4-16-1991

# The Thermal Response of Downhill Skis

S. C. Colbeck
*U.S. Army Cold Regions Research and Engineering Laboratory*

G. C. Warren
*Dartmouth College*

*Journal of Glaciology*, Vol. 37, No. 126, 1991

# The thermal response of downhill skis

S. C. COLBECK

*U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire 03755-1290, U.S.A.*

G. C. WARREN

*Thayer School of Engineering, Dartmouth College, Hanover, New Hampshire 03755, U.S.A.*

ABSTRACT. The temperatures in downhill skies were measured with thermocouples to investigate the heat generation associated with the sliding of skis on snow. In these tests we investigated the effects on ski temperature of the ambient snow temperature, snow type, speed, load and thermal conductivity. A significant temperature rise at the base of the ski was found at the onset of motion in all runs. The temperature rise increased for heavier loads and at lower ambient temperatures. Some ski runs lasted long enough to observe a steady-state temperature at the ski base; it increased with ambient temperature. Longitudinal and transverse temperature variations occurred and were sensitive to snow hardness and skiing technique.

We also investigated heat flow through the cross-section of the ski with a finite-element model to determine the effects of ski structure on heat retention at the base. We found that the thermal characteristics as determined by the structure of the ski had a significant effect on the temperature at the ski base. At lower temperatures we expect that friction will be greater in skis which have a large aluminum plate across their base. Steel edges have a lesser effect.

## INTRODUCTION

The low friction between any slider and snow or ice is thought to result from a thin meltwater layer caused by frictional heating during sliding. This heat accounts for nearly all of the frictional energy loss and is very sensitive to the ambient temperature, speed and load. We used both field measurements and a finite-element model to investigate both heat generation and the thermal characteristics of downhill skis. The heat generated and retained at the base of a ski should greatly affect its friction and thus information about ski temperature should help us understand how skis slide on snow and how skis could be designed to improve sliding.

The coefficient of kinetic friction ($\mu$) is the ratio of the frictional force ($f$) to the normal force ($N$). When two surfaces rub together, most of the heat generated ($Q$) is dissipated as the product of the relative speed ($v$) and the frictional force ($F$), or

$$Q = vf = \mu v N. \tag{1}$$

Under some conditions this heat production can cause melting of one or both of the materials at the frictional interface; in fact, frictional melting is of interest for a variety of materials, not just snow and ice. According to the theory of Colbeck (1988), the meltwater films in snow can be sustained by the heat generated from the shearing at the base of the ski. Thus, the mechanical energy is used in a process that minimizes the friction. The coefficient of friction appears to be influenced by a number of parameters including speed, ambient temperature, snow type, and themal conductivity and surface characteristics of the slider. Measurements of the interfacial temperature should provide a test of the extent to which these factors affect the thermal response and therefore the sliding resistance of materials on snow.

It would be helpful to know the temperature of the actual contact points of a slider on snow, but limitations on sensor size and response time restrict us to measurements of an average temperature of the surface. We could have chosen to do these tests in the laboratory where our ability to control and measure these factors would have been greater, but we felt that more useful information could be gained from the higher speeds and natural snow conditions found in actual skiing. In laboratory tests, neither real skis nor realistic speeds could have been used and the slider would have passed over the same section of snow repeatedly, thus allowing heat to accumulate in the snow sample.

## SOME PREVIOUS INVESTIGATIONS

Most of the previous investigators were proponents of

the meltwater theory, and measurements of the thickness of the meltwater layer have been made (Ambach and Mayr, 1981); only one argued that alternative processes were responsible for the low friction observed. Bowden and Hughes (1939) laid the foundation for understanding the small coefficient of friction between snow and a sliding ski. They used ice but the results apply, at least qualitatively, to snow. They showed that frictional heating, not pressure melting, is the cause of melting at the snow surface. Although much heat is lost by conduction into the snow and ski, a sufficient amount can be retained to cause local melting at the contact points (melt caps on snow grains are shown in Warren and others (1989)). They concluded that melting is dependent on the ambient temperature, so at very low temperatures snow would exhibit the same frictional characteristics as other non-lubricated materials.

Bowden and Hughes hypothesized that speed influenced only the temperature increase of the slider, and not the temperature increase of the snow, since a slider continuously receives heat during sliding, while a section of snow only receives heat while the slider passes over it. They concluded that a slider of poor thermal conductivity would cause more melting because of the greater retention of heat at the frictional interface. The effect of thermal conductivity on melting was thought to be more pronounced at lower temperatures. The electrical conductivity at the base was found to increase as the slider was set in motion, suggesting the formation of a meltwater layer. At lower temperatures, smaller values of the electrical conductivity were observed because the melting occurred only at localized points.

Klein (1947) suggested that the front of an aircraft ski was subjected to more wear because the ski was dry when it first came into contact with undisturbed snow. He proposed three types of sliding resistance at the base of a ski: solid friction at the front of the slider, viscous resistance due to shearing of the meltwater layer, and surface tension effects. Each component depends on the temperature, snow structure, pressure and material in contact with the snow.

McConica (1950) rejected the idea of meltwater lubrication and proposed an alternative explanation for the low friction of snow. McConica discovered that a highly conductive magnesium ski had a lower resistance to sliding than a well-lacquered wood ski at temperatures well below the melting point, and he showed that the formation of a meltwater layer at these temperatures was doubtful. He then concluded that the retention of heat at the ski base did not influence the coefficient of kinetic friction and predicted that the base would be at the ambient temperature of the snow when the ski was in motion. This conclusion is tested here.

