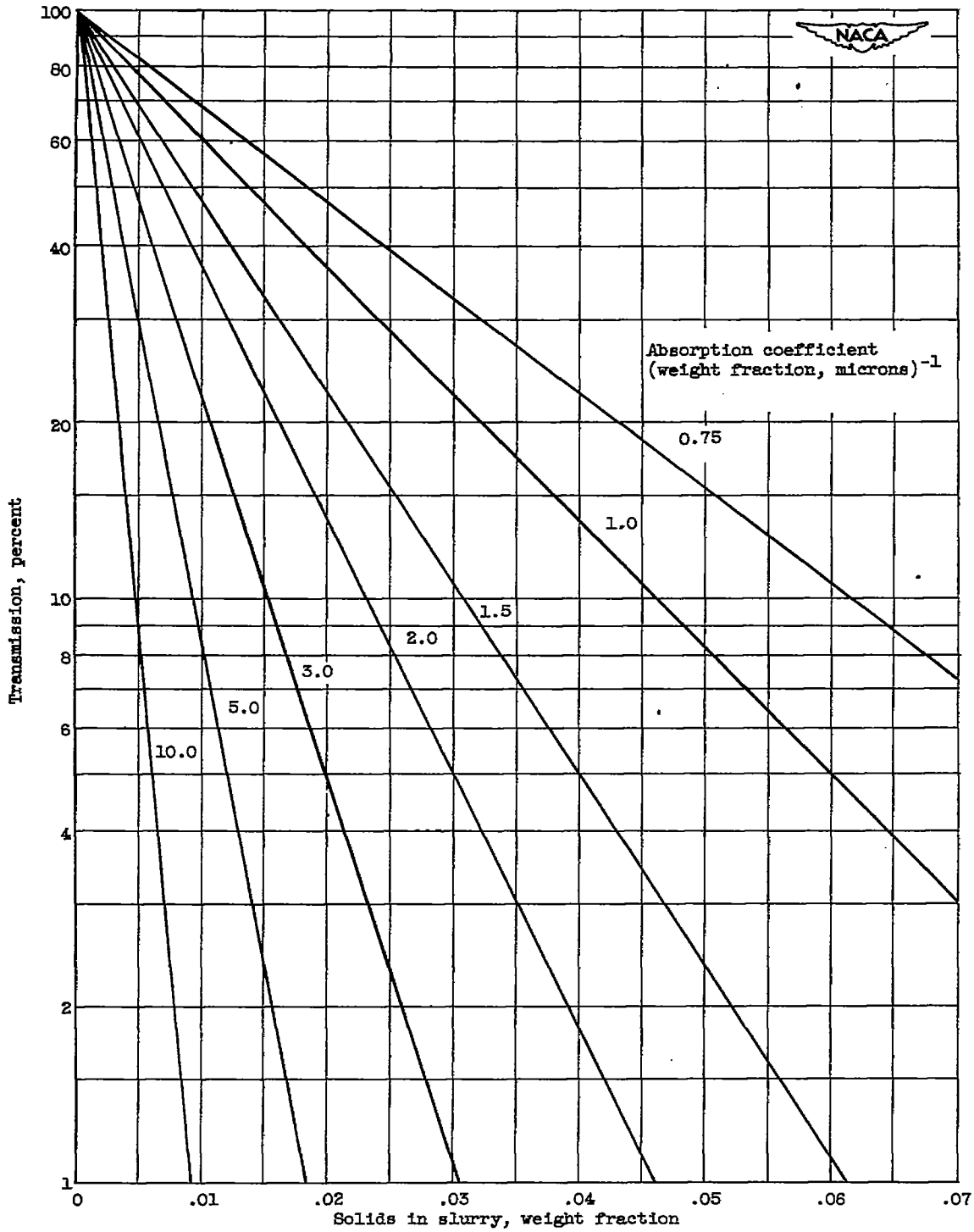

Figure 8. - Transmission of 50-micron-thick slurry film as function of concentration of slurry solids of varying absorption coefficient.

