

SNOWMAKING TECHNIQUES IN THE SKI INDUSTRY

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ABSTRACT

Machine-made snow has become an increasingly vital commodity for ski areas throughout the U.S. By 1985, the average ski area in the East and Midwest had installed enough capacity to cover nearly 80% of its skiable terrain with machine-made snow. Recent advances in snowmaking technology have provided the opportunity to construct ski resorts in areas that were previously thought to be too warm or had poor exposures. In this article the physical processes of atomization, heat transfer, particle nucleation, and dispersion in snowmaking machines are examined, and a survey made of the various types of snowmaking nozzles. The merits of each type of nozzle are identified, and the factors that influence proper nozzle selection discussed.

INTRODUCTION

In late December, 1949, Walter Schoenecht was faced with a problem. As owner of Mohawk Mt, a ski area in Connecticut, he stood to lose a major investment because no snow had fallen, and Christmas week was rapidly approaching. In desperation, Walter located 700 tons of block ice which he crushed and distributed on his trails to allow three rope tows to operate. After nursing his sore, aching muscles, Walt met with three friends to try to figure out a better way. Unknown to Walt Schoenecht his back-breaking achievement formed the impetus of a new technology which would revolutionize the ski industry - snowmaking.

Today nearly 80% of the ski terrain in the Eastern and Mid-Western U.S. is covered by machine-made snow. This figure is close to double the snowmaking capacity that was in service only six years ago (see Figure 1). An average size ski area in the East will spend \$240,000 annually on snowmaking operations, up more than 300% from the average expenditure in 1979. These investments allow ski resorts to open consistently for Thanksgiving and extend their seasons late into the spring. Last year a large resort in Vermont was able to open for skiing in October and close in June, giving them nine months of operation.

The objective of this article is to examine the physical requirements for the production of machine-made snow and to assess the present technology for achieving this end.

PHYSICAL PROCESSES

Aside from Walter Schoenecht's initial bout with crushing block ice, snowmaking developers have concentrated on producing snow by spraying water onto the ski trails in a manner that enables the water to freeze before it hits the ground. This objective involves four physical processes:

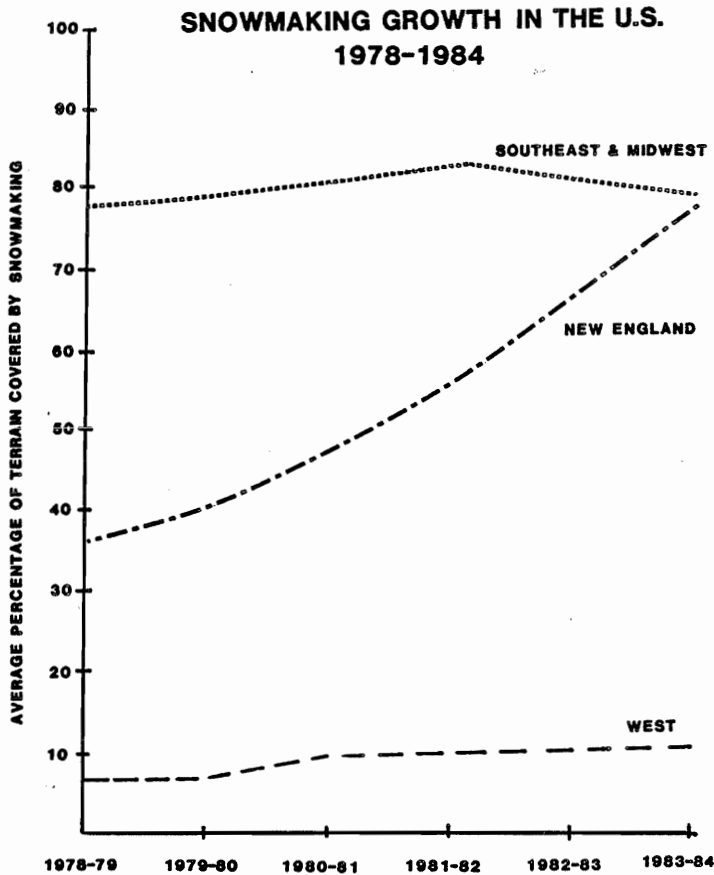


Figure 1

1. Atomization of the water into acceptable size droplets
2. Heat Transfer to cool the droplets enough to allow freezing to occur
3. Nucleation to initiate the phase transformation from liquid to ice
4. Distribution to deposit the snow in a desired location

Every model of snowmaking equipment on the market today accomplishes these tasks in a slightly different manner. However, for discussion purposes there are basically three basic categories of snowmaking devices.

