THE GEM DIAMONDMASTER AND THE THERMAL PROPERTIES OF GEMS

By D. B. Hoover

The GEM DiamondMaster is one of a number of thermal testing instruments introduced specifically to separate diamond from its simulants. Although originally reported to measure thermal conductivity, these instruments in fact measure the thermal inertia of the material being tested. This article explains thermal properties in general and thermal inertia in particular, and then describes the limitations and potential applications of thermal testing instruments such as the DiamondMaster. Included are suggestions for the use of the DiamondMaster to separate various colored stones.

ABOUT THE AUTHOR

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A number of methods and instruments have been introduced recently to distinguish diamond from its simulants on the basis of the unique thermal properties of diamond (Nassau, 1978; Read, 1978, 1980; Goldsmid, 1979; Goldsmid and Goldsmid, 1979, 1980; Thwaites et al., 1980; Hobbs, 1981). In particular, several thermal testing instruments—including the Ceres Diamond Probe®, the Kashan Diamond Detector, and the Rayner Diamond Tester—have been made available for this purpose. GEM Instruments Corporation is currently marketing the DiamondMaster®, a thermal testing instrument designed in Australia (Goldsmid, 1979) and manufactured by Presidium Diamond PTE Ltd., Singapore.

Most of these instruments are said to measure or compare thermal conductivity. This is not strictly true. The DiamondMaster and other similar instruments, with which the author is familiar, measure or compare *thermal inertia* (Hoover, 1982). Although this physical property is not commonly known by name, it is familiar to all gemologists as the cold feeling of crystals and many gems in contrast to the warmth of glass or plastic when touched by the finger or tongue (Webster, 1975, p. 387). This property has been known since at least the 16th century, and was mentioned as a qualitative test for gems by Agricola in 1546 (Sinkankas, 1981). By providing a semiquantitative measure of thermal inertia, the DiamondMaster has been found useful for distinguishing between several other gems in addition to diamond and its simulants.

This article will examine the operation of the DiamondMaster as a specific example of a thermal probe and then provide a brief qualitative introduction to thermal properties so that the gemologist can appreciate the operating principles behind these new instruments, their limitations, and their broader applications. With regard to these broader applications, the use of the

Figure 1. The DiamondMaster®, a thermal testing instrument manufactured by Presidium Diamond PTE Ltd. and marketed by GEM Instruments Corporation.

DiamondMaster to distinguish among gems other than diamond and its simulants is discussed. For this purpose, an extensive table of the thermal properties of gemstones, gem simulants, and metals used in jewelry is provided. It is believed that, as thermal testing instruments are improved, they will become important tools for gem identification.

The DiamondMaster used for evaluation and testing while preparing this article is a standard production model purchased by the author for his own use.

INSTRUMENT DESIGN

The DiamondMaster (figure 1) is a very simple instrument; its basic construction has been described by Goldsmid and Goldsmid (1980) and Goldsmid (1979). It consists of four main subunits: the probe, a power source, an amplifier, and an indicating meter. The amplifier and meter provide a means for obtaining a reading from the probe and need no further discussion here. The power source provides voltage to operate the electronics and to energize the heat source in the probe. Power is obtained either from 3-volt internal batteries, or from 110-volt lines. Operation with external power was found to result in significant line noise in the instrument reading, which was not present when batteries were used. It is assumed that the noise is due to insufficient filtering in the power supply. The use of batteries is recommended whenever discrimination between gems other than diamonds is attempted.

The heart of the unit is the probe, which contains a heat source and a temperature-difference sensor (figure 2). The heat source is a 22-ohm resistor that receives about 2 volts from the power source. This gives a constant quantity of heat to the probe of 0.18 watts (0.043 calories/sec). The temperature sensor is a 22-mm-long copper rod, 0.4 mm in diameter, with constantan wires attached at either end. The copper-constantan junctions form a thermocouple, a common temperature-measuring device. The different temperatures at the two junctions produce a voltage that is proportional to this temperature difference. This voltage, or temperature difference, is what is measured by the instrument. The heat source is placed about midway along the copper wire. All of these parts, except the tip, are contained within