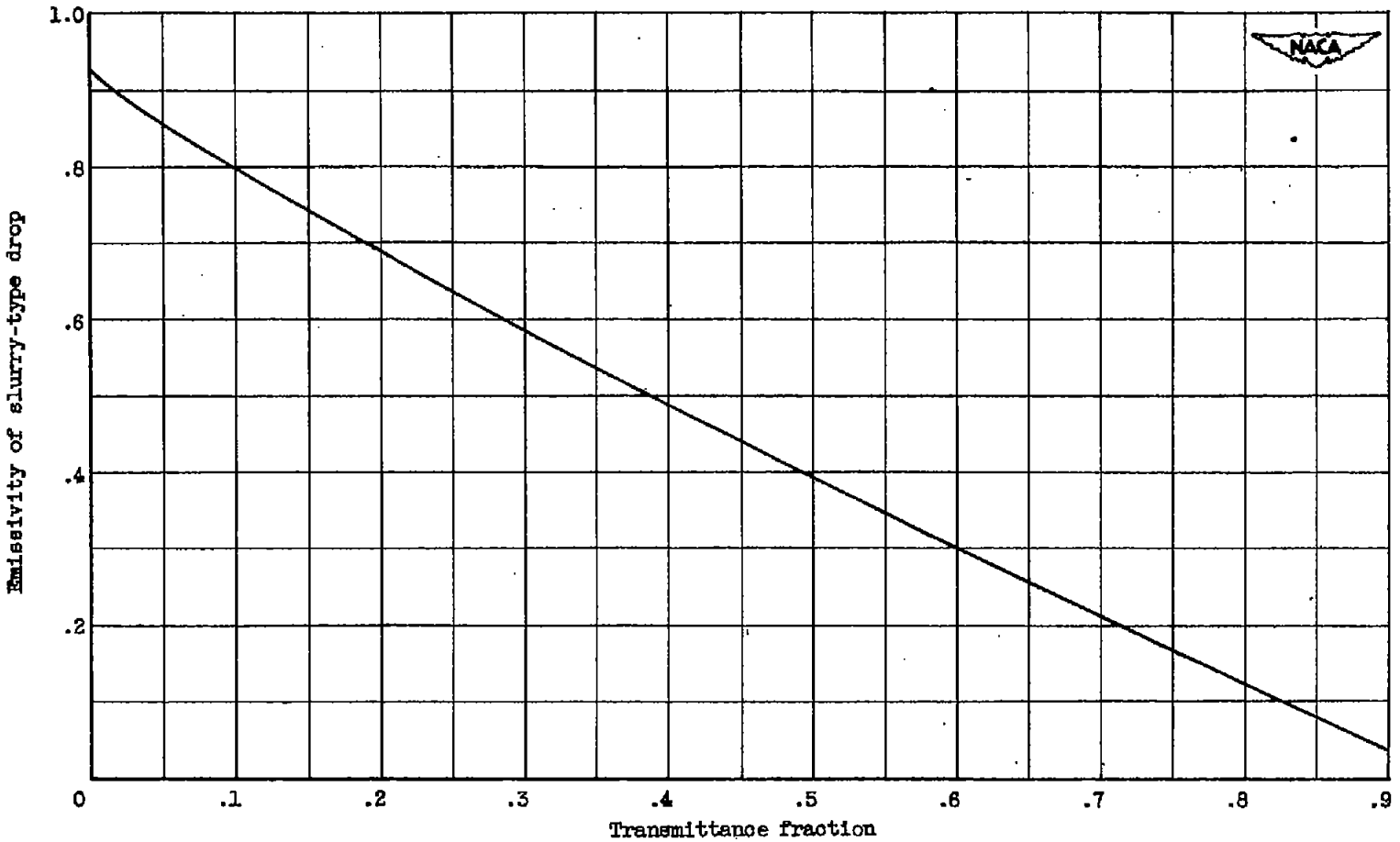

Figure 9. - Emissivity of slurry-type drop as function of transmittance of thin film of equal thickness and composition. Average refractive index μ, 1.4.

