This session incorporated a panel discussion into its format. Panel members were E.R. LaChapelle, H.K. Weickmann, J.R. Meiman, and R.H. Swanson.

Preparation of artificial snow and ice surfaces for XI Olympic Winter Games, Sapporo

Daisuke Kuroiwa and Edward R. LaChapelle

Institute of Low Temperature Science,
Hokkaido University, Sapporo, Japan
and
University of Washington, Seattle, Washington, USA

ABSTRACT: Modern Winter Olympic competitions have almost completely excluded natural snow and ice surfaces. A systematic study of artificially prepared snow and ice, begun in 1968, led to the definition of criteria and preparation methods that were used during the XI Olympic Winter Games. Extensive manpower was applied from the beginning of winter to attack the most difficult problem, that of preparing a sufficiently durable snow surface for the alpine ski events. Ice of exceptionally high purity and controlled crystal size was mechanically prepared for the skating events. Results demonstrated that proper management of the age-hardening process in snow could lead to a satisfactory racing surface when the Kinosita hardness exceeded 5 to 7 kg cm^2 , although this management is difficult during a winter of below-normal snowfall. The advantage of specially prepared ice for speed skating was less obvious, with the subjective impressions of competitors being clearly related only to ice surface temperature.

RESUME: De nos jours, la neige et la glace artificielle remplacent presque complètement la neige et la glace naturelle aux Jeux olympiques d'hiver. Une étude systématique des neiges et des glaces artificielles, commencée en 1968, a conduit à des critères et à des méthodes de préparation qui ont servi aux XIe Jeux olympiques d'hiver. Dès le début de l'hiver, des effectifs importants se sont attachés à résoudre le problème le plus difficile consistant à préparer une surface de neige suffisamment durable pour les épreuves de ski alpin. On a préparé par des moyens mécaniques une glace d'une pureté exceptionnellement élevée et à cristaux de dimensions contrôlées pour les épreuves de patinage. Les résultats montrent que si le processus de durcissement de la neige avec le temps est bien contrôlé, on pourrait obtenir des pistes à surface satisfaisante lorsque la dureté Kinosita ne dépasse pas 5 à 7 kg/cm^2 malgré que ce contrôle soit difficile si la chute de neige durant l'hiver est inférieure à la normale. Les avantages des glaces artificielles spécialement préparées pour les épreuves de vitesse en patinage ont été moins évidents et les concurrents ont eu l'impression que le seul facteur important était la température à la surface de la glace.

INTRODUCTION

At the request of the Sapporo Organizing Committee for the XI Olympic Winter Games, the Institute of Low Temperature Science, Hokkaido University, began in 1968 a systematic study of artificially prepared snow and ice surfaces. The objective of this study was to define standards of preparation, especially for alpine ski events, satisfactory for international competition, and to identify the most effective methods of preparation. Results of these studies have been reported in a total of fifteen papers published by members of the Institute Staff in Low Temperature Sciences, Series A for 1968, 1969, and 1970 (see Bibliography). These studies and the general conclusions derived from them have been summarized by Yosida (1971). We now briefly outline these studies and conclusions.

Extensive tests were made of snow hardness using the Kinosita hardness gauge [1]. These tests involved competition race courses, specially prepared test surfaces, and natural snow surfaces. Hardness tests were made on snow artificially compacted or reworked by foot-packing, ski-packing, and machine-packing (snow-cat). Structure, crystallography, and density of such artificially treated snow were also examined. Similar tests were made on naturally re-worked (wind-packed) snow sufficiently hard to qualify as a ski racing surface. The subjective impressions of expert ski racers were also sought for comparison with the quantitative measurements.

A systematic investigation was made of numerous speed skating rinks in Japan, where it was well-known among speed skaters that certain rinks tended to have faster ice where the best skating records could be made. The temperature, crystallographic structure, and mode of ice preparation were investigated at five natural and six artificial rinks. Studies were also made of the sliding mechanism on ice and a catapult-mounted camera was devised to measure sliding friction of test skates on various ice surfaces.

Consequent recommendations to the Sapporo Organizing Committee embraced the preparation of both snow and ice surfaces. In brief, a minimum Kinosita snow hardness of 7-10 kg/cm^2 would be necessary to support international-calibre competition on a ski race course without deterioration during the race. (By way of practical example, a shovel cannot be driven by hand into snow of Kinosita hardness 7-10.) This hardness could be achieved by reworking and age-hardening of snow only through footpacking; machine or ski-packed snow was found to be inadequate, although a final ski-packing was necessary to smooth the surface. In areas of intense ski use on slalom courses, especially on the steeper slopes, further hardening could be achieved by applying water and allowing it to refreeze after being mixed with the snow. The optimum snow thickness of race courses for the Sapporo climate was established as 30 cm, a compromise between the cost of reworking a deep snow layer and the risk of deterioration from depth hoar formation. The hardening process would have to begin with the first snows of autumn in order to assure sufficient strength throughout the snow layer. Adequate hardening of packed and reworked snow could not be expected in less than 10 to 15 days. Any snow falling on a race course closer to the Olympic event than this time should be removed rather than packed in place. Optimum conditions for speed skating were found to be on ice with a surface temperature between -2° and -3° C. This ice should be prepared from distilled water in a manner to insure a structure of large ice crystals.

One of us (LaChapelle) was asked by the Denver Organizing Committee for the XII Winter Olympic Games to evaluate these standards, the actual methods of snow and ice preparation in use at Sapporo, and the actual course conditions at the time of the XI Games. A joint effort was organized with the staff of the Institute of Low Temperature Science, who sought a similar evaluation, to investigate immediately after each competitive event the snow and ice surfaces in use during the Olympic Winter Games in Sapporo. Methods of snow course preparation in use during the winter of 1971-72 were documented and subjective impressions of the Olympic competitors collected. We report our joint findings in this paper.

PREPARATION OF THE ALPINE SKI COURSES

The labour of manufacturing the highly artificial snow surface required for a modern international competition was begun some three months before the Olympic Winter Games by detachments of the Japan Ground Self Defense Force (SDF). For the entire Olympic Games operation, 3,641 men from the Northern Army were assigned to the Sapporo Olympic Support Corps. We confine our discussion here to the detachments concerned with the alpine ski events. (Several hundred men were garrisoned at each site.) Similar groups were also at work on the jump hills and the cross-country and biathalon courses, as well as participating in many other aspects of the Winter Games. Table 1 lists the total man-hours of work and quantities of snow handled for the various Olympic events.

