INSTRUMENTS AND METHODS

SAMPLING CHARACTERISTICS OF NEUTRON PROBE MEASUREMENTS IN A MOUNTAIN SNOW PACK*

By CHARLES F. COOPER

(School of Natural Resources, The University of Michigan, Ann Arbor, Michigan, U.S.A.)

ABSTRACT. Advantages of neutron moisture probes over standard snow sampling tubes include integration of water content over a greater horizontal extent, easier measurement of snow layering, and possible increase in accuracy through elimination of the need to extract a full core. However, the neutron probe is better suited for evaluation of water content changes with time at a fixed location, as in soil moisture studies, than for measurement of the total water content of a variable snow pack. Field tests in the mountains of Idaho, U.S.A., showed statistically significant differences among mean snow densities determined by a neutron probe in closely spaced holes at a single sampling station. Within-station variance was about the same as with a conventional snow tube. There were significant differences in density for a given depth from hole to hole, but statistical interactions make it difficult to interpret these differences. There was a poor correlation between measurements made in the same hole with a neutron probe and with a snow sampling tube.

RÉSUMÉ. *Caractéristiques d'échantillonnage d'un névé de montagne par mesures neutroniques.* Les avantages des mesures neutroniques de l'humidité sur l'échantillonnage standard de la neige par tubes carottiers comprennent l'intégration de la valeur en eau pour une zone horizontale plus grande, la mesure plus facile des strates de neige et l'augmentation possible de la précision par élimination de la nécessité d'extraire une carotte complète. Cependant, la mesure neutronique est mieux adaptée à l'évaluation des variations de la teneur en eau dans le temps en un endroit déterminé, comme pour l'étude de l'humidité des sols, qu'aux mesures de la valeur totale en eau d'un névé variable. Des essais dans les montagnes de l'Idaho, U.S.A., ont donné de notables différences statistiques entre les densités moyennes de la neige déterminées par la technique neutronique dans des trous peu espacés en une même station d'échantillonnage. Les variations en une même station étaient les mêmes que celles obtenues par la technique normale des tubes carottiers. Il y avait de notables différences de la densité pour une profondeur donnée des différents trous, mais des interactions statistiques rendent l'interprétation de ces différences difficile. Il y avait une faible corrélation entre les mesures faites dans un même trou avec la technique neutronique et celle du tube carottier.

ZUSAMMENFASSUNG. *Probe-Charakteristiken von Messungen mit einer Neutronen-Sonde in einer Gebirgsschneedecke.* Die Vorteile von Neutronen-Feuchtigkeitssonden gegenüber üblichen Schnee-Rohrsonden bestehen unter anderem in der Integration des Wassergehaltes über eine grössere Horizontalerstreckung, der bequemeren Messung der Schneeschichtung und einer möglichen Genauigkeitssteigerung durch den Fortfall der Bedingung, einen vollständigen Kern zu ziehen. Doch ist die Neutronensonde für die Ermittlung von zeitlichen Wassergehaltsänderungen an einer festen Stelle, wie z.B. bei Untersuchungen der Bodenfeuchtigkeit, besser geeignet als für Messungen des gesamten Wassergehaltes einer veränderlichen Schneedecke. Feldversuche in den Bergen von Idaho, U.S.A., ergaben statistisch erhebliche Unterschiede zwischen den mittleren Schneedichten, die mit einer Neutronensonde in dicht beieinander liegenden Löchern an ein und derselben Probestation bestimmt wurden. Die Streuung innerhalb der Station war etwa dieselbe wie bei konventionellen Schneesonden. Es zeigten sich erhebliche Dichteunterschiede für eine bestimmte Tiefe von Loch zu Loch, deren Deutung jedoch durch das statistische Zusammenwirken verschiedener Ursachen erschwert wird. Zwischen den Messungen mit einer Neutronensonde und mit einer Rohrsonde im selben Loch bestand nur geringe Übereinstimmung.

NEUTRON-SCATTERING moisture meters, widely used for measurement of soil moisture, have occasionally been applied to snow studies. Tests have been promising (Anderson and others, 1963), but the neutron method will be widely adopted only after extensive investigation of its accuracy, reliability, and sampling response in many kinds of snow.

