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USE OF RADIOACTIVE SOURCES IN
MEASURING CHARACTERISTICS OF SNOWPACKS

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ABSTRACT: Use of radioactive probes inserted in mountain snowpacks may make possible more accurate appraisal and prediction of snowmelt water. Commercially available gamma and neutron probes were tested for their ability to measure snow density, ice lenses, and the thermal quality of individual layers in the snowpack.

Radioactive sources can be used to measure hydrologic characteristics of snowpacks. Preliminary test results also indicate that it may be possible to predict the start and rate of snowmelt from such measurements. Tests of gamma and neutron sources in measuring snow were begun in 1961 at the Central Sierra Snow Laboratory, near Donner Summit, California.^{2/} The results proved so encouraging that we asked the United States Atomic Energy Commission's Division of Isotopes Development to finance additional study. These investigations are part of the California cooperative snow management research program carried on by this Station in cooperation with the California Department of Water Resources.

Commercially available probes with gamma and neutron sources (Nuclear-Chicago P-20 and P-19 probes)^{3/} were tested for their ability to measure these characteristics of snowpack profiles: density, ice lenses, and thermal quality (free water). The probes were lowered into an aluminum access tube inserted into the snow, and the gamma and neutron counts taken at successive 6-inch depths.

^{1/} Snow research project leader and research foresters, respectively.

^{2/} Gay, Lloyd W. Measurement of snowpack profiles with radioactive sources. 30th Annual West. Snow Conf. Proc. 1962:14-19.

^{3/} The use of a trade name does not constitute endorsement of the product.

The gamma probe consisted of a Cesium 137 radioactive source and a Geiger-Muller tube. Gamma rays from the source are back scattered from the snow atoms, with the number of returning rays increasing as snow density increases.

In the neutron probe, fast neutrons from the radium beryllium source are slowed upon contact with the hydrogen atoms in the snow. The number of the slowed neutrons which is returning to the counter increases as snow density increases.

First, both probes were "calibrated" by comparing snow density measured gravimetrically at each layer of the snowpack with the gamma and neutron counts; about 200 such calibration samples were taken. These data were analyzed to show the relationship between snow density and gamma and neutron counts. The counts at each snow depth, at the point of measurement, and 6 inches above and 6 inches below it were used in the appraisal of snow density.

In other tests, we studied the effects of natural and artificial ice lenses on gamma and neutron counts and the relationship between these counts and the thermal quality of the snowpack. Throughout the spring of 1962, a total of 1,100 samples (gamma and neutron counts) were taken at 31 forest sites. From these measurements, we tested the relationship of gamma and neutron counts to snowmelt.

RESULTS

GAMMA PROBE

The relationship between gamma counts and snow density is well defined for densities of from 12 to 52 percent (fig. 1). The dispersion about the regression line involves errors both in the gravimetric determination of density and in the underlying relationship between gamma counts and density. By measuring the density over the much larger volume than the gravimetric determination, the gamma counts may be in effect a more accurate appraisal of the snow density at a given depth.

To improve prediction, the counts may be taken at a point 6 inches above and 6 inches below the measurement layer:

Gamma probe:^{4/}

Equation 1 - Depths ≥ 18 inches ; $S_{yx} = 3.5$, $n = 148$

$$\text{Density} = 11.8 + 0.02 C_g^2 - 0.72(C_{ga} - C_g) - 1.03(C_{gb} - C_g)$$

Equation 2 - Depth: 12 inches; $S_{yx} = 2.3$, $n = 20$

$$\text{Density} = - 2.7 + 1.25 C_g + 0.50(C_{gb} - C_g)$$

Equation 3 - Depth: 6 inches; $S_{yx} = 3.5$, $n = 21$

$$\text{Density} = - 2.6 + 1.33 C_g + 1.39(C_{gb} - C_g)$$

^{4/} S_{yx} is standard error of estimate; n is number of data; density is in percent; C_g = gamma counts in 1,000 c.p.m. minus 5,000 at a point; C_n = neutron counts in 1,000 c.p.m.; "a" and "b" subscripts indicate counts 6 inches above or below point of measurement.