The experimental study of Tusima and Yosida (1969) best replicated real skiing conditions and discovered that melting began when forward motion was initiated but that the rate of melting reached a constant value with time. They theorized that the points of contact were at 0°C after only 0.1 s of forward motion.

Evans and others (1976) measured the temperature rise caused by frictional heating on ice and quantified the effect of slider thermal conductivity on friction. They found that for a copper slider, between 40 and 60% of the heat was conducted away through the copper and this fraction was independent of the air temperature between -2° and -15°C. They found higher friction for the more conductive copper sliders than for other materials.

## METHODS

Both field measurements and numerical calculations of the temperature fields in skis were made to gain insight into their thermal response. Each approach provides some useful information about the behavior of skis.

### Field methods

Two ski types were selected for the temperature measurements: a 1.1 m child's plastic ski and a 2.25 m Rossignol downhill (DH) racing ski. The child's ski was a simple molded plastic with thermocouples implanted through holes bored from the upper surface (see Fig. 1). The DH ski was built by the Rossignol racing team who installed the thermocouple during construction. Its complicated structure, consisting of many different materials in a complex geometry and its thermocouple array are shown in Warren and others (1989). The interpretation of the data from the child's ski is easier because of its simple construction, while the racing ski is more typical of skis in use. Because of differences in length, flexibility and materials, the results of the two are only comparable qualitatively.

Type T thermocouples of about 0.1 mm diameter were used because of their small size and fast response, but they were fragile. During the field tests, a number of thermocouples either gave erroneous values or quit completely and were replaced in kind. The plastic ski had five thermocouples which gave one transverse and one vertical profile while the Rossignol ski had 32 thermocouples for a three-dimensional array. A data logger, carried by the skier in a backpack, had a real-time temperature read-out to show when the stationary ski was in thermal equilibrium. The thermocouples were recorded every second but had a response time of much less than that because of their small size. Our tests show that this system was capable of making repeated temperature measurements to ±0.1°C after calibration. The data for 30 runs could be stored in a solid-state storage module and, after collection, all of the data was smoothed by a 0.25 Hz filter.

Once the data-acquisition system was programmed, the ski rested flat on the snow until a steady temperature existed throughout. Each test consisted of a simple ski run, but speed and load varied due to changes in mic-

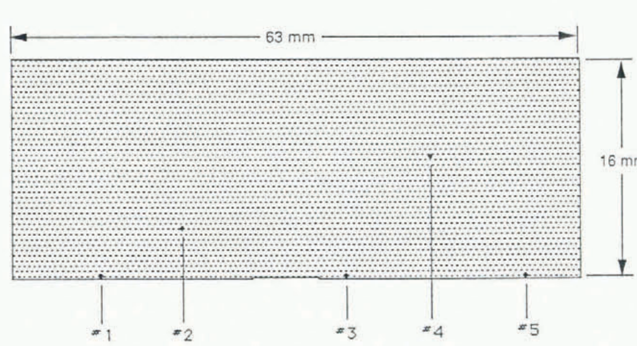


*Fig. 1. Locations of thermocouples in the plastic ski in a cross-section under the skier's foot.*

rotopography, temperature was affected by altitude and solar input, and snow type was affected by temperature, recent snowfalls and skier usage. However, as long as these conditions were recorded and reasonably constant during each run, the rsults were found to be repeatable and useful.

Repeated runs were made in which all of the conditions were nearly constant except snow temperatures which varied up to 4° or 5°C between the first and last runs on any given day. Tests to determine the effects of each parameter or variable were conducted as follows:

A. Test days were chosen in part to ensure the widest possible range of ambient temperatures.
B. Four types of tests were done to examine the effects of load which was varied by the placement of the skier's weight on one or both skis. (i) Tests at different loads at constant speed were done on a Poma lift by weighting and unweighting the ski with a cycle of approximately 20 s at a speed of about $2\,\mathrm{m\,s^{-1}}$. (ii) Very simple tests were conducted in which only the load varied as approximately $N/2$, $3N/4$ and $N$ applied to the test ski, where $N$ is the skier's weight. $N/2$ was applied when the skier distributed his weight evenly and $N$ was applied when all of his weight was on the test ski. The skier estimated $3N/4$ by distributing his weight accordingly. (iii) Tests of turning at slow speeds were conducted with the skier continuously turning either left or right to shift the weight as is normally done in turning. (iv) Tests were done with an even weight distribution while parallel skiing in the tuck (or crouch) to show the skier's weight distribution across the ski.
C. Tests were conducted to determine the temperature change with speed during the downhill runs where the skis were kept parallel and the speed was perceived to increase smoothly. This test was repeated for loads ranging from $N/2$ to $N$ and on different slopes.
D. Tests were conducted on separate days when the snow type had changed because of precipitation or changes in temperature, or both; snow conditions varied from soft, fresh snow to dry, hard-packed snow.
E. The effects of the thermal conductivities of the sliders were investigated by measuring the vertical profiles of temperatures in both skis. Although identical ambient conditions never occurred during testing of both skis because the skis were used on different days, differences in the vertical profiles still illustrate the effects of thermal conductivity.

