MEASUREMENTS OF THE THERMAL CONDUCTIVITY OF SEVERAL EXPLOSIVES BY THE CONDUCTIVE DISC METHOD

BY


Report to the
Fire Protection Section
Building Technology Division
NBS

U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS
THE NATIONAL BUREAU OF STANDARDS

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Heat Transfer Section
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By

R. E. Robinson, E. K. Flynn and E. C. Watson

1. INTRODUCTION

In connection with determinations of the thermal properties of explosives and solid propellants, undertaken by the Fire Protection Section of the National Bureau of Standards for the Naval Ordnance Laboratory, measurements were desired of the thermal conductivity of these materials. Because of possible danger of ignition of the materials, it was decided that the tests should be made on samples of limited size (less than 1 lb) in an available small underground vault, with controls and observations at a station outside the vault.

The Heat Transfer Section was consulted concerning the possibility of providing a suitable reliable apparatus for making these thermal conductivity measurements. A new type of thermal conductivity measuring apparatus, which had been under mathematical consideration, appeared more promising for this application than several alternative methods that were considered. Accordingly, the Heat Transfer Section constructed an appropriate apparatus of the new type, the design and calibration of which are described below.

2. DESCRIPTION

The essential elements of the "conductive disc" apparatus consist of a circular disc of metal sandwiched between two specimens of the same diameter, which in turn are sandwiched between two water-cooled plates of the same diameter (see Figure 1). The conductive disc is uniformly heated at its circular edge by means of electrical resistance wire set in a groove. The heat generated at the disc edge tends to flow in the disc radially toward its center, and also to flow from the disc through the two specimens to the uniform-temperature cold plates. Thus, the steady-state temperature of the conductive disc decreases toward its center. By measuring the temperature of the disc at its center and at a
suitable radius, the effective conductance of the specimens can be calculated, if the temperature of the cold plates and the conductivity and thickness of the disc metal are known.

The apparatus constructed has a 6-inch diameter disc of Type 303 stainless steel, fine-ground to a uniform thickness of 0.0625 cm. In addition to one thermocouple at the center, three additional thermocouple junctions are located at 120° angular spacing at a radius of 5.080 cm, all thermocouple junctions being inset in metallic contact with the stainless steel at one surface of the disc. The cold plates are 6-inch discs of brass, 1 cm thick, with several turns of 3/8-inch copper tube soldered to their non-working sides for circulation of coolant. The working surfaces of the cold plates were turned flat in a lathe after the soldering was completed. A thermocouple junction is inset in the brass disc at its center for measuring its temperature. The dimensions selected for the conductive disc of the apparatus were predicted on measurements on specimens 1/2 inch thick by 6 inches in diameter, having thermal conductivities in the range from 0.5 to 5.0 mW/cm °C.

The heater winding in the edge-groove of the conductive disc consists of approximately 13 ft of No. 30 constantan wire, bifilarly wound, insulated with aluminum-saturated fiberglass sleeving. Its electrical resistance is approximately 60 ohms.

Associated equipment includes a 20 gal. tank with a laboratory immersion pump for circulating water through the cold plate coils at about 1 gpm, a voltage regulator and a variable a-c transformer for power supply to the disc heater, and a precision potentiometer for thermocouple readings. All thermocouples are made of No. 30 copper and constantan wires, and are used with the reference junctions at 0°C.

3. USE AND ELEMENTARY ANALYSIS OF THE APPARATUS

An approximate analysis of the conductive disc method is given below, adequate for showing its chief operating characteristics, for designing the apparatus for the measurements desired, and for enabling certain computations of the test results.

A more rigorous analysis of the method is being made to develop a comprehensive mathematical treatment of the conductive disc apparatus, but is not needed for the apparatus.
described here. As used in the tests reported here, the apparatus was calibrated by means of a guarded hot plate thermal conductivity apparatus. The calibration curve thus established served as a means for translating the measurements made in the disc apparatus into conductivity determinations tantamount to those that would have been obtained in tests in the guarded hot plate.

For steady temperature conditions, an approximate differential equation for the disc apparatus (which neglects non-radial temperature gradients in the disc, and radial temperature gradients in the specimens) is

\[ 2\pi m \left( \frac{d^2 v}{dr^2} + \frac{1}{r} \frac{dv}{dr} \right) dr - 2\pi dr v \left( \frac{K}{L} + \frac{k^i}{L^i} \right) = 0 \]  

(1)

in which the first part represents the change in radially-directed heat flux in the disc in a radial distance \( dr \) at a radius \( r \), and the second part represents the flow of heat from the disc toward the cold plates through both specimens, through the disc surface area between \( r \) and \( (r+dr) \). In equation (1), \( m \) is the thickness of the conductive disc, \( K \) is its thermal conductivity, \( k \) and \( k^i \) are the thermal conductivities of the two specimens and \( L \) and \( L^i \) their thicknesses, and \( v \) is the temperature of the disc surface referred to the cold plate temperature as \( Q \). It is assumed in equation (1) that the conductivities of the disc and specimens are constant at values corresponding to their mean temperatures.