- I. "Air/Water"
- II. "Semi-Airless"
- III. "Airless"

Each category of equipment is described in the subsequent sections with reference to how they achieve the four fundamental processes of snowmaking.

AIR/WATER SNOWMAKING NOZZLES

When Schoenecht got together with three fellow ski enthusiasts that winter, they decided that there must be a better way of obtaining snow for their ski trails during a snowless winter. Adopting concepts from agricultural and irrigation spray devices, several prototypes were produced which mixed compressed air and water inside a confined chamber. When this air/water mixture expanded through a nozzle, the water was shattered into small droplets with a very high velocity. The momentum imparted to the droplets carried them 10-15 meters from the nozzle, giving them adequate time to freeze before they hit the ground.

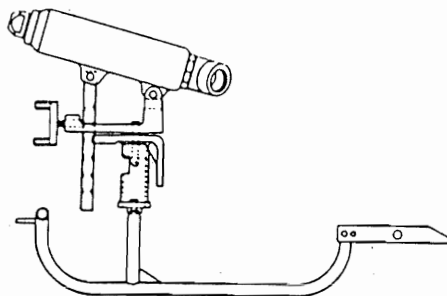


FIGURE 2 Typical Air/Water Snow Nozzle

This type of snowmaking device still dominates in the ski industry today. Most air/water snowguns can achieve a wide variety of droplet sizes, and therefore tend to work well over a range of atmospheric conditions. The nozzles are small, light, easily transported and very reliable, but the expense of compressing and distributing air makes their operation relatively costly. A typical air/water nozzle is illustrated in Figure 2.

A. Atomization in Air/Water Snowmaking Nozzles

In air/water snow nozzles, water is broken up into droplets or "atomized" by a high velocity differential between the water and compressed air phases. This velocity differential induces surface perturbations in the water jet which provide enough energy to overcome surface tension effects and "shatter" the fluid. By increasing or decreasing the flow of compressed air, the velocity differential between the air and water can be adjusted, creating a method by which droplet sizes can be altered. Air/water snowmaking devices today consume water to air mass ratios of (5:1) to (30:1) to produce sprays with mean droplet sizes ranging from 50 to 400 microns (see Figure 3).

Two developments introduced during the last few years have improved atomizing efficiency of snow-guns. The first involves the use of small orifices to pre-atomize the water before it contacts the compressed air. This generally produces smaller droplets which are an advantage during warmer snowmaking ambient temperatures (-1 to -5° C). However, these smaller particles will have less momentum when leaving the snow nozzle and will not be distributed as far. This can become a disadvantage under cold ambient conditions or when a uniform blanket of snow is desired.

Most ski resorts supply their snowmaking equipment with a compressed air pressure of 550-700 KPa (80-100 psi). Recently a few resorts have elevated this compressed air pressure to 1000 KPa (150 psi). Because droplet size in a snowmaking type of atomizer is inversely proportional to air pressure, this creates a spray with a smaller mean droplet size. However, the energy cost of compressing the air to 1000 KPa (150 psi) is increased by 40%. There is some disagreement within the ski industry whether this added expense is warranted or not.

