MEASURING SNOWPACK PROFILES WITH RADIOACTIVE SOURCES

By Lloyd W. Gay [1]

The use of radioactive sources to measure the moisture content and density of substances has become commonplace. Much of this work has been concentrated on determining soil moisture with fast-neutron probes, and soil density with gamma ray probes.

Snow hydrologists must measure the water content and density changes of the snowpack throughout the accumulation and the melt season. Present methods for detecting such changes are primitive and destroy the sampling site and prevent repeated measurements at the same point. Nuclear instruments using the "backscatter" principle offer a way out of this dilemma. If these devices prove satisfactory, we can study the snowpack profile without disturbing it and measure (a) changes in density of the profiles, (b) extent and formation of ice layers and lenses, (c) detection of free water ponded within the pack (d) movement of liquid water through the pack, and (e) extent and position of strata of different densities.

Results so far indicate that gamma-ray probes show some promise, but will require further development for use in making satisfactory measurements of snowpack profiles.

Moisture Probe Characteristics

The principle of neutron-scattering as applied to moisture determination has been in use for several years. Information on the theory has been presented by Van Bavel (1958) and the Nuclear-Chicago Corporation (1958), which claims that its equipment is accurate within plus or minus 2 percent of the absolute measurements.

The instrument includes a probe with a radioactive source that emits fast neutrons and a detector that is sensitive only to slow neutrons. An access tube is inserted into the soil, the probe is positioned, and fast neutrons stream out through the soil. This material scatters the neutrons, slows them down, and reflects a portion back into the detector. These neutrons are slowed primarily by collision with hydrogen atoms in the soil. In most soils, water provides the principle source of hydrogen. The amount of water in soil then can be related to the rate of returning neutrons.

Density Probe Characteristics

The Corps of Engineers (1956) and the Nuclear-Chicago Corporation (1960) have published information on the theory of density determination through the use of gamma rays.

The measurement of soil density is based upon the interaction of gamma rays with the electrons of the soil material surrounding the radioactive source. Gamma rays from the probe are scattered in all directions upon collision with electrons. In soil and similar material, the number of electrons per unit of volume determines its scattering power. An increase in the electron density increases the probability of multiple scattering of gamma rays. Thus, a portion of the scattered rays is returned to be counted. We found that the count rate is proportional to the density for low density materials. Still greater electron density increases the chances that the rays will be absorbed before they return to the detector. The denser the material, the higher the absorption. Thus, the count rate is inversely proportional to density within soil ranges of 48.5 to 150 pounds per cubic foot.

Method of Study

During the winter of 1960, we made an exploratory study at the Central Sierra Snow Laboratory near Donner Summit in Northern California to determine the usefulness of radioactive probes in measuring snow [2]. This medium has a much lower density but a moisture content similar to that of soil for which these instruments were designed.

For this study, we used a Nuclear-Chicago Model P-19 Subsurfact Soil Moisture Probe and a Nuclear-Chicago Model P-20 Depth Density Probe. Comparative density determinations were made with a Mount Rose snow tube and a SIPRE 500 cc. density sampling tube furnished by the Snow, Ice, and Permafrost Research Establishment of the United States Army.

We sank an aluminum access tube into the snowpack for each series of measurements with the probes. The tube measured 1,625 inches outside diameter and 1.555 inches inside diamter. We inserted a probe, lowered it to several depths into the snow profile, and recorded counts on a timer-scaler. We timed the probe count periods with a stopwatch to eliminate timer error and

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[2] The study was part of the cooperative snow management research program of the U. S. Forest Service in cooperation with the California Department of Water Resources.

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standardized the length of periods at two minutes, as suggested by Merriam and Knoerr (1961) and the Nuclear-Chicago Corporation (1960). After completing the profile count, we excavated a pit to expose the access tube throughout its entire length, and took gravimetric density samples at the same depth intervals with the SIPRE sampler. A sample was taken on each side of the access tube in a snow strata.

During the tests, we made 114 2-minute counts with the P-20 gamma ray density probe and 45 2-minute counts with the P-19 neutron soil moisture probe. We also took 89 SIPRE density samples to measure snow strata in 10 different snow profiles. The deepest snow profile measured was 85 inches.