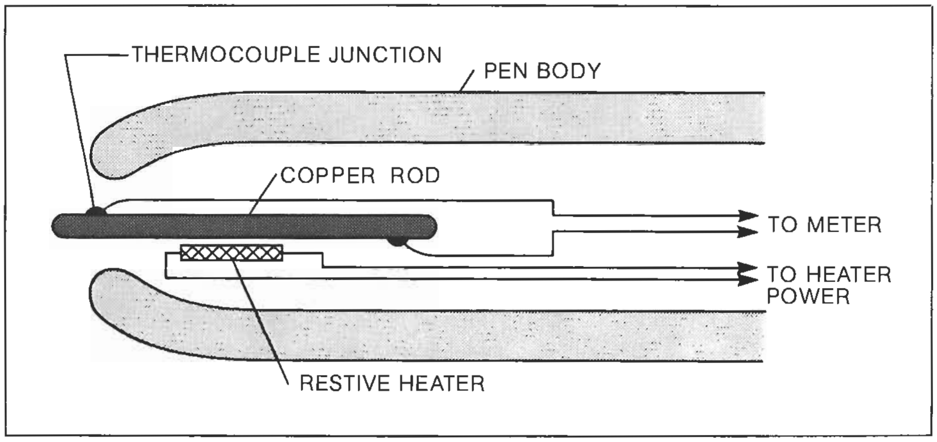

Figure 2. Diagramatic sketch of the DiamondMaster probe, showing the principal components of the sensor.

the insulating probe housing, as shown in figure 2. Thermal insulation provided by the probe housing keeps the internal junction at an elevated temperature. When the probe is in use, heat flows down the copper rod into the gem being tested. The temperature at the tip junction is then approximately the same as the surface temperature of the gem.

When not in use, the probe tip is left in contact with air, which is a good insulator and thus has low thermal inertia. In still air, the tip rises to a temperature near that of the internal junction (about 65°C in the author's instrument). The exact value is determined by the position of the heat source and heat loss through the pen body. In the author's unit, the meter reads below zero with the tip in still air. This suggests that the probe tip, in this case, is hotter than the internal junction. If drafts are present in the room, heat is removed from the tip and a fluctuating and positive reading will be observed, as is easily noted by blowing on the tip. This points out the need, when using the instrument, to avoid areas with much air movement, such as modern air-conditioned offices.

The DiamondMaster thus provides a constant heat source; part of this heat is conducted through the tip to the test gem. The instrument measures the temperature difference between the hot internal junction and the surface temperature of the gem or other material being tested. Our question now is: What physical property is being measured, or approximated, by the instrument? The answer requires some understanding of the thermal properties of solids, as discussed below.

INTRODUCTION TO THERMAL PROPERTIES

Heat energy can be transferred by three methods: conduction, convection, and radiation. In solids at room temperature, the principal means of heat transfer is by conduction. Consequently, in the following discussion, only conductive transfer will be considered.

The purpose of this section is to try to give a qualitative idea of the four intrinsic thermal properties that are important to an understanding of the operation and limitations of the new thermal probes. Those readers interested in a more technical discussion of thermal properties and the mathematical relationships between them are advised to consult any standard college physics text. For more advanced treatment, the classic text is Carslaw and Jaeger (1959).

The four intrinsic thermal properties of interest to us here are conductivity, diffusivity, inertia, and specific heat. The first three properties are not independent of one another. Given one of these properties plus the specific heat and density of a given solid, the other two can be calculated*. These calculations were made to obtain the values of inertia and diffusivity given in table 1, because conductivity is the most commonly measured of these properties. The mathematical relationships between these properties shows that a substance with high conductivity also will have high diffusivity and inertia, as can be seen in table 1. This may in part be the reason the probes are commonly thought to measure thermal conductivity.

