Reprinted from **Advanced Concepts and Techniques in the Study of Snow and Ice Resources**
ISBN 0-309-02235-5 NATIONAL ACADEMY OF SCIENCES Washington, D. C. 1974

MEASUREMENT OF SNOW AT A REMOTE SITE: NATURAL RADIOACTIVITY TECHNIQUE

V. C. Bissell
E. L. Peck
NOAA, National Weather Service
Silver Spring, Maryland 20910 U.S.A.

ABSTRACT

The use of natural gamma radiation from the soil as a basis for snow water equivalent measurements at remote sites has been under investigation by the National Weather Service since 1970. Results to date indicate that measurements with about five percent error in the five to forty centimeter water equivalent range can be obtained in periods uncomplicated by precipitation or considerable change in soil moisture. Periods of active melt can be subject to serious errors.

A new natural radioactivity method is also proposed. The use of highly penetrating cosmic radiation appears to have excellent potential for point snow water equivalent measurement in extremely deep snow.

INTRODUCTION

The accurate measurement of snow water equivalent at remote locations is in many parts of the country the most critical element in the formulation of water supply forecasts and continuous river stage forecasts during the spring melt season. Within the last two decades a great deal of work has been done developing automated snow measurement systems to supplement manned snow surveys. A fairly recent nuclear counting method involves the use of naturally occurring radioactive isotopes in the soil as the sole radiation source (Zotimov, 1968; Kogan, et al., 1971; Peck, et al., 1971). The feasibility of the technique for automated measurement at fixed remote locations has been tested since 1970 by the National Weather Service at the NOAA-ARS cooperative snow study site near Danville, Vermont. Test results during the 1970-71 snow accumulation period have been given by Bissell and Peck (1973). This paper provides an update on publication of test results as well as suggesting yet another nuclear counting method which appears to have excellent potential for measuring the water equivalent of deep snow.

EXPERIMENT AND RESULTS

In the autumn of 1970 a gamma radiation detector with a small (2.54 cm diameter by 3.81 cm length) NaI scintillation crystal was suspended about two meters above the ground and count rates during the snow season were monitored for several hours on the days the station was attended. Data were not obtained during the 1971-72 snow season until just prior to spring runoff. At that time an hourly recorder was hooked up to the detector. For the 1972-73 snow season a second (identical) detector was placed just above the first with a 2.5 cm thick lead slab between the two. This dual detector system was placed with the hope of differentiating between atmospheric- or cosmic-derived radiation and radiation coming from the ground. Separate hourly counting and recording systems (different from that used in spring 1972) monitored the count rates from the two detectors. An initial analysis of the dual detector system showed that its discriminating ability in improving water equivalent measurements is secondary to other error sources encountered. No further detailed analysis has yet been done. The water equivalent of the snow cover at the site during all three seasons was measured by snow tube on days the station was attended (most weekdays) at three snow courses, each within twenty meters of the detector. At least two cores were taken in each course area.

Time variation of the count rate within a given day is clearly shown by the hourly data obtained. The hour-by-hour count traces for three different three-day periods in 1973 are given in Figure 1. A marked diurnal effect is strongly evident in both the no-snow period (August 14-16) and during the period with greatest snow cover (February 24-26). This effect is attributed to the dynamic nature of radon, a radioactive noble gas which originates in the soil and whose daughter products ^{214}Pb and ^{214}Bi are major sources of the gamma radiation seen by the detector. During daytime hours the atmospheric mixing at the surface of the earth allows a great deal of the radon diffusing from the soil and through the snow to be transported beyond the range of the detector. When evening comes, cooling at the earth's surface weakens the transport mechanism and the radon concentration in and near the surface of the earth (snow or soil, as the case may be) increases. The dynamic nature of radon has long been known and is further discussed in another paper in this symposium [Bissell, paper 6.4]. Points to be made here are: (1) during daylight hours count rate fluctuations due to radon effects are reduced, (2) surface buildup of radon during the night is highly sensitive to slight meteorological effects and hence may disallow nighttime use of natural gamma radiation for snow measurement, and (3) the snow cover under study inhibited the diffusion of radon from the soil into the atmosphere, but not completely. The count rate trace for the March 14-16 period in Figure 1 shows the diurnal effect to a lesser extent, but contains two other points of interest as well. The first is the deposition of radioactive aerosols on the snow surface by precipitation, noted previously by Bissell and Peck (1973). The anomalously high count rates produced during precipitation require about three or four hours after the end of precipitation to decay back to their nominal values, as seen in the two events of March 15. A second point of interest is the considerable change in daytime count rate between March 14 and March 15 during a period of constant snow cover. More will be said of this event subsequently.