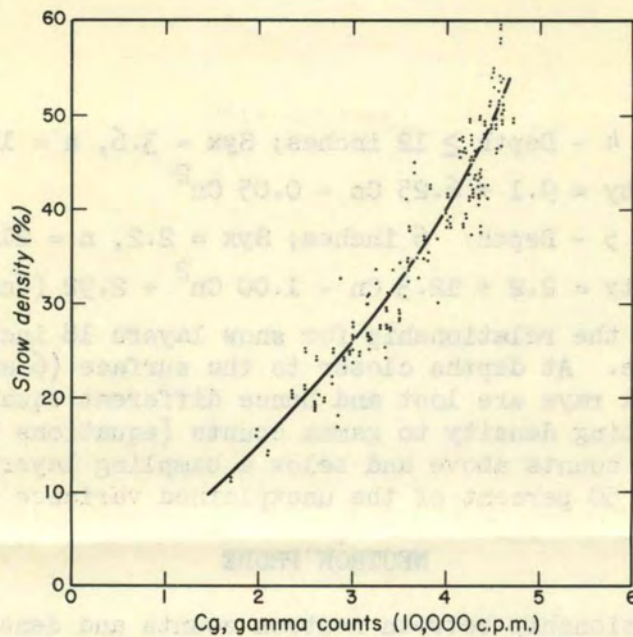


Figure 1.--Relation of snow density to counts made with radioactive gamma probe, for depth \geq 18 inches from snow surface.

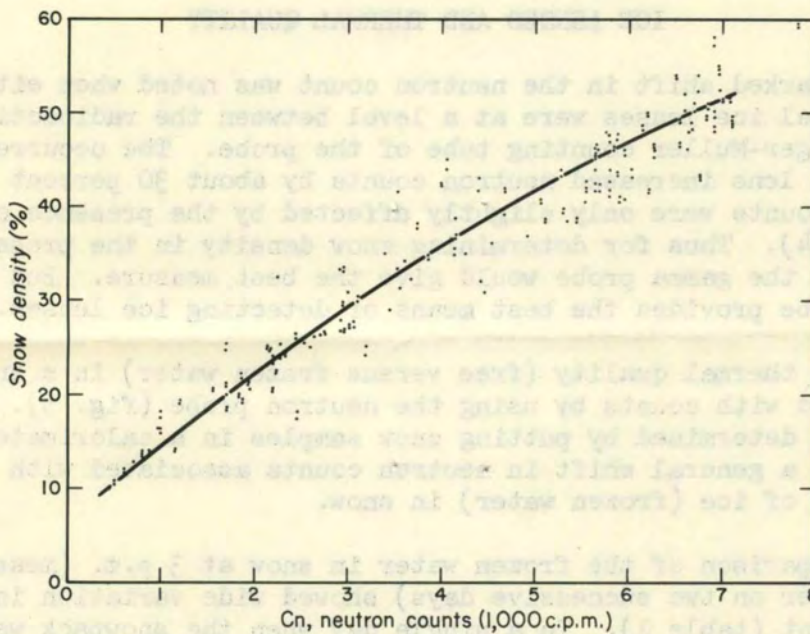


Figure 2.--Relation of snow density to counts made with radioactive neutron probe.

Neutron probe: ^{4/}

Equation 4 - Depth \geq 12 inches; $S_{yx} = 3.6$, $n = 176$

$$\text{Density} = 9.1 + 6.25 C_n - 0.05 C_n^2$$

Equation 5 - Depth: 6 inches; $S_{yx} = 2.2$, $n = 21$

$$\text{Density} = 2.2 + 12.3 C_n - 1.00 C_n^2 + 2.92 (C_{na} - C_n) + 11.2(C_{nb} - C_n)$$

Equation 1 gives the relationship for snow layers 18 inches or more below the surface. At depths closer to the surface (6 and 12 inches), part of the gamma rays are lost and hence different equations are involved in relating density to gamma counts (equations 2 and 3). The inclusion of the counts above and below a sampling layer explains an additional 22 to 50 percent of the unexplained variance ($1-R^2$).

