Prediction of Threshold Pain Skin Temperature from Thermal Properties of Materials in Contact

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Aerospace design engineers have long sought concrete data with respect to the thermal safety of materials in contact with human skin. A series of studies on this subject has been completed and some of the results have been reported earlier. In these studies over 2,000 observations were made of pain threshold during contact with materials at elevated temperatures. Six materials were used representing the full range of thermal properties from good conductors to good insulators. Previous reports gave methods for determining the maximum permissible temperatures for any material in safe contact with bare skin for 1-5 s solely from a knowledge of its thermal properties. This report presents the comparison of the theoretical and experimental contact temperatures at pain threshold and provides a method for deriving the skin temperature productive of threshold pain from the thermal properties of any material within the range of those studied. Ratios reflecting the heat transfer coefficient associated with the materials in contact are related to their thermal properties so that the skin temperature at pain threshold may be determined from that calculated from heat transfer theory. Tabular and graphical representation of these data permits interpolation within the range of properties so that any material of known thermal conductivity, density and specific heat may be assessed with respect to its effect on the skin temperature during contact to the end point of pain. These data, in conjunction with those already reported, constitute a system for the complete assessment of the thermal aspects of practically any material suitable for construction and manufacturing applications with respect to safe contact with human skin.

The hazards of producing pain and burn in the aircrewman due to excessive heating of cockpit and fuselage materials have been under investigation for some time. Earlier reports (1,3) have provided the biophysical data base and engineering guidelines for prediction of the highest temperature specific materials may attain without causing pain or burn on contact. The present report extends both the data base and the guidelines by providing interface temperatures measured during contact between materials and skin and relating these to the heat transfer coefficient in a manner which permits prediction of the skin temperature at pain threshold solely from a knowledge of the thermal properties of the material concerned.

MATERIALS AND METHODS

The materials and methods have been previously described in detail (3). Briefly, they consisted of fingertip contact with each of six materials representative of the range from good conductors to good insulators, heated to various levels of temperature and maintained constant until pricking pain was perceived. The interface temperature at the skin-material junction was measured continuously by means of a 40 gauge copper-constantan thermocouple affixed to the fingertip. The initial temperatures of both the skin and the material were measured radiometrically immediately before contact, the initial skin temperature being 32.5 ± 0.5°C in all instances. About 2,000 observations were made on skin sites on four normal subjects. All data except the present data were compared with the interface temperature to be expected from theory and then used to establish a system for predicting the observed temperatures from the theoretical temperatures. The factors so derived reflect the variations in heat transfer coefficient with the various materials in contact with skin and the procedure developed here enables simple and practical application within the time and property limits of the data.

RESULTS AND DISCUSSION

Unlike the data which could be obtained from initial temperatures and contact time observations alone, interface temperatures were technically difficult to obtain.
due to breakage of the delicate thermocouple wires and occasional poor contact. Consequently, about half of the observations were discarded and only 1,006 obtained from steady, reliable recorded traces were retained for analysis.

Theoretically, the interface temperature on contact should instantaneously attain a point intermediate between that of the initial temperature of the skin and the material and remain constant thereafter as long as the contact is maintained. This theory was described by Vendrik and Vos (5) in their method for measuring thermal conductivity of skin. They pointed out that, mainly because of the inhomogeneity of the skin, the interface temperature rises slightly throughout the course of the contact and indeed this rise was observed in the present data. Therefore, the interface temperature used in each instance was that observed at the time of pain threshold occurrence (TiPT) rather than immediately on contact (Tc) (Table I).

All the data were plotted individually as a function of the material temperature and a family of curves was obtained (Figure 1). The standard deviation of the data was within ±10% and, as seen in this figure by reference to the coordinates for the three epidermal thicknesses indicated, the slopes of the curves were independent of the thickness of the epidermis. Also, although the material temperature at which pain was perceived at any given pain threshold time relied heavily on the thickness of the epidermis, the interface temperature was quite independent of the contact material properties, being less than 1°C different from the best conductor to the best insulator.