### Computational procedure

The flow of frictional heat into the DH ski was calculated numerically by the finite-element method to quantify the effects of thermal conductivity and material geometry on heat removal from the interface. We used the software of Glovsky (1982) available on the computer network at Dartmouth College. The temperature distribution in a rectangle representing one-half of the cross-section of the ski was calculated and compared with the temperatures recorded in the field.

At the start of each run, the heat flowing into the ski was specified as about one-third of the frictional heat generated at the base of the ski. This fraction is somewhat arbitrary since the material properties of the ski were changed in the four cases studied but was chosen according to the usual procedure in tribology (Archard and Rowntree, 1988). Assuming that half of the weight of the skier is on each ski, a coefficient of friction of 0.06 and speed of $18\,\mathrm{m\,s^{-1}}$, the heat flow into the ski was taken as

$$q_s = 0.306\mu v N\,. \qquad (2)$$

In the field study we found that once the ski base reached a steady temperature, it was maintained for the duration of the run and was usually between −1° and 0°C. To simulate this temperature condition in the model, the program was stopped once the base had attained a temperature in this range and a fixed temperature was imposed on the base. The deceleration of the ski was simulated by decrementing the temperature of the basal nodes, as we observed in the field. Internal-heat generation due to flexing could have been included, but the significant heat was at the base of the ski. Heat loss due to motion occurred along the sides and top of the ski. The convection coefficient was determined using the equation of Kays (1960) for a speed of $18\,\mathrm{m\,s^{-1}}$.

Four combinations of materials were investigated to determine their effects on the retention of heat at the base. Both the transient and steady-state solutions for temperature were determined for the thermal properties given in Warren and others (1989). In case 1 the temperature distribution was calculated for the actual Rossignol DH ski, incorporating both the aluminum plate across the base and the steel edge. In case 2 the steel edge was replaced with a ceramic edge and in case 3 the steel edge was replaced with a ceramic edge and the lower aluminum plate replaced with a polymer. The vibration-dampening aluminum layer used in racing skis is a significant heat-flow conduit because of its very high thermal conductivity and location at the base of the ski. In case 4 the aluminum layer was replaced with the polymer and the steel edge was re-inserted. This configuration was analyzed to see if the metal components interacted to enhance heat removal.

## FIELD STUDY: RESULTS AND DISCUSSION

The temperature results given here are examples of the data taken. The results were generally found to be repeatable under similar circumstances. The three curves shown in Figure 2 are typical of the results from the base of the plastic ski. In general, the results from the plastic ski were easier to interpret because of its simpler structure and thus more of those results are given.

### Effects of ambient temperature

As shown in Figure 2, curve a, the basal temperature sometimes reached a state of quasi-equilibrium while the ski was still in motion. The temperature at which the base stabilized ranged from −6° to 0.2°C at ambient temperatures of −4.8° to −0.24°C (the value of 0.2°C is probably erroneous but that thermocouple was destroyed before calibration). Even when speed was still increasing, the base could reach a quasi-steady state that ap-

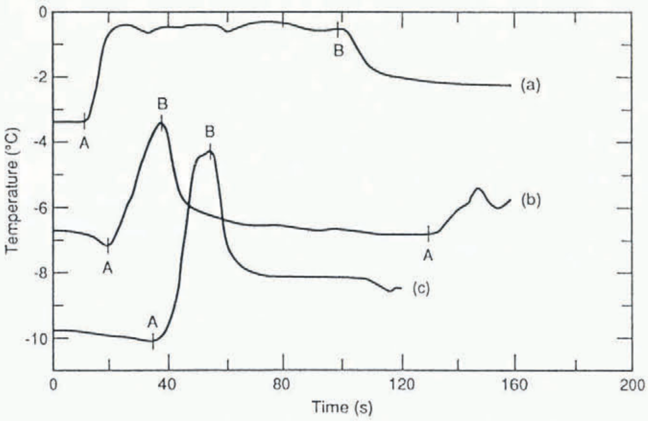


*Fig. 2. Basal temperature on left side of plastic ski during parallel runs down gentle slopes. (a) $T_0 = -3.5\,°C$; $v_{max} \approx 8\ m\,s^{-1}$; load N/2 on soft, fresh snow. (b) $T_0 = -6.7\,°C$; $v_{max} \approx 6\ m\,s^{-1}$; load N on hard-packed snow. (c) $T_0 = -9.7\,°C$; $v_{max} \approx 6\ m\,s^{-1}$; load N on hard-packed snow. A indicates starting of motion and B indicates stopping in all graphs.*

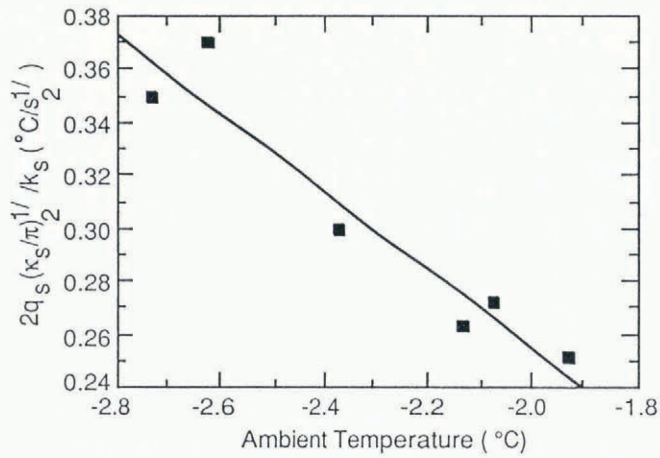


*Fig. 4. $2q_s(\kappa_s/\pi)^{\frac{1}{2}}/k_s$ versus ambient temperature. Other than ambient temperature, the conditions were similar during the various runs.*

peared to be an average temperature between 0°C at the contacts and a sub-freezing temperature over part of the surface that was not in contact. This result supports the idea that the area of contact depends only on the load.