Special difficulty was experienced with the downhill courses at Mt. Eniwa due to the unusually mild character of the 1971-72 winter in Hokkaido and the consequent scarcity of snow on the lower part of the mountain. In early December 30-40 cm of wet snow fell at Mt. Eniwa. This was foot-packed into a firm base during two days in which five-man packing teams were organized in such a fashion that each race course (men's and women's downhill) was packed five times each day. A prolonged snow-free period followed, during which difficulty was experienced with loss of snow to wind-drifting. Various experiments were conducted with the erection of snow ridges to trap drifting snow on the race course. The successful solution involved a rectangular grid of snow banks with a 2-metre spacing. These snow banks were constructed by stacking snow blocks 0.3-0.4 m wide to a height ranging from 1.0 m at the bottom of the courses to 0.3 m at the top.

Snow fell at Mt. Eniwa over the New Year's holiday, leaving an accumulation of 0.3 m on top and none at the bottom of the courses on 4 January. Snow-free weather persisted during January and rain fell in mid January, leading to loss of snow by melt. The large-scale organization of snow transport from the forest surrounding the race courses and from as far away as near the summit of Mt. Eniwa was necessary to assure an adequate skiing surface for the competition events in February. Snow was transported by sliding it along chutes constructed of corrugated aluminum sheets supported in the form of a trough by wooden frames. In all, a total of 2.1 km of such chutes were constructed to mine the limited snow resources on the flanks of Mt. Eniwa. On very steep slopes an alternate form of chute made of 0.4 m-diameter plastic tube was also used. As snow was delivered to the race courses in this fashion, it was continually foot-packed, with additional packing assistance from machines on the gentler slopes. As a final step, the racing surfaces were smoothed by side-slipping with skis.

Two falls of snow, each about 0.2 m thick, occurred on January 29-30 and February 2-3. This was too late to assure reliable harden-

Table 1

XI OLYMPIC WINTER GAMES, SAPPORO 1972

List of surface area, volume of conditioned snow and manpower used for preparations of race courses

Event	Manpower and ski-packed area	Manpower and foot-packed area	Manpower and area packed by vehicles	Manpower and snow volume removed from ski runs	Bare ground covered with snow blocks	Path and safety snow banks along courses	Manpower for maintenance	Manpower and water-sprayed area
Biathlon			1,760 mh 88,350 m^2	3,755 mh 1,580 m^3			12,768 mh 490 Km	
Cross-Country							21,760 mh 1,053 Km	
Slalom	9,845 mh 1,188,050 m^2	43,263 mh 3,485,625 m^2		36,369 mh 148,250 m^3	13,425 mh 9,203 m^2 6,637 m^3	1,116 mh 800 m^2 80 m^3		1,362 mh 6,850 m^2
Downhill	3,624 mh 471,400 m^2	5,868 mh 871,000 m^2		546 mh 15,600 m^3	25,388 mh 47,200 m^2 27,100 m^3	3,868 mh 10 m^3		
Jump	3,790 mh 143,160 m^2	3,781 mh 125,110 m^2		11,823 mh 20,708 m^3		2,261 mh 1,050 m		
Bobsleigh				3,068 mh 14,969 m^3				
Luge				1,437 mh 3,776 m^3		44 mh 800 m		

(mh = man-hours)

ing in time for the downhill events, so most of it was removed by shovels and hand-plows. A labor force of 250 SDF men plus another 100 volunteers was able to clear the men's downhill course in 2.5 hours. On some of the gentler parts of the race course, where the low gradient was not expected to encourage erosion by competition skiing, the new snow was packed in place by alternate machine- and foot-packing followed by side-slipping with skis after one day of age-hardening.

Snow was more abundant at Mt. Teine, the site of slalom events, than at Mt. Eniwa, but the requirement of snow processing was more severe due to the expected amount and nature of ski traffic during events. Poor accumulation of snow was found near the starting lines of men's slalom and giant slalom courses and at the steepest slope of the women's giant slalom course. In these areas, deposited snow was blown away by the wind action and ground surfaces were exposed. The most serious problem for preparation of the slalom courses was how to cover these exposed areas with snow. In order to trap drifting snow, various types of snow fences were tested, but they were not successful. During the slalom events of the International Winter Sports (Pre-Olympic Winter Games) held in Sapporo in 1971, exposed ground surfaces were successfully covered with snow blocks, using mixture of water and snow as a cementing material. On the basis of this experience, several concrete water tanks were installed near the problem areas of each course. The water tanks had capacities of 2 x 300 tons for men's and women's slalom courses, 300 tons for women's giant slalom, 250 tons for men's giant slalom.

Snow piled in drifts was compressed by snow vehicles and cut into many blocks, 30 x 30 x 40 cm^3 in size. After age-hardening for 1 or 2 days, these snow blocks were transported to exposed ground surfaces. Snow blocks were piled in horizontal rows against the slope to form parallel snow ridges at intervals 0.5 ~ 0.7 m. These snow blocks were frozen onto the ground surface by water sprayed and then cemented together with a mixture of snow and water. When the troughs between snow ridges were filled with fallen snow, foot- and ski-packings were applied. The total areas thus covered were 9,203 m^2 and the total volume of snow blocks used was 6,637 m^3. In compliance with advice from the International Ski Federation, the application of water on race courses was confined to the beginning of the preparation, because water application results in uneven hardness of snow.

About thirty men were deployed in four lines on the slope and snow surfaces were foot-packed four times each morning and afternoon every day. On the steepest areas foot-packing was carried out by the aid of ropes hung from the tops of the slopes.

SNOW CONDITION OBSERVATIONS DURING THE OLYMPIC GAMES

Observation teams were organized to record surface snow conditions on the race courses prior to and following each alpine skiing event. At Mt. Eniwa some measurements were made on the lower part of the race course immediately after both of the downhill events, with further measurements over the entire course the following day. At Mt. Teine the giant slalom courses were investigated the day following each event. The slalom course was not accessible for investigation until after the final event, which was immediately followed by a metre of new snow that precluded further hardness measurements on the racing surfaces. At all sites the hardness and structure of the prepared snow had been recorded during the weeks immediately preceding the Olympic Winter Games. Observations consisted of standard snow pit investigations of density, temperature and stratigraphy at selected points on each race course, and of systematic mapping of snow surface hardness and temperature throughout each race course. The surface hardness measurements were made along a series of transverse profiles across each course spaced at approximately equal altitude intervals from top to bottom.

