# CHAPTER 11
# SNOWMAKING

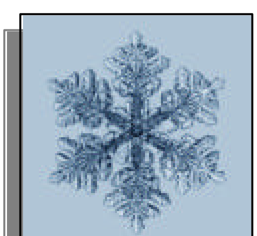
Ski areas rely on the ability to make snow in order to create and maintain quality skiing conditions on slopes during times of inadequate snowfall. In cold ambient conditions, the process of making snow requires three ingredients (sub-freezing conditions, water, and air) and can consume a great deal of water and energy. This chapter discusses various opportunities to improve the efficiency of snowmaking operations. Topics addressed are listed below.



Case studies are used to illustrate how ski areas have implemented the various opportunities described in this chapter. Cost savings and energy and emission reductions associated with the snowmaking case studies ranged from $8,200 to $123,000 and environmental benefits included millions of gallons of water conserved and over 200,000 kWh saved.

## 11.1 SNOWMAKING SYSTEMS

Understanding snow quality is important because, as many vendors and ski area snowmaking staff say: "snowmaking is an art". Snow quality ranges from dry to wet to slushy. Beginner trails are not as steep as advanced trails and often require a different depth and type of snow. Also, the quality of the snow affects the ease of grooming the slopes. For example, to achieve a particular quality, the snowmaker may want a layer of wet snow on the bottom and then a layer of dry, light snow on top.



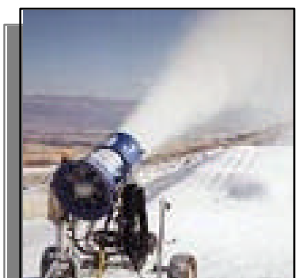
Snowmaking systems simulate nature's process of creating snow. In nature, snow is made by water vapor condensing into small ice crystals at sufficiently low temperatures and humidity. Pure water freezes below 32°F when a few water molecules attach to one another and form what are called embryos or nucleation sites. Surrounding water molecules continue to attach to these nucleation sites and form ice crystals. This process is called homogeneous nucleation. When there are impurities in the water, heterogeneous nucleation occurs. The foreign materials serve as nucleation sites for the water molecules. Heterogeneous nucleation increases the temperature at which ice forms, which is why ice can be formed at temperatures up to 32°F or 0°C. The temperature at which water molecules solidify into ice crystals is called the nucleation temperature. Snowmaking machines replicate this scenario using cool air, water, and sometimes additives (see Section 11.4) that act as nucleators.

There are three types of snowmaking systems: internal mix, external mix, and air/water/fan. Factors to consider when selecting a snowmaking system include weather conditions (wind speed, wind direction, air temperature, and humidity) and the availability of compressed air and an electricity supply.[1] The following paragraphs briefly describe the three snowmaking systems.

An ***internal mix system*** is an air/water system that mixes compressed air and water in an internal chamber in the snow gun nozzle. When this mixture exits the nozzle, it expands and supercools (cools to below 32°F). Tiny water droplets freeze into ice crystals that become nucleation sites that nucleate larger unfrozen droplets, and snowflakes form.

An ***external mix system*** is another type of air/water system. This system shoots compressed air and water out of discrete orifices; the air and water mix outside the snow gun to form snow crystals. The compressed air expands and supercools some of the small droplets from the water orifices to form nucleators. The spray of the external mix system has less speed than that of an internal mix system. Therefore, snow guns using the external mix system must be mounted on towers to give the water droplets enough time to nucleate and form into snowflakes before reaching the ground. A **waterstick system** is a recent version of an external mix system that eliminates use of compressed air or fan. This system uses additives and high-pressure, chilled water to create snow.

***Waterstick system***



***Air/water/fan snow gun***

An ***air/water/fan system (fan system)*** uses air from a fan instead of compressed air to suspend the droplets in air to allow enough time for them to supercool and freeze. A mechanical nucleator, sometimes made up of a small, on-board air compressor attached to a miniature internal mix snow gun, produces the nucleators that mixes with water outside the snow gun.