Results

Snow density determined by the SIPRE sampler was taken as the standard. The SIPRE tubes gave good results in homogenous snow strata, but samples from these tubes in icy or crusty strata or through the interface dividing two strata usually gave different density values. If two SIPRE samples from the same strata differed by more than 4 percent density, they were not used in the calibrations.

Densities determined by the SIPRE sampler ranged from 11 to 52 percent. Half of them fell within the 30-39 percent group. The distribution of density determinations was as follows:

Snow density (Percent)	Strata sampled	Snow density (Percent)	Strata sampled
10 - 14	1	30 - 34	13
15 - 19	4	35 - 39	14
20 - 24	7	40 - 44	10
25 - 29	3	45 or more	2

With the two probes, reduction in count rates became noticeable in low-density layers close to the surface of the snowpack because of loss of neutrons and gamma rays to the air. The influence of the soil increased the count rates in the bottom snow strata.

Gamma Ray Probe and Sipre Samples

Counts per minute made with the gamma ray probe and snow density as determined by the SIPRE sampler were closely related (Figure 1). The deviations from a smooth curve drawn through the data indicate an error of estimate of about 5 percent density. The data approximated a straight line when counts per minute are plotted against log snow density. The snow calibration curve is shown in relation to the Nuclear-Chicago soil calibration curve (Figure 2.) The water and soil counts cannot be compared directly because of differences in electron density between water and soil and because of small differences in count rates between our aluminum access tubes and the Nuclear-Chicago Corporation's steel tubes.

The snow-count rate (Figure 2, Curve A) increases in proportion to the density of the snow, peaking somewhere beyond 31.2 lbs./ft.^{3}, which corresponds to a 50 percent snow density. The count rate in soil (Figure 2, Curve B) decreases linearly for soil densities greater than 48.5 lbs./ft.^{3}.

As snow becomes denser a greater number of gamma rays are reflected back to the detector tube. With increasing density a point is reached at which more gamma rays are attenuated and absorbed than are reflected. Then the count rate begins to decrease with further increases in density. The point at which this maximum counting rate occurs lies outside of the range of snow densities we sampled.

Neutron Probe and Sipre Samples

Comparison of snow densities determined with the P-19 neutron probe and with the SIPRE density sample (Figure 3) shows a wide scatter of points. The neutron counts in snow are lower than for an equivalent amount of moisture in the soil. Count rate increases with snow density, because the increased number of hydrogen atoms moderates the speed of the neutrons and reflects the slowed neutrons back to the detector.

The apparent low count rates in snow may be caused by changes in either the moderating effect of hydrogen atoms bound into ice crystals or in the manner in which the slowed neutrons are reflected back to the detector tube. The scatter occurs in snowpack measurements near 40 percent snow density when appreciable quantities of melt water may be present in the snowpack. The presence of this free water greatly increases the count rate. A change of count rate due to change in state of water from liquid to solid was indicated by counts in ice and in water in a container 11.75 inches diameter and 13 inches deep. The count rate in ice was 12 percent lower than that expected from ice of 0.917 density. The discrepancies between ice and water counts are being