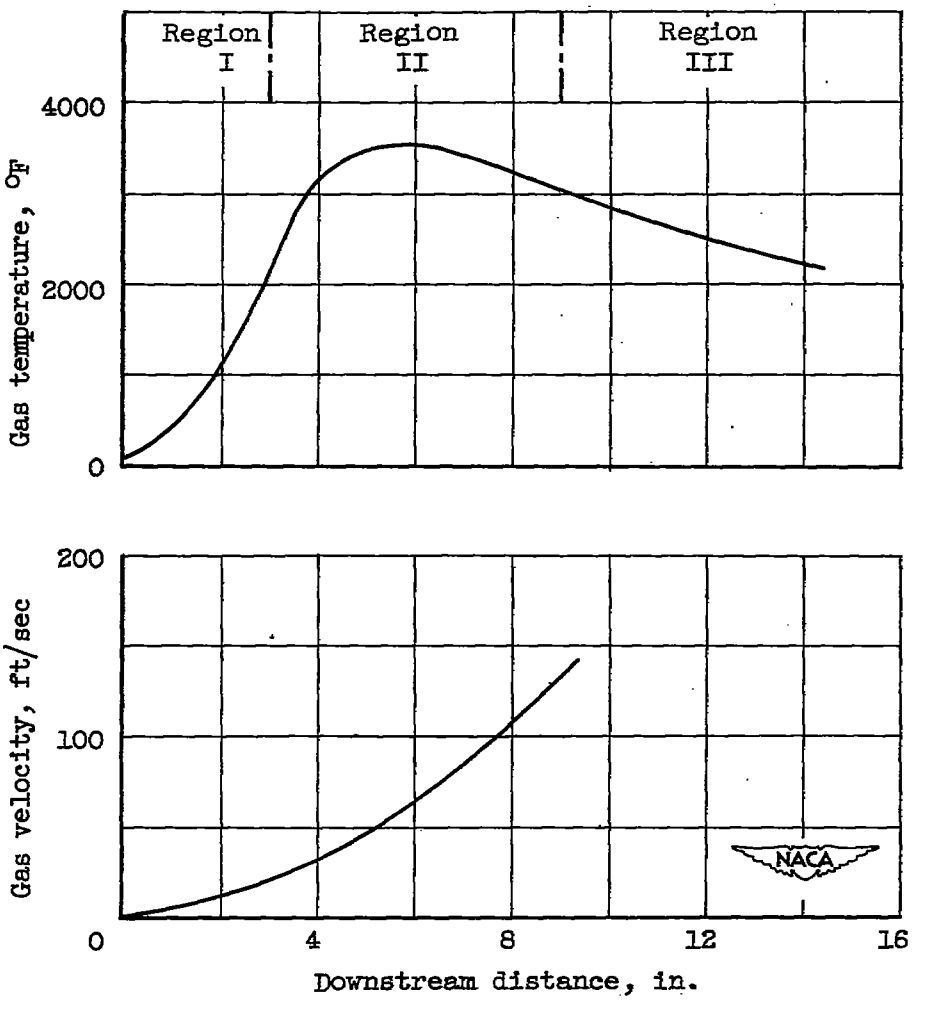

Figure 10. - Combustor regions, gas velocity, and temperature used in this analysis.