Snow guns used in internal mix and external mix systems do not require an external source of power at the snowmaking gun location, but utilize compressors and water pumps powered at remote sites. Air/water/fan snow guns do require electrical connections on the slope to power the fan and the nucleating compressor. Internal mix and air/water/fan systems offer the highest range of operating temperatures and the greatest control of snow distribution due to use of compressed air and/or fans. These technologies tend to be best for wider and early opening trails where control of snow coverage is important. External mix systems offer greater energy efficiency but have a limited range of operating temperatures. Another drawback of external mix systems is that snow distribution is affected by prevailing wind conditions. As much as 30 percent extra grooming time may be needed to provided a finished surface when using external mix systems over internal mix or air/water/fan systems. External mix systems tend to be better suited for narrower and later opening trails. When selecting snow guns for a new slope or for upgrading an old snowmaking system, consider not only the capital cost of snow guns but also the cost of supporting structures, such as towers or air compression systems, and the effectiveness and applicability (including snowmaking temperature, type of terrain, width of trail, intended opening date, and noise sensitivity) of the snow gun type on the particular slope it will be used on.

Table 11.1 summarizes the advantages, disadvantages, approximate costs, and efficiency associated with each system.

[1] Colorado State University. "Energy Efficiency Assessment Report for Aspen Skiing Company Snowmaking Operations." Draft. May 2000. Page 10.

**TABLE 11.1 ADVANTAGES AND DISADVANTAGES OF SNOWMAKING SYSTEMS**

| Snowmaking System | Advantage and Disadvantages[2] | Capital Cost (per gun)[a] | Efficiency[b] at 20 °C Wet Bulb Temperature[3] (kW/gpm) |
|---|---|---|---|
| Internal mix | ***Advantages:*** Less affected by wind; allows high wet bulb temperature; light and portable unit; covers wide trails; ability to adjust snow consistency ***Disadvantages:*** Inefficient due to its reliance on compressed air and noise generated by air compressors | $750 to $900 (other cost considerations: compressed air, pumping, and piping systems) | High energy system: 1.2 kW/gpm<br>Low energy system: 0.5 kW/gpm |
| External mix | ***Advantages:*** More energy efficient than internal mix because less compressed air required (lower air to water ratio); waterstick eliminates use of compressed air; quiet and easy to operate ***Disadvantages:*** Highly affected by wind forces; typically requires colder temperatures; either permanently mounted or difficult to move; little adjustment of snow consistency, thus increased losses from snow blowing off trail. | $1,200 to $3,500 (towers can range from $2,500 to $3,500 for purchase and installation) | Low energy system: 0.4 kW/gpm |
| Air/water/fan | ***Advantages:*** Uses minimal compressed air, thus is the most energy efficient per unit volume of water (except for watersticks, which are not widely used); quiet; can adjust snow consistency ***Disadvantages:*** Difficult to adjust position (requires machinery) because equipment is often bulky and large (increased labor requirement) | $15,000 to $40,000 | About 25 kW is required to operate small compressor and fan, at any temperature |

**Notes**:

a Costs are approximate for purchase of units only (do not cover piping; length of piping depends on layout of snowmaking system and mountain area) and were provided by three companies.

b Efficiency is measured in energy expended per unit flow of water, and do not include energy to pump water; efficiency for high energy internal mix based on Ratnik Snow Giant II, efficiency for low energy internal mix based on York V6, and efficiency for low energy external mix based on HKD snow gun.

kW = kilowatt
gpm = gallons per minute

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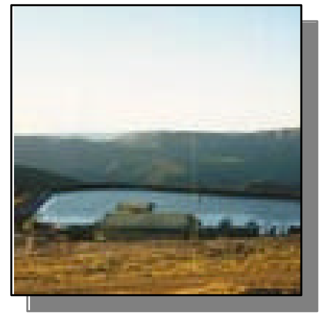
2 Scott Barthold, Snomatic.
3 Jay Collins, York Snow.

## 11.2 RESERVOIRS

Snowmaking requires large amounts of water. It takes about 75,000 gallons of water to create a 6-inch-deep layer of snow over a 200- by 200-foot area. Many ski areas can convert over 2,000 gallons of water into snow in about 1 minute, emptying one truckload of water in 3 minutes.[4] This large demand for water is often a problem for ski areas due to concerns about natural water supplies. Drawing from natural sources during times of low or reduced flow, such as the winter season, can have negative impacts on wildlife. To protect aquatic habitats, ski areas' draw on natural streams and lakes should be minimized by building reservoirs dedicated to snowmaking operations. According to the NSAA Sustainable Slopes 2001 Annual Report, several ski areas have begun or made plans to develop ponds or reservoirs in order to minimize the draw on natural water sources; a partial list of these ski areas include Angel Fire Resort in New Mexico, Loon Mountain in New Hampshire, Stratton Mountain in Vermont, Wachusett Mountain Ski Area in Massachusetts, and Snowmass in Colorado.