Thermal conductivity is familiar to most of us because of the recent interest in energy conservation in our homes. It is a constant that relates the quantity of heat-per-second passing through

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* $k = K/c\rho = K^2/I^2$ $I = \sqrt{Kc\rho} = K/\sqrt{k}$ $K = kc\rho = I\sqrt{k}$
where K *= conductivity,* k *= diffusivity,* I *= inertia,* c *= specific heat, and* ρ *= density.*

TABLE 1. Thermal properties of gem materials, synthetics, and simulants as well as some metals at room temperature.[a]

Material	Thermal conductivity (cal/cm °C sec)	Specific heat (cal/gm °C)	Density (gm/cm^3)	Thermal diffusivity (cm^2/sec)	Thermal inertia (cal/cm^2 °C sec$^{1/2}$)
Gem Materials, Synthetics, and Simulants					
Diamond	1.6–4.8	0.12	3.52[c]	3.79–11.4	0.822–1.42
Silicon carbide (synthetic)	0.215[d]	0.2*	3.17[c]	0.339	0.369
Periclase (synthetic)	0.110[d]	0.2*	3.575[c]	0.154	0.281
Corundum: c axis	0.0834[d]	0.206	4.0[c]	0.101	0.262
a axis	0.0772[d]	0.206	4.0[c]	0.0937	0.252
c axis	0.060[e]	0.206	4.0[c]	0.0728	0.222
Topaz: a axis	0.0446	0.2*	3.53[c]	0.0632	0.177
mean, Gunnison, Colorado	0.0269	0.2*	3.531	0.0381	0.138
Pyrite: Colorado	0.0459	0.136	4.915	0.0684	0.176
Kyanite: c axis	0.0413[d]	0.201	3.66[c]	0.0562	0.174
b axis	0.0396[d]	0.201	3.66[c]	0.0539	0.171
mean, Minas Gerais, Brazil	0.0338	0.201	3.102	0.0461	0.158
Hematite: Itabira, Brazil	0.0270	0.169	5.143	0.0310	0.153
Spinel: locality unknown	0.0281	0.216	3.63[c]	0.0358	0.148
Madagascar	0.0227	0.216	3.633	0.0288	0.133
Fluorite: locality unknown	0.0219	0.220	3.18[c]	0.0313	0.124
Rosiclare, Illinois	0.0227	0.220	3.186	0.0324	0.126
Sphalerite: Chihuahua, Mexico	0.0304	0.115	4.103	0.0646	0.120
Sillimanite: Williamstown, Australia	0.0217	0.203	3.162	0.0339	0.118
Andalusite: Minas Gerais, Brazil	0.0181	0.202	3.102	0.0289	0.107
Pyrophyllite: North Carolina	0.0194	0.2*	2.829	0.0343	0.105
Jadeite: Japan	0.0159	0.206	3.196	0.0242	0.102
San Benito County, California	0.0110	0.206	3.350	0.0160	0.0873
Gahnite: Colorado	0.0103	0.2*	4.163	0.0100	0.102
Magnesite: Transvaal	0.0139	0.236	2.993	0.0198	0.0992
Rutile: c axis	0.0231[d]	0.189	4.2[c]	0.0291	0.135
a axis	0.0132[d]	0.189	4.2[c]	0.0166	0.102
mean, Virginia	0.0122	0.189	4.244	0.0153	0.0990
Grossular: Connecticut	0.0135	0.196	3.617	0.0188	0.0979
Chihuahua, Mexico	0.0134	0.196	3.548	0.0193	0.0967
Crestmore, California	0.0124	0.196	3.318	0.0190	0.0898
Quartz: c axis	0.0264[d]	0.196	2.65[c]	0.0578	0.125
c axis	0.0264[e]	0.196	2.65[c]	0.0509	0.117
a axis	0.0140[d]	0.196	2.65[c]	0.0270	0.0854
a axis	0.0160[e]	0.196	2.65[c]	0.0308	0.0912
mean, Jessieville, Arkansas	0.0184	0.196	2.647	0.0354	0.0978
Spodumene: Maine	0.0135	0.2*	3.155	0.0214	0.0923
Diopside: New York	0.0133	0.196	3.270	0.0208	0.0923
Madagascar	0.00969	0.196	3.394	0.0146	0.0802
Dolomite	0.0132	0.221	2.857	0.0209	0.0911
Olivine (peridot, Fo$_{86}$Fa$_{14}$)	0.0115	0.2*	3.469	0.0166	0.0893
Elbaite: Keystone, South Dakota	0.0126	0.2*	3.134	0.0202	0.0889
Talc: Quebec	0.0124	0.221	2.804	0.0200	0.0878
Tremolite: Balmot, New York	0.0117	0.210	2.981	0.0186	0.0854
Ontario, Canada	0.0112	0.210	3.008	0.0177	0.0839
Amblygonite: South Dakota	0.0119	0.2*	3.025	0.0197	0.0850
Zircon: Australia	0.0109	0.140	4.633	0.0167	0.0839
Enstatite (En$_{98}$Fs$_2$): California	0.0105	0.2*	3.209	0.0334	0.0821
Bronzite (En$_{78}$Fs$_{22}$): Quebec	0.00994	0.2*	3.365	0.0148	0.0818
Spessartine: Haddam, Connecticut	0.00811	0.2*	3.987	0.0102	0.0804
Datolite: Patterson, New Jersey	0.0106	0.2*	2.996	0.0177	0.0798
Anhydrite: Ontario, Canada	0.0114	0.187	2.978	0.0204	0.0796
Almandine: Gore Mountain, New York	0.00791	0.2*	3.932	0.0101	0.0789
Staurolite: Georgia	0.00828	0.2*	3.689	0.0112	0.0782
Augite: Ontario	0.00913	0.2*	3.275	0.0140	0.0773
Pyrope: Navajo Reservation, Arizona	0.00759	0.2*	3.746	0.0101	0.0754