Equation (1) becomes, upon simplification,

\[ \frac{d^2 v}{dr^2} + \frac{1}{r} \frac{dv}{dr} - \mu^2 v = 0 \]  

(2)

where

\[ \mu^2 = \frac{1}{mK} \left( \frac{K}{L} + \frac{k^i}{L^i} \right) \]  

(2a)

Equation (2) is Bessel's equation of order zero, having the solution

\[ v = A I_0 (\mu r) \]  

(3)

since \( I_0(0) = 1 \),

\[ \frac{v}{V_0} = I_0 (\mu R) \]  

(4)

where \( V_0 \) is the temperature of the disc surface at radius \( R \), and \( V \) the disc surface temperature at radius \( R \), and where \( I_0 \)
is the modified Bessel's function of the first kind and of order 0.8.

The mean temperature of the disc within the radius R, referred to the observed temperature of the cold plates as zero, is given by

\[ V = \frac{1}{\mu R^2} \int_0^R 2\pi r I_1(\mu r) dr = \frac{2V_0 I_1(\mu R)}{\mu R} \] (5)

where \( I_1 \) is the modified Bessel's function of the first kind, of order 1. It is found, using tables of \( I_1 \), that

\[ \frac{2V_0 I_1(\mu R)}{\mu R} = \frac{V_0 + V}{2} \] to within 1/2\% for \( V/V_0 < 1.4 \).

Thus for the tests reported, wherein \( V/V_0 < 1.3 \), it is adequate to take the actual mean temperature of the disc in a test as

\[ t_d = 0.5(V_0 + V) + t_c \] (6)

where \( t_c \) is the observed temperature of the cold plates.

Similarly, the mean temperature of the specimen in a test is calculated as

\[ t_s = 0.5(t_d + t_c) = 0.25(V_0 + V) + t_c \] (7)

4. CALIBRATION

If the value of \( \mu R \) were known accurately, equations (4) and (2a) would serve to determine \((k'/l+k''/l')\), within the limit of exactness of the \( I_1 \) solution. However, it was not feasible to obtain a piece of the metal used for the disc, of size adequate for a direct measurement of its thermal conductivity, \( \kappa \).

Further, it was desired to use in a test only one specimen of explosive, rather than two, and therefore a permanent "dummy specimen" was used in all tests in place of a duplicate of the principal specimen. This consisted of a 6-inch diameter disc of 1-inch thick semi-rigid glass-fiber.

a/ Values of \( I_0(x) \) and \( I_1(x) \) are available to 5 places in tabulated form for values of \( x \) from 0 to 12, in increments of 0.001 (Tablitsy anachenni funktsii Besselia ot animofo arguments, ....... 1950, Moscow).
insulating board of stable low thermal conductivity (0.348 
$\text{mw/cm}^2\text{C}$ at 50°C) maintained at a constant thickness of 0.991
inch during use by three small fiber pegs thrust perpendicu-
larly through the board. The lower cold plate of the appara-
tus, the dummy specimen, and the conductive disc were
fastened together with rubber cement to form a sub-assembly.

To calibrate the test apparatus, tests were made on six
6-inch disc specimens of thermal conductance from 0.1 to
4.4 $\text{mw/cm}^2\text{C}$, each in combination with the dummy specimen of
thermal conductance of approximately 0.14 $\text{mw/cm}^2\text{C}$, and the
steady-state value of $V/V_0$ was observed in each case. The
conductances of the six principal specimens, and of the
dummy specimen, were determined by means of previous tests
conducted on them in the form of 6-inch squares in the
Bureau's guarded hot plate apparatus (ASTM Designation
C177-46).

The results of the calibration measurements are recorded
in Table 1, and there are plotted in Figure 2 the hot plate
values of conductance, $k/l$, of the principal specimens, versus
the observed values of $V/V_0$ from the conductive disc measure-
ments on them. A regular curve is fitted amongst the six
calibration points, to yield a smooth curve representing the
calibration of the conductive disc apparatus. Departures of
the experimental points and the curve do not exceed one per-
cent.