The hourly count rates obtained through the 1970-71 and 1972-73 snow seasons are shown plotted against water equivalent in Figure 2 and Figure 3, respectively. The earlier report by Bissell and Peck (1973) was based on points in Figure 2 which are indicated as observations during the snow accumulation period. To eliminate precipitation-induced error, only those observations which had no precipitation during or immediately prior to the counting period are shown in Figure 2 and Figure 3. The 1970-71 counts were generally obtained during the afternoon, while the 1972-73 plot includes average counts from 0900 to 1200 and from 1200 to 1600. Other hours from the 1972-73 data were not included because of the diurnal effect

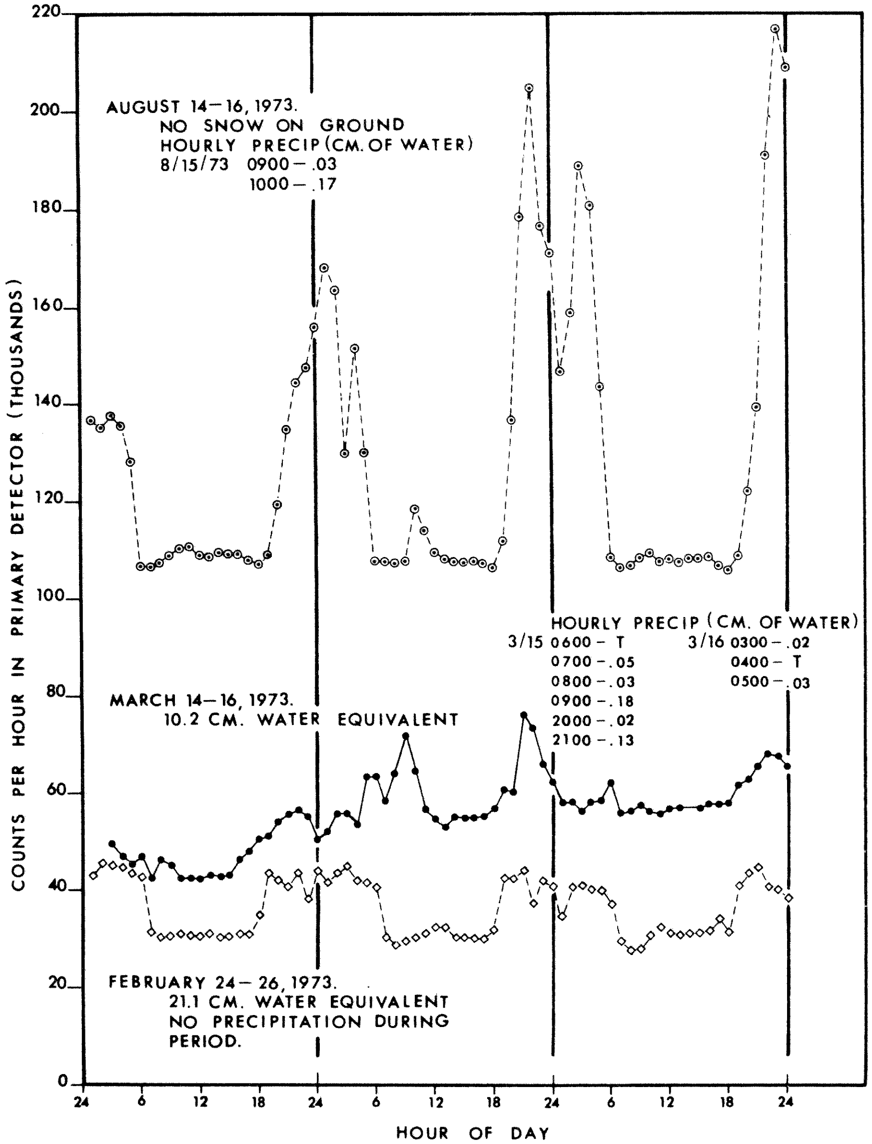

Figure 1. Hourly count rate traces in primary detector during February 24-26, March 14-16, and August 14-16, 1973.