For comparison with the experimental interface temperatures, the theoretical contact temperatures were obtained from the relationship for instantaneous temperature on contact:

![Normalized material-skin interface temperature (TiPT) vs. material temperature at pain threshold (TmPT); coordinates at 3-s pain threshold end points at three epidermal thicknesses indicated by horizontal lines PT at 3s.](image)

**TABLE I. OBSERVED AND THEORETICAL INTERFACE TEMPERATURES DURING HEATING TO PAIN THRESHOLD BY CONTACT WITH VARIOUS MATERIALS.**

<table>
<thead>
<tr>
<th>Material</th>
<th>Epidermal Thickness (mm)</th>
<th>TmPT* (°C)</th>
<th>Tc** (°C)</th>
<th>TiPT*** (°C)</th>
<th>TmPT (°C)</th>
<th>Tc (°C)</th>
<th>TiPT (°C)</th>
<th>Average TiPT ± σ</th>
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</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>0.090</td>
<td>53.6</td>
<td>52.3</td>
<td>0.933</td>
<td>51.0</td>
<td>49.9</td>
<td>0.924</td>
<td>0.936 ± 0.008</td>
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<td></td>
<td>0.254</td>
<td>58.7</td>
<td>57.0</td>
<td>0.933</td>
<td>54.6</td>
<td>53.3</td>
<td>0.931</td>
<td></td>
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<td></td>
<td>0.443</td>
<td>66.5</td>
<td>64.4</td>
<td>0.938</td>
<td>60.1</td>
<td>58.4</td>
<td>0.938</td>
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</tr>
<tr>
<td></td>
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<td></td>
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<tr>
<td>Steel</td>
<td>0.090</td>
<td>54.4</td>
<td>51.8</td>
<td>0.942</td>
<td>51.7</td>
<td>49.4</td>
<td>0.951</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.254</td>
<td>59.8</td>
<td>56.5</td>
<td>0.942</td>
<td>55.5</td>
<td>52.8</td>
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<td></td>
<td>0.443</td>
<td>68.2</td>
<td>63.9</td>
<td>0.945</td>
<td>61.3</td>
<td>57.9</td>
<td>0.947</td>
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<td>Hercuvit</td>
<td>0.090</td>
<td>61.2</td>
<td>49.3</td>
<td>0.991</td>
<td>57.1</td>
<td>46.9</td>
<td>1.002</td>
<td>0.944 ± 0.0039</td>
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<td>0.254</td>
<td>69.3</td>
<td>54.1</td>
<td>0.983</td>
<td>62.9</td>
<td>50.3</td>
<td>0.986</td>
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<td>0.443</td>
<td>81.9</td>
<td>61.4</td>
<td>0.984</td>
<td>76.6</td>
<td>55.4</td>
<td>0.982</td>
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<td>Glass</td>
<td>0.090</td>
<td>64.9</td>
<td>48.6</td>
<td>1.004</td>
<td>60.0</td>
<td>46.1</td>
<td>1.020</td>
<td>0.988 ± 0.0024</td>
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<td>0.254</td>
<td>74.4</td>
<td>53.3</td>
<td>0.998</td>
<td>66.8</td>
<td>49.5</td>
<td>1.002</td>
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<td>0.443</td>
<td>89.3</td>
<td>60.7</td>
<td>0.995</td>
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<td>1.002</td>
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<td>Teflon</td>
<td>0.090</td>
<td>74.1</td>
<td>47.4</td>
<td>1.030</td>
<td>67.3</td>
<td>45.0</td>
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<td>1.003 ± 0.0080</td>
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<td>0.254</td>
<td>87.3</td>
<td>52.1</td>
<td>1.023</td>
<td>76.8</td>
<td>48.4</td>
<td>1.025</td>
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<td>108.0</td>
<td>59.5</td>
<td>1.015</td>
<td>91.1</td>
<td>53.5</td>
<td>1.024</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.023</td>
<td></td>
<td></td>
<td>1.031 ± 0.0012</td>
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<tr>
<td>Masonite</td>
<td>0.090</td>
<td>82.0</td>
<td>46.8</td>
<td>1.043</td>
<td>73.7</td>
<td>44.4</td>
<td>1.059</td>
<td>1.038 ± 0.00056</td>
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<tr>
<td></td>
<td>0.254</td>
<td>98.4</td>
<td>51.6</td>
<td>1.031</td>
<td>85.4</td>
<td>47.8</td>
<td>1.038</td>
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<tr>
<td></td>
<td>0.443</td>
<td>124.0</td>
<td>59.0</td>
<td>1.024</td>
<td>103.1</td>
<td>52.9</td>
<td>1.036</td>
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</table>