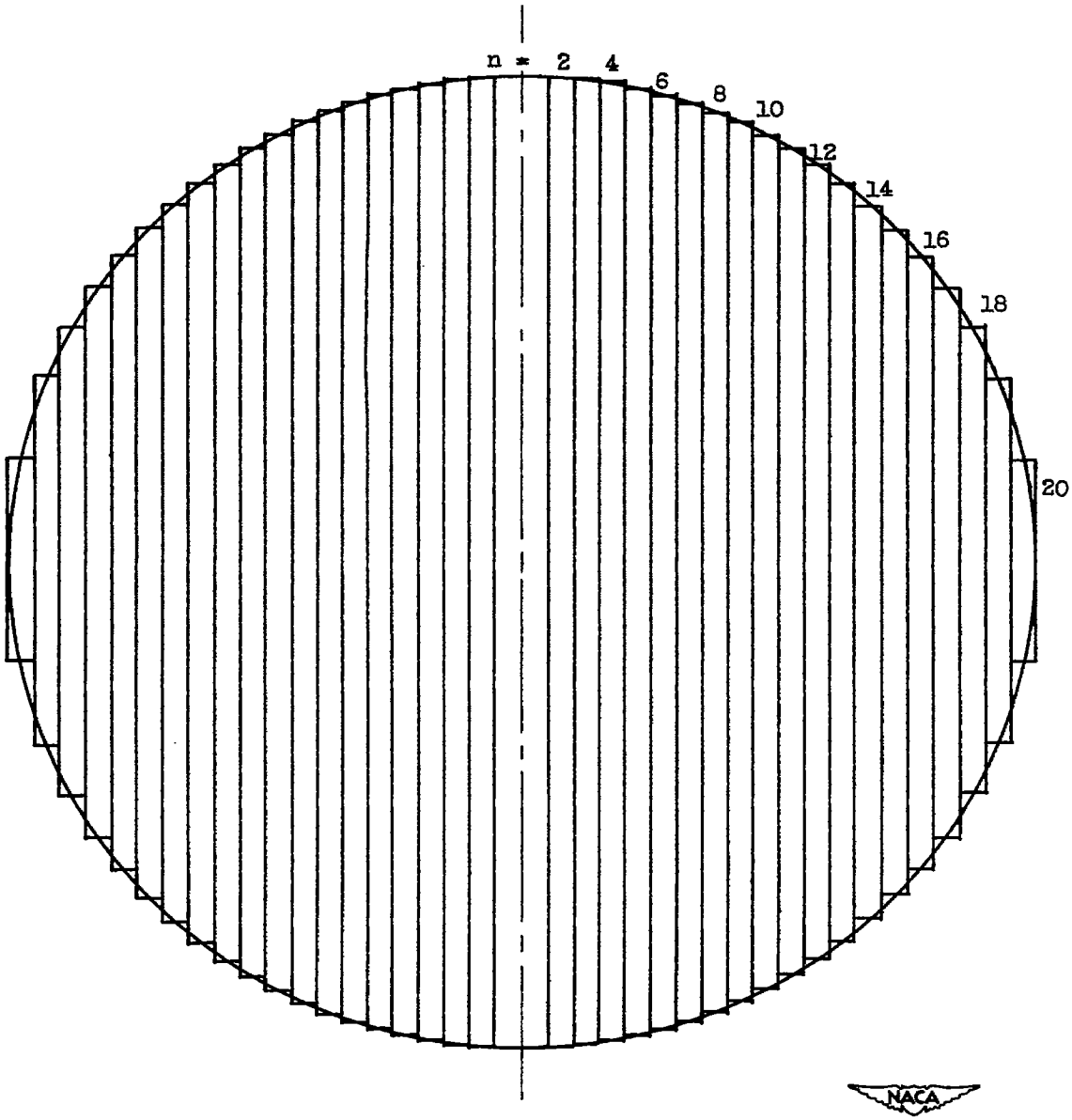

Figure 11. - Cross-sectional view of nonrefracting, nonreflecting spherical drop which is divided into 20 sections for calculation of emissivity properties.