SNOWNOZZLE ATOMIZATION CHARACTERISTICS

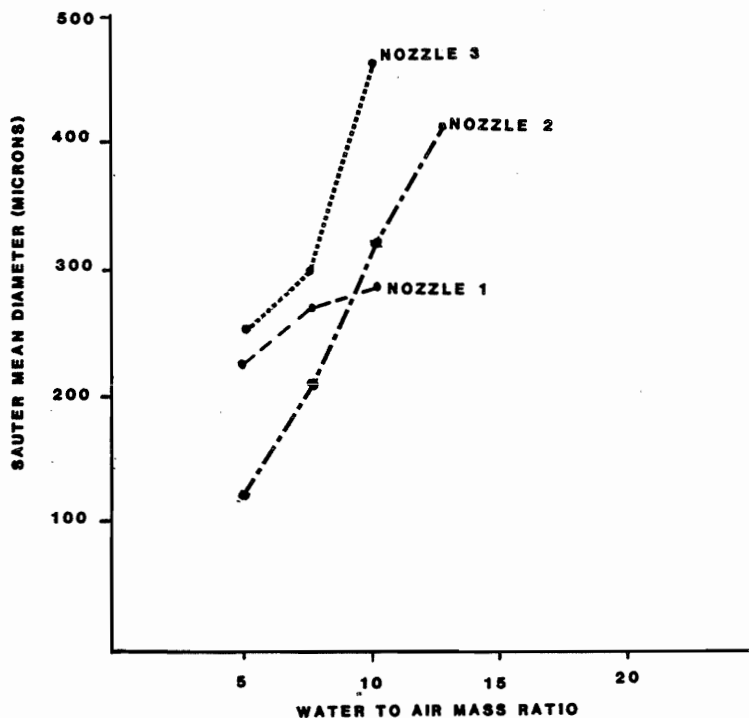


FIGURE 3

B. Heat Transfer in air/water snowmaking nozzles

Once atomization has occurred, cooling of the water droplets can occur by four heat transfer mechanisms:

1. Radiation
2. Expansion Cooling of Compressed Air
3. Convection
4. Evaporative Cooling

Radiational cooling can be ignored as it has a relatively minute effect. Expansion cooling is the result of acceleration of the compressed air to sonic or near sonic conditions at the exit of the nozzle. While this creates a zone at the nozzle throat with a temperature of -40 to -45° C, the heat transfer effect of this region is minimal, contributing only .5% to 3% of the total cooling required to freeze a 200 micron droplet.

The dominant heat transfer forces in air/water snowmaking are, therefore, convection and evaporation. The relative importance of each form depends on droplet size, ambient temperature, and relative humidity of the spray environment. Figure 4 indicates the relative importance of evaporation and convection for a 200 micron droplet. As can be seen from this figure, convective heat transfer dominates at temperatures below -6° C; above this temperature evaporation is the dominant mechanism. The low heat transfer rates indicated on this graph explain why it is very difficult and expensive to produce snow during periods of high ambient temperatures and relative humidities.