Snow surface hardness was measured by two separate instruments, often side-by-side at each measurement point. One was the standard Kinosita hardness gauge also used in the snow pits. The other was a special modification of the Kinosita gauge designed to reflect more accurately the character of snow hardness encountered by a ski edge. We refer to this latter instrument as a ski-edge hardness gauge. In operating principle it is identical to the Kinosita gauge, for it consists of a plane surface of known area driven into the snow by a falling weight which delivers a force at right angles to plane surface. For the Kinosita gauge this surface is a circular disk whose diameter can be varied according to the range of snow hardness encountered.

For the ski-edge hardness gauge the surface is a long, narrow rectangle. For the snow hardness encountered on the prepared race courses this rectangle was 163 mm long and 3 mm wide; thus it had the same area as the 25 mm diameter disk of the Kinosita gauge used for the race course measurements. The need for this ski edge hardness gauge arose when it was discovered that the reworked snow produced a terrazzo-like texture, which gave large hardness variations over distances of 100 mm or less and consequently a large scattering of Kinosita hardness from point to point. The modified gauge simulates the behavior of a ski edge, which responds largely to the hard domains within the snow and bridges across the soft ones (see Fig. 1).

Figure 2a shows a typical structure of processed snow made by snow vehicles. This pit was made near the finish of the men's downhill course at Mt. Eniwa immediately after the competition at 15.30 on February 7, 1972. Two distinct layers, f and h, were seen. The surface layer, f, consisted of fine grained snow less than 1 mm in diameter, and showed parallel stripes due to vehicle compression. The foundation layer, h, was composed of hard depth hoar, 2-4 mm in size, and showed no definite structure. The measurement of hardness of snow was made by both Kinosita and ski edge hardness gauges. The observed values were different from point to point, but the average values of Kinosita hardness were 5 kg/cm^2 for the surface layer, and 10 km/cm^2 for the foundation layer. The average density was 0.42 g/cm^3 for the surface layer and 0.5 g/cm^3 for the foundation. Similar pit observations were also made at the finish of women's downhill and at the middle site of the men's downhill course; in both cases the structure of processed snow was similar to the profile shown in Figure 2a and seems to be an adequate construction for a downhill ski course.

Figure 2b shows a typical structure of processed snow made by foot-packing. This pit was made near the starting line of the men's slalom course at Mt. Teine on February 1, 1972. Contrary to the structure shown in Figure 2a, the profile exhibited a more complex structure. Because there was little accumulation of snow near the start line of the men's slalom course, the exposed ground surface was covered with compressed snow blocks as described above. After each subsequent snowfall, the snow was dug up, turned over with shovels and compressed by foot-packing. The resulting multiple reprocessing led to a snow structure composed of hard chunks cemented together by a snow matrix. We term this artificial structure, seen in Figure 2b, "snow terrazzo." The values of Kinosita's hardness measured along the pit wall are indicated in the photograph. The average density of this processed snow was 0.45 g/cm^3.

We now distinguish between the race *course*, the zone of processed snow on the mountainside, and the race *track*, the actual line followed by the competitors from gate to gate within this zone, where extra attention to the snow preparation is often given and the passage of numerous competitors also removes any thin surface layers of softer snow. A sufficient number of points were tested for surface hardness (eg., 97 for the men's downhill, 68 for the men's giant slalom) to permit plotting a contour map of snow hardness for each race course. These maps are arranged with the arbitrary convention of altitude and normalized course width as coordinates. Two such maps are given in Figures 3 and 4. The varying position of the race track within the mapped areas of the course clearly appears as a zone of maximum snow surface hardness, in each case determined with the ski edge hardness gauge. For the downhill course of Figure 3, a similar map can be obtained from the concurrent Kinosita hardness gauge measurements. There is much less similarity between the two instruments for the patterns of ski edge hardness on the giant slalom course depicted in Figure 4. This is illustrated by the contrasting hardness pattern from the Kinosita hardness gauge for the same giant slalom course given in Figure 5. In the latter case the more heavily reworked snow of the Mt. Teine giant slalom course appears to have produced a wide scatter in the Kinosita hardness, so that the results from this instrument no longer serve to identify the race track alignment within the race course.

The hardness values illustrated by Figures 3 and 4, together with the data we have collected from the other Olympic alpine race courses, show that for the most part the race course hardnesses actually achieved by the time of the Olympic Winter Games equalled or exceeded the standards recommended by the Institute of Low Temperature Science to the Sapporo Organizing Committee.

ICE RINK OBSERVATIONS DURING THE OLYMPIC GAMES

In the speed skating competitions of the International Winter Sports (Pre-Olympic) held in Sapporo in 1971, none of the expected speed records were achieved on the Makomanai speed skating rink. Many participants criticized the quality of the rink ice. After discussion, possible reasons for the deterioration of speed records were considered to be: a) inadvertent contamination of ice due to machine oil; b) inclusion of paints into ice; c) impurities contained in the water used for the preparation of rink ice; and d) airborne particles precipitated on to the rink surface. Among these reasons, only d) appeared to be significant.

In 1972, at the request of the Japan Federation of Skating (J.F.S.), an apparatus for making de-ionized water was installed in Makomanai speed skating rink to cover the whole area of rink (15 m wide x 400 m) with de-ionized ice. This apparatus can produce de-ionized water at the rate of 2 tons an hour. The preparation of rink ice was begun at the beginning of winter. First, ordinary city water was sprayed on the previously cooled rink surface to prepare the base ice, whose thickness was then increased gradually by the intermittent spraying of water and careful control of the refrigeration. To ensure transparent ice any snow deposited on the ice surface was completely removed before the spraying. When the thickness of base ice attained 6-7 cm, the ice surface was planed by a Zamboni machine to smooth the rink surface, after which hot de-ionized water was sprayed through Zamboni's nozzles.

Figure 6 shows photographs of a vertical thin section of core sample of rink ice taken by the reflected light (a), and the polarized light (b). This core sample was collected at the Makomanai speed skating rink immediately after the final speed skating competition was finished on February 12, 1972. The thickness of ice was approximately 9 cm. As seen in this figure, the rink ice shows a well-defined layer structure originating in the intermittent growth of ice. The upper layers, indicated by an arrow, consisted of de-ionized ice containing few air bubbles, but the lower part, the base ice formed from city water, contained many air bubbles.

In order to examine vertical distribution of impurity content in the rink ice, four core samples were taken from different sites on the rink and sliced horizontally at 1 cm intervals. These sliced samples were melted individually to measure electrical conductivity at 25°C. The average values of the electrical conductivity measured are given in Table 2.

