THE ISOTOPE PROFILING SNOW GAGE: TWENTY YEARS OF EXPERIENCE

723-83

By

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INTRODUCTION

A promising new tool for snow hydrology, the isotopic profiling snow gage, came into use in the early 1960s. Since its development, the gage has been used at the Forest Service's Central Sierra Snow Laboratory in California for several investigations of snowpack dynamics and as a principal index tool for operational forecasting of water supply and floods. Similar instruments have been used in other states and countries. The experience gained during many years of use now permits a comprehensive evaluation of the utility of the profiling snow gage.

CONCEPT AND OPERATION

The radioactive profiling snow gage was designed to produce an incremental depth profile of snow density with minimal disturbance of the snowpack. Its principal value lies in its ability to repeatedly measure the same vertical section of snow and thus record profile changes through time. A series of horizontal density measurements are made by recording the attenuation of gamma photons which transverse the fixed horizontal distance in snow between the photon source and a detector. The source and detector are raised synchronously in a pair of parallel vertical access tubes topped by a lift mechanism (Figure 1).

A 10-millicurie Cesium-137 radioisotope source emits gamma radiation, and the detection system discriminates and records only those gamma photons that arrive at the scintillation detector at an energy peak of 661 keV. Collision of the gamma photons with water molecules in the liquid or solid phase in the snowpack lowers their energy level. The ratio of high energy gamma photons detected in the snow to those recorded in a reference standard is related to snow density through a simple calibration equation.

When not in operation, the source and detector are stored below ground in a reference standard. During a profile measurement, the probes are raised at a rate of 0.5 cm/sec. Density is electronically computed for 1.5-second detector count intervals and is recorded along with probe height on paper or magnetic tape, or optionally on a strip chart. These data are the basis for a depth-density profile (Figure 2). Additional details on the design, construction, and operation of the profiling snow gage are available (Smith *et al*., 1970, 1972; Randolph *et al*., 1973).

DEVELOPMENT HISTORY OF PROFILING SNOW GAGES

The first nuclear snow gage was developed at the Central Sierra Snow Laboratory (CSSL) by Gerdel *et al*. (1950) of the U.S. Army/Weather Bureau Cooperative Snow Investigations. A ground level Cobalt-60 source transmitted gamma photons up through the snowpack to a Geiger-Muller tube. This gage and several others built in the 1950's (Martinec, 1958; Robinson, 1960; Duncan and Warnick, 1963) measured the water equivalent of the entire snowpack from a single vertical attenuation measurement. Unfortunately, this configuration was reasonably accurate only for shallow snowpacks. Other devices were sought for measuring deep snow.

Presented at the Western Snow Conference, April 19-21, 1983. Vancouver, Washington

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"Reprinted Western Snow Conference 1983"