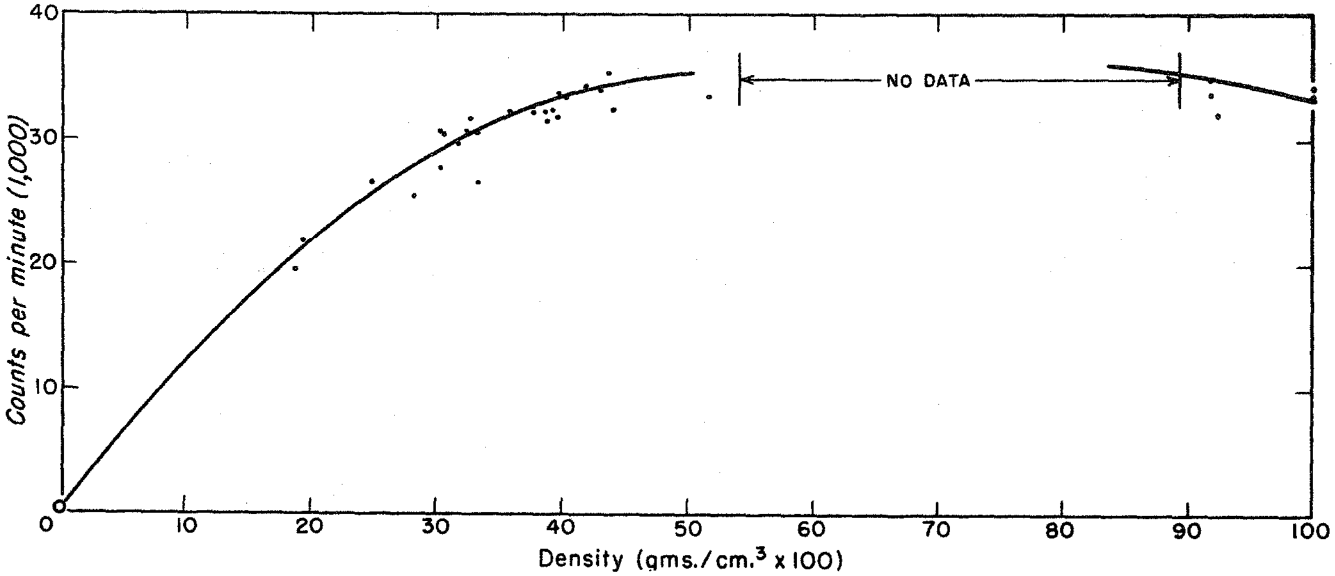


Figure 1.--Relation of counts with gamma ray density probe to snow density determined by SIPRE sampler

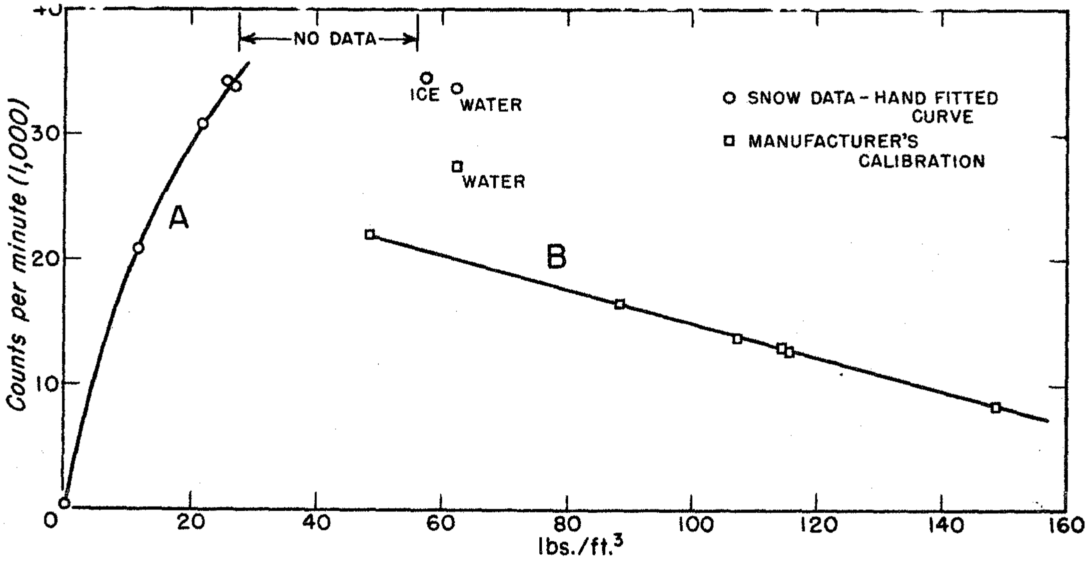


Figure 2.--Comparison of gamma ray density probe count rates in snow and in soil.

