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A thermometer technique for the determination of emissivities of finishes.

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UNIVERSITY OF LOUISVILLE

A THERMOMETER TECHNIQUE FOR THE DETERMINATION OF EMISSIVITIES OF FINISHES

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of the Graduate School
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N. P. Shah

September 1949

A THERMOMETER TECHNIQUE
FOR THE DETERMINATION OF
EMISSIVITIES OF FINISHES

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September 1949

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ABSTRACT

Two thermometer techniques for the determination of emissivities of surface coatings are presented. One procedure involving the attainment of steady state heat transfer relations in coated thermometers placed through the wall of a duct at right angles to the direction of air flow was found to give consistent results. Another procedure based upon the rate of change of thermometer temperature was found to give consistent results only with excellent control of air conditions.

The emissivities of a variety of paints, varnishes, and lacquers were determined for the temperature range 90° F. to 140° F. using silver and black coatings for standardization. The results obtained by means of the static technique were more satisfactory.

INTRODUCTION

One of the complex problems of heat transmission is the evaluation of radiant-heat transmission or interchange between a gas and its bounding surface or between surfaces separated by a nonabsorbing medium. The temperature at which radiation accounts for a significant amount of the total heat transmission depends on such factors as the emissivity of the surface and the magnitude of the convection coefficient. Early methods appearing in the literature (2) for the determination of the emissivity of different materials were complicated and required costly equipment. The improvement and simplification of many processes involving radiation have been desirable, but as in the case of many other heat transmission problems, the lack of data has prevented a rational approach to its solution.

This study was undertaken to obtain emissivity data of different finishes under the conditions encountered at moderate temperatures. In addition, a relatively simple thermometer technique was to be investigated. Two methods, one a dynamic procedure and the other a static method, were considered for obtaining the emissivity data of different surfaces and materials. To verify the correctness of the methods, a standard surface of silver whose emissivity was well established, would be suitable standard for evaluating the technique. With the establishment of a suitable experimental procedure, the emissivities of a number of different colored finishes could be selected for investigation.

HISTORICAL

The word emissivity (2) comes from the Latin 'emittere' meaning to send out. In accord with that primary meaning an emissivity for a given material is a measure of the ability of a surface made of that material to send out radiant energy. Such an ability might be expressed in terms of the rate of emission per unit of surface area. Accordingly, there is some use of the word 'emissivity' in this sense. However, general usage of emissivity is as a ratio comparing the ability of a radiating material with that of a perfect emitter, a black body, at the same temperature.

In the interior of an opaque body of uniform temperature throughout, at distances from its surfaces yielding practically complete absorption for entering radiation, black body conditions are found. If the body is a black body, the rate of emission of radiant energy from its surface will correspond to the unhindered passage of radiant energy from such an interior. If the body is a non-black body, the rate of emission will be lessened because of the hindrance, in the way of reflection occurring at the surface. With these facts in mind, it is natural to express an emissivity for a non-black body as a ratio of the sending out ability for an opaque body composed of the non-black material to the corresponding ability for a black body at the same temperature.

In accord with the usage that an "ivity" ending shall denote a characteristic of a material, the term "emissivity" is limited to a comparision with a black body under conditions that the individual characteristics of bodies composed of the material under consideration are eliminated. Since the radiating characteristics of a body depend in part upon its opaqueness and the roughness of its surface, these features must be considered in forming an acceptable definition of emissivity. Ease of specification and of reproduction are the obvious reasons for requiring that the emissivities of materials shall refer to comparisions made with opaque specimens whose surfaces are polished. Accordingly, the emissivity of a material is defined as the ratio of a rate of emission of radiant energy by an opaque body with polished surface composed of that material as a consequence of its temperature only, to the corresponding rate for a black body at the same temperature.

Two other terms, namely emissive power and emission factor, have been and are still used to some extent to indicate what is now meant by emissivity. In accord with the usage that an "ance" ending shall denote a characteristic of a body or a portion of a body rather than of the material composing it, an emittance for a body at some constant temperature is defined as the ratio of emission of radiant energy by the body in consequence of its temperature only to the corresponding rate for a black body at the same temperature. The condition of the surface of a body, polished or not, and the condition as to opaqueness are immaterial.

There are various standpoints from which the radiating ability of a non-black body may be considered. The two most common are the total heating effects per unit area, taking account of all wave-lengths of radiation, and the spectral heating effects, taking account of only a very limited range of wave-lengths. Accordingly total and spectral emissivities are obtained. If the stand-point is one of visual effects rather than of heating effects produced by the radiation, a luminous or visible emissivity is obtained.

For each of the foregoing types of emissivity, at least two subdivisions are recognized: a normal, and a hemispherical emissivity. The need for this subdivision results from deviations from Lambert's cosine law (2) exhibited by the radiation from non-black bodies.

As the following work deals with thermal radiation only, a hemispherical total emissivity and a normal total emissivity only are to be considered. Thermal radiation means the quality and quantity of radiant energy emitted per unit time depending solely on the temperature of the given body, referred to merely as radiation rather than by the more descriptive term "thermal radiation".

A hemispherical total emissivity for the polished surface of an opaque portion of material at constant temperature is the ratio of its radiancy to that of black body material at the same temperature. The radiancy of a source of radiation is its rate of emission of radiant energy per unit of area.

A normal total emissivity for the polished surface of an opaque portion of material at constant temperature is the ratio of its normal radiancy to that of black body material at the same temperature.

A number of different procedures are available for experimentally determining emissivities (2) involving to a great extent rather special and carefully calibrated apparatus.

THEORETICAL

In the derivations that follow, the apparatus is assumed to consist of suitable mercury thermometers in an air stream at right angles to the flow within an enclosing pipe. Further it is assumed that (a) all heat effects are sensible, i.e. latent heats of reaction are excluded; (b) the temperature throughout the stem of the thermometer and along the cross-section of the duct is essentially uniform; (c) the end area of the thermometer is small compared to the surface area of the immersed cylindrical portion of the thermometer; (d) the intensity of radiation is uniform, a difficult condition to obtain over large areas; and (e) the rate of heat flow between gas and pyrometer by the mechanism of gas radiation, and the heat conducted from the pyrometer to the walls confining the gas stream are negligible.

In the equations developed for the evaluation of emissivities of surface coatings, two different mercury-glass thermometer techniques were employed. In the first procedure steady state conditions of heat transfer were not obtained, and the process was called a dynamic technique. In the second procedure steady state conditions of heat transfer were realized and the process was termed a static technique.

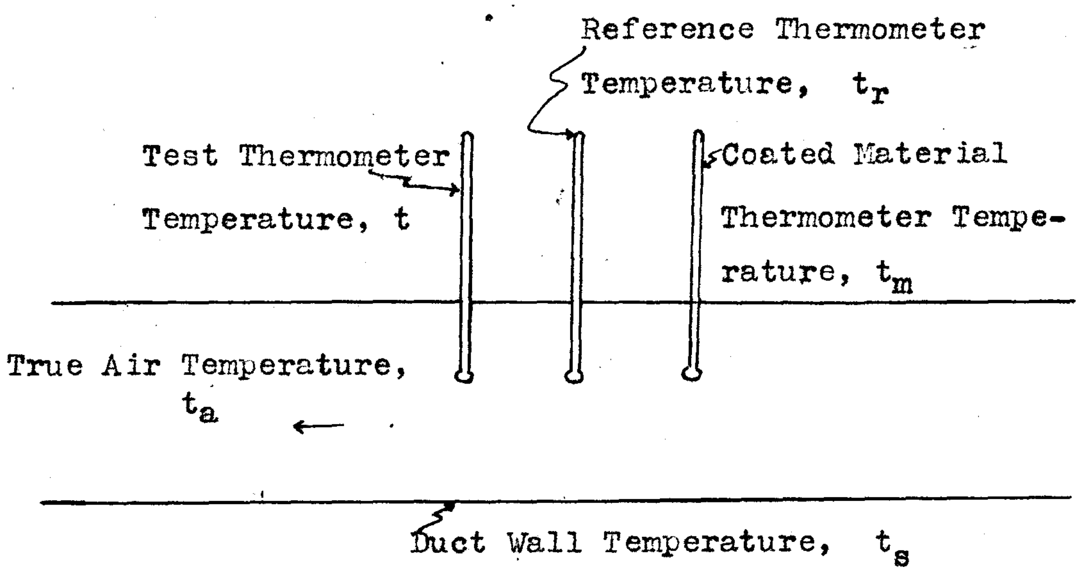

Figure 1

Diagrammatic Sketch of Apparatus
Showing Temperatures Used in Calculations

DYNAMIC TECHNIQUE

When a test thermometer, initially at some temperature above or below an air stream temperature, is inserted at right angles to the flow through a duct wall as shown in Figure 1, the quantity of heat dQ transferred to or from the immersed part of the test thermometer in time $d\theta$, can be expressed by the following equation:

$$dQ = C \rho V \, dt \tag{1}$$

where C = Specific heat of the immersed part of the test thermometer, B.t.u./(lb.)(°F.)