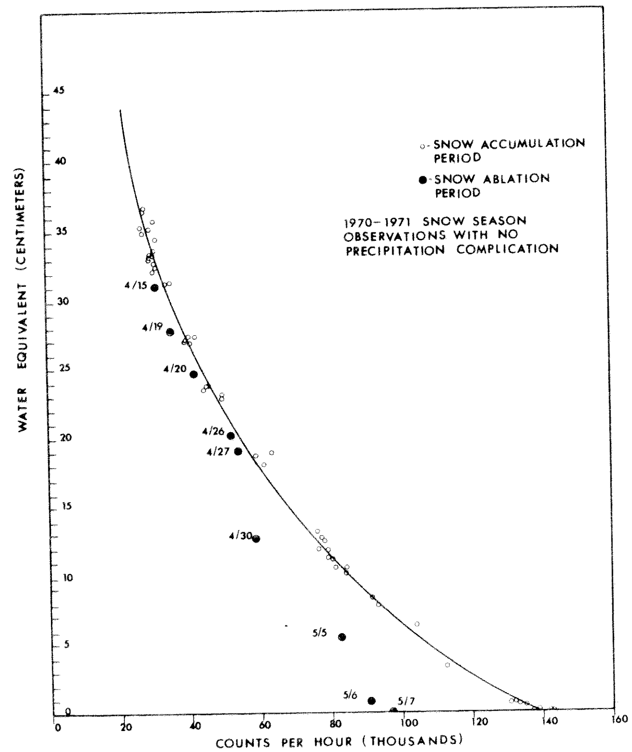

Figure 2. Count rate versus water equivalent relationship during 1970-1971 snow season at townline station.

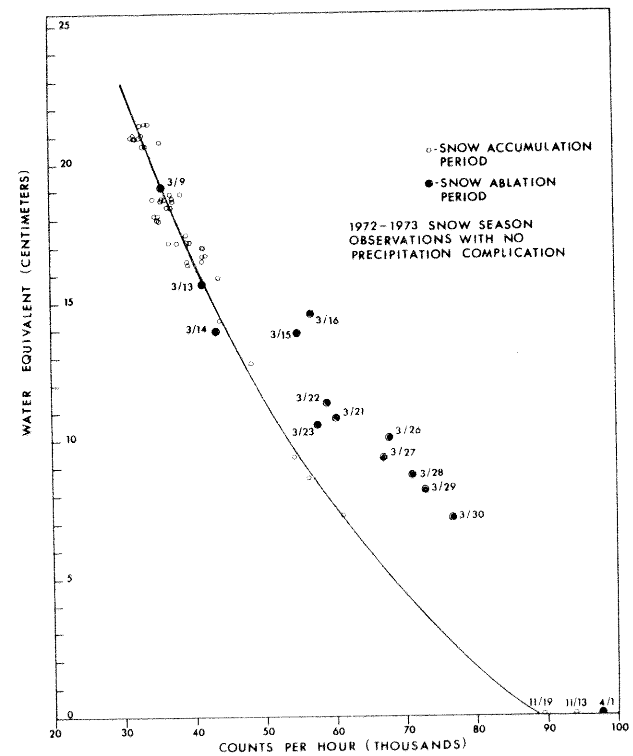

Figure 3. Count rate versus water equivalent relationship in primary detector during 1972-1973 snow season.

mentioned earlier. During periods of snow accumulation, the consistency of the counts-water equivalent relationship is evident. The root-mean-square deviations from best-fit lines through these points are given in Table 1.

Table 1. Root-mean-square deviations (cm) from best-fit lines during snow accumulation.

Range (cm)	1970-71 (precipitation events excluded)	1972-73 (precipitation events excluded)	1972-73 (coef. of var. less than 0.04)
5-13	0.58	0.25	0.91
13-25	1.14	0.89	1.03
25-40	1.27	no observations	no observations

In an operational framework separation of precipitation-complicated events could be difficult since it would require telemetering of site hourly precipitation data. Since the count rate is generally highly variable during occurrence of significant precipitation events, the coefficient of variation of the count rate is suggested as a screening criterion. The coefficient of variation of hourly counts was computed for the periods 0900 to 1200 and 1200 to 1600 during the 1972-73 snow accumulation period. The efficacy of two levels of application of this criterion in reducing error is given in Table 2. The effect of the coefficient of variation screening at high C_v levels is to eliminate only the most anomalous events. More restrictive values of the coefficient of variation would not appear to give additional benefit.