Figure 3 suggests a linear increase in steady-state temperature but a decrease in temperature rise with increasing ambient temperature. Bowden and Hughes (1939) theorized, and it is often observed, that the coefficient of friction increases with decreasing ambient temperature. This probably occurs because meltwater lubrication decreases at low ambient temperatures. Since the rate of heat generation is proportional to the coefficient of friction, it is likely that the greater rise in interfacial temperature at lower ambient temperatures shown in Figure 3 is due to greater heat production resulting

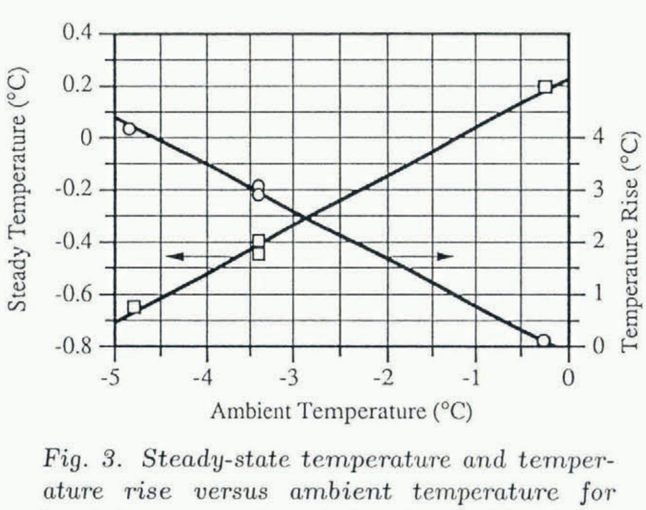


*Fig. 3. Steady-state temperature and temperature rise versus ambient temperature for basal thermocouples of the plastic ski. Other than ambient temperature, the other conditions were similar during the various runs. The steady-state temperature is less than 0°C because it is averaged over the actual contacts at 0°C and the colder non-contacting areas of the ski base.*

from a higher coefficient of friction. This effect was seen in many runs even though they did not reach a steady-state temperature. Comparing curves b and c in Figure 2 shows that, for an ambient temperature of -9.7°C, the temperature rise at the base of the ski was 5.3°C, whereas for an ambient temperature of -6.7°C the temperature rise at the base of the ski was only 3.3°C. Apart from the change in ambient temperature, these two runs were essentially identical.

To see how heat flow varied with ambient temperature, data obtained from the base of the skis were fitted against the solution for the onset of a constant heat flow $q_s$. From Carslaw and Jaeger (1959, p. 75),

$$T(t) = T_0 + \frac{2q_s}{k_s}\left(\frac{\kappa_s t}{\pi}\right)^{\frac{1}{2}} \tag{3}$$

where $T_0$ is the initial or ambient temperature, $t$ is time, and $k_s$ and $\kappa_s$ represent the thermal conductivity and diffusivity of the ski. At the start of a run the temperature generally rose as $t^{\frac{1}{2}}$, so values of $2q_s(\kappa_s/\pi)^{\frac{1}{2}}/k_s$ were obtained from fits to the initial temperature rises. In Figure 4 the heat flow at the base of the ski is shown to increase in a linear fashion as the ambient temperature decreases, at least over this range of temperatures. This again suggests that more heat is generated at lower temperatures because of the higher friction.

## Effects of load and speed

Curve a in Figure 5 shows a large response in the basal temperature of the plastic ski caused by changing the load on the ski from one-half to all of the skier's weight with a cycle of 20 s while being towed uphill at a modest speed. In each cycle the temperature increases during the greater load and decreases when the load is reduced. Similarly, curve b in Figure 5 shows temperature cycles as the ski accelerates downhill, stops and accelerates downhill again in three cycles. The time between stopping and starting was insufficient for the base to cool to the ambient temperature and thus, as heat accumulated in the ski, the ski attains a higher temperature during each cycle.

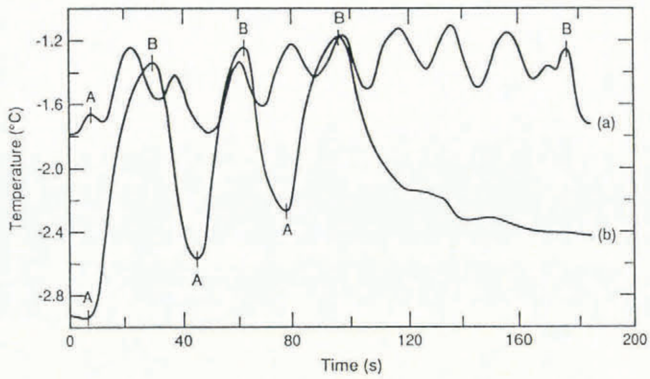


*Fig. 5. Basal temperature on right side of plastic ski. (a) Constant-speed ride up Poma lift while cycling the weight on the ski between N and N/2 with a period of 20 s; $T_0 = -1.8°C$; $v_{max} \approx 2\ m\,s^{-1}$; hard-packed snow. (b) Three periods of start and stop during a parallel run on a gentle slope; $T_0 = -2.9°C$; $v_{max} \approx 6\ m\,s^{-1}$; load of N on hard-packed snow.*