ρ = Density of the immersed part of the test thermometer, lb./cu.ft.

V = Volume of the immersed part of the test thermometer, cu.ft.

dt = Test thermometer temperature change during the interval $d\theta$, degrees F.

This quantity of heat is carried from or to the thermometer by convection and radiation, can be expressed mathematically:

$$dQ/d\theta = h_c A(t_a - t) - h_r A(t - t_s) \tag{2}$$

where A = Heat transfer area of the immersed part of the test thermometer, sq.ft.

h_c = Coefficient of heat transfer by convection for test thermometer, B.t.u. per hour per sq.ft. per degree F.

h_r = Coefficient of heat transfer by radiation for test thermometer, B.t.u. per hour per sq.ft. per degree F.

t_s = Temperature of the surface in sight of the thermometer, degree F.

t_a = True temperature of air, degree F.

t = Temperature of the test thermometer.

Using the relation $(t - t_s) = (t_a - t_s) - (t_a - t)$, and combining equations (1) and (2), the following relation is obtained:

$$\begin{aligned} dQ &= C \rho V \, dt \\ &= (h_c + h_r) A (t_a - t) - h_r A (t_a - t_s) \quad d\Theta \end{aligned} \qquad (3)$$

Rearrangement of equation (3) results in

$$d\Theta = \left[\frac{C \rho V}{A \, (h_c + h_r)} \right] \left[\frac{dt}{(t_a - t) - \dfrac{h_r (t_a - t_s)}{h_c + h_r}} \right] \qquad (4)$$

Integration of equation (4) between the limits t_1 and t_2, and corresponding values of Θ_1 and Θ_2 results in

$$\Delta\Theta = \frac{C \rho V}{A (h_c + h_r)} \quad \ln \left[(t_a - t) - \frac{(t_a - t_s)}{1 + h_r / h_c} \right]_{t_1}^{t_2} \qquad (5)$$

The heat gained by convection in case of a static reference thermometer, identical in every respect to the previously mentioned test thermometer, must equal the heat lost by radiation if the initial assumptions are valid and

$$q_c = q_r \quad \text{or} \quad h'_c A(t_a - t_r) = h'_r A(t_r - t_s)$$

where q_c = Rate of heat flow between gas and thermometer, B.t.u./hr.

q_r = Sum of the various terms representing the rate of the radiant heat interchange between the thermometer and the various surfaces that it "sees", B.t.u./hr.

h'_c = Coefficient of heat transfer by convection for reference thermometer, B.t.u. per hour per sq.ft. per degree F.

h'_r = Coefficient of heat transfer by radiation for reference thermometer, B.t.u. per hour per sq.ft. per degree F.

and $(t_r - t_s) = (t_a - t_s) - (t_a - t_r)$

Therefore,
$$(t_a - t_r) = \left[\frac{h'_r}{h'_c + h'_r}\right](t_a - t_s) \qquad (6)$$

Since the test thermometer and the reference thermometer are identical in every respect, $h_c = h'_c$ and $h_r = h'_r$

Substitution of the value of $(t_a - t_r)$ from equation (6) in equation (5) yields

$$\Delta\theta = \frac{C \rho V}{A(h_c + h_r)} \ln \frac{t_1 - t_r}{t_2 - t_r} \tag{7}$$

For the case in which the test thermometer and the coated material thermometer are identical in every respect, for the same cooling time, equation (7) results in

$$\Delta\theta = \frac{C_1 \rho_1 V_1}{A_1(h_{c1} + h_{r1})} \ln \frac{t_1' - t_m'}{t_2' - t_m'} \tag{8}$$

where A_1 = Heat transfer area of the immersed part of the coated material thermometer, sq.ft.

V_1 = Volume of the immersed part of the coated material thermometer, cu.ft.

ρ_1 = Density of the immersed part of the coated material thermometer, lb./cu.ft.

h_{c1} = Coefficient of heat transfer by convection for the coated material thermometer, B.t.u. per hour per sq.ft. per degree F.

h_{r1} = Coefficient of heat transfer by radiation for the coated material thermometer, B.t.u. per hour per sq.ft. per degree F.

t_1 = Initial temperature of test thermometer, identical with reference thermometer, $^{\circ}$F.

t_2 = Final temperature of test thermometer, identical with reference thermometer, $^{\circ}$F.

t'_1 = Initial temperature of test thermometer, identical with coated material thermometer, ° F.

t'_2 = Final temperature of test thermometer, identical with coated material thermometer, ° F.

t_r = Temperature indicated by the reference thermometer, ° F.

t_m = Temperature indicated by the coated material thermometer, ° F.

An inspection of equations (7) and (8) reveals that all the terms may be evaluated experimentally with the exception of the radiation heat transfer coefficient. The dimensions and properties of the thermometers will permit the evaluation of C, C_1, ρ, ρ_1, V, V_1, A, and A_1. The cooling time for the test thermometer is the value of $\Delta\theta$.

From a knowledge of the air velocity and properties as well as dimensions of the thermometers, h_c and h'_c may be evaluated as follows:

From the equations for single cylinders (3) with air flowing at right angles to the cylinder:

$$h_c D_o/k_f = 0.32 + 0.43\,(D_o G/u_f)^{0.52} \tag{9}$$

for a Reynolds Number range from 0.1 to 1,000

For single cylinders (3) in the range of D_oG/u_f from 1,000 to 50,000 the dimensionless equation (10) should be used:

$$h_cD_o/k_f = 0.26 \quad (D_oG/u_f)^{0.6} \quad (C_pu_f/k_f)^{0.3} \tag{10}$$

For air and diatomic gases (C_pu_f/k_f of 0.74), this reduces to

$$h_cD_o/k_f = 0.24 \quad (D_oG/u_f)^{0.6} \tag{11}$$

A plot of Reynolds Number vs h_c or air velocity vs h_c can be prepared, and the value of h_c read directly from a plot as shown in Figure 2.

Then h_r and h_r' can be evaluated by solving equations (7) and (8). The heat transferred by radiation is given by the equation

$$\begin{aligned} q_r &= h_r A (t_r - t_s) \\ &= 0.173 \quad F_A \quad F_E \quad \left[(T_r/100)^4 - (T_s/100)^4 \right] \end{aligned} \tag{12}$$

where F_A = A geometric factor (3), in this case the heat transfer area of the thermometer, A sq.ft.

F_E = An emissivity factor, in this case that of the thermometer.

T_r = Absolute temperature as indicated by the reference thermometer, ° R.

T_s = Absolute temperature of the surface in sight of the thermometer, °R.