OPERATING CHARACTERISTICS OF SNOW MEASUREMENT DEVICES

Seasonal snow packs are conventionally measured in the United States with a Federal Snow Sampler, an aluminum tube fitted with a steel cutter head and provided with slotted observation holes along its length. The diameter of the tube is such that one ounce (28·35 g.)

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of snow is equivalent to one inch (2·54 cm.) depth of water. Field tests have shown the Federal sampler to overestimate water equivalent by about 7 per cent in light and shallow snow, and by as much as 12 per cent in deep snow of high density (Work, 1964). The inaccuracy is related chiefly to the shape and arrangement of the cutting teeth and inspection slots.

A full core, from the snow surface to ground level, is ordinarily removed and weighed in one operation. A single snow sample thus integrates the water content of several inhomogeneous layers. It is often difficult to obtain a complete core, particularly under adverse snow conditions. It is likewise not easy to sample snow layer by layer; great care must be taken to avoid collecting snow from the walls of the hole when reinserting the cutter after weighing each layer, and small errors tend to accumulate.

The neutron probe depends for its effectiveness on the moderation and back-scattering of fast neutrons by hydrogen atoms in the surrounding medium. The theory of neutron probe operation and the use of the equipment for soil moisture measurement have been described by Van Bavel and others (1963). The number of neutrons counted depends upon the concentration of hydrogen atoms, and hence of water, within the radius of sensitivity of the instrument.

In practice, the neutron probe is lowered into an aluminum access tube set in the snow. Many commercial probes fit 2-inch (5·08 cm.) irrigation pipe, which can be forced into the hole made by a Federal Snow Sampler. Neutron probe counts, usually for one minute, are made at appropriate depths within the snow pack. These counts can be averaged to integrate the water content of the whole pack, or the separate counts can be used to evaluate conditions at several levels within it.

Because some of the change in observed neutron counts is the result of short-term fluctuations in equipment characteristics as well as of variations in ambient water content, neutron counts in the medium are ordinarily not used directly. Instead, the ratio of observed counts to the counts in a water or hydrocarbon standard is entered in a calibration curve appropriate to the particular instrument. Thus, the water content W per unit volume of the medium surrounding the probe is given by

$$W = \frac{a\mathcal{N}}{C} \tag{1}$$

where $\mathcal{N}$ is the number of counts per minute in the medium, C is the number of counts per minute in the standard, and a is the slope of the calibration curve at the point in question. When the probe is used in snow, the surrounding medium consists essentially only of water and air. W in equation (1) then becomes the specific gravity of the snow, or its density in g./cm.^{3}.

The flux of fast neutrons from a radioactive point source falls off exponentially with distance. In pure water, the maximum effective lateral measurement radius of a Nuclear-Chicago neutron probe is about 9 in. (23 cm.), and that of a Troxler probe is about 6 in. (15 cm.) (McHenry, 1963). The corresponding distances are somewhat larger in a medium such as snow.

The vertical dimension of the measurement volume depends in part upon probe geometry. The vertical sensitive length of a Nuclear-Chicago probe is about 14 in. (36 cm.), and that of a Troxler instrument is about 12 in. (30 cm.) (McHenry, 1963). The volume measured by both instruments is thus roughly spherical.

Even though a few neutrons are returned from as far as 6 to 9 in. (15–23 cm.) from the source, the exponential nature of their distribution means that most do not penetrate so far. A neutron probe does not uniformly integrate the water content of a sphere with some definite radius; conditions in the immediate neighborhood of the source are more influential than those farther away.

Snow–air or snow–ground interfaces influence neutron readings if the probe is brought so

close that the measurement sphere intersects the interface. According to McHenry (1963), consistent readings require that the bottom of the probe be at least 4 in. (10 cm.) from the bottom of the access tube. Indeterminate readings are likewise obtained when the center of the measuring volume is less than about 6 in. (15 cm.) below the snow surface.

Detecting ice layers is often important in snow-pack studies. Anderson and others (1963) had no difficulty identifying $1\frac{1}{4}$-in. (3·2 cm.) ice lenses in soft snow. In the laboratory, McHenry (1963) easily detected a one-inch (2·5 cm.) layer of wet soil imbedded in a dry mass. Two such layers, however, could be distinguished from one another only if they were 4 in. (10 cm.) or more apart.