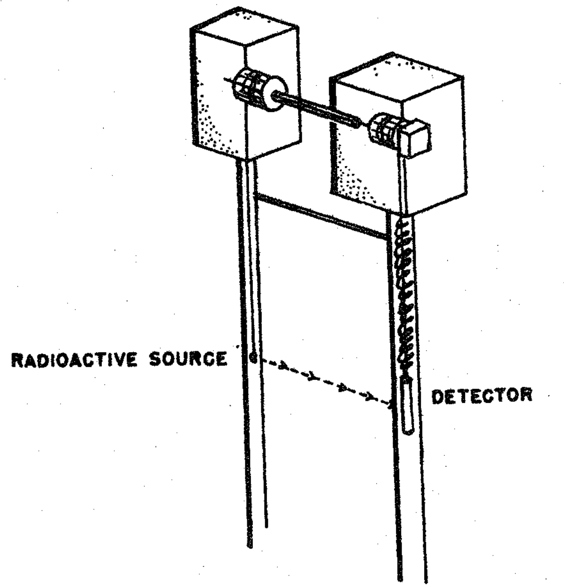

Figure 1. Isotope Profiling Snow Gage

DEPTH CM	AVG DENSITY $KG \cdot M^{-3}$	WATER EQUIV MM	TIME PST	DATE MO DY YR
220.4	319	704	1400	02/13/82

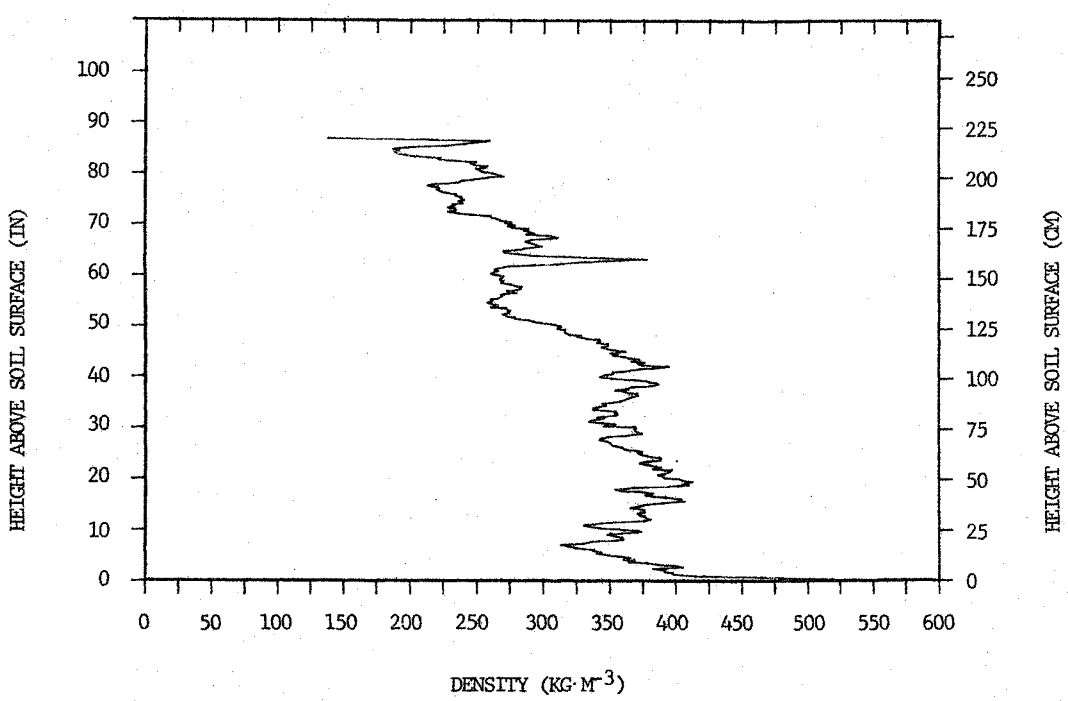

Figure 2. Snow Density Profile Example
Note high density layers at surface and 160 cm

Instruments initially designed for soil moisture measurement soon found application to snow density in glaciers (Danfors et al., 1962) and seasonal snow cover (Gay, 1962). These studies were the first attempts to obtain density information on the interior of the snowpack without excavation. Due to their large sphere of influence, these gages resolved only a low degree of density variations within the snowpack.

In the early 1960s, a major step forward occurred with the invention of the twin-probe nuclear snow gage by Smith and Willen (1969) at CSSL. This device was the first gamma transmission system that measured narrow horizontal increments of the snowpack with reasonable accuracy (Smith et al., 1965). A series of design changes gradually improved the gage, reduced the manual effort, and increased the reliability (Hannaford, 1982).

After the development of the prototype gage at CSSL, the Division of Isotopes Development of the Atomic Energy Commission contracted with Idaho Nuclear Corporation[2] to develop a remotely operated gage. A demonstration gage was installed at CSSL in the winter of 1970-1971 and was successfully operated by telephone from Berkeley, California, 300 kilometers from the measurement site (Randolph et al., 1973). Four additional gages were later installed at Mt. Baldy near Ketchum, Idaho; Mt. Hood, Oregon; Red Mountain Pass, Colorado; and Mt. Alyeska Ski Area, Alaska, and operated by telephone from a central base station in Idaho Falls, Idaho. Three of the gages were used by the Soil Conservation Service to forecast streamflow. The Red Mountain Pass gage was used by the Institute for Arctic and Alpine Research of the University of Colorado for snow physics and avalanche research. Apparently, all of the gages functioned quite reliably with little down time (Randolph et al., 1973).