For this case equation (12) becomes

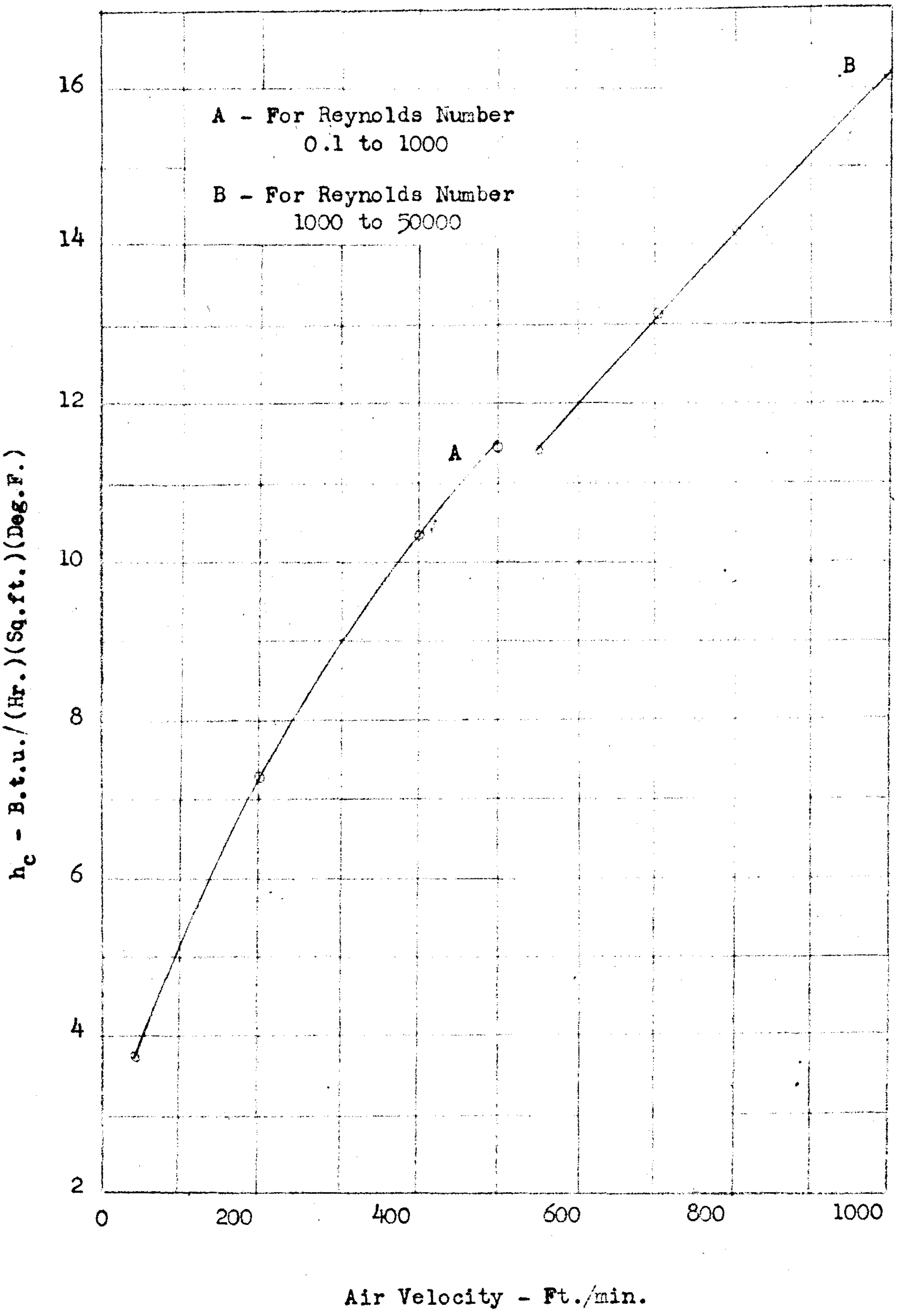

FIG. 2 - COEFFICIENT OF HEAT TRANSFER BY CONVECTION

$$h_r A \, (t_r - t_s) = 0.173 \, A \, \epsilon_r \left[(T_r/100)^4 - (T_s/100)^4 \right] \qquad (13)$$

and ϵ_m may be computed for the coated material thermometer by substituting h_{r1} for h_r , T_m for T_r , t_m for t_r and ϵ_m for ϵ_r in equation (13), where the subscript m refers to the coated material thermometer.

STATIC TECHNIQUE

In the derivation of the theoretical relations for the static procedure, essentially the same apparatus as shown in the diagrammatic sketch of Figure 1 is employed. The thermometer technique is varied somewhat in that all thermometers are allowed to attain constant readings in the air stream.

For using the dynamic procedure the true temperature of the air stream was not required, but in the static procedure the true air temperature must be evaluated. To compute the true temperature of a gas at moderate temperatures from the reading of a thermometer placed in a gas stream and in sight of surrounding walls that may be at temperatures different from that of the gas, an approximate heat balance for the thermometer may be used:

$$q_c = q_r$$

where q_c = Rate of heat flow between gas and thermometer by convection, B.t.u./hr.

q_r = Sum of the various terms representing the rate of radiant heat interchange between the thermometer and the various surfaces that it "sees", evaluated by equation (12) B.t.u. per hour.

In the simple case of an air stream having a true temperature t_a and flowing through a duct of a diameter large compared to that of a reference thermometer at temperature t_r , the inner surfaces of the walls having approximately constant temperature t_s , a heat balance on the thermometer gives the equation

$$q_c = q_r \quad \text{or} \quad h_c A (t_a - t_r) = h_r A (t_r - t_s) \tag{14}$$

where the air temperature t_a is above that of the thermometer t_r and the surface of the duct t_s .

Equation (14) may be written in the form

$$h_c A(t_a - t_r) = 0.173 \, \epsilon \, A \left[(T_r/100)^4 - (T_s/100)^4 \right] \tag{15}$$

also, equation (14) may be rearranged to

$$(t_a - t_r) = (h_r/h_c)\,(t_r - t_s) \tag{16}$$

Similarly for the coated material thermometer equation (16) may be applied:

$$(t_a - t_m) = (h_{r1}/h_{c1})\,(t_m - t_s) \tag{17}$$

Under the same conditions $h_c = h_{c1}$, for the thermometers of the same size equation (17) becomes

$$(t_a - t_m) = (h_{r1}/h_c) (t_m - t_s) \tag{18}$$

The value of h_c can be determined from the air velocity, thermometer dimensions, and air properties by means of equations (9) and (11) Or read directly from the air velocity vs. h_c chart (Fig. 2). The value of h_r can be obtained from equation (13). Knowing all other terms, t_a can be evaluated from equation (16). Substituting the value of t_a in equation (18), h_{r1} is obtained. Then using the value of h_{r1} and substituting h_{r1} for h_r, T_m for T_r, t_m for t_r and σ_m for σ_r in equation (13), the emissivity of the material in question can be determined.

EXPERIMENTAL

In this study one object was the development of a satisfactory thermometer technique for the determination of emissivities of surface coatings. Another object was the evaluation of the emissivities of a variety of surface coatings using the thermometer technique. To these ends experiments were carried out using the two different thermometer techniques to select the more satisfactory procedure.

APPARATUS

The apparatus used in this research was essentially a long duct 8 inches in diameter through which heated air was passed. Suitable openings permitted the placement of thermometers in the air stream. The apparatus is shown diagrammatically in Figure 1 and in more pictorial representation in Figure 3.

Two different heat sources, one a compartment dryer and the other an electrical resistance heater, were used for heating the air. In the compartment dryer, air was drawn through a fan and then over steam tubes. Steam was regulated by means of a reducing valve in the steam line and by a manually operated valve on the dryer, which in turn controlled the flow of steam and subsequently the temperature of the air. Finally, the heated air was passed through the exhaust duct, the test apparatus of this study.

When electrical heaters were used, air was drawn directly over heated resistance wire, the blower, and then passed

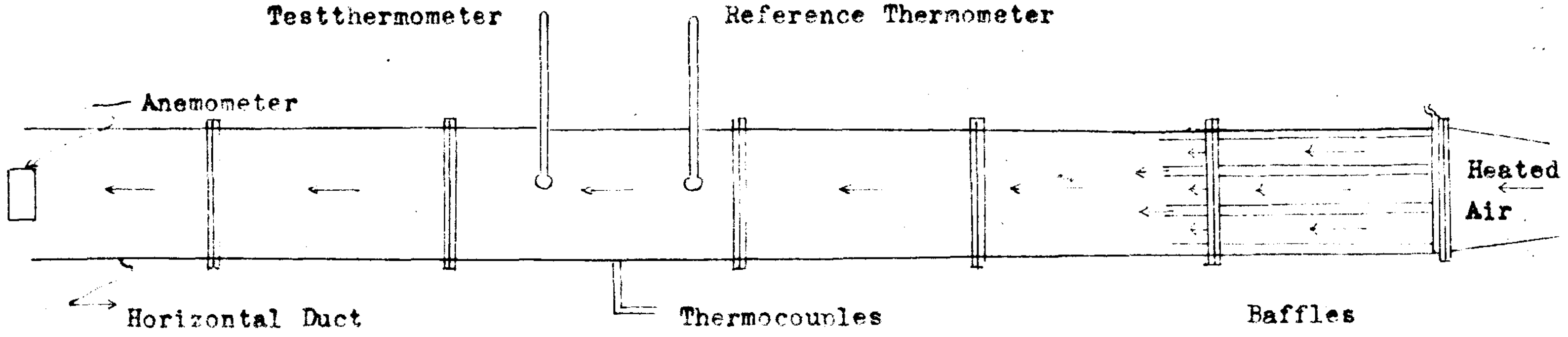

FIG. 3 - SKETCH OF APPARATUS

through a duct of the same dimensions as above.