Table 2
Vertical Distribution of Impurity Content in Makomanai Rink Ice

Sliced layers	σ	c	Remarks
8 - 9 cm	2.000×10^{-5} mho/cm	9.5 ppm	de-ionized ice
7 - 8 cm	1.120	5.5	
6 - 7 cm	2.480	13.8	base ice formed from city water
5 - 6 cm	5.945	28.5	
4 - 5 cm	4.855	23.5	
3 - 4 cm	3.195	15.0	
2 - 3 cm	9.505	45.0	
1 - 2 cm	13.50	64.0	
0 - 1 cm	11.45	55.0	

σ: Electrical conductivity measured at 25°C
c: Converted value for equivalent NaCl content at 25°C

For convenience sake, the values of σ were converted into the corresponding NaCl content, c, in aqueous solutions, in the third column of Table 2, which give the same value of the electrical conductivity at 25°C. It is obvious that the upper layers which consisted of de-ionized ice contained many fewer impurities than the lower base ice.

The impurity content of city water used for the preparation of the base ice was

$$\sigma = 21.65 \times 10^{-5} \text{ mho/cm}, \ (c = 103 \text{ ppm}).$$

After de-ionization, the impurity content of the city water was reduced to

$$\sigma = 2.045 \times 10^{-6} \text{ mho/cm}, \ (c = 1 \text{ ppm}).$$

The impurity content of de-ionized water discharged from the nozzle of the Zamboni was about one order of magnitude higher than that of the input. It is noteworthy that the base ice of the skating rink had on the average fewer than half the impurities (103 ppm) of the city water from which it was made. In an artificial rink the ice grows from the bottom upward, in contrast to natural ice surfaces which usually freeze from the top down. Impurities not trapped at ice crystal boundaries are excluded to the freezing surface, in the case of rink ice, the top surface where they can be removed by Zamboni planning. This suggests that substantial improvements in ice purity can be achieved by careful management of the rink freezing process and surface preparation.

SUBJECTIVE IMPRESSION OF THE COMPETITORS

During the Olympic Games we were able to obtain some significant comments from team coaches and to couple these with indirect reports from observers and comments reported in the press. Taken in total, these sources indicate a definite pattern of opinion regarding the competition snow and ice surfaces.

By way of background, it should be noted that alpine ski racers who participate in the international competition circuit are accustomed to racing on extremely hard and icy surfaces that bear little resemblence to snow. Such surfaces are commonly achieved in part by freezing of liquid water applied to the race course; a stable surface that will not deteriorate during a race can quickly be achieved this way. Conventional packed snow surfaces normally are avoided because they often break down and become rutted during competition.

There were numerous complaints about the "soft" conditions of the Sapporo alpine race courses, coupled with equally numerous expressions of puzzlement that the courses did not deteriorate during competition. There was also wide approval of the excellent general condition of the race courses and the extensive work that went into their preparation. The courses in fact were not soft, as we have demonstrated by our observations and illustrated above; but they definitely were snow and not ice, although snow processed to a carefully-specified degree of hardness. There were several comments about the problem of adjusting to the "soft" snow condition on the Sapporo race courses. We surmise that such comments arise from the general expectation among racers that they will compete on icy surfaces rather than on snow no matter how hard and durable. A significant question for the Denver Organizing Committee for the XII Olympic Winter Games is whether they should accommodate this expectation and prepare ice surfaces, or emulate the Sapporo experience and prepare age-hardened snow.

The speed skaters also found the ice rink at Makomanai "different". The ice at this rink had been prepared according to specifications, with the top 20-30 mm formed from distilled water. In general the skaters found this rink slow and the ice conditions difficult to adjust to. Our analysis of ice surface temperatures during competition shows that the best skating conditions and new competition records occurred on those days when the rink temperature was in the -2° to -3° C range, just as studies had predicted. Most of the dissatisfaction with slow ice occurred on days when external weather conditions enforced a lower rink temperature. We presently lack a theory to explain why the skaters found the Makomanai ice to be different in texture and "feel", quite aside from the temperature/speed question.

CONCLUSIONS

Modern understanding of snow-sintering and age-hardening has led to techniques whereby snow can be processed to almost any desired degree of hardness, even to the point where a snow runway can be prepared to support the landing of large jet aircraft [2]. Some of these same principles can be adapted to processing of snow on an alpine race course to meet predetermined standards of hardness. Snow so processed has density and hardness values comparable to the frozen firn produced by nature's slower methods of compression and metamorphism. In terms of manpower, the cost of the artificial product is notably high due to the necessity of dealing rapidly with low-density deposits of new snow on steep mountainsides inaccessible to machines. With sufficient organization and technical understanding it is possible, as was ably demonstrated at the XI Olympic Winter Games, to prepare a durable snow surface for skiing competition without converting it into ice. Whether it is *desirable* to do so is a subjective question to be determined by the racers themselves. Scientifically, the reaction of ski competitors to the hardness and character of race course surfaces is a problem in psycho-rheology [3]. Future tests of race course surfaces probably should be made from this point of view.

Efforts to prepare a speed skating ice surface from de-ionized water do not appear to have been particularly fruitful from the standpoint of improving skating speed or the subjective impressions of the contestants. The purifying action of the freezing process probably produces adequate ice surfaces if reasonably soft and pure city water is available. However, even if most impurities and dissolved gases are extracted from ice, serious resistance for skating may arise from contamination by airborne dust particles and hoar frost formation on the rink surface. In order to protect the rink surface from contamination by dust, the whole rink would have to be covered with a huge roof, or else the rink would have to be constructed far from a big city. On artificial skating rinks, the frost formation occurs mainly as the result of rapid ice cooling. Frost formation can be prevented by the careful control of the ice surface temperature or by the application of a suitable defroster, such as ethylene glycol. It has been demonstrated that the application of ethylene glycol on the rink surface is not only useful for the prevention of the frost formation, but is also very effective for the reduction of frictional resistance for skating. The ice surface wiped with a cloth containing a small quantity of ethylene glycol resisted the frost formation even when the surface temperature of rink was rapidly lowered. These facts suggest that defroster application on skating rinks can contribute to maintaining a smooth and speedy surface.

Finally, we note that the development of the Olympic Winter Games over the years has been accompanied by an ever-increasing reliance on artificially prepared and processed surfaces. Ice surfaces for skating, bobsleds, and luge are completely artificial, in many cases depending on artificial refrigeration and enclosed skating rinks independent of outside weather. Snow in its original state as it falls from the sky and has become a distinct nuisance to these international events: it has to be plowed from highways, prevented from avalanching, shovelled out of the way of spectators, and more often than not removed from the race courses themselves. (Tarpaulins were stretched over the Olympic jump hills in Sapporo between competitions to prevent contamination by natural snowfalls.) From the technical standpoint, it would be easier to process artificial snow generated by snow-making machines into a competition surface than to work with the natural product, for artificial snow is deposited at higher densities than natural snow and crystallographically is already in an advanced state of metamorphism. There seems to be only this one more technological step left before natural snow becomes irrelevant for the Winter Games except for reasons of atmosphere and tradition.