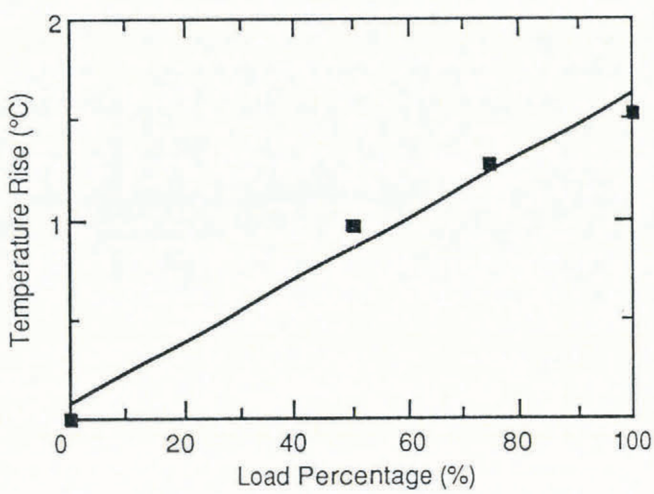


*Fig. 6. Basal temperature rise versus load in plastic ski. The 0,0 data point is assumed.*

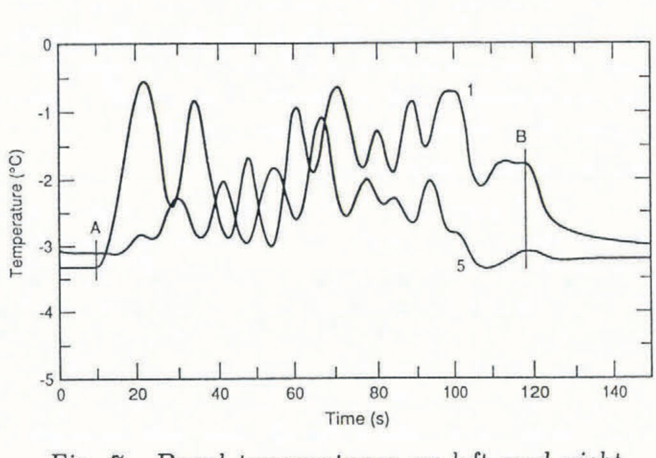


*Fig. 7. Basal temperatures on left and right sides of plastic ski during many turns. 1 is the inside and 5 is the outside of the ski. $T_0 = -3.2°C$; $v_{max} \approx 6\ m\,s^{-1}$; wide, smooth turns with load of N/2 on soft, fresh snow.*

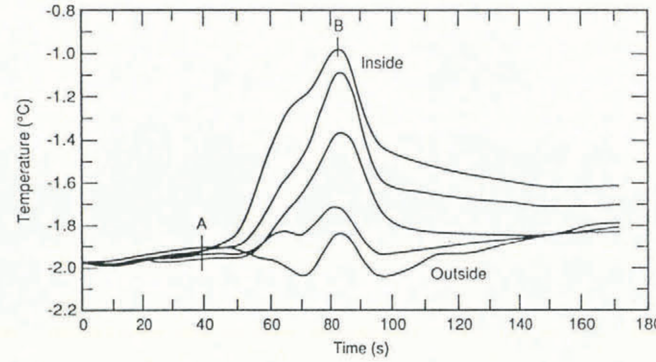


*Fig. 8. Basal temperatures from inside to outside of DH skis. $T_0 = -2°C$; $v_{max} \approx 9\ m\,s^{-1}$; parallel run down gentle slope with load of N/2 on soft, fresh snow.*

Figure 6 shows that temperature rise in the middle of the base of the plastic ski increases with load. Equation (1) shows that heat generation is proportional to the applied load, other things being constant. Figure 7 shows temperature cycling while turning the ski during a run on a long, gentle slope. The two basal thermocouples located on opposite sides of the plastic ski are out of phase by 180° and the steady-state temperature is approached but never reached because of the weighting and unweighting during turning. The average response of thermocouple 1 is greater than that of thermocouple 5 due to the fact the inside of the ski carries more weight than the outside.

Figure 8 shows a large temperature difference across the base of the DH ski even though the weight appeared to be evenly distributed during parallel skiing. This effect is probably due to edging by the skier even in the parallel or tuck position. As shown in Figure 9a, the temperature is more uniformly distributed across the ski when the snow is soft, probably because softer snow conforms to the shape of the ski. A similar effect of soft snow is shown in Figure 9b for longitudinal profiles. From these data, it seems clear that the load and therefore the frictional force vary across and along the ski, especially on hard snow.

The thermal response due to speed is shown qualitatively in Figure 10 for a downhill run of about $6\,m\,s^{-1}$ followed at 60 s by a slow ride on the Poma lift. Beyond the data shown in Figures 5 and 10, no systematic study of the effect of speed could be made.

## Effects of snow type

Figure 9b shows that the back of the ski experienced the greatest temperature increase in soft snow but the thermal effect is greatest in the center of the ski on hard snow. Again, this difference is probably due to the more even distribution of weight in soft snow, which allows for a more even distribution of heat production and, therefore, heat accumulation along the length of the ski. In hard snow, most of the heat production is under the skier and so no heat accumulation is seen. The temperature profile in soft snow supports Klein's (1947) idea that the front of the ski is dry and Colbeck's (1988) suggestion that with a uniform load the water film would reach an equilibrium value somewhere along the length of the ski.