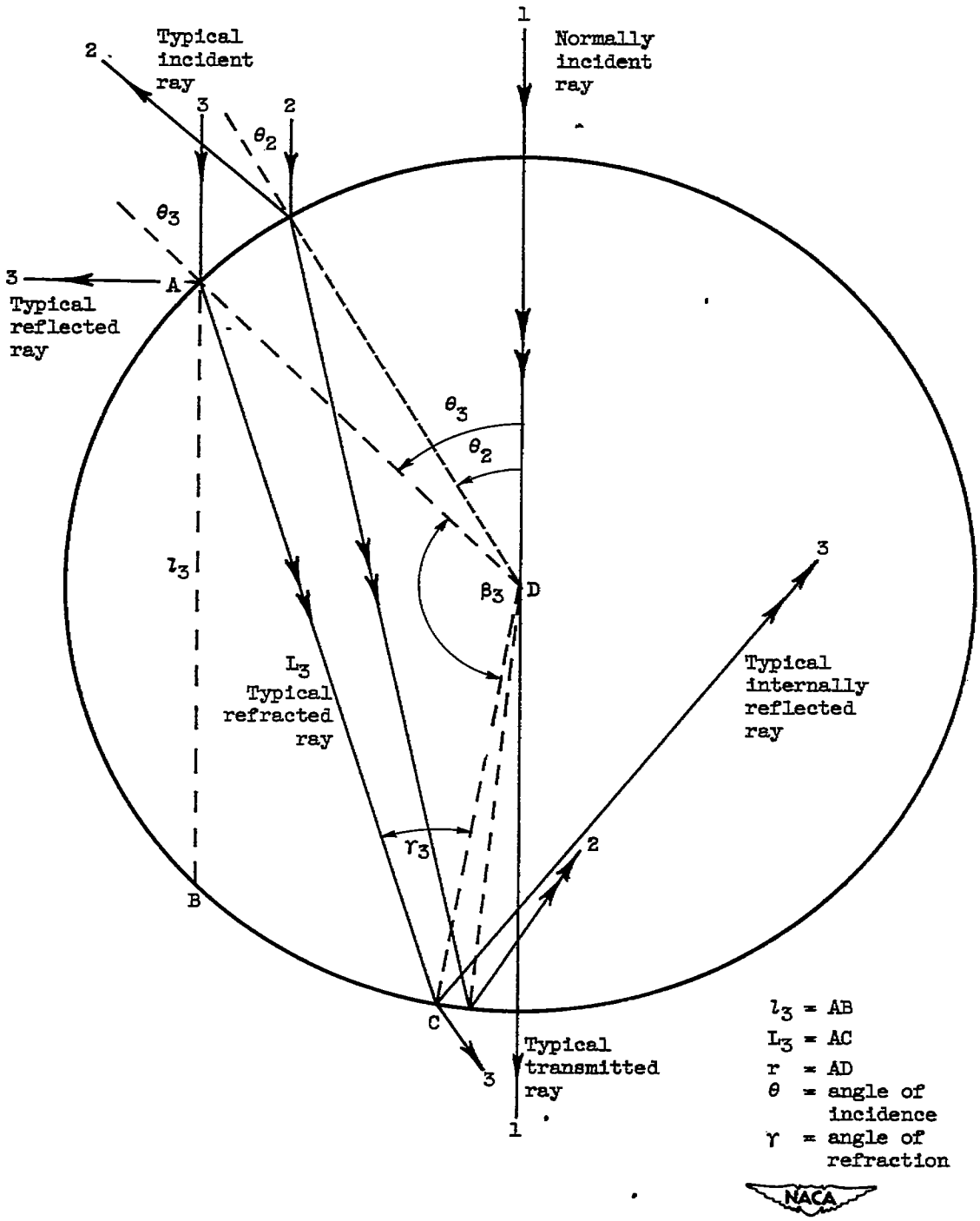

Figure 12. - Parallel radiation falling on slurry-type drop.