ACKNOWLEDGMENTS

We are indebted to the staff of the Institute of Low Temperature Science, Hokkaido University, for their energetic assistance in carrying out the many observations during the XI Olympic Winter Games. The Sapporo Olympic Support Corps of the Japanese Ground Self Defense Force offered much valuable cooperation, both in executing the observations and in furnishing detailed statistics of their work.

REFERENCES

[1] KINOSITA, Seiiti (1960). The Hardness of Snow. I.; Low Temperature Science, Ser. A, 19, pp. 119-134 (in Japanese with English summary).

[2] ABELE, G., et al (1968). Design Criteria for Snow Runways. U.S. Army Cold Regions Research and Engineering Laboratory, Technical Report No. 212, 36 pp.

[3] BLAIR, G.W. Scott (1969). Elementary Rheology. Academic Press, London and New York, 158 pp.

[4] YOSIDA, Zyungo (1971). Investigations on Snow Conditioning for the XI Olympic Winter Games, Sapporo, February, 3-13, 1972. In: Scientific Study of Skiing in Japan, Hitachi, Tokyo. (Note: The English translation of this paper in the cited book is condensed from a longer and more detailed paper in "Nippon no ski kagaku", the Japanese edition of the same book.)

[5] Staff of the Institute of Low Temperature Science, 1968-70
In: Low Temperature Science (Teion Kagaku), Ser. A, 26
HUZIOKA, T., SHIMIZU, H., AKITAYA, E., NARITA, H., and KINOSITA, S. 1968. Snow Cover Observations at Mt. Eniwa I (with English Summary, p. 275).
KOBAYASHI, T., and KITAHARA, T. 1968. Studies on the Properties of Ice in Skating Rinks (with English Summary, p. 313).
KUROIWA, D., and others, 1968. Preliminary Investigations on Ski and Luge Courses for 11th Olympic Winter Games to be Held at Sapporo in 1972 (with English Summary, p. 267).
OURA, H., KOBAYASHI, D., KOBAYASHI, S., NARUSE, R., HUZIOKA, T., SHIMIZU, H., AKITAYA, E., and NARITA, H. 1968. Hardening of Snow by Trampling and Accumulation of Induced Snow Drifts by Fences Set Up Along the Slalom Course at Mt. Teine (with English Summary, p. 295).
YOSIDA, Z. 1968. Studies on Snow and Ice for the Olympic Winter Games, 1972 (with English Summary, p. 246).
In: Low Temperature Science (Teion Kagaku), Ser. A, 27
HUZIOKA, T., SHIMIZU, H., AKITAYA, E., and NARITA, H. 1969. Snow Cover Observations at Mt. Eniwa II (with English Summary, p. 265).

KITAHARA, T., KAWAMURA, T., and KOBAYASHI, T. 1969. Hardness Measurements of Ice in a Laboratory and Skating Rinks (with English Summpary, p. 293).

KOBAYASHI, T., KITAHARA, T., and KAWAMURA, T. 1969. Studies on the Properties of Ice in Skating Rinks (with English Summary, p. 287).

KUROIWA, D., WAKAHAMA, G., and FUJINO, K. 1969. Snow-hardening Tests at Mt. Teine Ski Area for Sapporo Olympic Games, 1972 (with English Summary, p. 226).

KUROIWA, D., et al., 1969. The Coefficient of Sliding Friction Between Skis and Chemically Treated or Mechanically Compressed Snow Surfaces (with English Summary, p. 245).

TUSIMA, K., and YOSIDA, Z. 1969. Melting of Ice by Friction (with English Summary, p. 28).

In: Low Temperature Science (Teion Kagaku), Ser. A, 28

HUZOIKA, T., AKITAYA, E., and NARITA, H. 1970. Snow Cover Observation at Mt. Eniwa III (with English Summary, p. 242).

KOBAYASHI, T., KITAHARA, T., NAKAO, M., and SHINJI, Y. 1970. On the Measurement of Coefficient of Sliding Friction Between Test-Skates and Rink Ice. (with English Summary, p. 259).

KUROIWA, D., WAKAHAMA, G., and ENDO, Y. 1970. Snow Compaction with Snow Vehicle (Snow Master) (with English Summary, p. 223).

KUROIWA, D., and WAKAHAMA, G. 1970. Snow Hardening Tests by Trampling Carried out in Winter of 1969-1970 (with English Summary, p. 234).