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* TmPT = measured material temperature required to produce threshold pain at given contact time.
** Tc = theoretical instantaneous interface temperature on contact of material and skin.
*** TiPT = observed interface temperature at pain threshold (PT):
THERMAL PROPERTIES AND SKIN PAIN—STOLL ET AL.

\[
T_c = \frac{T_{mPT} + K T_{so}}{1 + K} \quad \text{(Eq. 1)}
\]

where

\[
T_c = \text{instantaneous contact temperature (C)}; \quad T_{mPT} = \text{material temperature at pain threshold (C)}; \quad T_{so} = \text{initial skin temperature (C)}; \quad K = \frac{(k_{pc \text{ skin}})^{1/4}}{(k_{pc \text{ material}})^{1/4}} \quad \text{(cal}^2/\text{cm}^4 \cdot \text{C}^2\text{)};
\]

and

\[
k = \text{thermal conductivity (cal/s'C cm)}; \quad \rho = \text{density (gm/cc)}; \quad c = \text{specific heat (cal/gm 'C)}
\]

using the TmPT values described earlier (3). The ratio of the average TiPT/Tc was then obtained for each material and epidermal thickness, Table I.

It is evident from this comparison that the theoretical contact temperature is greatly influenced by the thermal properties of the various materials. As seen in Table I, the ratio for the least epidermal thickness was almost always slightly higher than that for the greater thicknesses, probably due to the use of a constant kpc (thermal inertia) for skin throughout the calculations. Actually, the kpc is slightly lower where the epidermis constitutes a greater proportion of the total thickness from surface to pain receptor level as the epidermis is a better insulator than the dermis. However, the differences in ratios are so small as to be negligible in the present applications and therefore all values were included in the averages shown. The glass/skin ratio most nearly approximates 1.0 as the kpc of this substance most nearly matches that of skin. This fact was utilized by Vendrik and Vos (5) who used glass in their conductivity determinations to avoid the problems introduced by lack of a heat transfer coefficient in Eq. 1. This coefficient, though simple for steady state conduction, becomes quite complex for the transient state (2). In fact, it is common engineering practice to use values obtained empirically because of the deviations from theoretical values introduced by surface anomalies such as roughness, contact pressure, air bubbles, thin films of extraneous matter, etc., over and above possible slight gradients within the material. In the present instance the very presence of the thermocouple, no matter how fine, introduces an additional disturbance; however, the consistency of the measurements used indicates that the conditions were reproducible with each material. Furthermore, comparisons with radiometric measurements of skin temperature at PT (4) agree with the present TiPT values within about \(\pm 0.5^\circ\text{C}\) suggesting that the thermocouple effect was not large. Therefore, the ratio TiPT/Tc constitutes a reliable reflection of the actual local heat transfer coefficient in each instance.

To find the skin temperature at pain threshold from the properties of the material, the ratios obtained were plotted against the reciprocal of the root of the thermal inertia (Fig. 2), permitting interpolation of the appropriate ratio for a material other than those studied. This system has the added advantage of referring the ratios to the same base as used earlier for illustrating variations of TmPT with contact time and with epidermal thickness (3). To find the skin temperature at pain threshold for any given material, then, one may locate the material on the abscissa in Fig. 2 and find the corresponding TiPT/Tc ratio from the curve. Subsequently, by using the procedures described by Stoll et al. (3), TmPT is calculated for any given epidermal thickness and contact time up to 5 s. (Use of this system below 1s is not recommended as this time is insufficient to accomplish an adequately stable temperature. However, by 3 s the temperature is stable and, for all practical purposes, equal to that at 5 s.) From the TmPT the theoretical Tc is calculated and then multiplied by the appropriate ratio to yield the correct TiPT which is the skin temperature at pain threshold during contact.

Within the contact times of 3 to 5 s and the epidermal thicknesses of 0.254 and 0.433 mm the greatest difference in temperatures (TiPT - Tc) is \(\pm 0.3^\circ\text{C}\) using the system above. At a thickness of 0.090 mm the greatest difference amounts to \(-0.9^\circ\text{C}\) at 5 s and \(-0.4^\circ\text{C}\) at 3 s at the conductor end, comparable differences are \(-0.3^\circ\text{C}\) at 5 s and \(+0.1^\circ\text{C}\) at 3 s. In view of the fact that the original data are subject to errors as large as \(\pm 10^\%\) (3) these differences (of the order of 2\%) are not significant.