HEAT TRANSFER RATES FOR A 200 MICRON DROPLET

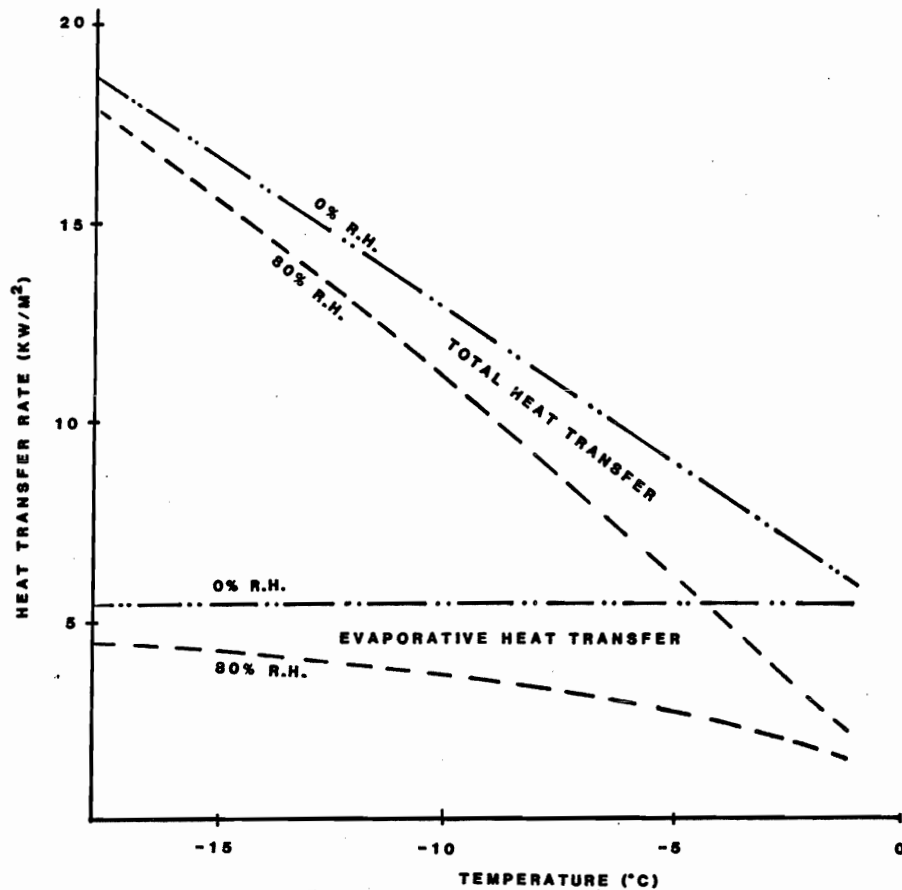


FIGURE 4

C. Nucleation in Air/Water Snowmaking Nozzles

In addition to heat transfer requirements, efficient snowmaking demands that water droplets be nucleated to initiate freezing as soon as possible. The sooner droplet nucleation and freezing occurs, the longer the snow particle has to grow in the humid environment of the spray and the less likely that collisions will result in the agglomeration of droplets. In order for a water droplet to nucleate, it must cool to its spontaneous nucleation temp or be introduced to a seed particle. Water tests at six New England ski areas have shown a remarkable difference in spontaneous nucleation temperatures ranging from -6°C to -12°C (see Figure 5).

In air/water equipment, particle nucleation is markedly enhanced by the presence of compressed air. As mentioned previously, the compressed air temperature as it accelerates through the nozzle reaches -40° to -45°C . At this temperature, the small water particles contained in the compressed air freeze instantly. These small particles form excellent nuclei to promote freezing of the water droplets in the spray of a snow nozzle. The temperature of the water droplets leaving the snow nozzle is very important because if the water is too warm, the nuclei will be destroyed before they can do their job.

For quite some time people have experimented with water additives in attempt to increase the nucleation temperatures of droplets from a snowmaking nozzle. Recently, a bacteria has been introduced which shows considerable promise for the ski industry. Tests at six New England ski areas last winter demonstrated an increase in nucleation

temperature between 3° and 10° C when the bacteria (*Pseudomonas syringae*) was added to the water source. The marketing reports for the company claim that increases in snow production yields average 30%. Since it is an abundant, naturally occurring bacteria which is killed in processing, the environmental impacts of distributing the bacteria are felt to be negligible.