TABLE 1. Thermal properties of gem materials, synthetics, and simulants as well as some metals at room temperature.[a] (Continued)

Material	Thermal conductivity (cal/cm °C sec)	Specific heat (cal/gm °C)	Density (gm/cm³)	Thermal diffusivity (cm²/sec)	Thermal inertia (cal/cm² °C sec½)
Andradite: Ontario, Canada	0.00738	0.2*	3.746	0.00984	0.0744
Smithsonite: Kelly, New Mexico	0.00612	0.2*	4.362	0.00701	0.0731
Beryl: c axis	0.0131[d]	0.2*	2.70[c]	0.0243	0.0842
a axis	0.0104[d]	0.2*	2.70[c]	0.0193	0.0750
mean, Minas Gerais, Brazil	0.00953	0.2*	2.701	0.0176	0.0718
Calcite: Chihuahua, Mexico	0.00858	0.218	2.721	0.0145	0.0713
Axinite: Baja California	0.00767	0.2*	3.306	0.0116	0.0712
Prehnite: Paterson, New Jersey	0.00854	0.2*	2.953	0.0145	0.0710
Rhodochrosite: Argentina	0.00731	0.184	3.584	0.0111	0.0695
Flint: Brownsville, Ohio	0.00886	0.2*	2.618	0.0169	0.0681
Epidote: Calumet, Colorado	0.00627	0.2*	3.413	0.00919	0.0654
Petalite: Rhodesia	0.00856	0.2*	2.391	0.0179	0.0640
Clinozoisite: Baja California	0.00574	0.2*	3.360	0.00854	0.0621
Idocrase: Chihuahua, Mexico	0.00576	0.2*	3.342	0.00863	0.0620
Sphene: Ontario, Canada	0.00558	0.188	3.525	0.00845	0.0607
Iolite: Madagascar	0.00650	0.2*	2.592	0.0126	0.0580
Zoisite: Liksviken, Norway	0.00513	0.2*	3.267	0.00785	0.0579
Aragonite: Somerset, England	0.00535	0.209	2.827	0.00906	0.0562
Microcline: Amelia, Virginia	0.00621	0.194	2.556	0.0126	0.0554
Ontario, Canada	0.00590	0.194	2.558	0.0119	0.0541
Albite (Ab_{99} An_1): Amelia, Virginia	0.00553	0.202	2.606	0.0105	0.0540
Serpentine (lizardite): Cornwall, England	0.00558	0.2*	2.601	0.0107	0.0539
Orthoclase: Goodspring, Nevada	0.00553	0.2*	2.583	0.0107	0.0534
Sodalite: Ontario, Canada	0.00600	0.2*	2.326	0.0129	0.0528
Lepidolite: Dixon, New Mexico	0.00460	0.2*	2.844	0.00807	0.0512
Anorthite (Ab_4An_{96}): Japan	0.00401	0.196	2.769	0.00737	0.0467
Fluor-apatite: Ontario, Canada	0.00328	0.195	3.215	0.00522	0.0454
Chlor-apatite: Snarum, Norway	0.00331	0.195	3.152	0.00539	0.0451
Labradorite ($Ab_{46}An_{54}$): Nain, Labrador	0.00365	0.2*	2.701	0.00676	0.0444
Barite: Georgia	0.00319	0.113	4.411	0.00639	0.0399
Apophyllite: Poona, India	0.00331	0.2*	2.364	0.00699	0.0396
Leucite: Rome, Italy	0.00274	0.2*	2.483	0.00551	0.0369
Vitreous silica (General Electric)	0.00325	0.201	2.205	0.0074	0.0379
Hyalite: Spruce Pine, North Carolina	0.00290	0.2*	2.080	0.0070	0.0347
Glass: obsidian	0.00330[d]	0.2*	2.4[c]	0.00688	0.0398
ordinary flint (lead)	0.0018[d]	0.117[c]	3.5[d]	0.00440	0.0272
very heavy flint (lead)	0.0012[d]	0.117*	4.5[c]	0.00228	0.0251
Metals					
Copper	0.927	0.092	8.89	1.13	0.871
Silver 100%	1.00	0.056	10.5	1.70	0.767
Silver 69%, gold 31% (weight)	0.237	0.048*	12.3	0.401	0.374
Silver 34%, gold 66% (weight)	0.152	0.040*	15.5	0.245	0.307
Gold 100%	0.707	0.031	19.3	1.18	0.650
Aluminum	0.485	0.214	2.7	0.839	0.529
Platinum	0.166	0.032	21.4	0.242	0.337
Platinum, 10% iridium	0.074	0.032*	21.6	0.107	0.226