In order to regulate air velocity, two alternately slotted discs of the same cross-section as the duct, were installed at right angles to the flow of air. One disc was permanently fixed, and the other was free to rotate for controlling the air velocity.

A number of tubular straighteners were installed as shown in Figure 4 to obtain a uniform temperature distribution throughout the cross-section of the duct. Three insertions (Fig. 5), one for thermocouples to measure the wall temperature of the duct, and the other two for thermometers, were made at one station in the duct about 90 degrees from each other and at a sufficient distance from the exit of the duct and from the baffles to give uniform temperatures and black body conditions.

A potentiometer was used to measure the wall temperature of the duct as indicated by copper-constantan thermocouples. Two mercury-glass thermometers, calibrated to one tenth degree Centigrade, were used as reference and material thermometers.

PROCEDURES

In order to test the theory, it was necessary to have values of emissivities of the standard selected surfaces, the coefficients of heat transfer, physical properties (4) of the finish under examination, and temperature-time data.

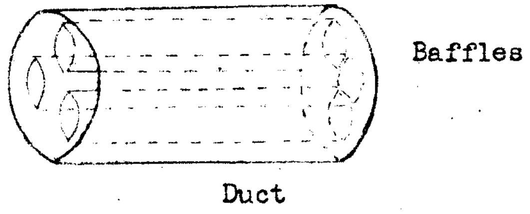

FIG. 4

Arrangement of Baffles

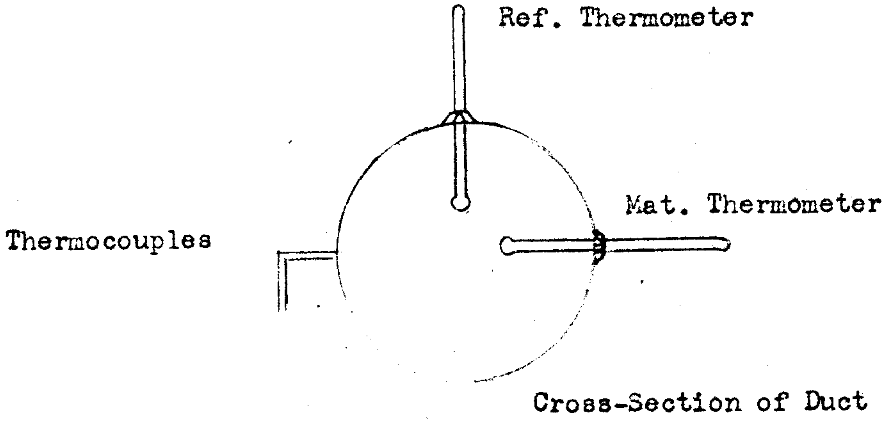

FIG. 5

Arrangement of Thermometers

For a very accurate recording of the true temperature of air by means of the reference thermometer, the surface of the reference thermometer should have low radiation characteristics. In other words, this surface should have a very low emissivity, which is true for a well polished silver surface. To obtain low emissivities the test and the reference thermometers were coated with silver by Brashear's method (5). The material thermometer was coated with the different finishes by means of a camel's hair brush, so that the final diameters of all the thermometers remained very nearly the same.

As the temperature distribution along the cross-section of the duct was found to be non-uniform, three points at equal distances from the insertions through the wall of the duct were selected, and a correction factor was obtained for each point; and each thermometer reading was corrected accordingly. This procedure in turn fixed a constant and equal length of immersion for all thermometers through the openings. However, a constant and equal surface area for all thermometers was desirable to minimize the calculations involved in determining the final value of emissivity.

The velocity of air was measured at different points along the cross-section of the duct by means of an anemometer, and the final value was determined by averaging all readings. Knowing the diameters and heat transfer areas of the thermometers, the heat transfer coefficient was computed by means of equations (9) and (11).

TESTS BY THE DYNAMIC TECHNIQUE

The air was passed over the steam or the electrical coils and adjusted to the desired air velocity and air temperature. The reference and the coated material thermometers were installed in the air stream through openings A and B of Fig. 5 where they were left for a sufficient period to obtain an accurate and steady temperature reading. The test thermometer was then placed in a beaker of hot water so that it registered some temperature considerably above the temperature of the air stream. It was removed from the hot water, wiped dry, and placed in the air current several inches from the reference thermometer in such fashion that the axis of the bulb was at right angles to the flow of the air. The time required for the temperature indicated by the test thermometer to fall some previously selected number of degrees was recorded. This time, and the temperature readings of the test, the material, and the reference thermometers along with the wall temperature of the duct were recorded. The air velocity was measured by means of an anemometer; and the final value of the emissivity of the material on the material thermometer was computed by equations (8), (11) and (13).

TESTS BY THE STATIC TECHNIQUE

In the static method, all steps were followed exactly in the same manner as above; however, the changing temperature readings and time intervals were not required. In other words, the temperature readings of the reference and the material thermometers, the temperature of the wall of the duct, and the air velocity were recorded. The value of the emissivity was computed by equations (9), (11), (15), (16) and (18).

COATINGS

For reference purposes a silver coating was applied to one of the thermometers used in these experiments. An additional reference coating lamp-black also was used. Six differently pigmented paints were used as experimental coatings. Compositions of these paints are given in the Appendix.

RESULTS

Although the dynamic thermometer procedure was used in a number of emissivity determinations, the extreme care necessary in adjusting air conditions and temperatures makes this procedure more difficult to use and, in general, less satisfactory than the static procedure. In Table I are shown typical data and emissivity values obtained using the dynamic technique.

In Table II are itemized the average experimental values obtained using the static technique. The complete data for the coatings are presented in Table III in the Appendix.

Emissivity values were found to vary from 0.375 for yellow paints to 0.954 for a mercury in glass thermometer or lamp black coating.

TABLE I Experimental Readings by Dynamic Technique

Run No.	t_m deg.F	t_s deg.F	t_1 deg.F	t_2 deg.F	time secs.	velocity ft/min	emissivity
Material: Silver							
1	132.35	118.00	149.00	140.00	26.30	990	0.0203
2	132.80	118.00	149.00	140.00	27.40	990	0.0203
3	133.34	119.00	149.00	140.00	28.70	990	0.0201
4	134.22	119.00	158.00	149.00	15.95	990	0.0201
Material: Glass-Mercury Thermometer							
1	134.60	122.00	158.00	149.00	15.00	1025	0.9380
2	135.14	122.00	158.00	149.00	15.15	1025	0.9490
3	134.96	122.00	158.00	149.00	15.20	1025	0.9480
Material: Lamp-Black							
1	136.58	123.00	158.00	149.00	17.50	925	0.9540
2	136.76	123.00	158.00	149.00	17.80	925	0.9550
3	136.94	123.00	158.00	149.00	17.40	925	0.9540
4	137.12	123.00	158.00	149.00	17.95	925	0.9560

All other data necessary to compute emissivities of different finishes and materials are presented in the Sample Calculations of this Thesis.

TABLE II Average Experimental Values of Emissivities of Different Finishes by Static Method for the Temperature Range 90°F. to 140°F.

Symbol	Finish	Emissivity
-	Glass-Mercury Thermometer	0.954
-	Lamp-Black	0.954
Y	Yellow	0.375
O	Orange	0.855
R	Red	0.815
G	Green	0.779
PB	Phthalocyanine	0.934
MB	Milori Blue	0.825

DISCUSSION

Both thermometer techniques for the determination of emissivities of different materials were based on the consideration that the rate of transfer of energy by radiation between two surfaces was a function of the normal total emissivities. Hence, it was essential that experimental readings be obtained with the thermometers sensitive enough to indicate the radiant energy variations realized with the various coating materials.