Table 2. Effect of coefficient of variation as screening a criterion, 1972-73 snow accumulation period

	Root-Mean-Square (cm)	Percent of observations
All points	1.27	100
C_v less than 0.04	1.02	80
C_v less than 0.015	1.02	50

Much of the above discussion about accuracy during snow accumulation must be tempered with one very critical consideration - the effect of soil moisture. An increase in soil moisture will produce a decrease in count rate which is difficult to separate from snow change effects. For a specific site and detector there will be an entire family of count rate versus water equivalent relationships, each characterized by a parameter relating to soil moisture. The apparently consistent relationships during snow accumulation in Figure 2 and Figure 3 could well range through a wide range of soil moisture values rather than representing a single curve in the family of relationships. If this is the case then the historical relationships would have diminished value in providing a basis for measurement in subsequent years unless proper allowance is made for soil moisture during both the calibration and operational periods. Unfortunately, use of different detector configurations and counters during each of the three years of this study disallows direct comparison of count rates between any two years.

Turning to the periods of snow ablation, inspection of Figure 2 and Figure 3 reveals that the observations during melt depart significantly from the accumulation period relationships between count rate and water equivalent. Further, the 1971 and 1973 departures are in opposite directions. The depressed count rate in the 1971 melt period is ascribed to some combination of the following two reasons: (1) Snow accumulation began in the fall of 1970 over a rather dry soil which received very little additional moisture from rain or melt events during the remainder of the fall and early winter. An estimated 0.025 cm per day melt due to ground heat at the site [Anderson, 1973] would have added roughly four centimeters of water to the soil by the time twenty centimeters water equivalent had accumulated in mid-February. It is important to note that much of this ground melt water may have been held in the upper soil layers by the temperature gradient in the soil [Peck, 1973]. Water percolating into the soil after active melt began in mid-April would then give only a small additional contribution to the top five or ten centimeters of soil from which the great bulk of terrestrial gamma radiation comes. (2) Water percolating through a rapidly melting snowpack and into the soil will carry with it some radon gas. This "washing out" of radon from the snow and upper soil levels would reduce the radiation source strength and hence further depress the count rate. This phenomenon is further discussed elsewhere in this symposium [Bissell, paper 6.4].

The 1973 melt period count trace in Figure 3 is somewhat of a mystery. A sharp departure from the accumulation relation occurred between March 14, 1973 and March 15, 1973. After this time count rates continued considerably higher during ablation than during snow accumulation days with similar water equivalents. The hourly count rate trace during March 14 and March 15 is shown in Figure 1 as mentioned earlier, and is well corroborated by the independent hourly trace (not shown) of the secondary detector. Due to a very wet fall it would be expected that the ablation observations would be reasonably aligned with the accumulation period observations. The two following considerations are put forward as possible reasons for the differences: (1) A common influence may have caused similar changes in both the primary detector and the secondary detector. The most suspect in this category would be the possibility of an earlier heater failure in the box housing both detectors. No indication of heater repair, however, was found in the station log. Further, previous calibration tests in a cold room with the primary detector yielded only a two percent reduction in count rate over the temperature range a heater failure would have produced. (2) The freezing rain which occurred the morning of March 15 may have produced a thin ice seal on the snow surface, producing a buildup of radon concentration in the snowpack and thus increasing the radiation source strength. A heavy rain (3.20 cm) March 17 followed by snow showers and five consecutive days during which air temperature never got above freezing produced an ice layer which was covered by about six cm of new snow. This ice layer was noted in the station log on March 22 and March 23, and could have provided a stronger and more enduring seal than the small precipitation event of the 15th. There are inconsistencies with the radon "capping" possibility however. First warm air temperatures on March 16 would have quickly removed a light crust which may have been formed on the 15th. This would have allowed the radon buildup in the snowpack to deplete and count rates during the afternoon of the 16th should have been back down to previous levels rather than remaining high as they did. Second, with the onset of heavy melt about March 26 it is questionable that the sealing would have been sustained through March 30 as Figure 3 would indicate.

A final observation regarding Figure 3 is that the post-melt count rate over bare ground on April 1 would be more in line with the accumulation relation. The lower no-snow count rates on November 19 and November 25 could be due to soil moisture. Although the soil was quite wet both in the fall and immediately following melt, the soil freezing in the fall could account for additional moisture in the top layers.

It is hoped that continuation of the study may provide some additional insights into the March 15-March 16, 1973 event since such a sustained anomaly would be especially difficult to detect in a remote measurement setup.