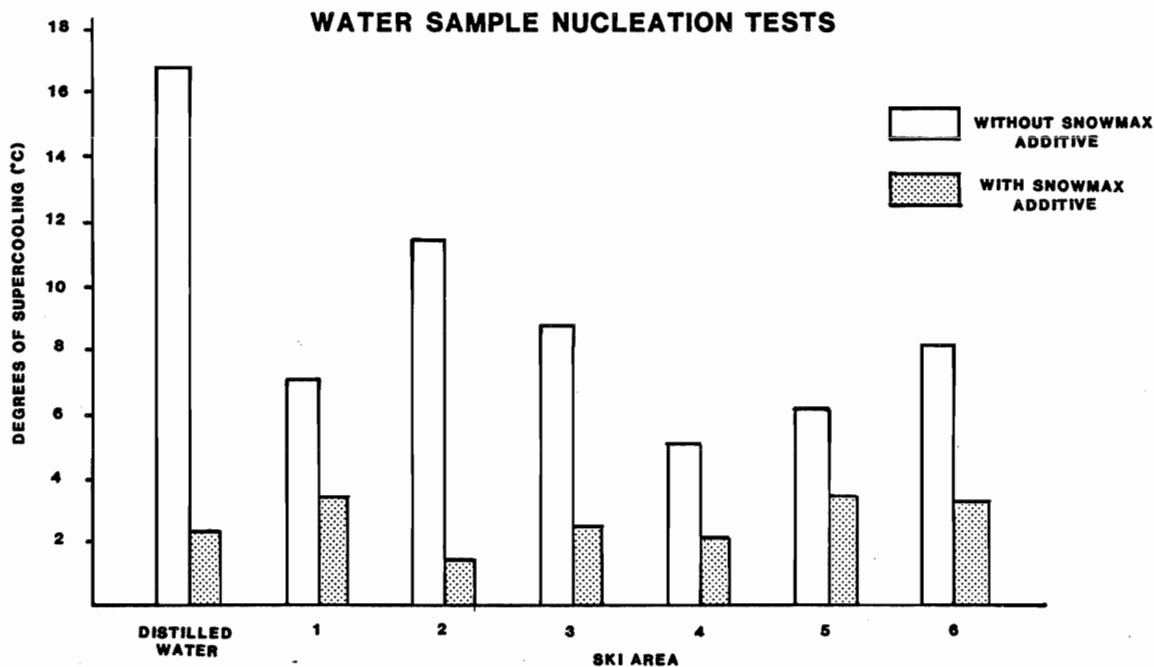


FIGURE 5

D. Dispersion in Air/Water Snowmaking Nozzles

A critical requirement in snowmaking is to propel the droplets in a trajectory that will allow them to freeze before they hit the ground. This last phase of the snowmaking process introduces a tremendous amount of variability in nozzle design and operation.

The dispersion of droplets in an air/water snowmaking nozzle is accomplished by the expansion of compressed air. This expansion process creates sonic or near sonic velocities at the nozzle exit, imparting enough momentum to throw the droplets up to 10m in the air before they reach terminal velocity. Normally, a recirculation zone created by entrained ambient air at the nozzle exit will cause some of the low momentum, fine droplets to settle out of the spray and deposit close to the nozzle. The larger droplets with more momentum deposit towards the middle of the accumulation pile, and the small droplets "float" down with low terminal velocities to collect towards the end of the pile. However, this "classic" distribution is not always the case; with swirling or wide angle cone nozzles the heavy, high momentum particles often deposit closest to the nozzle exit.

There are many different nozzle geometries in use which are designed to optimize the dispersion process. Each design is typically best adapted to a particular ambient or terrain condition, so most ski areas have an extensive arsenal of various air/water snowmaking nozzles. Recent advances in air/water dispersion design include:

1. Use of a slotted nozzle to produce a diffuse flat spray and a more uniform deposition pattern
2. Mounting guns on 5-10 meter high towers in wide open areas to increase the residence time for droplets in flight
3. Introducing a large fan behind the air/water nozzle to decrease drag on the droplets and retain any of the small particles that might otherwise recirculate and deposit close to the nozzle.

It is important to note that operational settings have a significant effect on the dispersion process. By tilting a nozzle at a steep angle, orienting it with or against the wind and placing it at the top of rolls in the terrain, an operator can adjust the residence time of the droplets and the location of the depositing snow pile. The selection of the optimal nozzle design, setting, and placement is an art which depends highly on the experience of the snowmakers.

AIRLESS SNOWMAKING

The requirement for large amounts of compressed air makes air/water snowmaking a relatively expensive process. For a ski area with a 450m vertical drop, roughly 85% of the system energy requirements will be consumed by the compressors when the ambient temperature is -4°C (25°F). To eliminate this expense, several snowmaking devices have been developed which do not use compressed air. These are called 'airless' machines despite the fact that they generate large volumes of low pressure air by means of a high speed electric fan. A tower mounted model is pictured in Figure 6. Most of the units incorporate a 15 KW fan, dropping the energy requirements of the air to approximately 25% of the total snowmaking system consumption.