NEUTRON PROBE

The relationship between neutron counts and density is also well defined (fig. 2). This relationship for snow depths greater than 12 inches is given in equation 4. No improvement in the relationship at those depths was obtained by using the counts 6 inches above and 6 inches below the point of measurement. The relationship for the 6-inch snow depth is given by equation 5. At this depth, counts above and below considerably improved the prediction of density--explaining 75 percent of the unexplained variance ($1-R^2$).

ICE LENSES AND THERMAL QUALITY

A marked shift in the neutron count was noted when either natural or artificial ice lenses were at a level between the radioactive source and the Geiger-Muller counting tube of the probe. The occurrence of a $1\frac{1}{4}$ -inch ice lens increased neutron counts by about 30 percent (fig. 3). But gamma counts were only slightly affected by the presence of the ice lens (fig. 4). Thus for determining snow density in the presence of ice lenses, the gamma probe would give the best measure. But the neutron probe provides the best means of detecting ice lenses.

The thermal quality (free versus frozen water) in a snowpack was compared with counts by using the neutron probe (fig. 5). Thermal quality was determined by putting snow samples in a calorimeter. The graph shows a general shift in neutron counts associated with shifts in the percent of ice (frozen water) in snow.

Comparison of the frozen water in snow at 3 p.m. (measured with a calorimeter on two successive days) showed wide variation in the free water content (table 1). In a single day when the snowpack was losing 2.2 inches (water equivalent), the thermal quality increased from 82 to 95. The amount of frozen water in the snowpack increased by 1.6 inches. Detection of such changes can be critical in any studies of the heat budget of snowpacks. Note that the neutron count reflects a change of state between the above 2 days when average snow density was identical (56 percent); higher neutron counts were associated with a greater proportion of frozen water in the snow.

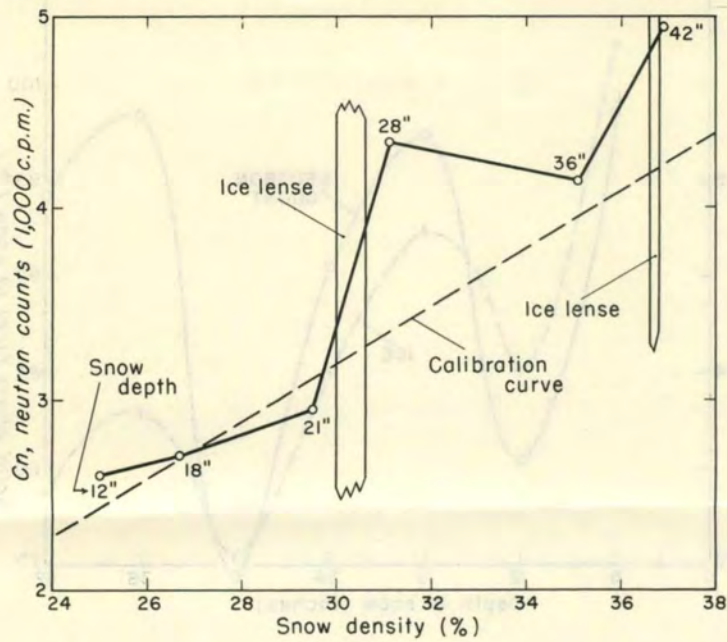


Figure 3.--Effect of ice lenses on the snow density and count relation, using a radioactive neutron probe.