***Snow reservoir***

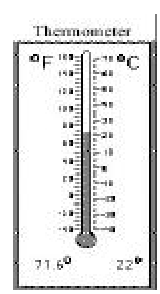
Reservoirs can help
- protect natural water resources
- protect aquatic habitat
- reduce energy consumption

In addition to preserving aquatic habitat, a reservoir can provide operational cost savings. Reservoirs can be located near the elevation of snowmaking systems so that the vertical distance that water needs to be transported to the system is reduced. Although water will still need to be initially pumped from the water source to the reservoir, this pumping process can occur during the utility's non-peak hours when the energy charges (non-coincidental peak electric demand cost) are lower. Snowmaking can then occur at any time with minimal utility peak hour charges (coincidental peak electric demand cost). Reservoirs located above the elevation of snowmaking systems can gravity-feed water and eliminate the energy consumption associated with finally pumping water from the reservoirs to the system.

### CASE STUDY: ASPEN SKIING (ASC) COMPANY USES RESERVOIR

ASC reduces its draw on Snowmass Creek by using a 1.5 million-gallon reservoir at the Snowmass Mountain ski area. The reservoir cost approximately $110,000.[5] ASC also uses a gravity-fed system for the reservoir.[6] ASC estimates that it saves about $14,000 per year from reduced electricity costs alone as a result of this project.

## 11.3 DRY BULB/WET BULB TEMPERATURE




Dry bulb temperature is the ambient (surrounding) air temperature. Humidity is the amount of water vapor in the atmosphere and is an important factor in snowmaking. Increasing the amount of water vapor in the air can inhibit the rate of cooling of water droplets to nucleation temperatures. Water cools by evaporating, releasing energy in the process. The more the air is saturated with water vapor, the slower the cooling process. Thus, efficient snowmaking requires low temperatures and dry air.

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4 SMI Snowmaking web site: http://www.snowmakers.com/smi_facts.html.

5 ASC. "Efficiency Overview for ASC Snowmaking Facility at Snowmass Ski Area." October 1997.

6 Auden Schendler, ASC Director of Environmental Affairs. "ASC Environmental Goals and Accomplishments 2000-2000."

Wet bulb temperature relates dry bulb temperature to humidity. A water droplet passing through a snow gun is typically at a temperature between 34 and 44°F. Once the droplet is in the air, expansive and convective cooling and evaporation work to lower its temperature. Wet bulb temperature is the equilibrium temperature that the droplet will eventually reach.

Wet bulb temperature has been an industry standard for determining when snow should be made because it accounts for ambient temperatures and humidity. However, dry bulb temperature should also be considered when making this determination because the efficiency of producing snow decreases with increasing dry bulb temperatures. Ideally, snow should be created when the dry bulb temperature is less than 32°F.[7]

**CASE STUDY: ASC STUDIES IMPORTANCE OF DRY BULB TEMPERATURE**[8]

> "Snowmakers must consider a longer time frame – in terms of the life-cycle of an ice particle – and base operation decisions on subfreezing ambient air temperatures."
>
> *Hal Hartman, ASC*

ASC conducted a study at Aspen, Buttermilk, and Snowmass Mountains in 1999 to assess the effects of temperature on snowmaking. ASC proposed that a water droplet released from a snow gun experiences subfreezing temperatures for only 3 seconds but melting conditions afterward as an ice particle. Thus, the life-cycle of the ice particle from a water droplet in the air to a melted ice particle on the slopes needs to be considered. Further research concluded that based on cost and efficiency, snow should not be manufactured at dry bulb temperatures greater than 32°F.

For example, during the study, snow was made at Aspen Mountain in November on eight occasions at ambient temperatures greater than 32°F and on seven occasions at ambient temperatures below 32°F. The eight events when ambient temperatures were greater than 32°F accounted for only 17 percent of the total amount of manmade snow produced in that month, and the other seven events accounted for the remaining 83 percent.