[a] *Unless another reference is indicated by a superscript letter, the values for conductivity and density were taken from Horai, 1971; for specific heat, from Robie and Waldbaum, 1968. * = Assumed value; not found in the literature.*

[b] *Burgemeister, 1978.*

[c] *Webster, 1975.*

[d] *Chemical Rubber Co., 1966.*

[e] *Clark, 1966.*

[f] *Washburn, 1929.*

a given thickness of material to the temperature difference across it. It is usually measured by steady-state experiments (Carslaw and Jaeger, 1959, p. 25). Typically, this consists of passing a known rate of heat through a slab of known thickness, and measuring the resultant temperature difference. Thus, in the case of our homes, we can reduce the rate of heat escape by putting in better insulation (a material of lower thermal conductivity) or by increasing the thickness of the insulation.

In crystalline materials, thermal conductivity is a function of the direction that heat flows, directly analogous to the refractive index. In general, the thermal and optical symmetry will be the same (Washburn, 1929, p. 230). Thus, non-isometric gems will have a conductivity dependent on the direction of heat flow during testing. The variation can be significant (Clark, 1966, p. 466); quartz, for example, shows a variation of 2:1. Unfortunately, the variation of conductivity with direction is known for relatively few gem species.

Specific heat is the amount of heat required to raise one gram of a substance one degree Celsius. It can be thought of as a constant which gives the amount of heat that can be stored in a given mass by raising the temperature. For most gem species, the specific heat varies little from 0.2 cal/gm °C. It has little value in discriminating between gems.

Thermal diffusivity is a parameter used to describe the velocity of heat flow in a substance. Consider what happens when a copper rod is heated on one end. Heat is conducted into the rod and starts to flow or diffuse along it. Some of the heat is used to raise the temperature of the rod; this is where the specific heat comes into play. The rest of the heat diffuses down the rod at a velocity characteristic of the material. The diffusivity specifies that velocity*. I have introduced this property because of its central importance to solutions of problems in heat flow and temperature distribution in solids. We will return to this in discussing stone size limitations for probe measurements.