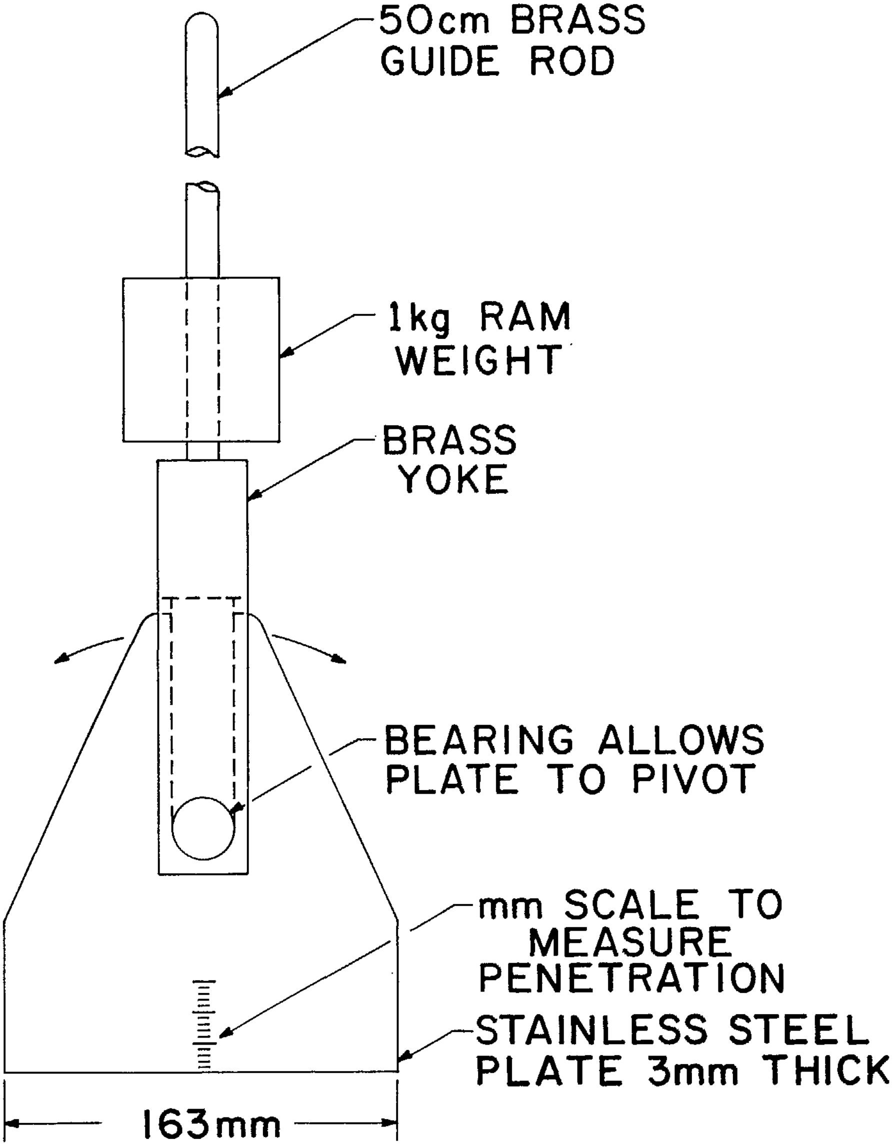


Fig. 1. The ski edge hardness gauge. Bottom of the stainless steel plate has the same area as the 25 mm diameter piston used with the Kinosita hardness gauge

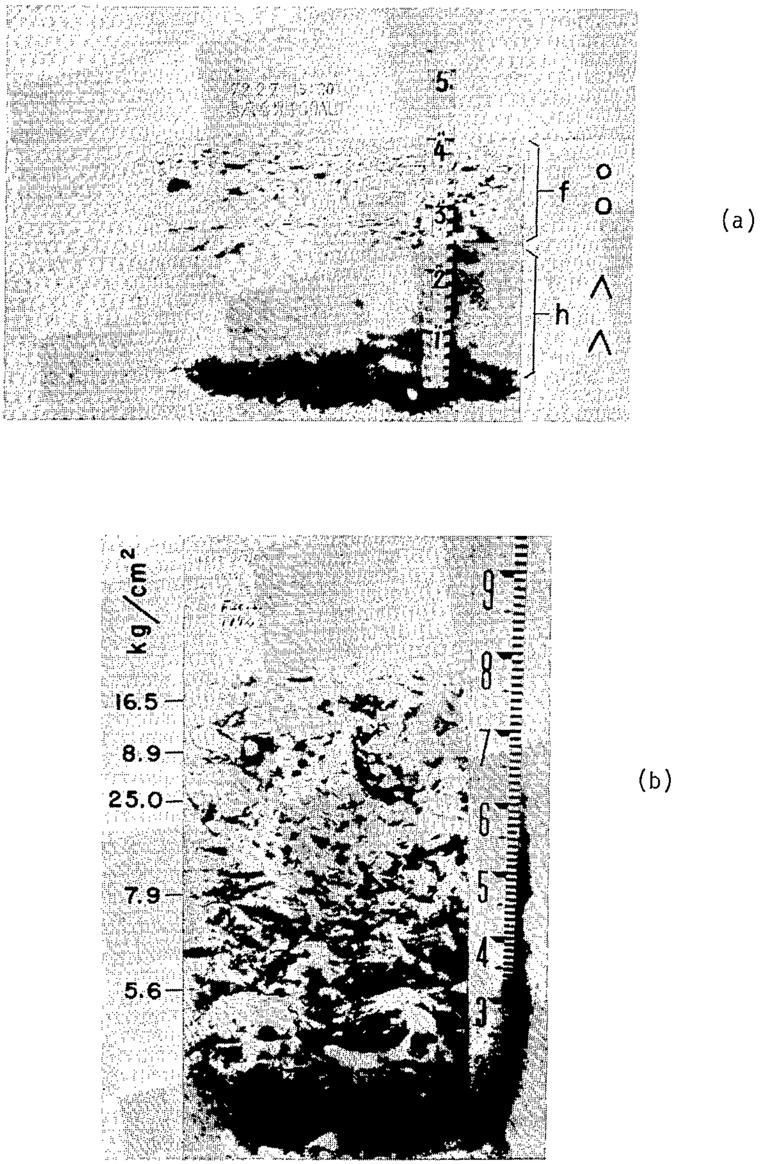


Fig. 2. Structure of processed snow. (a) Men's downhill course, Mt. Eniwa, showing principal crystal types. Scale is in decimeters. (b) Men's giant slalom course, Mt. Teine, showing Kinosita hardness in kilograms per square centimeter. Scale is in decimetres