In addition to evaluating snowmaking efficiency, ASC developed this equation relating the cost of making snow to dry bulb temperature:

$$C = (\$0.0027845/\text{gal})e^{(0.0322/°\text{F})T}$$

where

C = cost per gallon of water converted to snow, $

T = ambient dry bulb temperature, °F

Details of the derivation of this equation and the assumptions used can be found in the Colorado State University "Energy Efficiency Assessment Report for Aspen Skiing Company Snowmaking Operations" (pages 28 through 37),[9] which can be obtained from the ASC Environmental Affairs Department.

Annual cost savings were predicted based on weather data, hours of snowmaking operations, and the volume of water used to make snow. The weather data consisted of temperatures that ASC proposed were not ideal for snowmaking (that is, when wet bulb temperatures were at or below 30°F and when

7 Colorado State University. "Energy Efficiency Assessment Report for Aspen Skiing Company Snowmaking Operations." Draft. May 2000. Page 10.

8 Hal Hartman. "More on Snowmaking." June 2000.

9 Colorado State University. "Energy Efficiency Assessment Report for Aspen Skiing Company Snowmaking Operations." Draft. May 2000. Pages 28 through 37.

dry bulb temperatures were above 32°F). The weather data were collected at Snowmass Mountain during the snowmaking seasons in 1997, 1998, and 1999 and averaged for typical weather conditions at Aspen, Buttermilk, and Snowmass Mountains. The average hours of snowmaking operations for each ski area were also estimated. The following results were found:

At Aspen Mountain, from November 1 through January 28,

- 202 hours of snowmaking was conducted under non-ideal temperature conditions.
- 10.6 million gallons of water was converted to snow.

At Buttermilk Mountain, from November 1 through December 12.

- 231 hours of snowmaking was conducted under non-ideal temperature conditions.
- 9.4 million gallons of water was converted to snow.

At Snowmass Mountain, from October 16 through December 31,

- 143 hours of snowmaking was conducted under non-ideal temperature conditions.
- 16.2 million gallons of water was converted to snow.

Annual cost savings were calculated using the following equations:

$$CS_i = AV_i \times [(\$0.0027845/\text{gallon})e^{(0.0322/°F)T_i} - (\$0.00600/\text{gallon})]$$

$$\text{where } AV_i = HV \times H_i$$

where

$CS_i$ = annual cost savings, \$/year
$AV_i$ = annual volume of water converted to snow at temperature $T_i$, gallons/year
$T_i$ = ambient dry bulb temperature, °F
$0.00600 /gallon = cost per gallon of water to make snow at 24°F dry bulb temperature
HV = hourly volume of water converted to snow, gallons/hour
$H_i$ = annual number of hours of snowmaking at dry bulb temperature $T_i$, hours/year

Finally, the implementation cost associated with using dry bulb temperatures to make snowmaking decisions was estimated to be roughly $5,000 for each mountain. $5,000 was the cost to train snowmakers about the ideal times to make snow at their ski areas.

Table 11.2 summarizes the cost results of the study.[10]

**TABLE 11.2 COST ANALYSIS FOR DRY BULB TRAINING AT SNOWMASS**

| Mountain | Annual Cost Savings | Implementation Cost | Simple Payback Period (months) |
|---|---|---|---|
| Aspen | $34,700 | $5,000 | 2 |
| Buttermilk | $33,300 | $5,000 | 2 |
| Snowmass | $55,000 | $5,000 | 1 |
| **Total** | **$123,000** | **$15,000** | **1.5** |

[10] Colorado State University. "Energy Efficiency Assessment Report for Aspen Skiing Company Snowmaking Operations." Draft. May 2000. Page 37.

## 11.4 ADDITIVES

In snowmaking, additives are natural substances that act as nucleators to increase the nucleation temperature at which water droplets begin to form ice particles. As described in Section 11.1, this type of nucleation is called heterogeneous nucleation. Much like particles found in clouds, these proteins provide effective nucleation sites for water molecules to attach and grow from. Use of additives also increases the number of nucleators in the water and thus the likelihood that a droplet will contain a nucleator. Having a sufficient number of nucleators, whether they are natural impurities or added proteins, is an important factor in efficient water use. Given a desired snow quality, the goal should be to convert the right amount of water into snow while not wasting any water by having droplets descend unfrozen on the slopes. The decision to use additives depends on the purity of the water and the presence or lack of naturally occurring nucleators. If there is a sufficient number of naturally occurring impurities, additives can be excluded from the snowmaking process.