An independently designed profiling snow gage was built by Guillot and Vuillot (1968) in France, and modified by Gosselin in Canada (Paulin, 1978). This gage, currently manufactured by Neyrpic in Grenoble, differs from its American counterparts in that the rate of travel determined by a variable-speed motor is proportional to the count rate of the detector and, thus, snow density. Density is computed from the time necessary to traverse a fixed depth of snow where travel time increases with density. This gage is currently used by Electricite de France and the Quebec Meteorological Service.

A portable profiling snow gage employing a single probe source/detector combination that uses gamma backscatter was developed in 1973 (Blincow and Dominey, 1974). Although only a few were produced, the instruments have seen widespread use in California, Oregon, Montana, and Canada.

Another radioactive snow gage, popularly known as the zig-zag gage, measures snow water equivalent by depth zones. It is the most widely used isotopic gage in the United States due to its simplicity, reliability, and ease of operation. This gage consists of two vertical tubes located about 50 cm apart. Each tube contains several sources and detectors, set at fixed locations in the tubes. Each source emits two collimated gamma photon beams aimed diagonally at corresponding detectors. The counts recorded for each depth interval are used to obtain the average snow density or total water equivalent for each 60 cm interval (Shreve and Brown, 1974). The measurement accuracy is roughly comparable to that of snow pressure pillows (U.S. Dep. Agric., 1978).

THE SNOW GAGE AT THE CENTRAL SIERRA SNOW LABORATORY

Smith et al. (1970) enumerated the information categories available from the profiling snow gage: (1) total depth and water equivalent of the snowpack; (2) snow density at 1.2-cm vertical intervals and average pack density; (3) changes in the water equivalent of the pack and where they occur; (4) amount of new snow since last measurement; (5) rainfall amount and crude intensity until such time as the snowpack begins to discharge water; and (6) crude melt rate between measurements. The gage output used the most has been total snowpack water equivalent. Besides Forest Service and other research uses, the daily water equivalent measurement has seen extensive service in operational hydrologic forecasting. The California Department of Water Resources, the

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2/ Trade names and commercial enterprises are mentioned solely for information. No endorsement by the U.S. Department of Agriculture is implied.

Soil Conservation Service, and field offices of the Pacific Gas and Electric Company have made frequent use of the CSSL snow gage data. The CSSL gage serves a unique function for these users by providing a consistent index to changes in the snowpack. The gage data have also been heavily used by the news media, particularly during extremes of weather, such as severe storms or drought. The use, however, of the profiling snow gage in a forecasting system where a network of these gages is the fundamental information source (Limpert and Smith, 1974) has not yet occurred.

Many snow research studies have used CSSL gage data. The first major research results, presented at the 37th Western Snow Conference, showed that the gage was capable of discerning wetting fronts and changes in snowpack density structure caused by the natural or artificial addition of liquid water (Smith and Halverson, 1969). The gage has also been used to study recent rain-on-snow events (Bergman, 1983); to test the performance of a snowpack energy balance model in simulating snowmelt runoff (Halverson, 1972); as a principal tool to study snowpacks of the Sierra Nevada west slope (Smith, 1974); and to document the formation, development, stability, and disappearance of crusts and layers in a Sierra Nevada snowpack (Berg, 1982).

CSSL snow gage data have been central to the development of a snowpack water balance simulation model (Kattelmann et al., 1982) and a statistical snowpack estimation model (Berg and Hannaford, 1983). In addition to the past data used to formulate and test these estimation procedures, current snow gage data will provide essential input for the application of these models to the Bureau of Reclamation's Sierra Cooperative Pilot Project.

Accuracy

Testing gage accuracy is difficult due to the inadequacy of standards for comparison. A large excavation for volumetric weight determination is perhaps the best method. The only known full snowpack test of the snow gage was performed in April 1971 and gave excellent results (California Department of Water Resources, 1976). In a snowpack of over 1020 mm water equivalent, a 2.8-m^2 area measured twice by the profiling snow gage and by a Federal snow sampler was excavated and the snow weighed to determine "true" snow water equivalent. One measurement with the snow gage indicated no error and the other had only a 5 mm error, while the Federal sampler overmeasured by 86 mm.