Many readers may have noticed that a sterling silver spoon when used to stir hot coffee will get too hot to handle much faster than a stainless steel spoon. This is a direct result of the much greater diffusivity of silver.

Thermal inertia is a property that measures how fast the surface temperature of a material can be changed by application of a given quantity of heat-per-second to the surface. If a material has high thermal inertia, then the surface temperature will rise very slowly. The name comes from analogy to mechanical inertia.

As mentioned above, the physical significance of thermal inertia is well known by gemologists who recognize the cold feeling of crystalline gems in contrast to glass or plastic. In this case, the fingers provide a source of heat that tries to raise the temperature of the material. If the material has high thermal inertia, the heat from the fingers cannot raise the surface temperature at a fast rate. The nerves in the finger tip sense this as a cold feeling that persists longer than for a substance such as glass or wood, which has low thermal inertia. The DiamondMaster works in exactly the same way except that it gives a more quantitative measurement.

Although thermal inertia is not a well-known property, its measurement has important applications in several areas. Geologists working in the field of remote sensing measure the variation of the surface temperature of the earth due to solar flux by means of airborne or satellite infrared photography. Through computer processing of these data, they are able to map variations in thermal inertia at the earth's surface. These maps provide an important means of discriminating between rock types (Watson, 1975; Watson et al., 1981; and Watson, 1982). The Ceres Diamond Probe operates in a similar manner, except that the heat source has a period of one second rather than the sun's one day (Read, 1980; Hoover, 1982).

In my article on the Ceres Diamond Probe (Hoover, 1982), the propagation of a thermal wave (i.e., a single-frequency sinusoidally varying temperature wave) down a thin insulated rod was explained. The results show that thermal waves travel at very slow velocities and are rapidly attenuated. The thermal pulse applied to a gem by the DiamondMaster may be considered as made up of all frequencies. However, since the reading is taken after about one second at maximum scale, the predominant frequency will be near one hertz (cycle per second). Thus, the heat penetration and

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The velocity is given by $V = \sqrt{4\pi fk}$, where f = frequency and k = thermal diffusivity.

volume of gem material measured will be about the same as is measured by the Ceres Probe.

The depth of heat penetration into the gem and the limitations it imposes on measurement accuracy can be estimated by considering the case of a simple one-dimensional flow of heat down a thin rod of various material. For this case, and no matter what the material, the amplitude of the thermal wave is attenuated to 0.0019 of its surface value after traveling only one wavelength.

At a frequency of one hertz, diamond has a velocity of 10 cm/sec and beryl, 0.47 cm/sec, giving corresponding wavelengths of 10 cm and 0.47 cm. If a rod of diamond or beryl, for example, were cut off at a half wavelength, 5 cm or 0.235 cm, then heat would be reflected back to the starting end, travelling a total distance of one wavelength. On return to the starting end, the thermal wave would have less than a 0.2% effect on the surface temperature. In effect, measurement of the temperature on one end would not be able to distinguish if the rod is one wavelength long or infinite in length. However, if the rod or the stone being tested is too small, sufficient heat will be reflected from rear and side facets so that the surface temperature will be greater than on a larger stone. This will give an incorrect value, making the stone appear to have too low a thermal inertia. The size problem is important in the quantitative measurement of colored stone melee and with most diamonds. If we wish to keep the size error under 5%, assuming a rod model as discussed above, the stone must have a minimum dimension that is not less than one-quarter wavelength. Corundum gives a useful guide because it has the largest thermal inertia, next to diamond, a gemologist is apt to encounter. For corundum, this minimum dimension is 0.27 cm. For diamond, the corresponding depth is 2.5 cm, or about one inch! Clearly, most diamonds give too low a response on these instruments. I must add that the above are conservative estimates, because heat in a gem flows in three dimensions, giving increased attenuation over that predicted by the one-dimensional assumption.