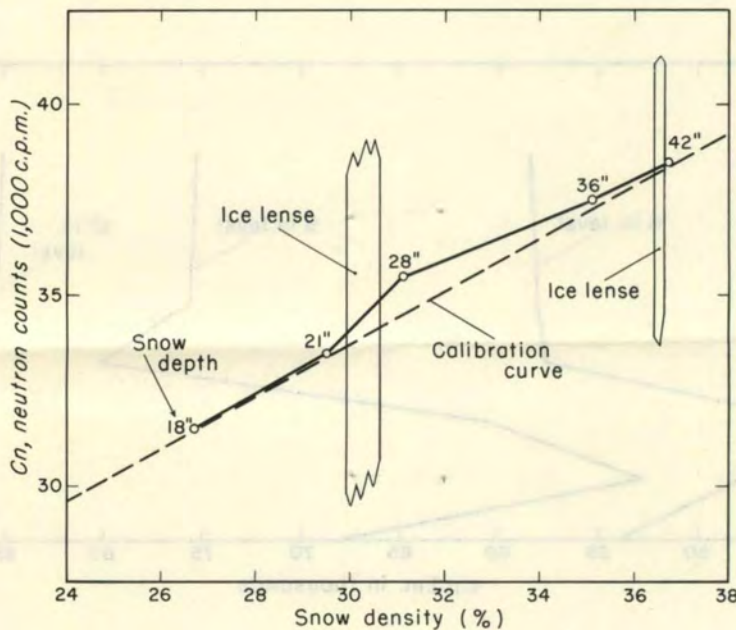


Figure 4.--Effect of ice lenses on the snow density and count relation, using the radioactive gamma probe.

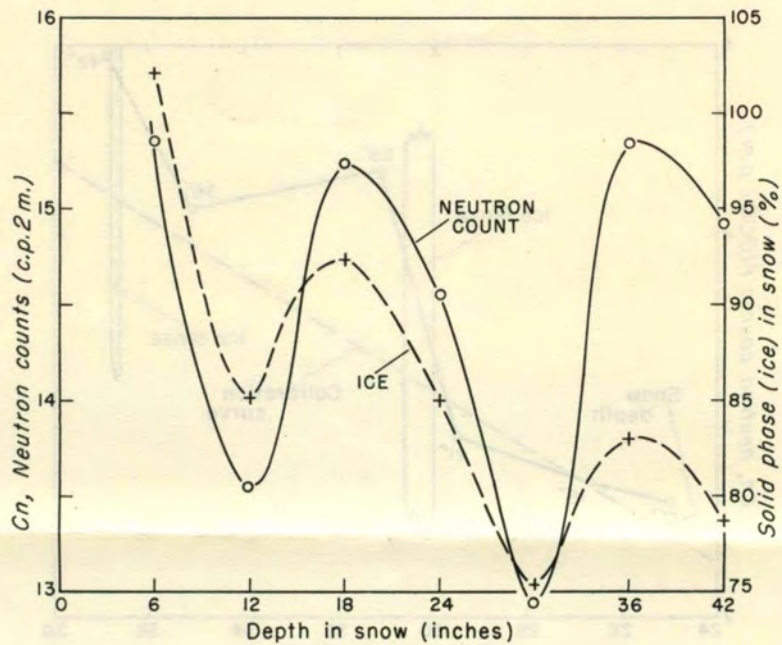


Figure 5.--Comparison of relative solid state water in snow with neutron count, June 2, 1962, 10 a.m., Central Sierra Snow Laboratory.

