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Pressure pillows for measurement of snow water content were first installed at Mt. Hood, Oregon, the winter of 1961-62 and some evaluation of the accuracy of this measurement system has continued through 1973 at this and other sites in the West. (Beaumont, 1965; Peterson, 1968; and Warnick and Penton, 1971).

Although pillows have been widely used for the measurement of snow water equivalent, their performance has had little evaluation, except for two major test sites (SCS site at Mt. Hood in Oregon and California Department of Water Resources ALPHA site in California). Standards to ensure adequate installation have not been universally available or accepted. Many questions have arisen as to (1) the adequacy of all pillows under some snowpack conditions; (2) the adequacy of design of some pillows; (3) the relative merits of pillows made from the various available materials; (4) the type and amount of fluid used; and (5) the correct installation procedures.

The Soil Conservation Service appointed a team in 1977 to evaluate the adequacy of the snow pillows used in its SNOTEL system. This team examined all records to determine the success-failure ratio of the pillows and to identify causes for any failures. This paper summarizes some of these findings.

Snow Pillow Experience

Based on early tests at the Mt. Hood and ALPHA sites, butyl rubber pillows were chosen as the standard for use by the Soil Conservation Service and the State of California. The original 12-foot butyl rubber pillows were filled with 200 to 300 gallons of fluid. The first butyl pillows were expensive, susceptible to puncture by rodents, and some leaked from imperfections in manufacturing.

Attempts to eliminate or reduce some of the undesirable features of butyl pillows led to the development of metal pillows. The first of these were made of galvanized sheet metal in various configurations and sizes but, because of the size of materials, most were about 4 feet wide. Early metal pillows used at the ALPHA site in California, the SCS Mt. Hood site, and at various sites in Idaho and other states, were of galvanized metal 4 feet by 5 feet and one-half inch thick. These pillows were of the same size as the current SNOTEL stainless steel pillows. Many users adopted galvanized metal pillows because they cost less and required less fluid for filling than butyl pillows.

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The galvanized pillows were used in sets of two, three, four and six plumbed together. It was believed that fewer of these pillows nested together could be used in the shallow snowpacks and still maintain the required accuracy. Six of these metal pillows have about the same surface area as a single 12-foot butyl pillow.

In either very alkaline or very acid soils, galvanized pillows rusted and developed leaks within 5 years. In an effort to alleviate this problem, the Soil Conservation Service, State of California, and others, specified that pillows be manufactured from stainless steel. A few stainless steel pillows were installed for observation at test and operation sites by the State of California and by SCS.

Based on results of the tests conducted at Mt. Hood and at the ALPHA site (State of California, CDWR, 1976), the SCS selected the 4- by 5-foot stainless steel pillow as the basic snow measurement instrument for its automated-telemetered SNOTEL system. This pillow differed from those previously used in that the shell was made of thinner material for greater sensitivity, and angle-iron bracing was added to the bottom for greater stability. Because several of these pillows failed in service, the adequacy of metal pressure pillows for sensing changes in snow water content and the adequacy of the SNOTEL design came into question.

The Snow Sensor Evaluation Team appointed by SCS, USDA, evaluated data from all SCS and State of California snow sensors for all the years of record. Analysis of 1135 years of record showed that, when pressure pillow data were compared with those obtained with the Federal Snow Sampler, correlation coefficients of from 0.939 to 0.954 were obtained (Table 1). Further, stainless steel pillows had a correlation of 0.941 compared with 0.954 for the butyl pillows.

Table 1.--Correlation of Federal snow sample measurements with those by butyl, metal, and stainless steel pillows.

State	Years of Record	Correlation Coefficient of Snow Tube Vs.:		
		Butyl Pillows	Stainless Steel Pillows	All Metal Pillows
Alaska	34	.962	--	--
Arizona	33	--	.875	.889
Colorado	91	.942	.967	.969
Idaho	36	.975	--	--
Montana	415	.953	.966	.966
Nevada	110	.953	.896	.920
New Mexico	13	--	.977	.965
Oregon	135	.980	.956	.945
Utah	59	.995	.951	.892
Washington	36	.989	--	.966
Wyoming	74	.938	.942	.919
Mt. Hood	82	.964	.931	.964
California	17	--	.970	.970
Total	1135	Average .954	.941	.939

Although evidence is overwhelming that pillows do work, problems are involved in their use. The snow pillow measuring system seems much more simple than it is. Success or failure depends on several critical installation and operation criteria.

Operational Problems

The accuracy and precision with which snow pillows operate depends on site physical characteristics, installation techniques, equipment operations, and maintenance.