Thus the design of a particular thermal testing instrument, in particular the frequency of the thermal wave, determines the minimum size of stone on which accurate thermal inertia measurements can be obtained. This is not, however, the minimum size of stone that may be tested. Knowing that melee diamonds, for example, will give too low a response, one can use known diamond melee to calibrate the instrument response as a function of size. The much greater thermal inertia of diamond over its simulants still permits easy differentiation even on very small stones. Loose melee may also be tested by placing the stones on a silver or copper plate, which effectively increases the apparent stone size, making it easier to distinguish diamond from its simulants. The Kashan Diamond Detector provides a special tip and plate for this purpose. Similarly, mounted diamonds benefit from the contact with the mounting, which provides an increase in apparent thermal inertia over a loose stone. One must, of course, be careful not to touch the mounting when testing because of the high thermal inertia of the metal.

CATALOG OF THERMAL PROPERTIES

It is hoped that the preceding discussion has given the reader a better understanding of how thermal probes operate, and a basis by which they may be used to discriminate between various gem materials. In table 1, the author has collected thermal properties for a number of gem species and related materials. Thermal diffusivity and inertia were calculated from the other listed properties. Because of the relationship between the thermal properties, it should be apparent that for nonisometric gems, diffusivity and inertia will vary with the direction of heat transfer in the same way conductivity varies.

The majority of conductivity values are from Horai (1971), and were made on powdered samples. Because of the random orientation of the grains, these are mean values of conductivity. As can be seen from the table, conductivities range from 0.002 cal/cm-sec-°C for glass to 4.8 for diamond, a range of over 2000:1. Thermal inertia, however, spans a range of about 50:1. The table is arranged in order of decreasing inertia, except where more than one value is given for a particular gem. Conductivity follows in almost the same order. Note also that the order is quite distinct from an ordering of gems based on density or refractive index. This can be advantageous for testing, especially if more precise instruments are developed. Comparison of the relative response of the DiamondMaster, given in figure 3, with corresponding values from table 1 shows that the in-

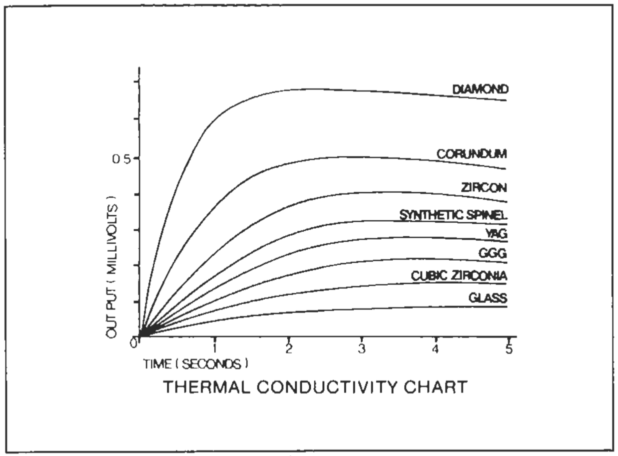

Figure 3. Graph provided with the DiamondMaster to show the measured response of the instrument for various gem materials.

strument gives a reasonable measure of inertia rather than conductivity.

DISCUSSION

Caveats When Using the DiamondMaster. For gem testing the important question is: How does one use the instrument to assist in separating gems, and for what separations does it have practical utility? Reasonable repeatability of measurements is of primary importance, and this is somewhat of a problem with the DiamondMaster. Remember that the instrument was only intended to distinguish diamonds. Small variations in the surface of the probe tip and contact angle make exact reproducibility impossible. Practice and care in use, however, will give reasonable results. If one then averages three or more readings, it should be possible to distinguish between the gems discussed below. Because of differences in each probe tip and in the setting of the calibration level on each instrument, known gems should always be used to establish the calibration of each instrument, and this should be checked periodically.

If the probe tip has flat areas or is rough, the difficulty of obtaining good repeatability will be increased. This can result from wear on the soft copper tip. When this occurs on my DiamondMaster, I very carefully dress and polish the tip. A more durable tip of spherical form, so that the contact angle would not affect the measurements, would make the instrument much better for quantitative measurements.