A. Atomization in Airless Snowmaking Equipment

Airless snowmaking devices achieve atomization by directing the water into a manifold behind the fan blades. Small orifices drilled in this manifold direct the water into narrow jets which impinge upon the blades of the fan. The centrifugal motion of the fan forces these water jets into a film which breaks up into droplets as it flows off the tip of each blade. The resulting spray consists of relatively fine droplets, often interspersed with occasional ice chunks which have built up on the blades of the fan.

B. Heat Transfer & Nucleation in Airless Snowmaking Equipment

The modes of heat transfer for airless snowmaking machines are not much different than what occurs in the air/water snowmaking process. One subtle difference is that lower air velocities and generally small particle sizes result in much lower droplet momentum. Consequently the particles rapidly reach terminal velocity, and the dominant portion of heat transfer takes place during the free fall of the droplets, with much less airstream turbulence than in air/water snowmaking. This is a disadvantage as it decreases the convective heat transfer coefficient.

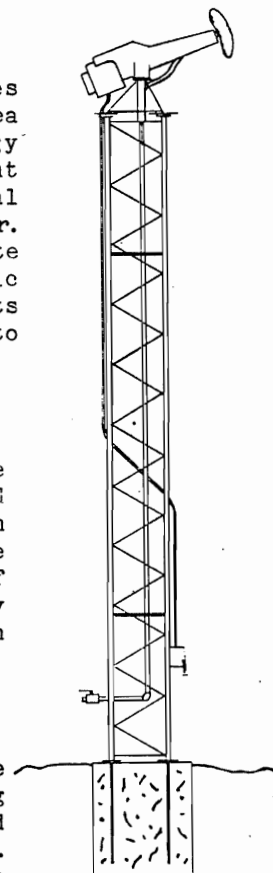


Figure 6
Airless Snow
Machine Mounted
on Tower

Another disadvantage of airless snowmaking machines is that the elimination of the ice nucleants, found in expanding compressed air, severely restricts the nucleation process. This requires that the droplets in the spray be subcooled to a much greater extent before the freezing process can be initiated. This has important ramifications on the design and application of these machines, as heat transfer must be maximized by decreasing the size and increasing the flight times of the particles. In general, the production of snow from airless snow machines drops markedly at marginal snowmaking temperatures (above -4°C or 25°F), or with high water temperatures (above 2°C or 36°F).

C. Dispersion in Airless Snowmaking Equipment

When the water in airless machines collides with the rotating fan blades, the droplets are given a high tangential velocity in addition to the axial velocity induced by the airflow from the fan. As a result, the spray expands rapidly and the droplets quickly reach terminal velocity. To achieve the desired particle 'hang' times, the machines are frequently mounted on 7-10 meter towers. This increases the amount of water that can be converted to snow, but restricts the application of the machines to wide areas or periods with very little wind because of the distances the particles can be carried from the gun location.

One advantage of airless snowmaking machines is that they are much quieter than air/water nozzles. The expansion of compressed air and the resultant sonic velocities through air/water nozzles creates a rocket-like sound measuring 100-110 dBA at a distance of 6 meters. Although the fan which accomplishes atomization and dispersion on airless machines has a very high tip speed, noise levels are reduced to about 90 dBA at a distance of 6 meters. This represents a significant reduction in noise in view of the logarithmic basis of the decibel scale. For this reason, airless machines are often deployed in noise sensitive areas such as ski trails running alongside condominium developments.

SEMI AIRLESS SNOWMAKING EQUIPMENT

To reduce the nucleation constraints on airless snowmaking devices, a third category of machines has been developed which are referred to as "semi-airless". These units consist of a bank of nozzles directing their spray into an airstream produced by a large ducted fan. To enhance the nucleation process, a small amount of compressed air is used to run a small air/water nozzle. This nozzle, known as the 'nucleator', directs a fine spray of rapidly freezing droplets into the main airstream to promote nucleation of the snowcloud plume. The presence of a 1-2 meter diameter ducted fan makes these machines much larger than their airless or air/water counterparts, particularly if a small compressor is mounted on the carriage to provide air for the nucleator. This creates problems with mobility, especially on steep and uneven terrain. However the nucleating source markedly improves their performance above airless machines when the ambient temperatures climb above -6°C . Two types of semi-airless snowmaking units are illustrated in Figure 7.