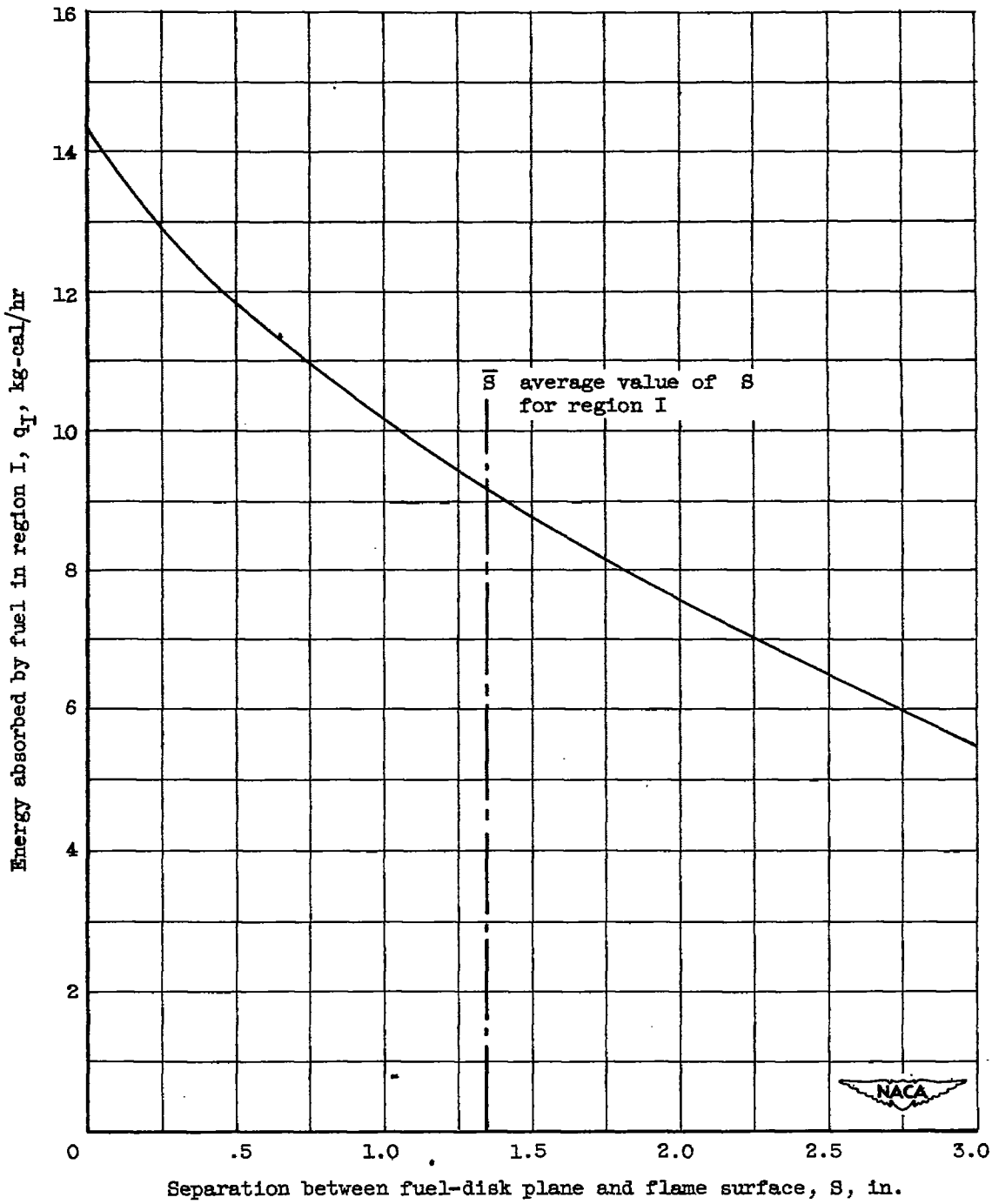

Figure 13. - Energy absorbed per hour by porous, partly transparent disk of fuel drops as function of distance from flame surface to plane of disk.

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