One of the favorable features of the dynamic thermometer technique for the evaluation of emissivities of surface coatings was that no reference coatings were required. The technique may be employed merely using two thermometers in an air stream of known velocity. In addition, the temperature of the surface in sight of the thermometers was required although an accurate value of the true air temperature was unnecessary. The procedure was satisfactory when air stream irregularities were at a minimum. However, when velocity and temperature fluctuations were present, the procedure was unreliable.

When the static procedure was used, although a widely fluctuating air stream was undesirable, minor variations could be tolerated. However, with this procedure a reference coating was necessary, and all results in effect were compared with the emissivity value of the reference coating.

In addition, it was necessary to evaluate the true temperature of the air stream. Nevertheless, the static procedure was found to givethe more consistant results primarily because slight variations in the air stream could be tolerated.

With reasonable precautions and the relatively simple equipment required for these procedures it was felt that quite accurate emissivity values could be established for non-black body coating materials.

SUMMARY AND CONCLUSIONS

As a result of this study of thermometer techniques in the determination of emissivities of surface coatings several conclusions were obtained. In general, it was found that the static technique gave the more satisfactory results primarily because of the tolerence of minor air stream fluctuations. Nevertheless, the dynamic technique gave satisfactory results when a sufficiently uniform air stream was obtainable.

For non-transparent surface coatings the thermometer technique for evaluating emissivities were considered sufficiently accurate for most engineering calculations requiring information of this nature.

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APPENDIX

LIST OF SYMBOLS

A	Heat transfer area of the immersed part of the reference thermometer, sq.ft.
A_1	Heat transfer area of the immersed part of the coated material thermometer, sq.ft.
C	Specific heat of the immersed part of the reference thermometer, B.t.u./(lb.)(deg.F.)
C_1	Specific heat of the immersed part of the coated material thermometer, B.t.u./(lb.)(deg. F.)
C_p	Specific heat of air at constant pressure of 760 m.m. of Hg., B.t.u./(lb.)(deg.F.)
D_o	Diameter of thermometer, ft.
h	Coefficient of heat transfer, B.t.u. per hour per sq.ft. per deg. F.
h_c	Coefficient of heat transfer by convection for test thermometer, B.t.u./(hr.)(sq.ft.)(deg. F.)
h'_c	Coefficient of heat transfer by convection for reference thermometer, B.t.u./(hr.)(sq.ft.)(deg.F.)
h_{c1}	Coefficient of heat transfer by convection for coated material thermometer, B.t.u./(hr.)(sq.ft.)(deg.F.)
h_r	Coefficient of heat transfer by radiation for test thermometer, B.t.u./(hr.)(sq.ft.)(deg.F.)
h'_r	Coefficient of heat transfer by radiation for reference thermometer, B.t.u./(hr.)(sq.ft.)(deg.F.)

k_f	Thermal conductivity of air, B.t.u./(hr.)(sq.ft.)(°F/ft)
Q	Quantity of heat transferred, B.t.u.
q	Rate of heat transfer, B.t.u./hr. ; q_c and q_r are defined on page 13.
t	Temperature, degree F.; t_a true temperature of air; t_r temperature recorded by the reference thermometer; t_m temperature recorded by coated material thermometer.
t_1	Initial temperature of test thermometer, identical with reference thermometer, deg. F.
t_2	Final temperature of test thermometer, identical with reference thermometer, deg. F.
t_1'	Initial temperature of test thermometer, identical with coated material thermometer, deg. F.
t_2'	Final temperature of test thermometer, identical with coated material thermometer, deg. F.
V	Volume of immersed part of reference thermometer, cu.ft.
V_1	Volume of immersed part of coated material thermometer, cu.ft.
v	Velocity of air, ft./hr.
ϵ	Emissivity, ϵ_r emissivity of the material on the reference thermometer; ϵ_m emissivity of the finish on the material thermometer.
ρ	Density of the immersed part of the reference thermometer lb./cu.ft.

ρ_1	Density of the immersed part of the coated material thermometer, lb./cu.ft.
ρ'	Density of air, lb./cu.ft.
θ	Time in hours.
θ_1	Time in seconds.

SAMPLE CALCULATIONS

TABLE I Experimental Readings by Dynamic Technique

Material: Lamp-Black, Run No. 2

Data:

t_m, deg. F.	136.76
t_s, deg. F.	123.00
t_1, deg. F..	158.00
t_2, deg. F.	149.00
θ_1, in seconds	17.80
Velocity of air, ft./min.	925.00
D_o of all thermometers, ft.	0.02196
k_f of air, B.t.u. per hour per sq.ft. per deg. F./ft.; between 130 to 160 deg. F.	0.0166
ρ', density of air, lb./cu.ft.	0.0660
u_f, viscosity of air, lb./(hr.)(ft.)	0.0470
C_p, specific heat of air, B.t.u./(lb.)(°F.)	0.2530
$V = V_1$, volume of immersed part of the thermometer, cu.ft.	$D_o^2/4\ L$
Length of immersion of all thermometers, ft.	L
$A = A_1$, heat transfer area of the thermometer, sq.ft.	D_oL
$\rho = \rho_1$, density of the immersed part of the thermometer, lb./cu.ft.	(2.24)(62.4)

$C = C_1$, specific heat of the immersed part of the thermometer, B.t.u./(lb.)(°F.) 0.194

Evaluation of h_c or h_{c1} :

$$\text{Reynolds Number} = D_o v \rho' / u_f$$
$$= (0.02196)(0.066)(55{,}500)/(0.047)$$
$$= 1714$$

Therefore, substitution in equation (17) gives:

$$h_{c1} = (0.26)(k_f/D_o)(C_p u_f/k_f)^{0.3} \; (D_o G/u_f)^{0.6}$$
$$= (0.26)(0.756)(\ 0.905\ ) \quad (\ 1714\ )^{0.6}$$
$$= (0.1775)\ (87.10)$$
$$= (15.425) \qquad \text{B.t.u./(hr.)(sq.ft.)(}\ ^{o}\text{F.)}$$

Evaluation of constant $C \rho V/A\theta$ in equation (10):

$$C \rho V/A\theta = \frac{C \ \rho \ (D_o^2/4)\ L}{D_o\ L\ (\theta_1/3600)}$$
$$= (900)\ (C)\ (\rho)\ (D_o)/\theta_1$$
$$= (900)(0.194)(140)(0.02196)/\theta_1$$
$$= 535/\theta_1 \quad \text{B.t.u./(hr.)(sq.ft.)(}^{o}\text{ F.)}$$

Substitution in equation (10) gives

$$h_c + h_{r1} = 535/\theta_1 \ \ \ln\ (t_1' - t_m)/(t_2' - t_m)$$
$$= 535/17.8 \ \ \ln\ (158.00 - 136.76)/(149.0 - 136.76)$$
$$= (30.7)(0.5508) = 16.78 \ \text{B.t.u./(hr.)(sq.ft.)(}^{o}\text{F.)}$$

Therefore,

$$
\begin{aligned}
h_{r1} &= (h_{r1} + h_{c1}) - (h_{c1}) \\
&= (16.78 - 15.425) \\
&= 1.355 \text{ B.t.u./(hr.)(sq.ft.)(° F.)}
\end{aligned}
$$

Changing the subscript r to m and substituting h_{r1} for h_r in equation (13), σ_m could be expressed in the following form:

$$
\sigma_m = \frac{h_{r1}\,(t_m - t_s)}{0.173\left[(T_m/100)^4 - (T_s/100)^4\right]}
$$

$$
= \frac{(1.355)(136.76 - 123.00)}{(0.173)\left[(5.9676)^4 - (5.83)^4\right]}
$$

$$
= (1.355)(13.76)/(0.173)(1268.3 - 1155.3)
$$

$$
= (1.355)(13.76)/(0.173)(113.00)
$$

$$
= 0.955
$$

TABLE III Experimental Readings by Static Technique

Material : Lamp-Black, Run No. 3

Data:

t_r , deg. F.	137.75
t_m , deg. F.	136.58
t_s , deg. F.	123.00
Velocity of air, ft./min.	920.00