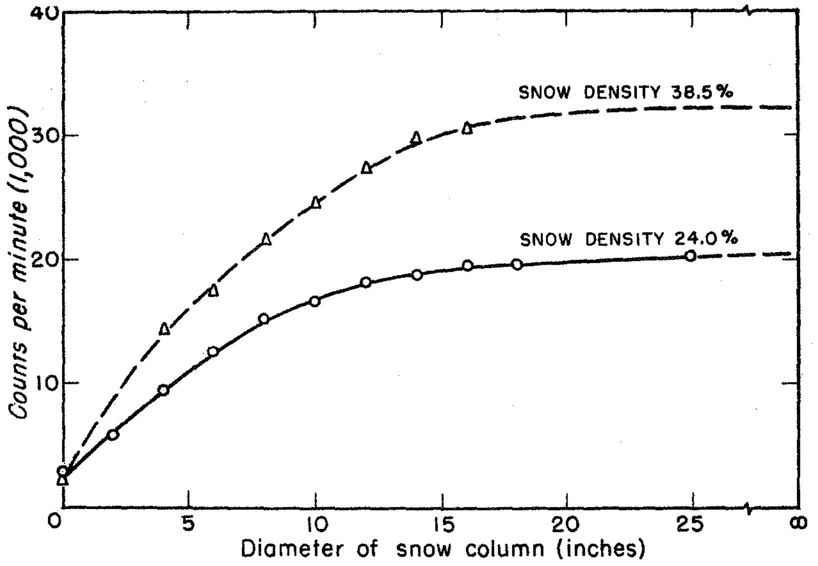


Figure 5.--Count rate of the P-20 gamma ray density probe in snow columns of different diameters and different densities.

further investigated in laboratory tests.

Detection of Ice Layers

The gamma ray density probe was tested as a detector of ice lenses in a 28-inch profile of new and old snow that contained four prominent ice layers. SIPRE sampler densities ranged from 16.6 to 30.3 percent (Figure 4). Thirteen inches of new snow lay over the four ice layers which had a total thickness of 1.6 inches and occupied the 13.5- to 20-inch zone. The presence of ice layers raised the density of this zone to 41.5 percent as compared with an average density of 24.9 percent for the interspersed fine-grained snow strata.

To determine the effect of the ice layers, we made gamma ray density counts at 1-inch intervals and compared the change in count rate at each observation level with the profile characteristics. The count rate change increased as the center of measurement of the probe left the influence of the snow surface. It decreased as the measurement center became affected by the ice layers, and then increased again after leaving the ice zone. Within the range of count rate of change of 299 to 1,369 c.p.m., the maximum approximate error to be expected ranges from 145 to 310 c.p.m.

We found an unexpected influence of the ice layers when we compared the count rate change with the snow profile characteristics (Figure 4). Although the general trend was an increase with denser snow at depth, the curve flattens as the center of measurement of the probe enters the ice layers at the 14-inch depth. This flattening effect indicates lower density. The counts did not resume an increase with depth until the center of measurement passed beyond the last ice layer.

This effect is probably due to the geometrical relationship between the source and the detector tube. The effective center of measurement is on a plane midway between the source and the detector (Nuclear-Chicago Corporation, 1960). In the gamma ray density probe, the source is 10 inches below the detector. This position allowed the source to penetrate all the ice layers in this particular profile before the detector entered them. We expected that the count rate in ice would be more than a third higher than that for snow of 25 percent density. However, the count rate change indicates that the ice layers acted as shields and prevented the expected amount of reflected gamma radiation from returning to the detector. This effect does not appear to indicate adequately the presence of ice layers or lenses in the snow profile. Detection of ice layers and free water is further limited in dense snow profiles by the non-linear calibration curve. The density probe count rates for dense snow cannot be separated from that of solid ice and free water because the maximum count rate lies somewhere between snow density of 50 percent and ice and water.

Tests for Sphere of Influence

Because of the promising calibration curve of the gamma ray density probe, we made two tests of the distance that gamma rays will penetrate into the snow and still be reflected back to the detector. This distance was called the radius of the sphere of influence. We made the tests in snow profiles of different densities to determine the sensitivity and the resolution of the probe. The radius of the snow column surrounding an access tube was reduced by 2-inch intervals, between successive counts at a given level. Snow density in each strata was obtained with SIPRE density samplers.

We made our first study with the gamma ray density probe positioned with the center of measurement at the 12-inch level in a heterogenous winter snowpack having an average snow density of 25 percent. A maximum count rate was obtained from the undisturbed profile, and then counts were begun with a snow column radius of 18 inches. The count rate dropped with a decrease in snow column radius (Figure 5).