The conductances in Figure 2 are values corresponding to
the mean temperature of the specimen in the conductive disc
test when the cold plate temperature was about 27°C and the
disc mean temperature was about 67°C. In tests made with
the conductive disc apparatus, using the calibration curve of
Figure 2, the conductance obtained requires correction,
as indicated below, to compensate for the change in disc
conductivity if the disc mean temperature departed signifi-
cantly from 67°C. The corrected conductance corresponds to
the actual mean temperature of the specimen in the conduc-
tive disc test.

The temperature coefficient of conductivity of Type 303
stainless steel (in the equation $k=K_0[l+\alpha(t_d-69)]$) is
0.9$\times10^{-2}$, approximately. Accordingly, the conductance
obtained from the calibration curve, $k/l(\text{c.c.})$, should be
corrected by the relation

$$k_l(\text{at } t_d) = k_l(\text{c.c.})x[1+0.9\times10^{-2}(t_d-69)]$$ (8)
Taking the value of \( k/L \) (2.31 \( \text{mW/cm} \cdot \text{K} \)) from the calibration curve at \( V/\phi = 1.15 \), and the value of \( k'/L = 0.137 \) at 48°C mean temperature, and using Equations (4) and (2a), the conductivity of the Type 303 stainless steel of the disc is calculated to be 0.159 \( \text{w/cm} \cdot \text{K} \) at 69°C. A measurement made here in 1936 on a sample of Type 303 rod 1 inch in diameter indicated its conductivity to be 0.141 \( \text{w/cm} \cdot \text{K} \) at 69°C. NB3 Circular 556, "Thermal Conductivity of Metals and Alloys at Low Temperatures: a Review of the Literature" (1954), gives data (Figure 23) which indicate that the conductivity of S.S. 303 at 69°C is about 0.153; the Stainless Steel Handbook of the Allegheny Steel Corporation indicates a value of 0.155 \( \text{w/cm} \cdot \text{K} \) at 69°C. The value of disc conductivity obtained from the disc calibration measurements is seen to be intermediate between available values from other measurements.

5. PROCEDURE AND OPERATION

In the present use of the apparatus, the lower cold plate, the dummy specimen, and the conductive disc formed a sub-assembly, and it was necessary only to interpose the single test specimen between the conductive disc and the upper cold plate. For good thermal contact, the test specimen must be flat and of uniform thickness, and the contacting surfaces must be clean. To improve thermal contact between the working surfaces and the specimen, an 18-lb weight was centered on the upper cold plate, resulting in a pressure on the specimen of approximately 0.6 psi. Care was taken to assure that the several circular parts and the weight were positioned coaxially.

Ball bearings are set near the edges in the outward faces of both cold plates at angular spacings of 120°. Micrometer measurements of the axial distance across the ball bearings in the two cold plates, with and without the test specimen in place, enabled the thickness of the specimen to be accurately determined.

Thermal insulation of the working parts of the assembled apparatus was accomplished by pouring around it within a removable 12-inch diameter container a free-flowing powder insulation (silica aerogel). The powder insulation was readily drained from around the apparatus by opening a sliding gate at the bottom of the container.
To start a test, the disc heater winding was energized at a reasonable power input rate (an initial setting of about 6 watts input was used for these measurements), and if the power input and the cooling water temperature were constant, the apparatus reached a substantially steady temperature condition in from 2 to 3 hours. Readings of \( V \) and \( V_0 \) were then made periodically for an hour or more to assure that steady-state conditions existed. The value of the ratio \( V/V_0 \) does not depend on the rate of power input, but to determine this ratio with good precision, it is desirable that the difference between \( V \) and \( V_0 \) be determinable with a precision of better than 1 part in 200, and therefore that the rate of power input be adjusted to yield an adequate difference of \( V \) and \( V_0 \). In testing explosives, however, it was desirable that the maximum temperature of the disc in contact with the test specimen be limited to some safe value. For this apparatus the maximum disc temperature, which occurs at the rim, is approximately equal to

\[
t_{\text{max}} = t_0 + V_0 (V/V_0)^2
\]

for values of \( V/V_0 \) up to 1.3.

6. RESULTS OF MEASUREMENTS ON EXPLOSIVES

Table 2 summarizes the data obtained with the conductive disc apparatus on explosives.

The six materials were found to have thermal conductivities between 1.9 and 2.6 mw/cm°C.