Potential advantages of the neutron probe over conventional snow tubes include integration of a greater horizontal extent of snow than is sampled by the standard snow tube, which can be either an advantage or disadvantage, depending upon information desired; greater ease of measurement of snow layering; and improved accuracy through elimination of the necessity to obtain a core of precise dimensions under adverse conditions. Disadvantages include transportation difficulties resulting from the weight of the equipment, and the possibility of an equipment breakdown at a crucial time in a remote locality.

Theoretical Variance of Neutron Probe Measurements

A neutron meter does not ordinarily yield the same number of counts in two successive observations at a single point. The counts in any given time period are a random sample of the infinite population of counts at that point. Neutron probe counts are known to conform to a Poisson distribution, with variance equal to the mean.

Snow density or water content (W in equation (1)) is thus the ratio of two quantities, each of which has a sampling error associated with it. The variance of the ratio of two such quantities N and C is given by

$$\mathrm{Var}\left(\frac{N}{C}\right) = \frac{N^2}{C^2}\left[\frac{\mathrm{Var}\,(N)}{N^2} + \frac{\mathrm{Var}\,(C)}{C^2} + \frac{2\,\mathrm{Cov}\,(NC)}{NC}\right] \qquad (2)$$

where Var refers to variance and Cov to covariance (Hewlett and others, 1964). There is unlikely to be any appreciable covariance between sample counts and standard counts, so the last term may be neglected. Because of the Poisson nature of the sampling distribution, Var (N) may be taken equal to N, and Var (C) to C.

With a count in the standard of 16,000, the 95 per cent confidence limits of a single one-minute neutron meter observation in snow of various densities calculated from equations (1) and (2) are as shown in Table I. In spring snow with density about 0·40 g./cm.^{3}, there is 95 per cent probability that the true density of the snow within the effective measuring volume of the probe will be within about 0·014 g./cm.^{3} of the value estimated by a single one-minute observation. The confidence limits in Table I are inversely proportional to the square root of the counts in the standard; altering the scaler setting to lower the standard counts will increase the error.

Table I. Theoretical 95 Per Cent Confidence Limits of a Single Neutron Probe Measurement of Snow Density

Density g/cm.^{3}	*Confidence limits* g/cm.^{3}
0·10	0·0043
0·20	0·0065
0·30	0·0083
0·40	0·0136
0·50	0·0163

Timing error, resulting from the inability of even the best electronic equipment to reproduce a fixed time interval precisely, also contributes to the variance of the estimate. This contribution is small with modern equipment. According to timing data and formulas given

by Hewlett and others (1964), variance due to timing error is much less than 5 per cent of the counting variance at normal instrument settings.

Because of the weight of the equipment and the time required to set it up, a sampling design that permitted only a single measurement at each station would be highly inefficient. A more suitable plan involves successive counts at several depths within a hole, spaced perhaps at one-foot (30·5 cm.) vertical intervals. This provides at least four or five observations at each location under most conditions where there is enough snow to justify intensive surveys. Information about vertical stratification is obtained from the individual readings, and the whole group is averaged to compute mean snow density. Water equivalent is computed from the product of measured snow depth and mean snow density.

The variance of the mean snow density or water content at a sampling station, if the small timing error is ignored, is given by

$$\mathrm{Var}\,(W) = a^2\left[\mathrm{Var}\,(L) + \frac{\mathrm{Var}\,(N/C)}{T}\right] \tag{3}$$

where Var (L) is a location variance representing the expected difference between the mean observed counts per minute independent of instrument and timing error and the true population mean of counts throughout the entire snow column at that sampling station, and T is the total counting duration (number of sampled depths if each is sampled with a single one-minute observation) (Hewlett and others, 1964). If four or more depths are sampled, the last term in equation (3) is small compared to the location variance. Calculations through the range of snow depths and densities apt to be sampled in the field indicate that sampling error due to inherent characteristics of the neutron meter is unlikely to exceed 0·005 g./cm.^{3}. This is small enough to be neglected. It may be assumed that most of the observed variance in field observations of snow density obtained with a neutron probe is due either to real variations in the nature of the snow pack or to failure of the instrument to conform to theory. These two effects cannot readily be separated, and are confounded in the analysis of sampling characteristics of snow cover.