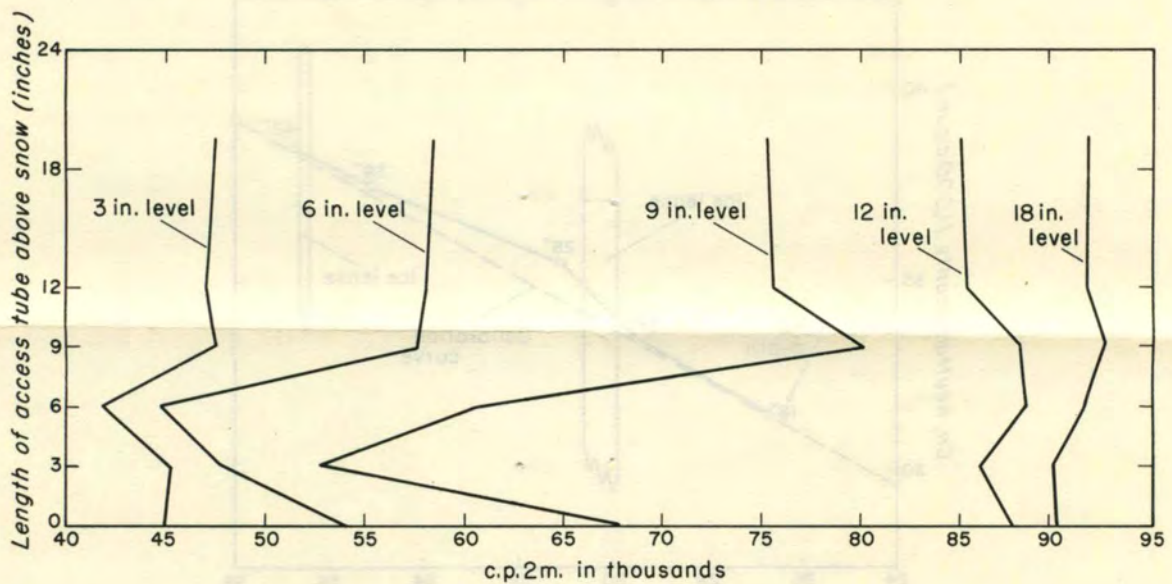


Figure 6.--Effect of access tube length above the snow on gamma counts.

Table 1.--Comparison of snow depth, water, quality, and frozen snow as related to neutron and gamma counts for two successive days, 3 p.m.

Date	Snow : depth : - Inches -	Snow : water : - Inches -	Snow : quality : Percent ice	Neutron : counts : - 1,000 c.p.m. -	Gamma : counts : - 1,000 c.p.m. -	Frozen : snow : Inches
June 1, 1962	51.5	29.2	82	6.7	48	24.1
June 2, 1962	48.5	27.0	95	7.2	49	25.7
Difference	- 2.2					+ 1.6

MEASUREMENT TECHNIQUES

Several tests were made to appraise the performance of radioactive probes which might affect their effectiveness as hydrologic tools. The volume of snow being sampled by each probe was tested by inserting the probe in the snow and then systematically narrowing the cylinder of snow around the probe until the counts dropped. The results showed that a 5 percent reduction in count (95 percent of total counts) arose when the diameter of this cylinder was between 12 and 13 inches for the neutron probe and between 16 and 17 inches for the gamma probe.

Simple tests were made (a) to test the relationship between the extension of the aluminum access tube above the snow and the counts obtained, and (b) to test the effect of proximity of the probe to the ground. We found that with the gamma probe the length of the access tube had drastic effects on counts near the snow surface (fig. 6). Only when the access tube extended at least 12 inches above the snow were reasonable counts obtained at the shallow snow depths.

The effect of nearness to the soil surface was important in the use of the gamma probe. Densities of snow closer than 8 inches to the soil surface could not be determined by this probe. Proximity of the probe to the soil had no apparent effect on the neutron count, perhaps because the water contents of the snow and of the soil were similar in these tests.

SNOWMELT

The rate of melt of spring snowpacks has been found in preliminary tests to vary widely from year to year, even when the melt is expressed in terms of the amount of heat rather than time alone.^{5/}

^{5/} Anderson, Henry W. Forest cover effects on snow accumulation and melt, Central Sierra Snow Laboratory. Amer. Geophys. Union 37(3):307-312. 1957.

How many degree-days will be required before the melt of the pack starts and at what rate does the pack melt per unit of degree-day after the start? By comparing three conditions (fig. 7) which had widely different snowpack characteristics early in spring (April 3-7, 1962), we found that the lag in the beginning of melt and the rate of melt under these conditions were related to the neutron and gamma count profiles in the snowpack (table 2). The lower layers of the snowpacks had remarkably uniform gamma and neutron counts (43,000 gamma counts and 5,800 to 6,000 neutron counts per minute). But the top layers of the snowpack showed fewer counts and widely different counts among the three conditions. The counts in the top snow layers appeared to be related to the delay in start of the snowpack melt and to the rate of melt after it starts (fig. 7). This possibility that the contribution of snowmelt to streamflow can be predicted by using radioactive probes deserves further exploring.

Table 2.--Spring snowmelt at three sites as related to neutron and gamma counts at top and bottom of snowpack, Central Sierra Snow Laboratory, elevation 7,500 feet, 1962

Condition	Neutron counts		Gamma counts		Lag in melt (degree-days)	Melt rate (inches per degree-day)
	Top ^{1/}	Bottom ^{1/}	Top ^{1/}	Bottom ^{1/}		
	----- 1,000 c.p.m. -----					
Open	5.2	6.0	39	43	60	0.15
Shaded	3.5	6.0	35	43	90	0.11
Forest	3.5	5.8	35	43	130	0.10

^{1/} One foot from top and bottom of snowpack.