A practical problem serves to illustrate the use of these data and methods: Consider the need for a material to be contacted by the bare skin, perhaps a knob on a control panel. The question is whether the material should be a metal or a plastic, or possibly, rubber, as the panel may be subject to rather severe heating. The information required for this decision is: first, the maximum skin temperature permissible to prevent appreciable pain and, second, the material temperature at which pain will occur in a reasonable contact time. Assume that a reasonable contact time is 3 s and that the epidermal thickness of the fingertips is average or about 0.25 mm.

Solution: Table I shows that the metals would not be suitable because under severe heating conditions they would be expected to exceed the 3 s TmPT (58 - 60°C). However, if metals are dictated because of some structural problems, they may be coated with an insulating...
material, silicone rubber, for instance. Then, to pick a specific example, consider RTV 20 (GE) as a candidate material. Properties supplied by the manufacturer are 
\[ k = 6.4 \times 10^{-4}, \quad \rho = 1.35, \quad \text{and} \quad c = 0.35 \] 
all in cgs units; thermal inertia \((k \rho c) = 0.303 \times 10^{-3}\) and \(1/(k \rho c)^3 = 57.5 \text{ cm}^2 \text{ C s}^5/\text{cal.}\) Reference to Fig. 2 shows that this material will behave much like Teflon since its thermal inertia is almost the same, and reference to Table I indicates that the TmPT will be about 87°C, and the Te, about 52°C. However, an exact solution may be obtained by use of the equations or the charts in Stoll et al. (3)(qq.v.):

To find TmPT from the data given, applying equations Stoll et al. (3):

- Intercept \(0.490 (3) - 0.412 = 0.078\)
- Slope \(1.094 (3) - 0.184 = 0.910\)
- \(\log \text{Slope} 0.910 (0.25) + \log 0.078 = -0.315\)
- \(\text{Slope} 0.5214\)
- \(T_{mPT} 0.5214 (57.5 + 31.5) + 41 = 87.4\)°C

Then from the present Eq. 1:

\[ T_c = 87.4 + 1.8167 (32.5) / 2.8167 = 52.0\)°C;\]
and from Fig. 2, TiPT/Te at 57.5 = 1.028
so that TiPT = 1.028 (52) = 53.4°C.

It is seen from this analysis that a metal control knob coated with a sufficiently thick layer of silicone rubber would reach 87°C, and that contact could be maintained for up to 3 s without pain. Stoll et al. (3) indicates also that at a material temperature of about 128°C pain will occur almost instantaneously (0.3 s) and at 180°C, a blister will result from a 0.3 s contact with this substance.

Finally, while the present treatment of the data circumvents the need for use of the heat transfer coefficient in terms of cal/sec cm² °C, should this information be desired, all the data are available and may be adapted to use as follows (2):

\[ h_c = \frac{dQ/d\theta}{A (T_m - T_s)}, \quad \text{Eq. 2} \]

where: \(h_c = \text{heat transfer coefficient for conduction (cal/s cm² °C)}\)
\(dQ/d\theta = \text{rate of heat transfer per unit area (cal/cm² s) available from Fig. 1, (3)}\)
\(T_m = \text{initial material temperature (°C); and} \)
\(T_s = \text{initial skin temperature (°C) }\)

Since this coefficient is specific to each situation of heat flow, it is necessary to choose individual term values appropriate to the conditions of use and, where an appreciable gradient exists (as from skin surface to pain receptors), to apply an appropriate form of the conduction equation (2).

SUMMARY AND CONCLUSION

The present data, viz., interface temperatures during heating of living skin by contact with various materials, complete the study of thermal conduction effects in human skin. They reflect the effect of the local heat transfer coefficient on the measured and the theoretical contact temperature throughout a wide range of material properties. Taken together with the information reported earlier, methods are provided for the complete analysis of thermal safety of any material considered for contact with bare skin. Such analyses permit pre-selection of suitable construction and manufacturing materials simply from a knowledge of the thermal properties of the materials and the heat transfer characteristics of the environmental hazard.

ACKNOWLEDGMENT

The authors are grateful to Mr. Dom Zaccaria for his excellent technical assistance.

Work supported by the Naval Air Systems Command and the U.S. Consumer Product Safety Commission. The voluntary informed consent of the participating subjects was obtained as requested by existing U.S. Navy regulations. Opinions or conclusions contained in this report are those of the authors and do not necessarily reflect the views of the Navy Department or Consumer Commission.

REFERENCES