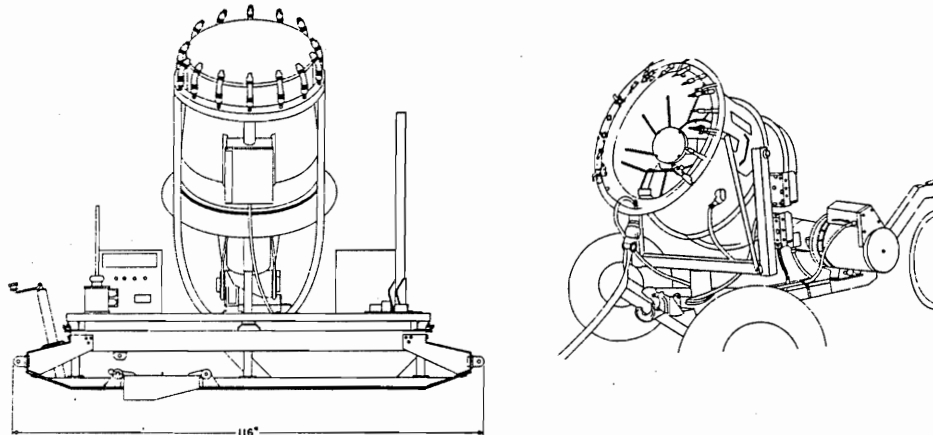


Figure 7 Typical Semi-Airless Snow Machines

a. Atomization in Semi Airless Snowmaking Equipment

Without the benefit of compressed air or mechanical collisions, semi-airless snowmaking machines must employ pressure jet nozzles to create a fine spray. There are several types of nozzle design presently in use, ranging from spiral units such as illustrated in figure 8 to orifices which are water jacketed and heated to prevent freezing. All these designs involve the use of small flow geometrics which are prone to blockage by ice or particulate matter. Inline strainers and heated nozzles attempt to minimize this problem, but during very cold ambient conditions considerable care must be taken to keep all the nozzles free and clear. Another problem is that the exposed nozzles are easily nicked or bent during storage, movement, or de-icing. This alters the spray pattern of the plume and can create severe icing problems around the nozzle.



FIGURE 8
Typical Semi-Airless
Machine Atomization
Nozzle

b. Heat Transfer and Nucleation in Semi-Airless Snowmaking Equipment

As mentioned above, semi-airless units include a small air/water nozzle to assist in the nucleation of the snow plume. These nucleators utilize a relatively low water to air mass flow ratio (approximately 4:1) to minimize droplet sizes and promote spontaneous nucleation of the water particles in the compressed air stream. To limit the consumption of compressed air, the nucleator orifices are fairly small, and are therefore prone to blockage due to the build up of ice. Most of the newer designs provide a water jacket or heater around the orifice to minimize this problem.

The requirement for compressed air to operate the nucleator presents an additional expense for semi-airless snowmaking equipment. Compressed air is either supplied by a small compressor mounted on the frame of the machine or through a network of mountain piping supplied by a large central compressor. Very often semi-airless machines are applied to supplement an air/water based snowmaking system; in these cases the existing supply of compressed air can be used. However, icing again becomes a problem if the compressed air supplied to the nucleator is too cold and/or moist.

c. Dispersion in Semi-Airless Snowmaking Equipment

Dispersion in semi-airless machines is accomplished by directing the water spray into an air stream produced by a ducted, axial vane fan. Fan sizes vary from 75cm to 140cm diameter, and produce airstream velocities between 18m/sec and 30m/sec. This velocity is sufficient to propel the water droplets 5-10 meters up in the air, resulting in snow particle depositions up to 60 meters from the unit.

As with the airless machines, the noise level emissions of semi-airless machines are much less than those from air/water nozzles because dispersion is accomplished by means of a fan rather than the expansion of compressed air. Actual noise levels vary depending on the size and speed of the fan, but generally run between 85-90 dBA 6 meters in front of the unit.