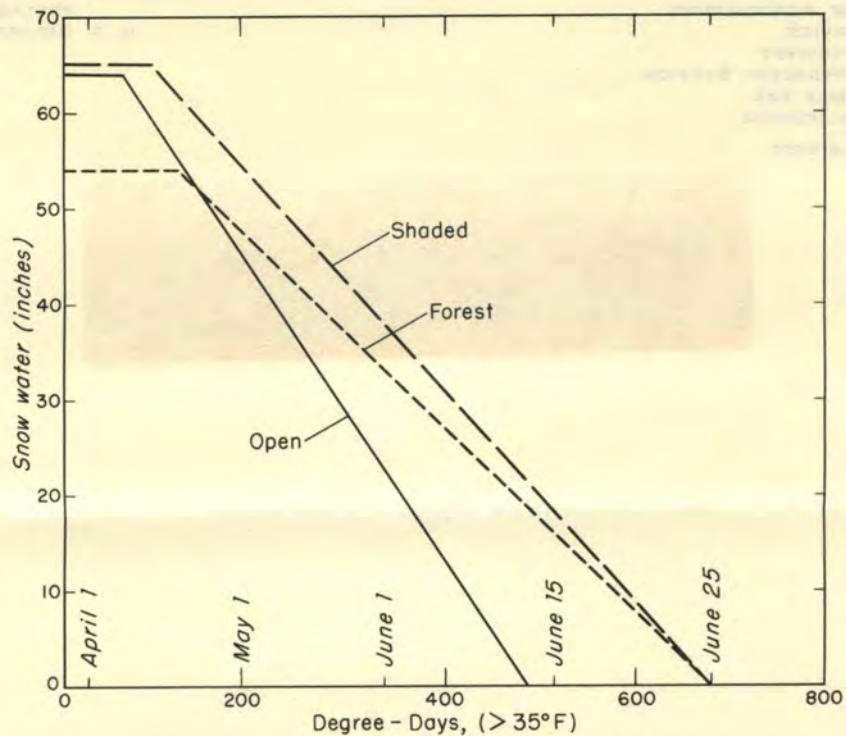


Figure 7.--Snowmelt start and melt rate related to degree-days. 15 percent N.E. slope, elevation 7,500 feet, Central Sierra Snow Laboratory. April 1, 1961 - June 25, 1962.

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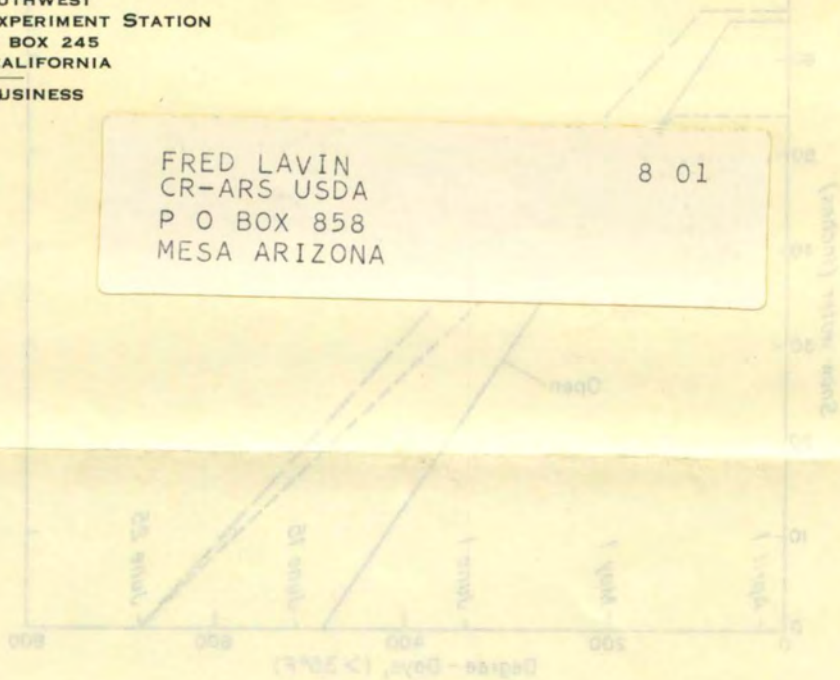


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