Field Measurements

Field measurements were made with a neutron probe and a Federal Snow Sampler near the head of Reynolds Creek, at an elevation of 6,800 ft. (2,070 m.) in the Owyhee Mountains of southwestern Idaho. Intensive samples were taken at two different locations, and were duplicated on two dates at one of these locations. Additional observations were made at randomly located sampling stations in the area. A Troxler soil-moisture probe with a nominal external diameter of 1·865 in. (4·737 cm.) was used in conjunction with a Troxler Model 200B scaler. The probe was equipped with a 3-mC. radium-beryllium source.

For detailed analysis of snow sampling characteristics, an aluminum access tube was inserted successively in each of three newly cored holes spaced 2 to 3 ft. (60–90 cm.) apart. Neutron probe readings were taken from the bottom up at one-foot (30 cm.) intervals. To avoid interface effects at ground level and at the snow surface, the lowest reading was taken with the center of the probe's sensitive volume one foot (30 cm.) above the soil surface, and sampling was discontinued when the probe approached closer than one foot (30 cm.) to the snow surface.

Two successive one-minute neutron counts were made at each depth before the probe was raised to the next level. After the entire series had been completed, the probe was dropped to its initial position near the bottom of the hole. This time only a single reading was made at each depth before the probe was raised. This series was then repeated, so that there were 4 readings at each depth. The entire procedure was repeated in each of the other two holes at that sampling location. The snow was about 8 ft. (240 cm.) deep, permitting measurements at 7 depths within the pack. A total of 84 observations was thus obtained: 4 readings at each

of 7 depths in each of 3 holes. These 84 readings were repeated on two dates, 21 March and 6 April, 1964. New holes were cored on the second date, since weathering had altered snow conditions around the old holes.

A similar set of observations was made at a second location on 3 April 1964. The snow at this point was only 5 ft. (150 cm.) deep, permitting measurements at 4 depths. There were 48 measurements at this station: 4 readings at each of 4 depths in each of 3 holes. On all three dates the air temperature was slightly above freezing. The snow was approaching its maximum spring density but held no detectable free water.

A single set of observations at one-foot (30 cm.) depth intervals was made at 20 additional sampling stations on 7 April and 21 April 1964. Snow depth ranged from 2 to 8 ft (60–240 cm.). Each access-tube hole was made with a standard snow sampler. The snow depth was measured and the core extracted by the sampler was weighed. Resulting values were used to compute snow density for comparison with the density determined from the mean of the neutron probe measurements in the same hole.

Statistical Analysis

Analysis of variance was used to test the reproducibility of neutron probe measurements made in snow. All the observations at a single sampling location were completed in 3 to 4 hr., without altering the scaler settings. Readings were taken in the standard after every 7 or 8 measurements in the snow. The standard readings remained consistent throughout the day, showing no appreciable instrument drift. Direct neutron readings could, therefore, be compared with one another in the analysis of any single day's results, without the necessity of dividing by counts in the standard. The instrument setting varied from day to day and from station to station, however, so observed differences in neutron counts among stations reflect instrument variation as well as snow variation. Because neutron probe counts follow a Poisson distribution, all data were transformed to the square root before analysis.

Each hole at a sampling station was analyzed individually, then the three holes at that station were combined in a single analysis. This was done separately for each of the two dates upon which observations were made, and finally the data for both months were combined into one overall analysis. Certain degrees of freedom were pooled because there was no experimental reason for pairing the first set of readings in any one hole with the first or any other particular set in another hole.

Sampling Characteristics of Neutron Probe Data

In no case was there a significant difference between the means of the paired readings when successive observations were made without moving the probe. A consistent difference would indicate an instrument defect or malfunction which would invalidate any later conclusions.

There was in general no significant difference among the mean counts obtained from successive observations in the same hole, with the probe relocated at the specified depths each time. There were 9 such comparisons, with three sets of readings in each. In two cases there was a statistically significant difference among the means of the three sets of observations in one hole; in the other 7 there was not. In both the significant cases one set of counts averaged appreciably higher or lower than the other two. The actual density difference in one case was less than 0·005 g./cm.^{3}, but in the other it was more than 0·03 g./cm.^{3}. This last is too much to tolerate, and is more than could logically have been expected as an extreme value in the observed sampling distribution.