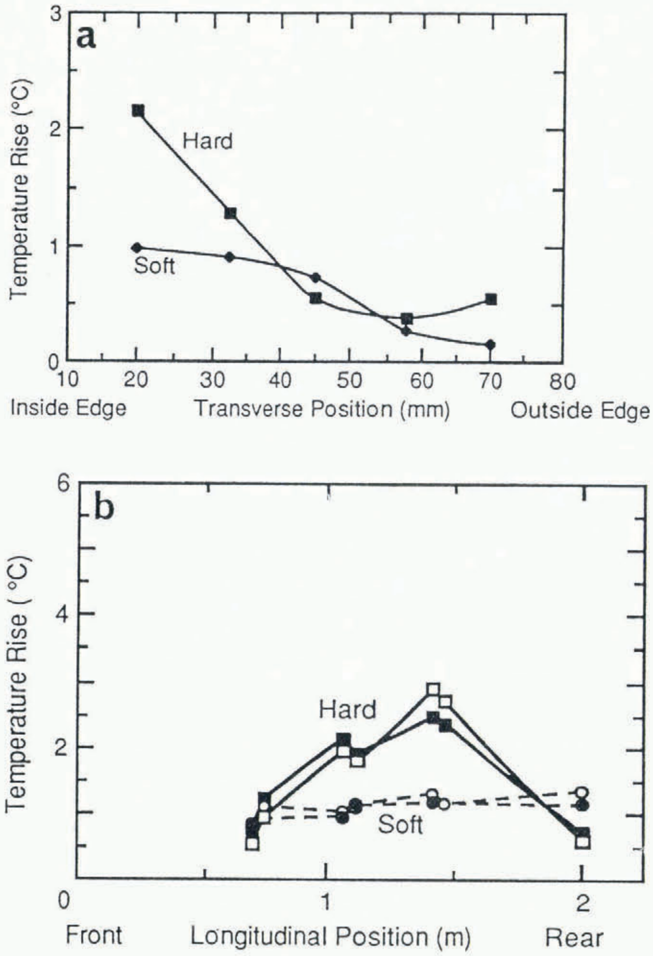


*Fig. 9. Basal temperature rise versus position in DH ski runs on days with hard and soft snows. (a) Transverse position, two runs. (b) Longitudinal position, four runs.*

### Effects of thermal conductivity

Figure 11 shows that the thermocouples away from the base in the DH ski respond much less and much later. However, as shown in Figure 12, the thermocouples away from the base in the DH ski had a proportionally greater response than those in the plastic ski due to a highly conductive aluminum plate which crossed the entire DH ski 2 mm above the base. In general, the thermocouples placed on the steel edges responded more quickly than those near the base of the DH ski because of the higher thermal conductivity of the steel.

## FINITE-ELEMENT MODEL: RESULTS AND DISCUSSION

The calculated temperature fields show transients propagating up through the ski for some time although, by about 200 s, fairly constant temperatures are established in the lower one-third of the ski. Near the base, a fairly steady profile is established after 50 s, but heat loss from the side of the ski continues to increase as more heat is transferred laterally along the aluminum plate. Although the time for the entire ski to achieve steady state is far longer than the time a ski would normally experience steady conditions, the base of the ski probably experiences quasi-steady conditions in downhill racing.

The heat flux perpendicular to the base was computed at four places along the base and is shown in Figure 13, where it is clear that the local heat flux is strongly affected by material composition and location. As expected, heat flux increases with increasing thermal conductivity, but the effect is not uniform throughout the complex geometry of the DH ski. Figure 13a shows that the steel edge dominates the basal heat flux 3 mm

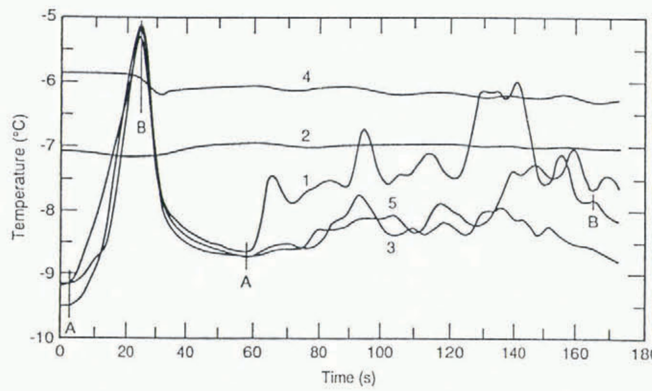


*Fig. 10. Temperatures in plastic ski. 1, 3 and 5 are on base in left, middle and right side. 2 is 3.8 mm above and 4 is 9.7 mm above base. $T_0 = -9.3°C$; $v_{max} \approx 6\ m\,s^{-1}$; parallel run down gentle slope with load N on hard-packed snow then up Poma lift at $\approx 2\ m\,s^{-1}$.*