When compared with snow pillow and Federal sampler measurements at other locations, results are mixed. At Mt. Hood, the profiling gage and pillow generally agreed throughout the first half of the season; and then both snow pillow and sampler measurements of water equivalent exceeded those of the snow gage by 38-51 cm (U.S. Dep. Agric., 1972). Pillow data generally exceeded gage data by only 1.3-5.1 cm in Montana (U.S. Dep. Agric., 1975). Pit studies at the Red Mountain Pass, Colorado, gage indicated a mean deviation of 17 kg m^{-3} in density and a 5-10 percent difference in total water equivalent in shallow snow cover (Armstrong, 1976).

Direct tests at CSSL have been carried out in the past with materials of known density. Smith and Halverson (1969) stated that snow gage density data were "accurate to within 1.5 percent of true density." Similarly, Smith et al. (1972) stated that from tests with ice blocks of known volume "actual snow density could be determined with a standard error of ±15 kg m^{-3} in the range of 1 to 686 kg m^{-3}." More recent tests by the Forest Service's Snow Hydrology Research Unit at Berkeley, California, have examined repeatability and error sources in greater detail.

Evaluation of error sources

Gage results may be distorted by three classes of error: gamma emission, electronic variations, and physical variations. Changes in the mean rate of gamma emissions have been shown to be minor over the long term, but individual readings may vary.

Electronic and emission errors encompass deviations from the true value due to calibration, sensing, and processing of the attenuated gamma counts. These errors can be subdivided into within-run and between-run errors. Of the total error, within-run error accounts for 5 percent while between-run error accounts for 95 percent. Extensive within-run tests have shown that density values during a run are reasonably accurate: the error is only 2 to 3 percent of the density value in the standard snow density range of 80 to 500 kg m^{-3}. This inaccuracy is due to emission variation and minor changes in the performance of the detection/processing system during a run.

While we can do little to reduce the within-run error, we have eliminated much of the between-run error. Before changes in the electronics in 1974 and to a lesser extent since then, repeated measurements occasionally showed a deviation of 20 to 50 mm water equivalent between successive runs. Plots of the profiles, when superimposed, showed identical patterns, but often one of the profiles would be shifted 10 to 30 kg m^{-3}. Absolute densities are dependent on delicate voltage settings before each run. Therefore, in addition to the electronics changes, we now precede and follow each run with extended counts in the reference standard. This allows standardization of each run's values, thereby largely removing the between-run error. For example, for a measurement on 13 February 1982 with a 200-cm snowpack, we are 95 percent confident that the true water content was 702 mm plus or minus 21 mm. With the between-run error corrected, we can narrow our confidence limits from 21 mm to less than 5 mm.

Physical errors can be traced to disturbance of the snowpack caused by the presence of the two access tubes. The tubes influence windflow and snow deposition, hence minor drifts form in the lee of the tubes. Snow may adhere to the tubes, so its settlement may be retarded. The gage oscillates in the wind, compacting the adjacent snow and creating air gaps a few centimeters wide between the tubes and snow. The gap is enlarged at the snow surface by longwave radiation from the sun-warmed tubes. Throughout the winter, melt cones appear around the CSSL gage tubes within a few days after a storm. During storms, these small melt cones are filled with low-density fresh snow which may distort density and water equivalent values. In spring, the melt cones become quite large, often attaining a depth and diameter in excess of 20 cm. The melt cones both reduce effective surface density and have the potential to significantly alter the pathways of water flow in the snowpack around the gage. The cones, the air gap, and the tubes themselves may provide a rapid drainage path through otherwise impeding layers.

A principal design assumption of the profiling snow gage is that the layers between the tubes are horizontal. However, the measured layers may be tilted due to the access tube effects described above. Convex layers between the tubes may be produced when snow surface topography includes melt cones. Additionally, visual depth observations frequently show the surface snow between the tubes to be uneven, sloping, or both. A photograph of a 1971 excavation of a snow gage at CSSL (Randolph et al., 1973, p. 76, figure 29) appears to show definite curvature or slope in several layers. If a thin, high-density layer were to have even a very minor slope (2 to 5 degrees), its measured density would be greatly reduced. While many profiles show large changes in density over short vertical increments, if the layers are not level, they may be even more dense than the snow gage measurements indicate.