The variation could have arisen in several ways. Instrument drift could have changed all the readings more or less uniformly. This should have been reflected in a change in the standard reading taken at the end of each series. One or more readings could have been transcribed incorrectly from the scaler glow tubes, but this should have been apparent as an

outrageously deviant value. A temporary undetected instrument failure is possible but unlikely. Finally, the probe might not have been repositioned at exactly the same point each time. In this case, compensating errors would probably have prevented the overall variation from becoming as large as it did. An unidentified blunder is the most likely cause of the unacceptably large deviation of one of our measurements. The fact that this occurred despite considerable care points a warning to users of neutron probe equipment.

There was a highly significant difference in the mean densities measured in the three closely spaced holes at a sampling station, but the magnitude of this difference was no greater with the neutron probe than with the conventional snow sampler. In both cases, the sample standard deviation of snow density at a single station was about 0·01 g./cm.^{3}.

To get additional information about density variations at a point, we compared 12 sets of 2 observations made by both methods at randomly located sampling stations. The two observations of a pair were about 2 ft. (60 cm.) apart.

The within-station mean-square variance of the sampling tube observations was 0·0001047; that of the neutron probe observations was 0·0001307. These variances correspond to standard deviations of 0·010 and 0·011 g./cm.^{3} respectively, too little difference between methods to be of any practical consequence.

In both cases, the observed variances are comprised partly of real differences in the density of snow at closely adjacent points and partly of instrumental variation. Data from Table I suggest that in this instance about 40 per cent of the observed neutron probe sample variance is due to instrument characteristics. Real differences in the snow are responsible for the rest.

There was, as expected, a highly significant difference among the densities measured at various depths. The possibility of measuring the thickness and density of separate snow layers in place is one of the principal attractions of the neutron probe method.

Although differences in density with depth could readily be distinguished, another sampling characteristic increases the difficulty of interpreting the data. There was a highly significant interaction between depth and individual holes at a sampling point. This interaction arises because the pattern of change in density with depth is not constant even over a lateral extent of two or three feet (60 or 90 cm.).

The preceding relationships are summarized in Table II, which shows the combined analysis of variance for two months' data at one sampling station. The nature of the sampling scheme required pooling some of the interaction terms with the principal effects, as shown in the table. In the table, M stands for month, H for holes at a sampling station, R for replication within a hole, D for depth, and combinations of these letters for interactions involving more than one component.

Table II. Summary Analysis of Variance, Two Months' Data obtained with a Neutron Probe at a Single Sampling Station

Source	*Degrees of freedom*	*Mean square*
Main effects		
Month	1	16539·53
Holes (H+MH)	4	45·46
Depth	6	155·05
Replications (R+HR+MR+MHR)	12	8·47
Interactions		
Month × depth	6	39·06
Hole × depth (HD+MHD)	24	10·43
Residual (RD+RHD+MRS+MRHD)	72	2·78
Total	125	

All terms not statistically significant when tested with a variance ratio test against the four-factor interaction were lumped in the residual variance. The other terms were all significant at the 1 per cent probability level. The statistical significance of the replication term is due solely to the one anomalous value discussed above. The large difference between months

reflects not only change in average snow density between the two dates but also a difference in operating characteristics of the instrument on the two occasions. The latter difference would ordinarily be corrected for by dividing the raw neutron counts by counts in the standard. The month–depth interaction is a consequence of expected changes in the pattern of depth variation with time.

Comparison of Neutron Probe and Snow Sampler Densities

All the holes for the neutron probe access tubes were made with a standard snow sampler. The snow core removed from each hole was used to compute the density of the snow at that point. This density was then compared with the density derived from the neutron probe counts at the same point.

The relationship was not too close (Fig. 1). The regression equation of the two sets of data was

$$p = -0{\cdot}087 + 1{\cdot}11T \tag{4}$$

where p is snow density measured with the neutron meter and T is density at the same point as determined with the snow sampling tube. Equation (4) was not significantly different from a simpler equation passing through the origin:

$$p = 0{\cdot}90T. \tag{5}$$

There was no statistically significant non-linearity in the fitted equation.