Certain other factors should be kept in mind when using the instrument. The surface finish of the material being tested can affect the measurement by changing the contact area with the tip. In fact, similar devices have been used to measure surface roughness (Powell, 1957). Thus, care should be used in interpreting readings on badly scratched or chipped gems. Internal features also can give rise to changes in thermal inertia. Zircon is an excellent example because it is a metamict mineral. Destruction of the crystal lattice is associated with a decrease in inertia. Thus, high zircon has a value near that of spinel, while some low zircons in the author's collection approach glass in value. This very large range for zircon limits the value of thermal methods in testing for this gem.

Gem species that form solid solutions, such as the garnet, plagioclase, and olivine groups, will show a change in inertia related to composition. The interesting point is that the thermal inertia is not a linear relation between end-member values, but will show a minimum value at some intermediate composition (Horai, 1971, p. 1299). As quantitative instruments that permit better reproducibility and increased precision of measurement are developed, this property may be particularly helpful when used with refractive index measurements in distinguishing between various members of such groups. Gemtek Gemmological Instruments manufactures the Gemmologist, a thermal device reported to distinguish between many colored stones as well as diamond (Read, 1983). To the author's knowledge, this is the only instrument specifically designed to have the increased sensitivity for effective measurement of colored stones.

Use of the DiamondMaster for Gems Other than Diamond. On the basis of the preceding discussion, the author has investigated the use of the DiamondMaster to help distinguish between various other gems. It was determined that while the instrument should not be used as the only test, it can be helpful as an ancillary test to confirm an identification. A careful observer should find the instrument useful in several determinations, as described below.

The distinction between ruby, red spinel, and pyrope (figure 4) is readily made. For these gems, the inertias given in table 1 are 0.222, 0.133, and 0.0754, respectively. Each differs from the other

Figure 4. These three stones, often indistinguishable by color, are easily separated on a thermal testing instrument like the DiamondMaster. In the author's experiments, representative samples of pyrope, similar to the 1.36-ct stone on the left, showed 0% of full scale on his instrument; samples of red spinel, similar to the 0.68-ct stone in the center, registered 35% of full scale; and ruby, similar to the 1.16-ct stone on the right, registered 60% of full scale, a measure of the high thermal inertia of corundum.

by about a factor of 2, a difference that appears to be easily measured by the instrument. Representative samples of these gems gave average readings of 60%, 35%, and 0% of full scale (remember that in air the meter reading is well below zero). The higher the thermal inertia of the stone is, the higher its reading on the scale will be. Similarly, sapphire, blue spinel, and benitoite also may be separated. Benitoite is not listed in table 1; however, tests on several stones show it to have an inertia near that of pyrope. On these and the following examples, the user should always keep in mind the discussion of the effect of size on measurements of materials of various thermal inertias. Known reference material is necessary for calibration of the instrument, and testing of very small stones should include reference stones of similar size.

A glance at table 1 shows that topaz has a relatively large inertia of 0.138. One would infer that it, too, could be easily distinguished from aquamarine, which has a value of 0.0718. This is the case, providing a simpler test for these gems than a refractometer.

Quartz also has a fairly large inertia. This is useful in helping to distinguish it from some of the other, similar-appearing gems. Likewise fluorite, with an inertia of 0.126, often may be separated from gems with which it might be confused.

In my experiments, I found that the DiamondMaster can be used to separate jadeite from nephrite, but that care is required. Jadeite gives a reading about 10% of full scale, while nephrite is near 0%. This is useful in testing carvings that are difficult to place on a refractometer. It is interesting to note that the values of inertia shown in table 1 for jadeite and some amphiboles would suggest that the differentiation could not be made, at least with the present instruments. Either the literature values cited here are not representative, or the listed amphiboles are not representative of nephrite.

Lastly, it was found that sinhalite could be easily separated from peridot. Sinhalite is not listed in table 1, but readings with the DiamondMaster show that it has an inertia about the same as topaz and much greater than peridot.

It is hoped that the preceding discussion will permit the practicing gemologist to make more effective use of these new thermal testing instruments. Unfortunately, at present, the state of knowledge of thermal properties of gem materials is quite limited. Advances in this knowledge for practical use in gem testing will probably first come through experience in the use of the instruments. Advances in the instrumentation, particularly directed toward improvements in the precision and reproducibility of readings, will also go far to making these devices important tools in gem testing.

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