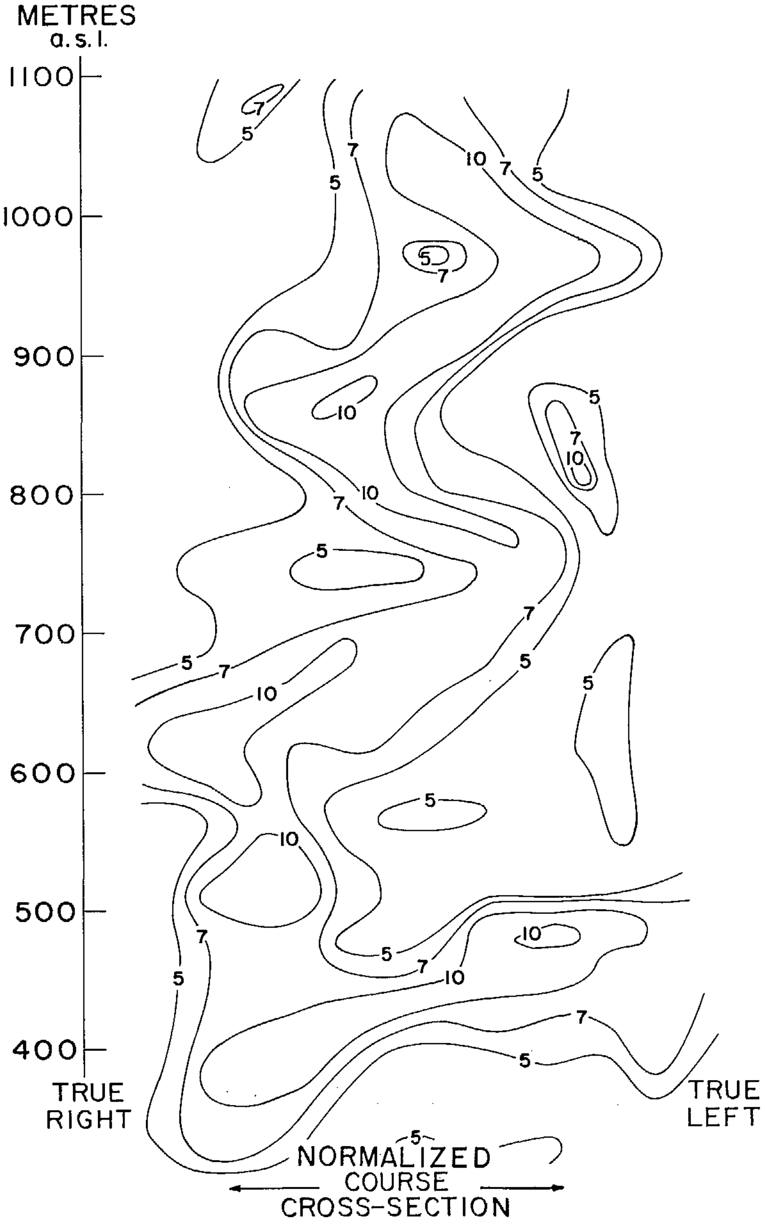


Fig. 3. Men's downhill course, Mt. Eniwa. Snow surface hardness observations of 8 February 1972 with ski edge hardness gauge. Contours plotted from 97 test points give hardness in kilograms per square centimetre

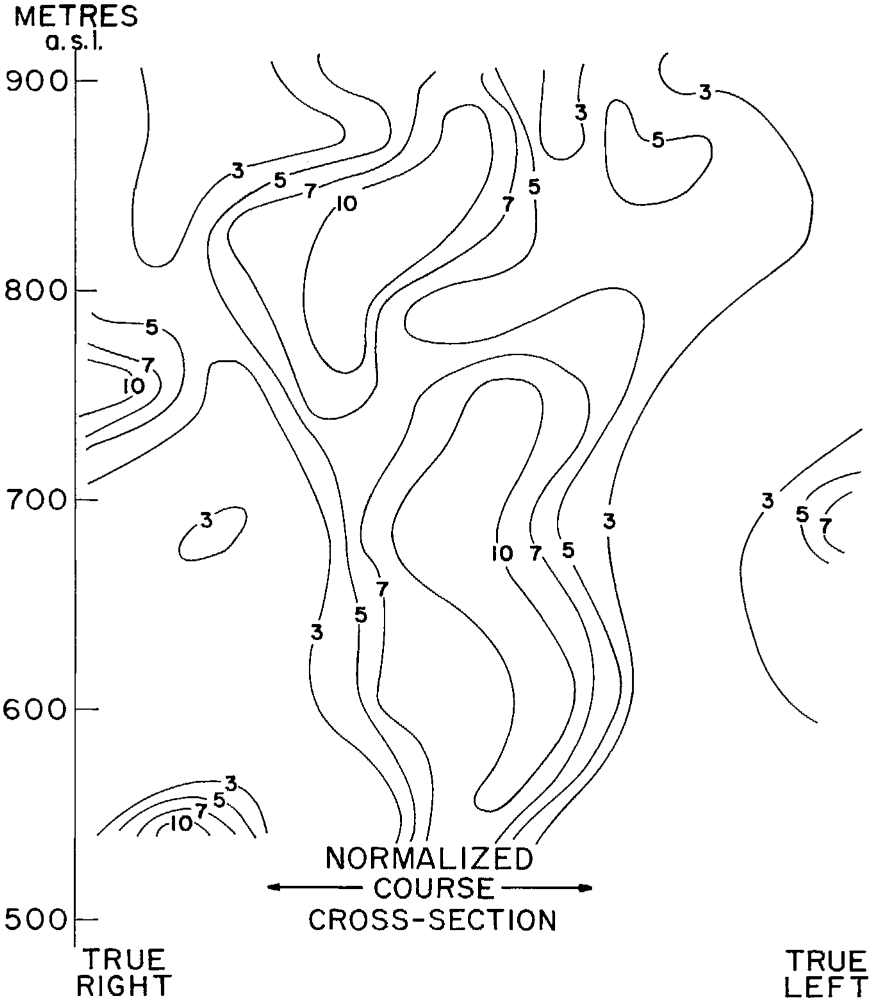


Fig. 4. Men's giant slalom (B-leg), Mt. Teine. Snow surface hardness observations of 11 February 1972 with ski edge hardness gauge. Contours plotted from 68 test points give hardness in kilograms per square centimetre