Now let's look at the 1972 spring melt. Six-hourly water equivalent values inferred from the radiation count rate are shown in Figure 4. These are "hindsight" measurement values since snow tube water equivalent measurements taken during the period were used to generate a count vs. water relationship which in turn was used to go back and produce the continuous water equivalent trace. Precipitation-complicated measurements are distinguished in the figure by asterisks. The point to be made here though is found in Figure 5, which provides better detail of the April 28-May 1, 1972 heavy melt period. Under ideal conditions of heavy melt and low radon interference, the gamma method appears to have good potential for measuring hourly decreases in snowpack water equivalent, especially as noted on April 29 and May 1, 1972. Snowpack runoff appears to have begun around noon both days. The heavy melt during the afternoon of both days appears to end in the evening around 1900 hours. Anomalies in the water equivalent trace during the late morning and early afternoon of April 30 magnify the obvious fact that hourly count traces would require careful screening and review before application to compute hourly runoff.

USE OF COSMIC RADIATION TO MEASURE DEEP SNOW

At this point we would like to depart somewhat from the main thrust of this paper to document a proposal for a natural radiation method of point snow measurement which may find application in extremely deep snow. In the preceding discussion, cosmic radiation was regarded as a noise component in the count rate. A slight realignment of viewpoint, however, allows cosmic radiation to be viewed as signal rather than noise. Cosmic radiation is extremely penetrating as demonstrated by the fact that ionization intensity from cosmic radiation decreases by only a factor of ten between the surface of a water body and at 50 meters depth (Wilson, 1952). Cosmic radiation, however, has several components and the actual attenuation of detector response by water depends on the detector's efficiency of response to the various components. To get some idea of what a NaI scintillation crystal response might be to cosmic radiation under various depths of water we have considered the count rates between three and six MeV at various altitudes over Lake Meade reported by Burson and Fritzsche (1972). Essentially all counts above 3 MeV are due to cosmic

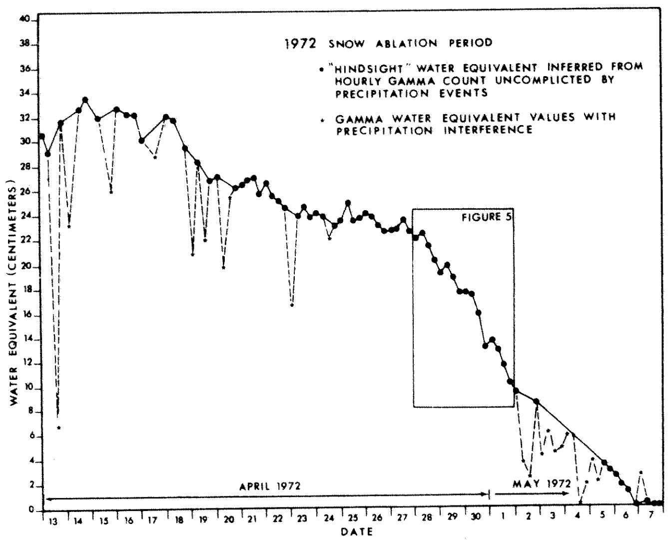

Figure 4. Six-hourly water equivalent trace inferred from gamma counts during 1972 snow ablation period.

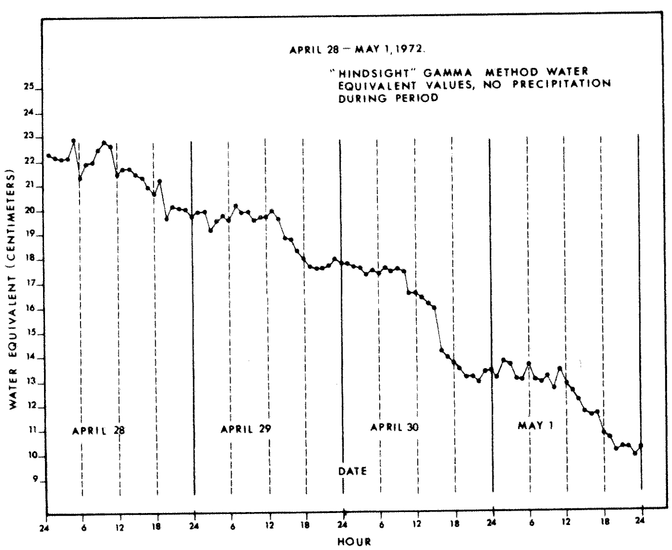

Figure 5. Hourly water equivalent trace inferred from gamma counts April 28-May 1, 1972.