Delineation of the air/snow and soil/snow interfaces is another problem. The air/snow interface is located by using measured densities of 50 kg m^{-3} and 100 kg m^{-3}, depending on the age of the snow. When the snow surface is uneven or sloping, the interface may not be represented by these density threshold rules. In discerning snow from soil, the first density value below 500 kg m^{-3} is usually considered to signify the presence of snow. The soil/snow interface should be at a constant depth, but by the 500 kg m^{-3} criterion, it occasionally fluctuates by approximately one centimeter. Ponding of water subsequent to melt or rain water drainage through the snow is a likely cause of the apparent interface shift, although mechanical aberrations in the lift mechanism may contribute to the variability.

Service and limitations

More than 15 years of operation have shown the CSSL gage to be highly reliable. Modular construction has allowed replacement of separate components when they fail. The lift system has been especially prone to damage due to operator error. The annual calibration takes about four hours, and little routine maintenance has been required. Operator training requires one-half day.

The installation of a microcomputer at CSSL in 1982 modernized the data collection and processing system by incorporating diskette storage and dataphone transmission capabilities.

The principal limitations preventing a widespread network of gages are the complexity of the device and the expense. A large number of moving parts enhance the likelihood of mechanical malfunction in remote installations. The radioactive source requires special attention and regulatory involvement. Analysis and interpretation of profile data is complicated and time consuming. Further, current hydrologic models were not designed to use the detailed profile data that the gage produces.

Due to the impracticality of deploying the profiling snow gage in large numbers throughout a basin, questions arise about the representativeness of a single gage. Although it can certainly be used as a highly accurate index tool, a major effort will be required before we adequately understand basinwide snowpack variability so as to be able to take advantage of the information provided by the profiling snow gage.

Design Modifications

If the snow gage were to be redesigned, we would suggest the following modifications:

Replacing the simple direct current lift motor with a precision stepping motor. This change would eliminate the need for the depth sensing system and would allow measurements to be made with the source and detector held stationary for a fixed time or number of counts.

Using alternative tube materials or surface finishes to reduce melt around the gage. Although assessment of tube materials was part of the early gage development, recent material science advances should be reviewed.

Adding a second detector tube to improve our understanding of both the spatial variation of snow properties and the inherent error variances of the instrument. This change would, however, increase the detection system complexity.

Programming the on-site microcomputer to control gage operations and move the gage in the desired pattern.

Incorporating an electronic medium (preferably a solid state exchangeable memory pack) for automatic processing and storage.

Supplying electric power with a SNOTEL-type or solar cell/rechargeable battery system for a remote facility.

Using a variety of mechanisms to retrieve data manually or to telemeter data to a central point.

Research Potential

The profiling snow gage will continue to be used chiefly as a research tool. The gage still has great potential for investigating snow metamorphism, snowpack settling, rain-on-snow dynamics, avalanches, and snowmelt runoff generation, particularly when used in combination with other instruments. For example, three new melt pans at CSSL should yield relevant information on water movement and release from the pack when coupled with snow gage profile data. Snow stratigraphy can be studied with the gage to an extent impossible with traditional pit analysis. The gage is invaluable wherever repeated density measurements are desired for the same volume of snow. If an operational device for monitoring snowpack liquid water can ever be developed, the snow gage density profile information may be extremely useful in determining and forecasting snowpack response to rain or rapid melt situations. If input variables in snowmelt models were reformulated to include detailed profile data, presumably melt forecasting precision would be improved. The increased precision and convenience stemming from the new computer interface will facilitate collection of higher quality data on which researchers can rely. As techniques are developed to quantify various snowpack processes, operational application of density profile data in runoff and water supply monitoring and flood management may become feasible.

SUMMARY

For over a decade, the isotope profiling snow gage at the Central Sierra Snow Laboratory has been in both research and operational use, but has not become a common forecasting tool. For routine applications, the current form of the gage suffers from excessive mechanical and electronic complexity, rendering it costly and unreliable in remote installations. Although it has more faults than originally realized, the snow gage monitors snow density and water equivalent at a high level of accuracy.

For research purposes, the gage provides snowpack information that is unavailable otherwise. The device has been essential to a variety of studies and should continue to be an important means of investigating snow processes and properties. Recently instituted operating procedures have substantially reduced a major error source. Changes have also been proposed to correct design problems that have limited the absolute accuracy of the current snow gage. Nevertheless, the profiling snow gage remains a unique means of providing a view of the interior of the snowpack.

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