At air velocity of 920 ft./min.;

$$h_c = h_{c1} = 15.42 \text{ B.t.u./(hr.)(sq.ft.)}(^\circ \text{ F.})$$

Using equation (15), and relation

$$h_r(t_r - t_s) = 0.173 \quad \epsilon_r \left| (T_r/100)^4 - (T_s/100)^4 \right|$$

where ϵ_r and t_r readings were obtained with a silver coated reference thermometer; and the value of the emissivity of silver is taken 0.02 (Table I).

$$ta = \frac{0.173 \quad \epsilon r \left| (Tr/100)^4 - (Ts/100)^4 \right|}{h_c} + t_r$$

$$= \frac{(0.173)(0.02) \left| (5.9775)^4 - (5.83)^4 \right|}{15.42} + 137.75 \quad {}^\circ\text{F.}$$

$$= (0.000223)(1275.3 - 1155.3) + 137.75 \quad {}^\circ\text{F.}$$

$$= (0.026 + 137.75) \quad {}^\circ\text{F.}$$

$$= 137.77 \quad \text{deg. F.}$$

Equation (18) can be written as:

$$\epsilon_m = \frac{h_c \; (t_a - t_m)}{0.173 \left| (T_m/100)^4 - (T_s/100)^4 \right|}$$

$$= (15.42)(137.77 - 136.58)/0.173 \quad (5.9658)^4 - (5.83)^4$$

$$= (15.42)(1.19)/(0.173)(1266.6 - 1155.3)$$

$$= (15.42)(1.19)/(0.173)(111.3)$$

$$= 0.955$$

Information on Different Finishes (4)

Composition of Color Paints

The vehicle for all the colors was the same, namely, Glyptal #2504 reduced with mineral spirits to 50% N. V. and naphthenate driers and National Aniline Anti-Skin Agent added as follows: 0.075% Cobalt, 0.5% Lead and 0.4% Anti-Skin Agent, based on the non-volatile. Viscosity of above F-G.

Constants on Glyptal #2504

Constants of Solution

Solids Content - weight	59-61%
Solvent - Petroleum Spirits	
Viscosity (G.H.)	U-W
Color (Gardner)	8 Max.
Acid No. of solution	4 - 6
Pounds per gallon	7.7

Resin Solids Constants

Phthalic Anhydride	24%
Rosin or derivatives	None
Phenolic Resins	None
Oil acids content	60%
Type of Oil	Soya

Information on Different Finishes (continued)

Phthalocyanine Blues (TiO_2)

3-Pb-1	-	4 oz.	#4845	Zulu Blue	per gal. Vehicle
1-PB-2	-	6.5 oz.		Ti-Pure R-610	per gal. Vehicle
PB-1	-	4 oz.	#4845	Zulu Blue	per gal. Vehicle
		8 oz.		Ti-Pure R-610	per gal. Vehicle
1-PB-1	-	4 oz.	#4845	Zulu Blue	per gal. Vehicle
1-PB-2	-	5 oz.		Ti-Pure R-610	per gal. Vehicle
1-PB-1	-	4 oz.	#4845	Zulu Blue	per gal. Vehicle
3-PB-2	-	3.5 oz.		Ti-Pure R-610	per gal. Vehicle
PB-2	-	4 oz.	#4845	Zulu Blue	per gal. Vehicle
		2 oz.		Ti-Pure R-610	per gal. Vehicle

Ti-Pure R-610 is Rutile non-chalking titanium dioxide.

Milori Blues (Iron Blues - TiO_2)

MB-1	-	4 oz.	#4022	Milori Blue	per gal. Vehicle
		8 oz.		Ti-Pure R-610	per gal. Vehicle
3-MB-1	-	4 oz.	#4022	Milori Blue	per gal. Vehicle
1-MB-2	-	6.5 oz.		Ti-Pure R-610	per gal. Vehicle
1-MB-1	-	4 oz.	#4022	Milori Blue	per gal. Vehicle
1-MB-2	-	5 oz.		Ti-Pure R-610	per gal. Vehicle
1-MB-1	-	4 oz.	#4022	Milori Blue	per gal. Vehicle
3-MB-2	-	3.5 oz.		Ti-Pure R-610	per gal. Vehicle
MB-2	-	4 oz.	#4022	Milori Blue	per gal. Vehicle
		2 oz.		Ti-Pure R-610	per gal. Vehicle

Information on Different Finishes(continued)

Reds

R-1	-	12 oz. #1077	Ex. Lt. Toluidine	per gal. Vehicle
2-R-3	-	8 oz. #1073	Dk. Toluidine	per gal. Vehicle
1-R-5	-	4 oz. #1073	-D.D.D. Toluidine	per gal. Vehicle
R-3	-	12 oz. #1073	Dk. Toluidine	per gal. Vehicle
1-R-3	-	4 oz. #1073	Dk. Toluidine	per gal. Vehicle
2-4-5	-	8 oz. #1078	-D.D.D. Toluidine	per gal. Vehicle
R-5	-	12 oz. #1078	D.D.D. Toluidine	per gal. Vehicle

Greens (Chrome Green)

G-1	-	16 oz. #8405	Lt. Green	per gal.Vehicle
G-2	-	16 oz. #8410	Med.Green	per gal.Vehicle
2-G-2	-	10.67 oz. #8410	Med.Green	per gal.Vehicle
1-G-3	-	5.33 oz. #8425	Dk. Green	per gal.Vehicle
1-G-2	-	5.33 oz. #8410	Med.Green	per gal.Vehicle
2-G-3	-	10.67 oz. #8425	Dk. Green	per gal.Vehicle
G-3	-	16 oz. #8425	Dk. Green	per gal.Vehicle

Information on Different Finishes (continued)

Yellows ($PbSO_4$ - $PbCrO_4$)

Y-1	-	3#	-	#2518	Ex. Lt. Yellow	per gal. Vehicle
1-Y-1	-	1½#	-	#2518	Ex. Lt. Yellow	per gal. Vehicle
1-Y-2	-	1½#	-	#2601½	Lt. Yellow	per gal. Vehicle
Y-2	-	3#	-	#2601½	Lt. Yellow	per gal. Vehicle
1-Y-2	-	1½#	-	#2601½	Lt. Yellow	per gal. Vehicle
1-Y-3	-	1½#	-	#2303	Med. Yellow	per gal. Vehicle
Y-3	-	3#	-	#2303	Med. Yellow	per gal. Vehicle

Oranges ($PbCrO_4$)

O-1	-	3#	-	#2604	Lt. Yellow	per gal. Vehicle
1-O-1	-	1½#	-	#2604	Lt. Orange	per gal. Vehicle
1-O-2	-	1½#	-	#2213	Med. Orange	per gal. Vehicle
O-2	-	3#	-	#2213	Med. Orange	per gal. Vehicle
O-3	-	3#	-	#2209	Dk. Orange	per gal. Vehicle
O-4	-	3#	-	#2206	Ex. Dark Orange	per gal. Vehicle

TABLE III Experimental Readings by Static Technique

Run No.	$^*t_r$ deg.F	t_m deg.F	t_s deg.F	velocity ft/min	emissivity
Material: Glass-Mercury Thermometer					
1	134.60	133.88	122.00	990	0.949
2	135.32	134.60	122.00	990	0.950
3	135.32	134.24	121.00	975	0.955
4	135.14	134.06	121.00	975	0.957
5	134.60	133.52	121.00	975	0.958
Material: Lamp-Black					
1	136.94	136.04	123.00	920	0.954
2	137.12	136.22	123.00	920	0.955
3	137.48	136.58	123.00	920	0.954

$^*t_r$ readings were obtained with a silver coated reference thermometer.

All other data necessary to compute emissivities of different finishes and materials are presented in the Sample Calculations of this Thesis.