The second sphere of influence test was made in a fairly homogenous spring snowpack and the probe positioned at a depth of 23 inches. The average density in the zone of measurement was 37 percent.

In these tests, a count rate of 95 percent of that in the undisturbed profile was produced in a 25 percent snow column of 13-inch radius and in a 37 percent snow column of 16-inch radius. We had expected that the denser snow would require a smaller radius than the less dense snow to produce this count rate. Some snow structure factors such as crystal size and orientation may affect the reflection of gamma rays back to the detector tube. Drainage of free water from the cut faces of a snow column could also cause changes in sphere of influence measurements under some snowpack conditions. However, at these two sites, drainage did not appear to be a factor.

These tests indicate that the gamma ray density probe integrates the density within a sphere with a maximum radius of about 16 inches. This radius appears to vary with changes in snow density and composition.

Depth - Integrated Sampling

We made five tests of the feasibility of securing an estimate of the average snowpack density by obtaining a gamma ray density count which would integrate the entire snow profile. Counts igure 3.--Relation of ounts with neutron soil oisture probe to snow ensity determined with IPRE sampler.

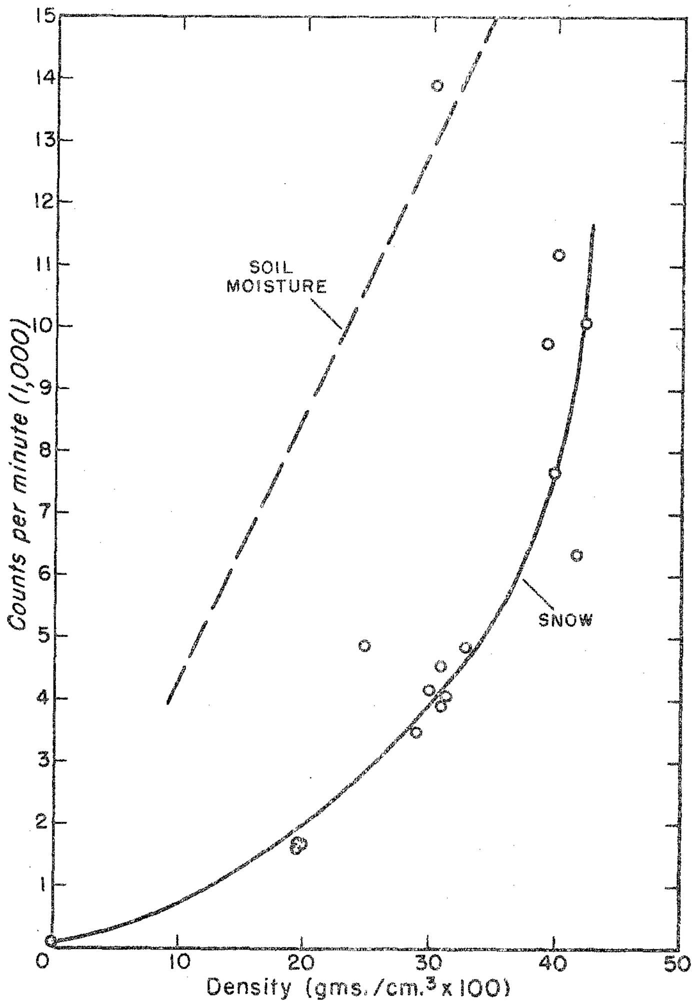
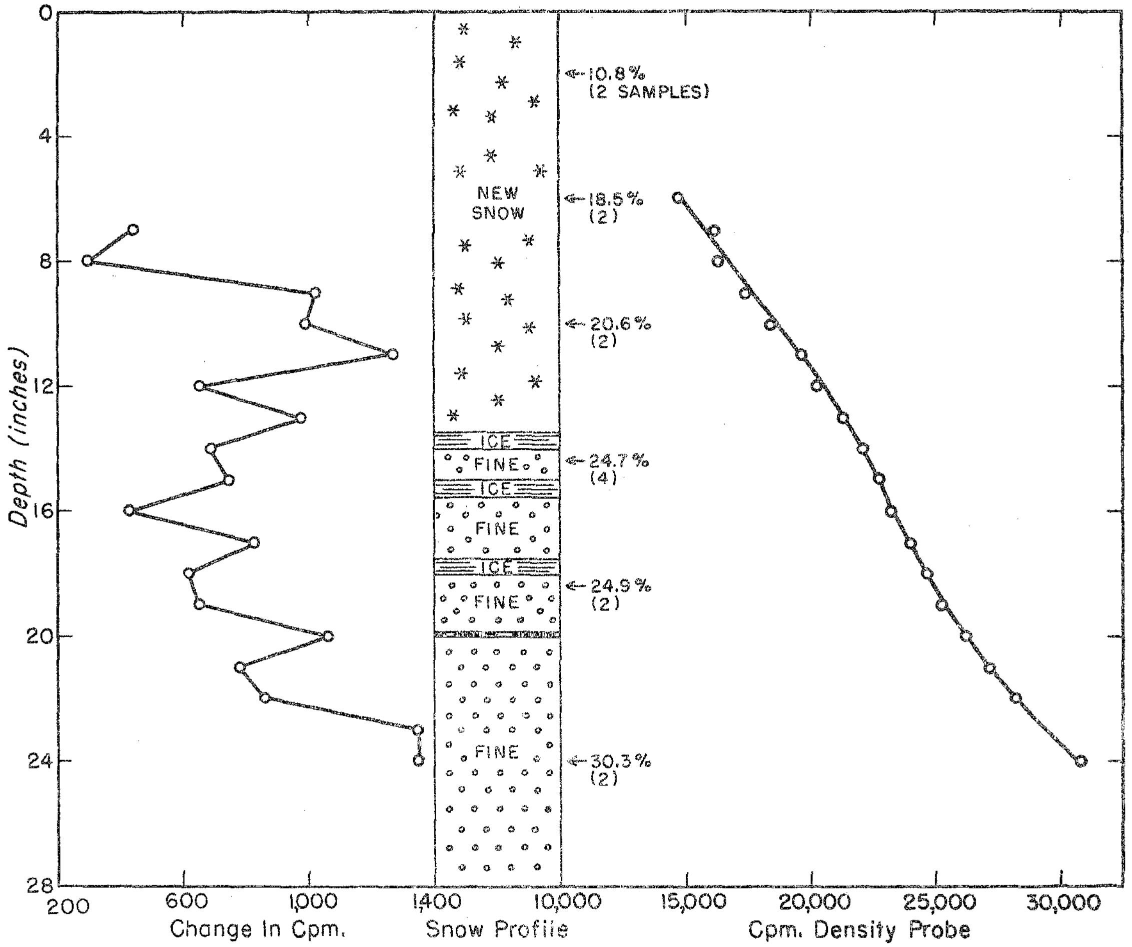