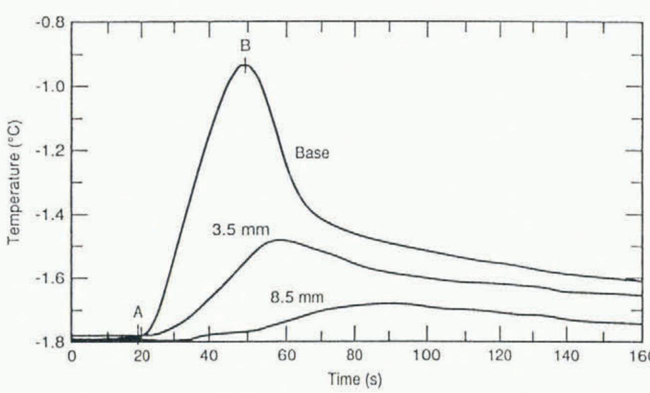


*Fig. 11. Vertical temperature profile of DH ski showing basal, 3.5 and 8.5 mm responses. $T_0 = -1.8°C$; $v_{max} \approx 9\ m\,s^{-1}$; parallel run down gentle slope with load N/2 on soft, fresh snow.*

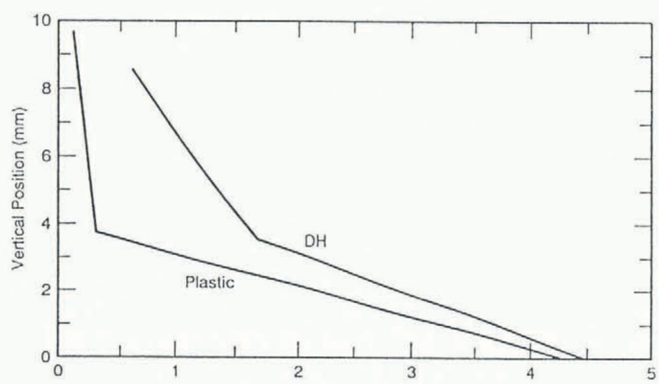


*Fig. 12. Relative temperature rise versus vertical position for both skis.*

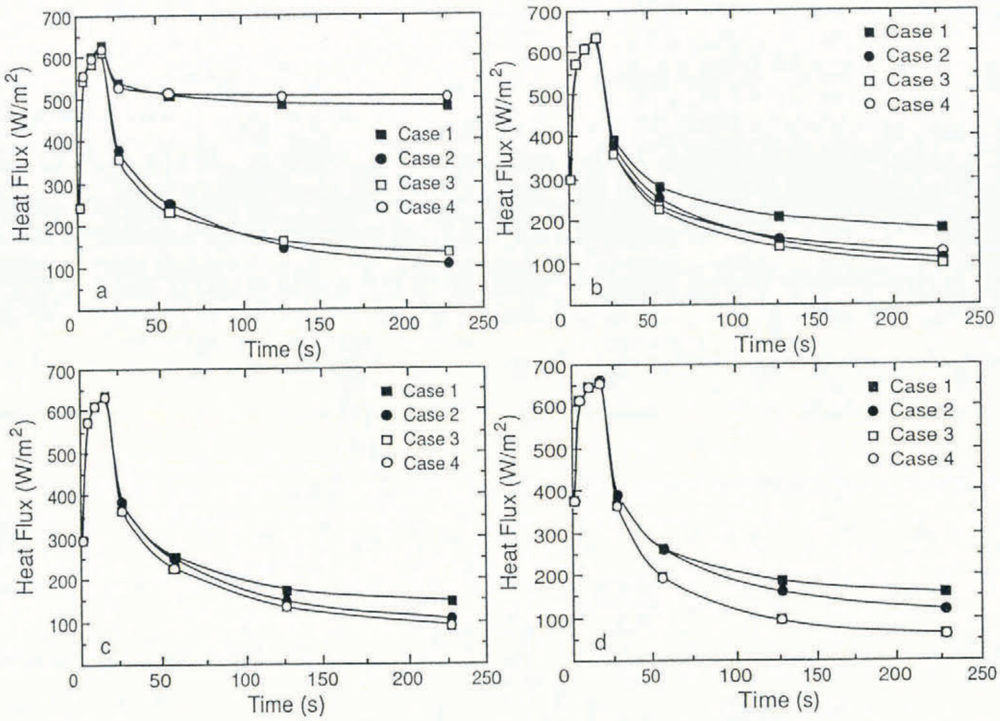


*Fig. 13. Computed heat flux versus time for four transverse positions and four cases of different materials as described in the text. $T_0 = -5°C$; $v = 18\ m\,s^{-1}$; load N/2. (a) 3 mm from edge; (b) 100 mm from edge; (c) 25 mm from edge; (d) on center line, 37 mm from edge.*

from the edge of the ski. The heat flows in cases 1 and 4 with the steel edge are about four times greater than in cases 2 and 3 with the ceramic edge, at least at a time of 227 s, which should represent very steady conditions in the lower part of the ski. The effect of the steel edge and the aluminum plate on the heat flux at the base are about equal at 10 mm from the edge, as shown in Figure 13b. In this case, both the steel edge and the aluminum plate are needed to make a great difference. Clearly, the heat flux becomes more dependent on the aluminum plate than on the steel edge as the distance away from the edge increases. The basal heat flux at 25 mm away from the edge is shown in Figure 13c, where the heat fluxes for cases 3 and 4 are very similar to but slightly less than case 2 (aluminum plate, ceramic edge). The aluminum plate dominates at the center line as shown in Figure 13d. Cases 1 and 2 with the aluminum plate show the greatest amount of heat flow and would reduce the amount of heat at the base of the ski in its mid-section by 50% or more.