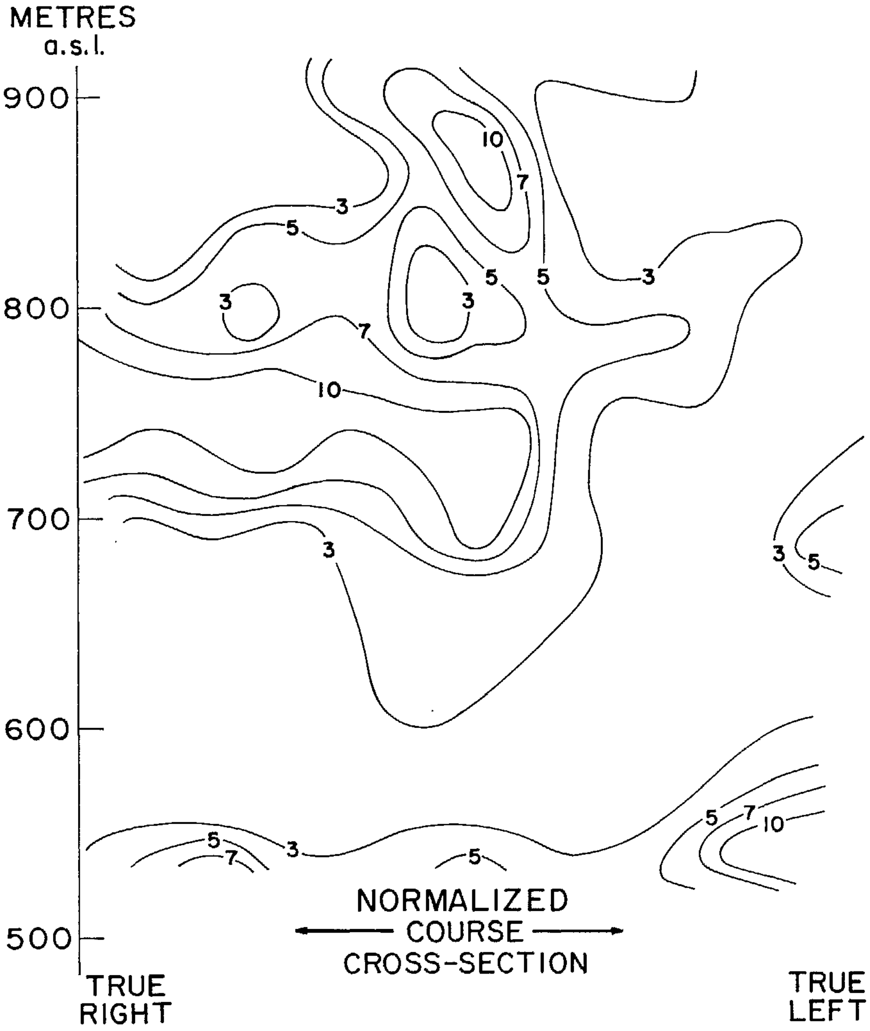
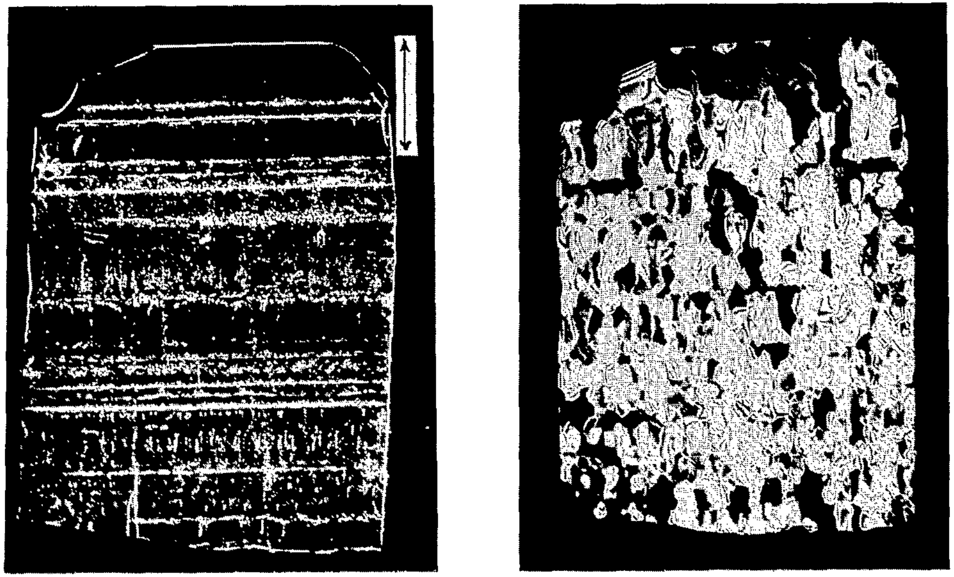


Fig. 5. Men's giant slalom (B-leg), Mt. Teine. Snow surface hardness observations of 11 February 1972 with Kinosita hardness gauge. Contours plotted from 68 test points give hardness in kilograms per square centimetre



(a) (b)

Fig. 6. Vertical thin sections of Makomanai Speed Skating Rink ice. (a) Photographed by reflected light and (b) photographed by polarized light

DISCUSSION

W.E. Howell (U.S.A.) - Were measurements of snow density taken, and if so, what was the average density?

E.R. LaChapelle (U.S.A.) - Yes, density was measured. Pits were dug and density profiles were determined throughout the race courses. Packed-snow densities were generally about 0.5 gm/cm^3 or higher which approached the densities that were sought in the compaction process.

H.K. Weickmann (U.S.A.) - What comments did the skiers express about the prepared snow slopes?

E.R. LaChapelle (U.S.A.) - Comments from the skiers varied widely, depending, perhaps, on who won the gold medals and who did not. In general, the skiers were somewhat puzzled by the snow conditions. International ski racers are accustomed to skiing on very icy surfaces. The surfaces for the Winter Olympics at Sapporo were prepared to a carefully calculated hardness of snow. This has a slightly different feel to the edge of the ski for a racer. It was compacted hard enough that it did not deteriorate during the race; this is the purpose of compacting snow, or of preparing an icy surface. The first and last racers had approximately the same conditions for any run. The skiers were puzzled because it was soft; that is, it appeared to be snow rather than ice but did not deteriorate. Racers expect soft snow to deteriorate rapidly when they ski on it. In Sapporo, it did not. Racers, especially Europeans, had to adjust to the slightly different surfaces. Many compliments were directed to the Japanese for their excellent preparation of the courses. Incidentally, the ski jumpers were unanimous in their praise of the ski jump snow conditions. Some of them told me that the surface was the best that they had ever used.

R. List (Canada) - Was artificial snow used? If not, why not?

E.R. LaChapelle (U.S.A.) - No. There was no artificial snow created. In all cases where necessary, natural snow was imported from the slopes of nearby mountains.

R. List (Canada) - What were the reasons for that? Why was a water-air mixture not sprayed into the air?

E.R. LaChapelle (U.S.A.) - The plan followed in preparing the snow surfaces for the Winter Olympics was based on the assumption that natural snow on the Sapporo courses would be adequate.

P.A. Schaerer (Canada) - How were the cross-country ski courses prepared?

E.R. LaChapelle (U.S.A.) - The preparation of the cross-country runs required a much lower standard of hardness and durability than did the alpine runs. Cross country skiers do not make sharp turns on steep slopes. Most of the initial preparation in packing for the cross-country runs was done by machines, in fact, by snowmobile. The final packing was done by foot and ski. Early experiments indicated that preparation of surfaces by machine packing was not adequate for alpine events. Alpine events require a harder snow.

C. Obled (France) - Comment proposez-vous de mesurer la température en surface sur l'ensemble d'une piste de ski (descente ou slalom géant)? (Le problème du fartage, aussi important que celui de la dureté de la neige, dépend en effet des caractéristiques de la couche superficielle).

E.R. LaChapelle (U.S.A.) - The method used for measuring the hardness and temperature of the snow surface was illustrated in the paper. The measurements were done immediately after each olympic event as well as during the week prior to them. Each time a surface hardness measurement was made, it was necessary to modify the snow surface slightly to provide a small level surface rather than the slanting surface itself. Also at the time of these measurements, the surface temperature was measured with a mercury-in-glass thermometer inserted just underneath the surface of the snow. The records of our observations include the surface hardnesses that are mapped in our paper, plus numerous profiles of temperature, density, and structure obtained from snow pits.