Figure 4.--Changes in counts with P-20 gamma probe with changes in snow density and with occurrence of ice layers in a snowpack.



were accumulated as we moved the gamma ray probe at different rates through the profile. The accumulated counts were converted to a count rate and an average density value was obtained for the snowpack from the calibration curve. We compared this depth-integrated density with the average snowpack density as obtained through measurements with the Mount Rose snow tube.

	A	B	C	D	E
	Inches				
Snowpack depth	57	35	85	85	85
	Percent				
Mount Rose snow tube	36.1	36.2	36.9	36.9	36.9
P-20 gamma probe	31.4	29.6	29.5	30.5	31.0

The gamma probe consistently underestimated the average snowpack density, because of loss of counts to the air as the probe nears the surface, and because the non-linear shape of the calibration curve "weights" the low density strata. Thus, the averages from an integrated sample will fall below the actual vertical density of the snowpack, depending upon the extent and distribution of the profile's density gradient.

Conclusions

1. The Nuclear-Chicago Model P-20 depth density probe provides a useful measure of snowpack density profiles within the range of 20-40 percent. As now designed for soil use, it integrates a large volume of snow at each sample point. This volume reduces its sensitivity and effectiveness in making detailed studies of moisture and density changes in snow. The non-linear calibration curve precludes the use of the probe to detect and measure ice layers and free water within the snowpack.

2. The Nuclear-Chicago Model P-19 soil moisture probe did not provide a satisfactory measure of snowpack density profiles in these tests.

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