Statistically significant regression coefficients could easily be attributed to improper calibration of the neutron probe. We made no attempt to calibrate the instrument in snow, but used the manufacturer's general calibration curve for soils. Failure of the neutron probe and

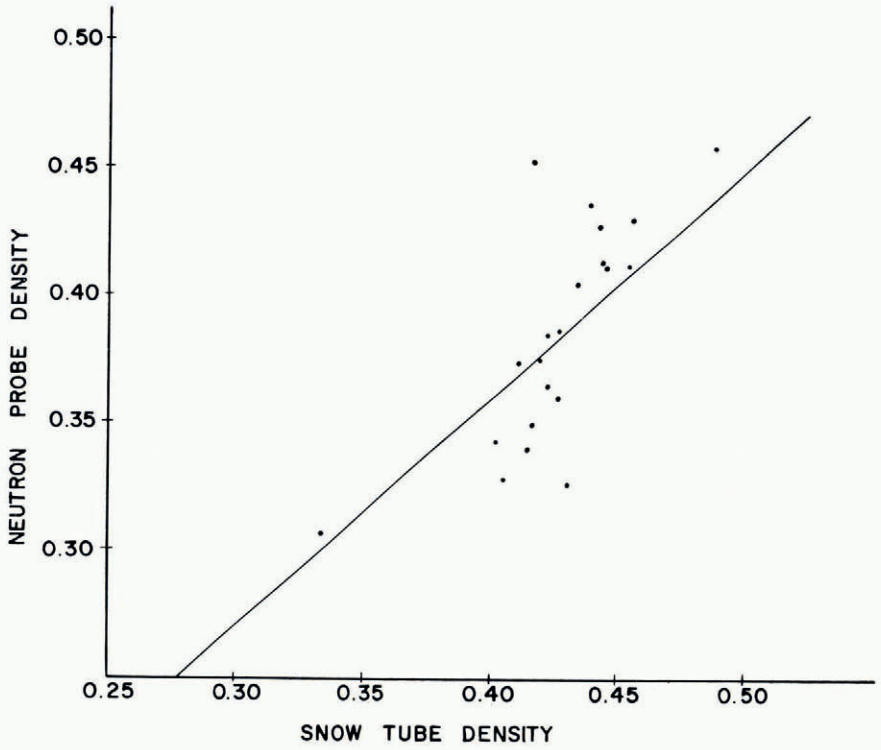

Fig. 1. Relation between snow density in g./cm.³ as determined in the same sampling hole with a snow sampling tube and a neutron probe

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snow sampler densities to conform to the expected 45 degree line would be unimportant if they fell closely along some other line that could be used to shift the instrument calibration. As is evident in Figure 1, they did not; there is considerable scatter of the plotted points. The best regression equation that could be fitted to the data accounted for only 54 per cent of the observed variance. This corresponds to a correlation coefficient of 0·73.

The poor correlation between snow densities determined by the two methods does not of itself point to any inaccuracy in the neutron probe measurements. We made no attempt to compare the densities observed in the field with those determined by some objective technique in which one can have full confidence. The known difficulty of obtaining accurate snow estimates with the snow sampler (Work, 1964) suggests that the latter device may have been more in error than the neutron probe.

Part of the scatter of points in Figure 1 might have been due to the presence of appreciable free water at some but not all of the stations sampled with the neutron probe. Anderson and others (1963) reported that with no change in snow density, lower neutron probe counts were associated with the presence of free water in the snow pack. Some physical chemists with whom the subject has been discussed have suggested that this observation may have been an artifact. In any case, a change in neutron counts of the magnitude reported by Anderson and others (1963) to accompany a change of state would be inadequate to account for the scatter of points in Figure 1, particularly since the samples were taken when daily temperatures and visual observations of snow conditions both indicated that little free water had yet appeared in the pack.

The main conclusion to be drawn from the poor correlation between densities determined by the two methods is that conversion of an existing snow tube sampling program to neutron probe observations may not yield compatible results. Comparisons of current neutron probe observations with past snow-tube data must be made cautiously.