TABLE III Experimental Readings by Static Technique (continued)

Run No.	$^*t_r$ deg.F	t_m deg.F	t_s deg,F	velocity ft/min	emissivity
		Finish: R-1			
1	140.72	140.00	118.00	490	0.299
2	140.90	140.18	118.00	490	0.305
3	141.08	140.36	118.00	490	0.304
4	141.26	140.54	118.00	490	0.298
		Finish: R-3			
1	132.98	132.08	119.00	916	0.785
2	133.34	132.44	119.00	960	0.787
3	133.70	132.80	119.00	1000	0.784
4	129.20	128.30	119.00	430	0.788
		Finish: R-5			
1	134.78	133.88	121.00	975	0.820
2	134.96	134.06	121.00	975	0.868
3	132.80	131.90	121.00	975	0.875
4	129.20	128.60	120.00	975	0.865

TABLE III Experimental Readings by Static Technique

(continued)

Run No.	*t_r deg.F	t_m deg.F	t_s deg.F	velocity ft/min	emissivity
		Finish:	1-R-3 2-R-5		
1	133.52	132.80	120.00	1240	0.765
2	131.71	131.00	120.00	940	0.768
3	129.92	129.20	120.00	700	0.769
4	128.12	127.40	120.00	405	0.763
		Finish:	2-R-3 1-R-5		
1	131.54	130.82	119.00	975	0.734
2	132.26	131.54	119.00	1085	0.738
3	129.20	128.48	119.00	680	0.739
4	125.60	124.88	119.00	235	0.735
		Finish:	Y-1		
1	147.92	147.56	144.00	310	0.625
2	148.18	147.92	144.50	310	0.626
3	148.82	148.46	145.00	310	0.628
4	149.08	148.82	146.00	310	0.629

TABLE III Experimental Readings by Static Technique

(continued)

Run No.	*t_r deg.F	t_m deg.F	t_s deg.F	velocity ft/min	emissivity
		Finish: Y-2			
1	144.68	144.32	141.00	310	0.660
2	145.06	144.86	143.00	310	0.661
3	145.40	145.22	143.00	310	0.659
4	147.20	146.93	144.00	310	0.660
5	147.92	147.56	144.00	310	0.662
		Finish: Y-3			
1	130.28	129.92	114.50	295	0.320
2	130.46	130.10	116.00	295	0.317
3	130.82	130.46	122.00	295	0.325
4	131.54	131.18	123.00	295	0.315
		Finish: 1-Y-1 1-Y-2			
1	138.74	138.20	120.00	490	0.342
2	138.20	137.66	120.00	490	0.345
3	137.48	136.94	120.00	490	0.344
4	137.94	137.48	120.00	490	0.343

TABLE III Experimental Readings by Static Technique

(continued)

Run No.	*t_r deg.F	t_m deg.F	t_s deg.F	velocity ft/min	emissivity
		Finish:	1-Y-2 1-Y-3		
1	134.24	133.88	126.00	285	0.349
2	134.42	134.06	126.50	285	0.348
3	134.60	134.24	127.00	285	0.350
4	134.78	134.42	128.00	285	0.349
5	135.32	134.96	128.00	285	0.351
		Finish:	MB-1		
1	131.36	130.46	119.00	935	0.892
2	127.40	126.50	119.00	375	0.894
3	129.20	128.30	119.00	655	0.898
4	130.64	129.38	119.00	385	0.891
		Finish:	MB-2		
1	140.00	139.10	126.00	1225	0.899
2	139.82	138.92	126.00	1185	0.895
3	139.64	138.74	126.00	1170	0.896
4	139.10	138.20	126.00	1080	0.898

TABLE III Experimental Readings by Static Technique

(continued)

Run No.	$^{*}t_r$ deg.F	t_m deg.F	t_s deg.F	velocity ft/min	emissivity
		Finish:	3-MB-1 1-MB-2		
1	140.00	138.74	126.00	680	0.702
2	139.82	138.56	126.00	665	0.703
3	140.18	138.92	126.00	700	0.705
4	140.54	139.28	126.00	740	0.707
		Finish:	1-MB-1 3-MB-2		
1	131.00	130.10	119.00	870	0.973
2	131.60	130.46	119.00	925	0.975
3	129.20	128.30	119.00	650	0.982
4	127.40	126.50	119.00	375	0.974
		Finish:	PB-1		
1	124.34	123.62	114.00	970	0.890
2	126.59	125.78	114.00	970	0.887
3	131.90	131.00	118.00	970	0.888
4	130.10	129.20	117.00	970	0.891

TABLE III Experimental Readings by Static Technique

(continued)

Run No.	*t_r deg.F	t_m deg.F	t_s deg.F	velocity ft/min	emissivity
		Finish:	1-MB-1 1-MB-2		
1	145.04	143.96	130.00	1220	0.910
2	145.40	144.14	130.00	980	0.908
3	145.76	144.50	130.00	1020	0.907
4	146.12	144.86	130.00	1070	0.905
5	144.32	143.06	130.00	865	0.905
		Finish:	PB-2		
1	132.62	131.72	120.00	975	0.938
2	132.80	131.90	120.00	975	0.939
3	131.00	130.10	119.00	975	0.937
4	127.10	126.50	119.00	975	0.940
		Finish:	1-PB-1 1-PB-2		
1	133.52	132.62	120.00	1060	0.915
2	131.72	130.82	120.00	830	0.925
3	129.92	129.02	120.00	585	0.920
4	128.12	127.12	120.00	340	0.918

TABLE III Experimental Readings by Static Technique (continued)

Run No.	$*t_r$ deg.F	t_m deg.F	t_s deg.F	velocity ft/min	emissivity
		Finish:	3-PB-1 1-PB-2		
1	132.26	131.18	120.00	695	0.910
2	133.16	132.08	120.00	695	0.915
3	132.80	131.72	120.00	695	0.920
		Finish:	1-PB-1 3-PB-2		
1	127.58	126.86	117.00	975	0.896
2	129.02	128.30	117.00	975	0.894
3	125.42	124.88	117.00	975	0.898
4	129.92	129.20	117.00	975	0.895
		Finish:	O-1		
1	130.55	130.10	121.00	285	0.331
2	130.28	129.92	122.00	285	0.321
3	129.83	129.26	121.50	285	0.342

TABLE III Experimental Readings by Static Technique

(continued)

Run No.	*t_r deg.F	t_m deg.F	t_s deg.F	velocity ft/min	emissivity
		Finish: 0-2			
1	154.58	154.04	148.00	310	0.5376
2	154.76	154.22	148.50	310	0.5925
3	154.94	154.40	149.00	310	0.5970
4	155.14	154.58	149.20	310	0.6220
		Finish: 0-3			
1	136.40	136.04	132.50	315	0.6625
2	138.56	138.20	135.00	315	0.7214
3	139.46	139.10	136.00	315	0.7404
4	140.72	140.36	137.00	315	0.6813
		Finish: 0-4			
1	148.64	148.28	145.00	310	0.640
2	149.00	148.64	145.00	310	0.639
3	149.18	148.82	145.00	310	0.636
4	149.72	149.18	144.50	310	0.637
5	149.72	149.36	145.00	310	0.638

TABLE III Experimental Readings by Static Technique

(continued)

Run No.	$*t_r$ deg.F	t_m deg.F	t_s deg.F	velocity ft/min	emissivity
Finish: 1-0-1 1-0-2					
1	140.00	139.64	136.50	315	0.6880
2	140.53	140.18	136.80	315	0.6705
3	140.90	140.54	137.00	315	0.6437
Finish: G-1					
1	134.96	134.60	126.00	1570	0.655
2	134.78	134.42	126.00	1475	0.658
3	134.60	134.24	126.00	1420	0.659
4	134.06	133.70	126.00	1260	0.656
Finish: G-2					
1	127.94	127.04	119.00	315	0.755
2	129.38	128.48	119.00	440	0.757
3	129.92	129.02	126.00	45	0.759
4	130.28	129.38	126.00	55	0.754

TABLE III Experimental Readings by Static Technique

(continued)

Run No.	$*t_r$ deg.F	t_m deg.F	t_s deg.F	velocity ft/min	emissivity
		Finish: G-3			
1	127.04	126.32	119.00	405	0.778
2	130.28	129.38	119.00	600	0.775
3	132.08	131.18	119.00	805	0.779
4	133.88	132.98	119.00	1010	0.776
		Finish: 1-G-2 2-G-3			
1	132.62	131.90	126.00	290	0.764
2	131.00	130.10	126.00	90	0.765
3	129.20	128.30	119.00	440	0.766
4	127.40	126.50	119.00	285	0.768
		Finish: 2-G-2 1-G-3			
1	131.54	130.64	126.00	165	0.765
2	132.08	131.36	126.00	300	0.766
3	132.44	131.72	126.00	325	0.769
4	132.80	132.08	126.00	375	0.764