Most problems can be identified by examination of the data produced and some can be corrected soon after they are identified. This is particularly true if several types of sensors are located at the same site.

If a pressure pillow and the associated precipitation-snowpack measurement devices at the site are operating properly, all sensors at the site should be responding to the event that is occurring. The reason for lack of response by any sensor must be determined. At locations where a water equivalent sensor and a rain gage are present, the two sensors, during certain accumulation events, should react in the same way to the associated input.

Vapor or Pinhole Leaks.--Vapors and liquid methanol leaking from a very small hole in the pillow surface or along an edge melt the snowpack above the hole, creating a cavity having a relatively thick ice layer. When a cavity is present the pillow system performs erratically and underweighs the pack. This condition persists until melt begins in the spring. Water flowing over the snow pillow dilutes and dissipates the methanol. The ice layer softens and the weight of the snowpack settles down onto the pillow. The pillow returns to a near-normal performance level near the end of the melt period.

The records from such a site can be salvaged. The ice cavern can be located by probing. Then, by digging down beside the pillow, a sheet of visqueen* can be placed over the pillow surface. The ice layer can be collapsed and the cavern filled with uncontaminated snow. Minor adjustments may be necessary to correct for too much or too little snow added to the cavern. This can be determined by measurements with snow tube, other sensors, or comparison of past records with other sensors.

Canopy Effects.--There should be a minimum canopy effect upon snow accumulation on the snow pillow. Usually sites can be located so that there is no canopy within 30° from the vertical. If trees grow tall enough to influence accumulation, they should be removed.

Drainage Problems.--Improper drainage can occur when melt water flows downslope onto the pillow during or following heavy melt periods and/or rain on snow. This extra water on the pillow increases the pressure above that of the snowpack. Such problems can be solved by providing adequate drainage around the pillow site or, in some cases, moving the pillow to a new location that provides adequate drainage.

Long Wave Radiation Melt.--Fences, trees, or an instrument house too close to a pillow may cause additional melting. Usually the problem object is on the northerly side of the sensors. As the temperature of these objects increases, the melting of the surrounding snowpack also increases due to long wave radiation and increased sensible heat input. These effects are easily recognized during the latter part of the season. Usually the snow on the pillow nearest the object melts off, leaving the pillow only partly covered. An alert observer should look for these problems when he visits the site. Comparisons can be made between sensors, if more than one is present at the site. The obvious solution is moving either the pillow or the object.

Creep.--Placing a pillow on a slope invites not only increased pressure from off-slope melt, but also creep. If creep is present the pillow will indicate more or less snow water equivalent than should be present. This can be determined quite early in the season if ground truth measurements are taken during each visit and compared with the on-site manometer readings. The problem may be solved by levelling a larger area for the pillow. The leveled area should be at least twice the size of the pillow installation. Pillows should not be placed in areas having slopes in general more than 5 to 10 percent.

Leaks in Fittings.--Leaks in fittings cause the pillow to lose fluid pressure until it reaches zero. Such leaks can be prevented by careful preparation at the time the pillows are installed. All fittings should be treated with pipe dope and double checked for tightness and, if possible, all connectors and lines should be left uncovered for at least 24 hours and then checked again. When pressure levels of pillows decrease during no load periods, leaks should be suspected.

*Trade names are mentioned for the benefit of the reader and do not imply endorsement or preference of the name mentioned over others available by the U.S. Department of Agriculture.

Exposed Fluid Lines.--Exposed fluid lines heat up during sunny days, thus causing a pressure increase in the system. All fluid lines should be buried to the instrument house, and should enter the house through the bottom and not on the south-facing wall. The transducer should also be protected from temperature change by mounting it low in the shelter, on the north wall.

Air Locks in System.--The system will not operate properly if any part of the fluid lines contain an air lock. Air lock problems can be detected when the pillow is installed by putting pressure on the pillows and observing the responses. If operating properly, the system will respond immediately to increasing or decreasing pressure on each pillow in the system.

The air lock problem may sometimes be solved by opening up the fitting in which the air lock is located and bleeding the line. But in most cases the system must be drained and refilled. Filling metal pillows from the top and not through the lowest point in the instrument house usually adds to this problem. Chances of getting air locks are great when one pillow is replaced in a cluster of two or more. The instrument house should always be lower than the pillow.

Air in Pressure Transducer and Pillows.--Temperature-induced effects are increased if all of the air is not removed from the system. These effects become less variable with increasing snow depth, but are increased when air temperature increases. However, data will be so variable when air is in the system that it will be useless in most cases. Air should be removed from the pillows and pressure transducers when they are installed and they should be rechecked before the snow season begins. Some pressure transducers are also subject to variations because of temperature. These problems can be identified by using dummy loads to check the transducer.