During the course of the measurements made in the underground vault on the explosives, two check measurements were made on the original 1.25-cm Neoprene specimen used in calibrating the apparatus. The first was made on initially setting up the apparatus in the vault prior to the first TNT measurement. Following the second TNT measurement, it was necessary to clear the vault for other work, and the second check test was made when the apparatus was reinstalled, just prior to the measurement of the 8R specimen. The conductance of the Neoprene specimen, as determined by the hot plate and used in the calibration test, was 2.494 mw/cm°C at 45°C mean temperature. In the first check test, the conductance obtained was 2.50 at 45°C; in the second, 2.50 at 40°C. There was therefore an observed variation in results of 0.4 percent, to which the results on the explosives must be considered subject.
The two measurements made on TNT, at 33 and 38°C, indicate a negative temperature coefficient of conductivity ($\alpha = -0.011$ per deg C). Because of the small difference in test temperatures, the uncertainty in this value of $\alpha$ is probably large. Hot plate tests conducted on paraffin (129°C M.P.) and Hollowax at 70° to 90°C mean temperature have indicated temperature coefficients of -0.005 and -0.0043 per deg C, respectively, for these waxy materials.
<table>
<thead>
<tr>
<th>Principal Specimen</th>
<th>Hot Plate Data</th>
<th>Conductive Disc Data</th>
<th>Mean Temp. (0&lt;r&lt;8)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>k/L[^a] (mw/cm^2°C)</td>
<td>Heater Volts</td>
<td>V/Vo</td>
</tr>
<tr>
<td>Fiber glass board</td>
<td>0.3093</td>
<td>25</td>
<td>1.0272</td>
</tr>
<tr>
<td>Gum rubber</td>
<td>1.10 cm</td>
<td>1.342</td>
<td>30</td>
</tr>
<tr>
<td>Neoprene 91.7 pcf</td>
<td>1.28 cm</td>
<td>2.494</td>
<td>42</td>
</tr>
<tr>
<td>Neoprene 94.0 pcf</td>
<td>1.32 cm</td>
<td>2.999</td>
<td>43</td>
</tr>
<tr>
<td>Neoprene 97.3 pcf</td>
<td>1.32 cm</td>
<td>3.117</td>
<td>45</td>
</tr>
<tr>
<td>Gum rubber</td>
<td>0.36 cm</td>
<td>4.379</td>
<td>55</td>
</tr>
</tbody>
</table>

[^a]: k/L is corrected to correspond to the mean temperature of the specimen in the conductive-disc test. The conductance of the dummy specimen, k'/L', was 0.116 (1+0.0039t_0) mw/cm^2°C, where t_0 is its mean temperature.

[^**]: Average of three temperatures at r=5.08cm, at 120° angular spacing.
TABLE 2 - THERMAL CONDUCTIVITY, $k$, OF EXPLOSIVES

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Thickness (cm)</th>
<th>Y/Yo</th>
<th>Cold Plate Temp. (°C)</th>
<th>Center Temp. (°C)</th>
<th>Ave. Temp. at $r=5.08cm$ (°C)</th>
<th>Specimen Mean Temp. (°C)</th>
<th>$k$ cm°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>TNT</td>
<td>1.272</td>
<td>1.1694</td>
<td>24.72</td>
<td>40.18</td>
<td>41.97</td>
<td>41</td>
<td>33</td>
</tr>
<tr>
<td>&quot;</td>
<td>1.272</td>
<td>1.1629</td>
<td>24.57</td>
<td>58.36</td>
<td>53.01</td>
<td>52</td>
<td>38</td>
</tr>
<tr>
<td>H</td>
<td>1.272</td>
<td>1.1316</td>
<td>18.89</td>
<td>44.25</td>
<td>47.21</td>
<td>46</td>
<td>33</td>
</tr>
<tr>
<td>CYCLOTOL</td>
<td>1.271</td>
<td>1.1358</td>
<td>6.74</td>
<td>18.17</td>
<td>19.72</td>
<td>19</td>
<td>13</td>
</tr>
<tr>
<td>DPA</td>
<td>1.270</td>
<td>1.1275</td>
<td>0.05</td>
<td>12.00</td>
<td>13.52</td>
<td>13</td>
<td>6</td>
</tr>
<tr>
<td>RX</td>
<td>1.282</td>
<td>1.1083</td>
<td>21.97</td>
<td>51.19</td>
<td>54.35</td>
<td>53</td>
<td>37</td>
</tr>
<tr>
<td>&quot;</td>
<td>1.273</td>
<td>1.1394</td>
<td>23.24</td>
<td>47.17</td>
<td>50.42</td>
<td>49</td>
<td>36</td>
</tr>
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</table>
THE NATIONAL BUREAU OF STANDARDS

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