From the spatial positions of the isotherms for case 1, the calculated heat flux along the aluminum plate is about 40 times greater than the flux into the wood core above the aluminum plate. In case 2, the replacement of the steel with ceramic reduces this ratio to about 15. In cases 3 and 4, this ratio is reduced to approximately 1, thus showing a greatly reduced heat transfer to the sides. This analysis shows how much the replacement of conductive materials would reduce the lateral heat flow at the base. The heat flow in the wood core above the aluminum plate is not greatly affected by the change in material composition, perhaps by no more than 20%. In case 1, so much heat is conducted along the aluminum plate that heat even flows downward through the steel edge, which acts as a radiator for the aluminum.

The results of the computer simulation are qualitatively similar to the amplitude-dampened, phase-lagged behavior observed in the real ski and shown in Figure 11. The basal thermocouples reached a temperature of approximately −1°C rather quickly, while the thermocouples located higher in the ski reached lower peaks more slowly, as expected from standard solutions to the heat-conduction equation.

## SUMMARY AND CONCLUSIONS

Although the results are qualitative because of the lack of control over test conditions and the approximate nature of the numerical model, some conclusions can be drawn:

1. The large thermal responses due to frictional heating observed at the bases of both test skis (Figs 2 and 11) disprove McConica's (1950) idea that the ski base would remain at the ambient temperature. The idea of Bowden and Hughes (1939) that frictional heating could provide meltwater for lubrication is affirmed even though the base does not reach 0°C because of the small contact area.
2. The steady-state temperatures reached at the bases of the skis (Fig. 2a) support existing ideas about the discontinuous meltwater layer. This temperature was consistently close to, but less than, the melting temperature of the snow. At higher ambient temperatures, it approaches the melting temperature (Fig. 3) but it appears to be independent of speed. This suggests that it is associated with melting and contact areas, and is not just the result of balancing heat production with heat loss.
3. The rate of temperature rise depends on the ambient temperature (Fig. 4) in a way that shows more heat production at lower ambient temper-

atures due to lower meltwater production and higher friction.

4. The temperature rise increases with load, possibly because of more heat and meltwater production, or simply more contact area. If the temperature rise increases linearly with load, as suggested in Figure 6, then the coefficient of friction is independent of load as has often been suggested and is used in theories like those of Colbeck (1988).
5. The transverse (Fig. 9a) and longitudinal (Fig. 9b) distributions of frictional heating are sensitive to the style of skiing and the hardness of the snow surface. In the tuck position, the weight is concentrated on the inside edge (Fig. 8), which shows that the ski is not flat on the snow even when the skier perceives it as such.
6. Both the measured (Fig. 11) and computed vertical temperature profiles exhibit phase-lagged, amplitude-dampened responses expected when heat is generated on one surface. The aluminum plate about doubles the heat loss from the base of the DH ski and thus a material of lower thermal conductivity would inhibit the flow of heat away from the base and increase the supply of meltwater for lubrication. The lateral heat flow is also increased by the steel edge, but not as much as by the aluminum plate.

In general, the heat-flow characteristics of downhill skis are predictable from theory and the model could be used to predict the effectiveness of different materials and geometries. Also, temperature measurements of the type reported here could be used for judging the effectiveness of ski waxes.

## ACKNOWLEDGEMENTS

We thank N. Huber of Rossignol for supplying the instrumented ski and Salomon for the bindings. Dr J.-C. Tatinclaux provided extensive review comments that were very helpful in preparing this manuscript. Careful reviews from the *Journal* were also appreciated. This work was funded by 4A762730AT42 at CRREL.

## REFERENCES

Ambach, W. and B. Mayr. 1981. Ski gliding and water film. *Cold Reg. Sci. Technol.*, **5**(1), 59–65.

Archard, J.F. and R.A. Rowntree. 1988. The temperature of rubbing bodies. Part 2. The distribution of temperatures. *Wear*, **128**(1), 1–17.

Bowden, F.P. and T.P. Hughes. 1939. The mechanism of sliding on ice and snow. *Proc. R. Soc. London, Ser. A*, **172**(949), 280–298.

Carslaw, H.S. and J.C. Jaeger. 1959. *Conduction of heat in solids. Second edition.* London, etc., Oxford University Press.

Colbeck, S.C. 1988. The kinetic friction of snow. *J. Glaciol.*, **34**(116), 78–86.

Evans, D.C.B., J.F. Nye and K.J. Cheeseman. 1976. The kinetic friction of ice. *Proc. R. Soc. London, Ser. A*, **347**(1651), 493–512.

Glovsky, R.B. 1982. Development and application of THERMAP: a finite element method (FEM) computer program for predicting the temperature distribution in sliding systems. (M.E. thesis, Thayer School of Engineering, Hanover, NH.)

Kays, W.M. 1960. *Convective heat and mass transfer.* New York, McGraw-Hill.

Klein, G.J. 1947. *The snow characteristics of aircraft skis.* Ottawa, National Research Council Canada. (Aeronautical Report AR-2.)

McConica III, T.H. 1950. *Sliding on ice and snow; some considerations of the mechanism. A technical report.* Clare, MI, American Ski Company.

Tusima, K. and Z. Yosida. 1969. Melting of ice by friction. *Low Temp. Sci., Ser. A*, 27, 17–30. [In Japanese; English summary.]

Warren, G.C., S.C. Colbeck and F.E. Kennedy. 1989. Thermal response of downhill skis. *CRREL Rep.* 89-23.

*The accuracy of the references in the text and in this list is the responsibility of the authors, to whom queries should be addressed.*

*MS received 18 December 1990 and in revised form 16 April 1991*