Improper Bedding of Pillows.--Improper bedding of the pillows will result in erroneous pressure readings because the top weighing surface will be larger than the bottom supporting surface. This problem is peculiar to metal pillows and usually becomes apparent when pillow readings are compared with ground truth measurements or readings from other sensors. It can be solved by preparing a bed of sand, or sawdust, and soil and then laying out two level boards on each side of the site and screeding the entire bed to level before installing the pillows. Rodent activity can be minimized by placing a layer of one-fourth inch hardware cloth under the pillow. The bedding must be checked each year, because settling and rodent activity may deteriorate it.

Levelling of Site.--For the pillows to function properly the snow cover must be uniform over the pillows and extend to the area around it. An area extending at least 3 feet beyond the outer edge of the pillows must be levelled.

Tin-Canning of Snow Pillows.--One of the problems specific to the SNOTEL stainless steel pillow is tin-canning, whereby the pillow becomes severely deformed as a result of ballooning and collapsing (Figure 1). One or more of the following practices, actions, or conditions contribute to pillow tin-canning:

1. Use of 100 percent methanol fluid rather than half water-half methanol.
2. Pillow surfaces painted a dark, heat-absorbing color.
3. Air not completely vented from pillows and air locks in plumbing lines.
4. Pillows not completely filled with fluid, allowing space for air entrapment.
5. Presence of underside bracing and framing making proper bedding difficult.

Installation Techniques

The records showed that those pillow systems that were carefully installed and maintained by trained personnel produced the best results. These guidelines have been developed for installing snow pillows:



Figure 1. This stack of "tin-canned" pillows in Utah illustrates the common points of failure of the pillows.

Site Selection.--

1. Pick a site far enough away from adjacent slopes so creep and downslope melt water will not interfere, but with enough slope so that the pillows can be placed at a level higher than the instrument house.
2. Avoid low meadow areas that become ponded during snowmelt, or areas with high water table.
3. Select an area open enough to eliminate canopy effects and long-wave radiation melt from adjacent trees, and small enough to eliminate or at least minimize drifting at the site.
4. Pick a site that is well hidden and paint all sensors earth tones in order to minimize vandalism.

Site Preparation for Metal Snow Pillows.--

1. Level an area large enough to provide at least a 3-foot border around the pillow perimeter.
2. Provide adequate drainage channels so that melt water moves around the pillow bed and away from the site.
3. Prepare a bed of either sand or soil-sawdust mixture 1 to 2 inches deep over the entire site.
4. Add air to pillows to obtain an approximate shape of a filled pillow.
5. Work pillows into the bed so the bottom surface is in full contact with bedding surface and the edges of the pillow are flush with the surface. Burying pillows under soil may cause erroneous readings in shallow, cold snowpacks, particularly if there are rains before snowfall and/or early season melt. The soil or sawdust will absorb moisture and then freeze, which will affect readings until the ice layer melts. The surface of the metal pillows should be about one-half to one inch higher than the surrounding soil with the soil groomed so any melt water or foreign water will run away from the pillows and not pond on or around their edges. In some areas, such as California, weather conditions may not severely affect the performance of buried pillows. Also, some wilderness areas may require that pillows be buried.
6. Use at least 3/8-inch diameter lines for all plumbing: copper flare, copper sweat, or galvanized pipe. Air removal is easier with 1/2-inch lines.
7. Plumb pillows around outside perimeter, keeping the length of the fluid lines for all the pillows about equal.
8. Use pipe dope on all pipe connections.
9. Dig trenches at least 6 inches deep for all lines around pillows and to the instrument house.
10. Install pressure line from house to pillow with a gradual upward slope with no traps or loops that will develop air locks.
11. Provide a vertical vent in the plumbing in the house for removing air from lines and the pressure transducer.
12. Provide a fitting in the inside plumbing for putting fluid in the pillow system from the lowest point. Use a manometer at least 3/8-inch diameter and plumbed to remove air from lines and transducer.
13. Fill pillows from the lowest point in the house, using a mixture of 50:50 water:methanol or 50:50 water:glycometh.

14. Place 2-inch nipples in top bungs of each pillow so that no more than a 2-inch pressure head is put on any pillow.

15. Fill with a gravity system, being careful not to entrain air into the liquid during filling. Do not pump fluid.

16. Remove fluid source and leave all pillows open until equalization has occurred.

17. Work air out by flexing pillows periodically over a 24-hour period.

18. Remove nipples or open bleeder valves one at a time and let fluid flow out until about one-half inch of head remains.