One of the limitations on 'dispersion' of the snow comes from the physical size of these units. Weighing between 225 and 700 kg, they must be towed behind a tracked vehicle to each position along the trail. Several recent models have mounted the semi-airless machines directly on a tracked vehicle to improve their portability. This makes the units extremely maneuverable, but substantially increases their price.

SUMMARY OF SNOWMAKING EQUIPMENT CHARACTERISTICS

The relative performance characteristics of the various types of snowmaking equipment are summarized in Figure 9. However, the selection of the proper snowmaking equipment for a given locality depends on many considerations. Outside of the performance parameters outlined in this figure. These considerations include:

1. Climate

When labor, maintenance, and equipment depreciation is considered, the operating cost advantages of airless and semi-airless snowmaking generally become minimal above -3°C . For this reason, many ski areas in warm climates or with high early season coverage requirements opt for air/water snowmaking.

2. Terrain

In steep and rolling terrain, it can be very difficult to maneuver airless and semi-airless snowmaking machines. In addition, providing electrical power on long trail networks, especially on mountains with shallow soils, can be cost prohibitive.

3. Noise

In noise sensitive areas, air/water snowmaking can be extremely annoying. Airless and semi-airless machines are often deployed in these locations to minimize the disturbance while allowing snowmaking operations to continue throughout the night.

4. Employees

Airless and semi-airless snowmaking requires attentive and conscientious operators to achieve profitable production rates. Ski areas in locations with a high percentage of transient labor often find it difficult to hire and retain an experienced snowmaking crew that is willing to spend the effort necessary to efficiently operate and maintain airless and semi-airless machines.

5. Energy Costs

The cost of energy plays a major role in determining the cost-effectiveness of airless and semi-airless snowmaking.

These and other site-specific parameters are tabulated in figure 10, and document why it is necessary to evaluate each area separately to assess the optimal combination of snowmaking machinery.

Figure 9

SNOWMAKING EQUIPMENT COMPARISON

Type of Equipment	Snow Production (M ³ /hr)	Energy Consumption (kw-hrs. per M ³ of Snow Produced)		Capital Cost (\$U.S.)	Weight (kg)	Noise 6m from source (dBa)
		-12°C	-4°C			
Air/Water	15 - 50	3.5	8.4	600-1200	25-35	100-110
Airless	10 - 35	1.0	3.7	6500	80-225	90
Semi-Airless	15 - 50	1.1	2.3	12,000-50,000	225-700	85-90

Figure 10

SNOWMAKING EQUIPMENT EVALUATION

	Advantages	Disadvantages
Air/Water	<ol style="list-style-type: none"> 1. Best Marginal Snowmaking Temperatures 2. Very Mobile 3. Low Maintenance and Down Time 4. Easy to Operate 	<ol style="list-style-type: none"> 1. Expensive to Operate 2. Loud
Airless and Semi-Airless	<ol style="list-style-type: none"> 1. Inexpensive to Operate 2. Quiet 	<ol style="list-style-type: none"> 1. Low Conversion Rates at Marginal Snowmaking Temperatures 2. Difficult to Maneuver Particularly on Steep or Rolling Terrain 3. Diffuse Plume 4. High Maintenance 5. More Difficult to Operate 6. More Susceptible to Freeze-Ups 7. Cost

CONCLUSION

Snowmaking has come a long way since Walter Schoenecht's early battle with an ice crusher. Modern snowmaking plants are multi-million dollar investments, with connected power loads often between 6-8 MW. Annual operation costs of \$500,000 are not uncommon, and represent an average of 10% of the operating budget of a ski area. In spite of the costs involved, the ability to provide good, consistent skiing during the early season and throughout a snowless winter can generate substantial financial rewards. As a result, demand for snowmaking capacity is expected to continue to increase for at least the next 5-10 years, and product developments are anticipated that will combine the operating cost advantages of airless and semi-airless snowmaking with the reliability and simplicity of air/water snow nozzles.

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