radiation and hence would be free of terrestrial radiation interference. The data show that a single 10 cm diameter by 10 cm length NaI crystal at 1800 meters above mean sea level would produce roughly 6500 counts per hour between three and six MeV energy. A single discriminator counting all detector pulses above three MeV would produce about twice this number (Burson, 1973, personal communication), or 13000 counts per hour. A cursory analysis of the data shows that if the attenuating effect of a unit mass thickness of water can be roughly equated to the effect of a unit mass thickness of air (similar atomic weights make this reasonable) a 100 cm thick layer of water overlying the detector would reduce the 13000 counts per hour to around 6500 counts per hour. If two detectors were placed one at ground level and one above the snow surface, daily measurement of a 100 cm water equivalent by the ratio of counts in the two detectors would have a standard deviation of roughly 0.5 centimeter due to random statistical fluctuations of count rate alone. The feasibility of such a method would depend on cost, availability of required technology (e.g., automatic gain stabilization on detectors), and most of all on what the attenuation of cosmic count rate in a NaI scintillation detector due to snow water equivalent really looks like.

SUMMARY AND CONCLUSIONS

The natural terrestrial radiation method has both advantages and disadvantages in comparison with other unmanned snow measurement methods. Among the advantages are: (1) Since the radiation source is spread out in the soil over the surface of the earth, the measurement is representative of a larger area than other methods with remote capability; (2) Since the output of a nuclear counter is digital in form, the analog-to-digital conversion and attendant calibration required for weighing devices is bypassed; (3) In contrast to the artificial radiation method, there is no hazard from radiation source transport and placement, nor is continuous exercise of safety precautions necessary; (4) The source strength may be increased by mixing into the top soil mantle some material with a higher radioisotope concentration.

Among the method's disadvantages are: (1) Measurement accuracy decreases as water equivalent increases since the signal-to-noise ratio is diminished. Forty centimeters is probably a reasonable upper limit of measurable water equivalent; (2) Measurement accuracy is strongly affected by soil moisture changes. Some estimation of soil moisture in an operational framework will be required; (3) Due to the transport of radon gas, the radiation source is a dynamic one subject to both meteorological and hydrologic processes; (4) The strength of the natural background radiation and the way it is attenuated by snow differ from site to site. Supplemental control measurements taken at periods of different snow cover would be required initially to formulate a relationship between count rate and water equivalent at each site; (5) Precipitation events sharply perturb gamma radiation levels near the ground. The frequent precipitation in most areas where remote snow measurement is needed presents a problem because there could be long periods during which no measurements free of this effect could be obtained.

Overall, the use of terrestrial gamma radiation for low and midrange snow water equivalent measurements appears quite promising, especially during periods of snow accumulation. For maximum accuracy counting periods should be limited to daylight hours to allow stabilization of radon effects, and simulated soil moisture values should be used to account for the attenuating effect of soil water. Due to the magnitude of other effects, initial analysis of the dual detector for atmospheric radiation delineation was inconclusive.

REFERENCES

Anderson, E. A., 1973. National Weather Service River Forecast System - Snow Accumulation and Ablation Model. NOAA Tech. Memo. NWS HYDRO-17. U.S. Department of Commerce, NOAA, National Weather Service, Washington, D.C. 86 pp.

Bissell, V. C., and E. L. Peck, 1973. Monitoring Snow Water Equivalent by Using Natural Soil Radioactivity. Water Resources Research, 9 (4). pp. 885-890.

Burson, Z. G., and A. E. Fritzsche, 1972. Snow Gaging by Airborne Radiological Surveys - Status through September 1972. EGG-1183-1565, Tech Rep. L-1078. E G & G, Inc., Las Vegas, Nevada. 48 pp.

Kogan, R. M., I. M. Nazarov, and S. D. Fridman, 1971. Gamma Spectrometry of Natural Environments and Formations. Translated from Russian, TT70-50092, Israel Program for Sci. Transl., Jerusalem. 337 pp.

Peck, E. L., V. C. Bissell, E. B. Jones, and D. L. Burge, 1971. Evaluation of Snow Water Equivalent by Airborne Measurement of Passive Terrestrial Gamma Radiation. Water Resources Research, 7 (5). pp. 1151-1159.

Peck, E. L., 1973. Soil Moisture - A Critical Factor in Snowmelt Runoff?. Paper presented at the Fifty-Fourth Annual Meeting of the American Geophysical Union, April 16-20. Washington, D. C. 17 pp.

Wilson, J. G. ed., 1952. Progress in Cosmic Ray Physics. North-Holland Publishing Company, Amsterdam. 510 pp.

Zotimov, N. V., 1968. Investigation of a Method of Measuring Snow Storage by Using the Gamma Radiation of the Earth, Soviet Hydrology Selected Papers 3:254-266.