19. Put pipe thread dope on plugs and seal in place or close bleeder valves.

20. Connect pressure transducer, making sure all air has been removed.

21. Secure the pressure transducer at least 2 to 3 inches below the fluid level in the manometer.

22. Check bedding and replace any removed during the filling process.

23. Apply pressure to each pillow and note manometer level and transducer response. A sluggish response indicates air entrapment or blockage in the system and requires immediate attention.

24. Check all connections for tightness and leaks and bury all lines to pillows and instrument house.

25. Check the system again before the first snowfall to be sure all air has been removed from transducer, lines, and pillows and that there are no leaks.

Butyl Snow Pillows.--

Many guidelines for installing metal pillows also apply to butyl snow pillows. The following are a few guidelines specific to butyl pillows:

1. Cover butyl pillows on top and bottom with 1/4-inch galvanized wire cloth to deter small rodents from the bottom side of the pillow and large animals like deer and elk from the top side.

2. After the pillow is filled with 50 percent methanol or glycometh-water solution (about 110 gallons for a 10-foot diameter or 165 gallons for a 12-foot diameter pillow), the area around the edges should be backfilled so the surface of the pillow is about one-half to one inch higher than the surrounding surface.

3. With butyl pillows, it is possible to obtain records with an on-site water level recorder. The A-35, Type F, or comparable water level recorder with 4-inch floats and 6-inch stilling wells have been used successfully on 10- and 12-foot diameter pillows. Larger stilling wells and floats are not recommended because of the increased amount of fluid that is drawn from the pillow as snowpack increases.

4. A vacuum pump can be attached to the top valve and used to extract the air. Since some air becomes entrained in the methanol solution during filling, the air should be checked and removed sometime after installation. It is easy to check for air. Small bulges on the pillow that collapse when pushed show that air is present. A pillow with no air will have a smooth surface and the fluid can be felt by patting the surface of the pillow.

Snow pillows made of nylon-reinforced hypolon are currently being field tested. Hypolon seams can be welded with heat or adhesive so that they are as strong as the material. The manufacture of hypolon is more closely controlled so that wicking through any nylon fibers is eliminated. A hypolon pillow weighs about half as much as butyl and is expected to cost about the same.

Equipment Operations and Maintenance

1. Carry a field log book to each site and document all observations. Operational problems cannot be accurately defined unless a historical record is available for comparisons with current readings.
2. Check the calibration of the pressure transducer at the initial installation, and recheck it each season. A field check can be made by closing the fluid line to the pillows and adding solution to the manometer, filling it up to the expected maximum range. Read the pressure transducer output and then bleed the fluid from the manometer by increments, and check the transducer output at each point until the zero point is reached. Also, a plot of manometer readings (adjusted for specific gravity of the fluid) vs transducer readings can provide a check over the years of record.
3. Check battery voltages and note them in the log book each time the site is visited. Low batteries should be replaced or recharged or additional batteries should be added in series to insure sufficient power. One of the major causes of lost records at remote sites is insufficient battery power.
4. Note in the log book when the solar panels are covered with ice and snow. This should be removed if possible. Some solar panels have a rougher surface and will not sluff snow as well as others. The rougher ones can be covered with a clear plastic film or silicone spray that will improve snow removal. Panels should be checked for cracking or weathering each season. Output can be determined with a good quality VOM meter and compared to design output. Inferior panels should be replaced.
5. Air in transducer lines should be immediately removed. (Be sure to note in log book if air is present and when removed.)

6. When the snow has melted, pillows should be inspected for white powdered residue or discoloration that indicates small leaks; they should be bled of any entrapped air that might have accumulated during the year, and they should be rebbed if necessary.

Summary

About 15 years ago the first snow pillow was installed to measure snow water equivalent of the snowpack. Since that time, two major types have evolved--the butyl rubber pillow and the stainless metal pillow. These snow pillows have been accepted by SCS and CDWR as their standard snow water equivalent sensor. Several years of record have demonstrated that snow pillows can accurately measure snow water equivalent, but problems can exist when using these devices. Although pillows appear to be rather simple devices, they are quite complex.

Trained personnel must be available to install and maintain these devices to obtain good quality data. Certain procedures must be followed in order to obtain a satisfactory operational record.

The evidence up to now indicates that this device has been, and probably will be for years to come, an accepted standard for snow water equivalent measurements. However, good records will be obtained only if proper pains are taken in its care and feeding.

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