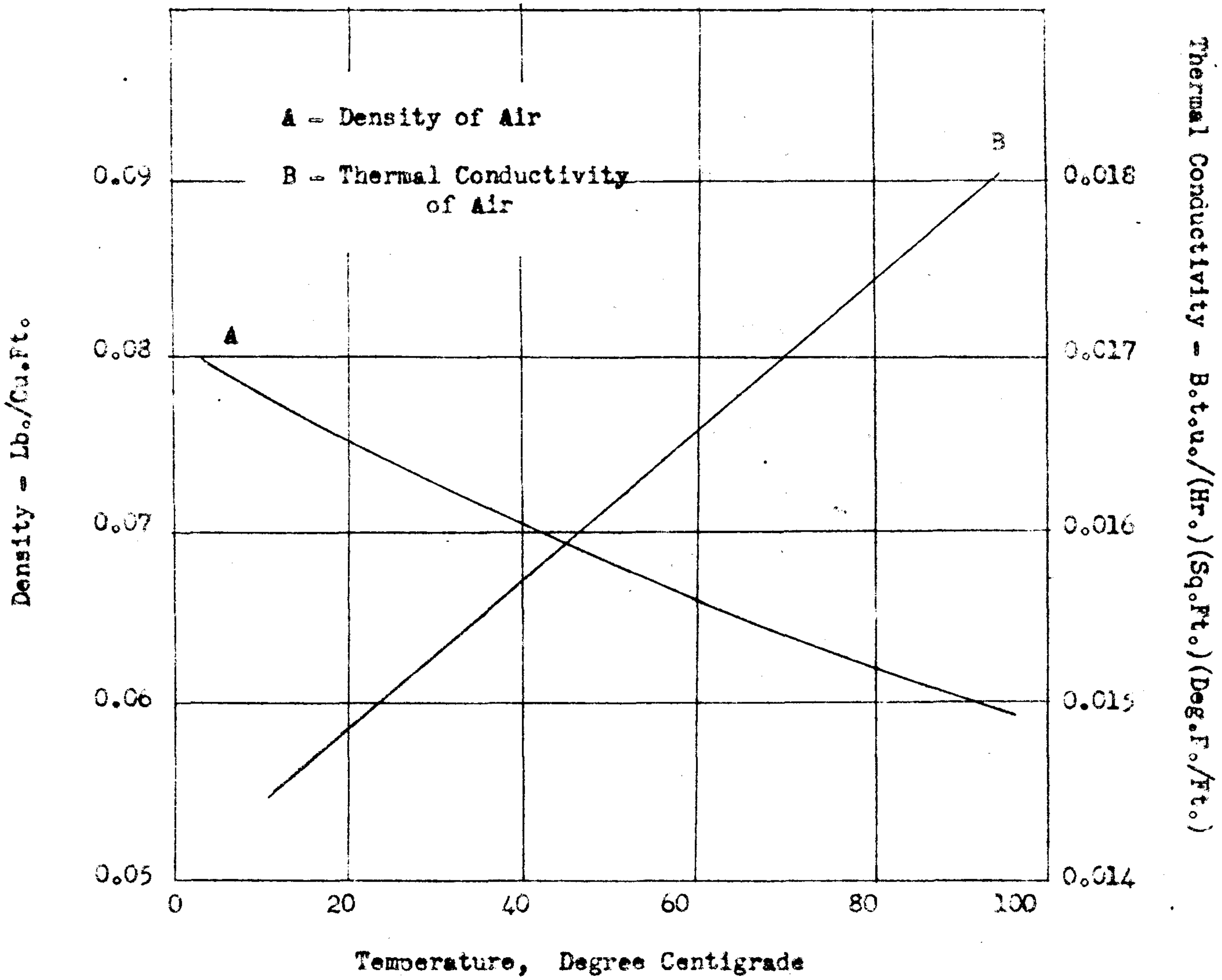

FIG. 6 – DENSITY AND THERMAL CONDUCTIVITY OF AIR

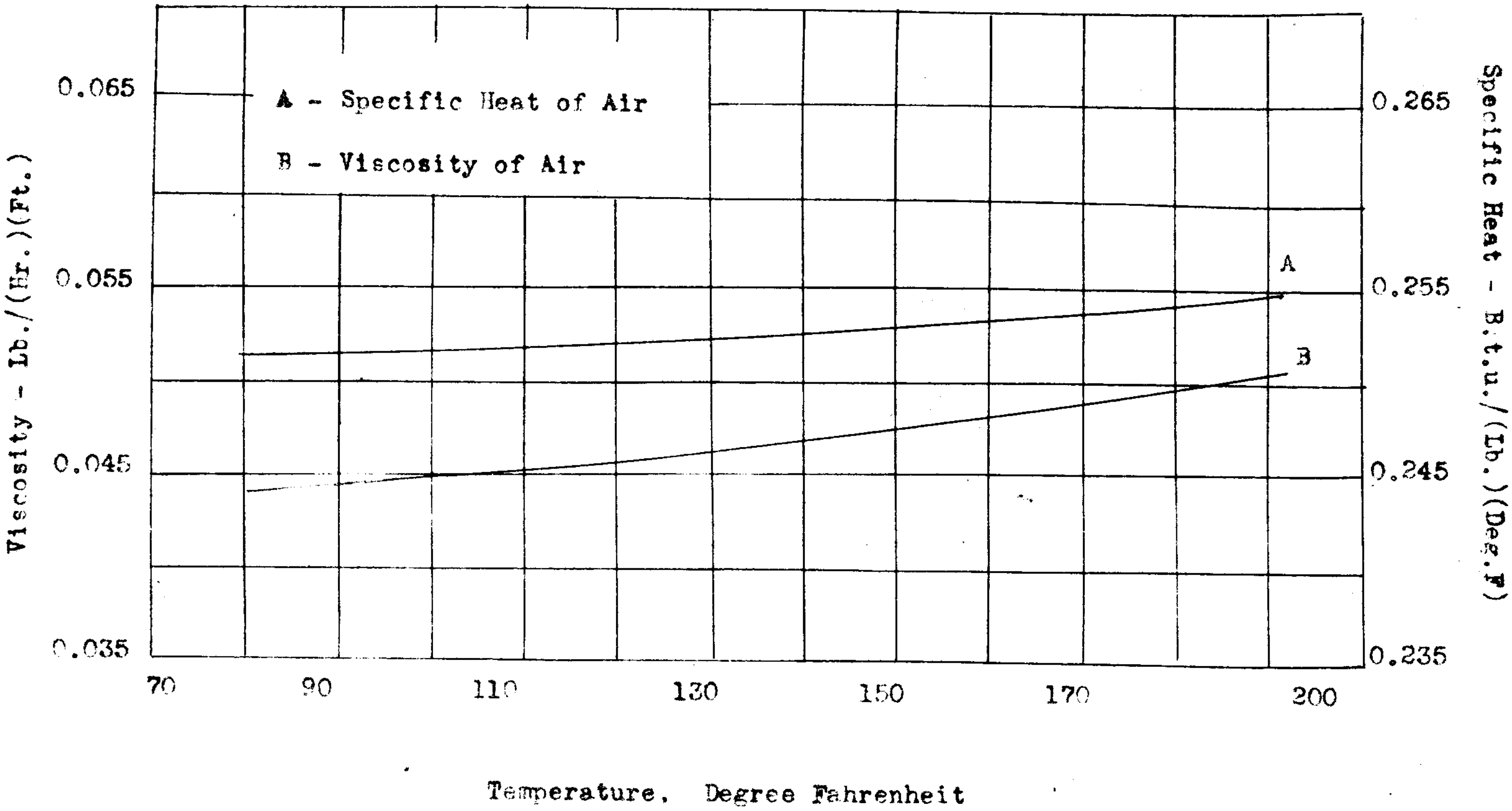

FIG. 7 - SPECIFIC HEAT AND VISCOSITY OF AIR

VITA

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