Temperature Sensitivity of Equipment

There is no evidence that any appreciable part of the variance in neutron probe sampling was the result of erratic equipment operation in cold weather. To test the sensitivity of the equipment to temperature, the scaler and probe were placed in a refrigerator at 37°F. (3°C.) and at room temperatures of 68° and 85°F. (20° and 29·5°C.). Operation was tested with the scaler in the refrigerator and the probe at room temperature, the probe in the refrigerator and the scaler at room temperature, both in the refrigerator, and both at room temperature. In each case, a stabilization period of at least 12 hr. preceded the test.

The probe showed no evidence of temperature sensitivity over the entire range tested. Temperature variations within the snow therefore did not contribute to the observed variances. The probe was not tested in extreme cold, but the snow pack during this study was at or near freezing throughout.

The scaler did not operate when taken from the refrigerator. It began to work normally after it had warmed to about 42°F. (5·5°C.), and showed no further change in operating characteristics as its temperature increased.

In the field, the scaler was kept in an insulated box and was operated from inside a heated over-snow vehicle (Fig. 2). The probe, shielding, standard, and scaler together weigh nearly 100 lb. (45 kg.), necessitating mechanical transportation. Keeping the scaler warm is thus no real problem. Lighter equipment which incorporates a rate-meter instead of a scaler might be carried by one man. The cold-weather operating characteristics of such a unit would have to be evaluated before it could be recommended for use in snow.

Discussion and Conclusions

Many writers have pointed out that in most experiments in agriculture, forestry, and hydrology which involve moisture measurements, interest centers on changes in moisture

Fig. 2. Neutron probe in use, showing over-snow vehicle used for winter access to remote locations

status with time rather than on the absolute water content of the profile. Neutron probes are well suited to this type of analysis. The same soil mass can be measured repeatedly, so losses or gains can be determined for each sampling point. Analysis of changes at specific locations automatically introduces a covariance between measurements made at the same point at different times, and so reduces experimental error. Moisture changes, being numerically less than total water content, give a smaller error in terms of moisture volume or inches of water per foot of soil than if the total water content of the profile is evaluated. For a given precision level, an analysis of changes requires only about one-tenth as many samples as a total moisture survey (Douglass, 1962).

Many of these advantages are lost when the neutron probe is used in snow. It is ordinarily not possible to sample exactly the same spot at successive intervals, if those intervals are separated by more than a few days. Soils are sampled with permanently installed access tubes which alter surrounding soil conditions only slightly, but the presence of a metal access tube during sunny weather materially changes the snow around it. Absorption by the tube of solar radiation penetrating the snow results in accelerated melt or metamorphosis of the snow around it.

Measurement of water content of snow is more often aimed at determining the total amount of water stored in the pack than in evaluating day-to-day changes or differences. Total water content, for example, is required in run-off prediction equations. The statistical advantage of neutron probe data in dealing with differences in water content thus loses much of its importance in snow studies. The evidence from the measurements reported here indicates that the variance of estimates of total water content is about the same whether obtained by neutron probe or snow sampler.

Even where periodic changes in water content are the principal variable of interest, the sampling error of these differences is likely to be larger in snow than in soils because of the relatively small covariance of successive measurements in snow. If instrument errors are

disregarded, the variance of the difference between two moisture measurements m_1 and m_2 is given by

$$\text{Var}\,(m_1 - m_2) = a^2[\text{Var}\,(L_1) + \text{Var}\,(L_2) - 2\,\text{Cov}\,(L_1\,L_2)] \qquad (6)$$

where Var (L_1) and Var (L_2) are the variances of the measurements at different depths within a location; Cov $(L_1\,L_2)$ is the covariance between counts at the same depth at different times; and a is the calibration coefficient for converting counts to moisture volume (m). Because settling and metamorphosis change the relative position of separate density layers as the season progresses, the covariance between measurements at identical depths on successive dates is relatively small compared with that of measurements in a more stable medium such as soil. The calculated covariance of measurements made at the same station on two dates three weeks apart at Reynolds Creek was less than half of the separate variances of the two sets of measurements.

Neutron probes are relatively new, expensive, and somewhat glamorous. They may prove to have advantages for measurement of snow, but these advantages may be offset in part by the bulk, cost, and complexity of the equipment. All factors need to be carefully evaluated before initiating a large-scale snow sampling program with the neutron probe.

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