The effectiveness of heterogeneous nucleators is described by ice nucleating activity (INA) and ice nucleating temperature (INT). INA is the number of ice nucleating sites available (one foe every droplet of water to be frozen is perfect). INT is the temperature at which the nucleator causes the water to change to ice.

## 11.5 WATER COOLING SYSTEMS

Water cooling systems cool the water supplied to snowmaking systems. Reducing the temperature of the water increases the efficiency of the snowmaking process by reducing evaporative losses when the water is released to the atmosphere. If a water droplet is already near freezing, less energy is required to convert that droplet to an ice particle. Water droplets will start freezing earlier in the spray, so they will have a longer time at 32 degrees to freeze (they are at sub-32 degrees before nucleating). Also, warmer water will destroy many small ice crystals formed in the snow gun, thereby decreasing the number of nucleants in the plume. Therefore, the cooler the water, the less water is left unfrozen and more snow is produced. Furthermore, observation has shown that cooler water allows centrifugal compressors to run more efficiently and produce more air.[11] Snowmaking efficiency losses have been estimated by Ratnik Industries and York Snow at 2 to 3 percent for every degree that the water temperature is above 32°F.

***Water cooler***

Water cooling systems have different designs that depend on various elements of the snowmaking system. Spray cooling systems have lower costs than cooling towers, but water reservoirs or ponds are required for spray cooling systems. Cooling towers allow snow to be made earlier in the winter, which can reduce "peak" water demands and improve snowpack conditions. Also, waterstick snowmaking guns require cold water (at or less than 40°F) for maximum efficiency, so greater cooling is required than for other snowmaking gun types.

### CASE STUDY: ASC USES COOLING TOWER[12]

At ASC, the Snowmass Mountain ski area uses a cooling tower to reduce water temperatures from 42 to 34°F. Snow can be made earlier in the winter with the cooling tower, so snowmaking water

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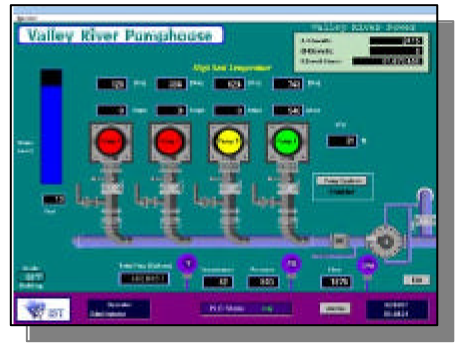
[11] Allen Behbehani, Major Account Manager, Ingersoll-Rand Air Solutions Group.

[12] ASC. "Efficiency Overview for ASC Snowmaking Facility at Snowmass Ski Area." October 1997.

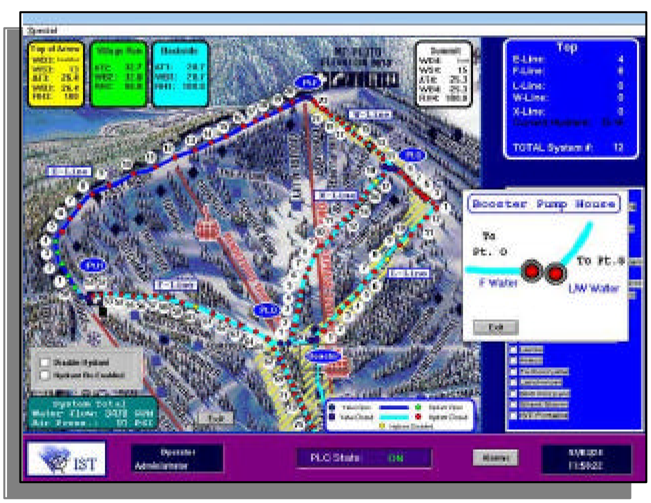
demands are reduced later in the season. As a result, peak water use is reduced because Snowmass Village and the ski area use the same water supply source. ASC estimates negligible cost and energy savings, but continues to use the cooling tower to be able to make snow earlier in the season and thus open the ski area earlier.

## 11.6 SYSTEM CONTROL AUTOMATION

System control automation can increase the efficiency of a snowmaking system. Automated snowmaking systems can precisely adjust to varying weather conditions. Weather information such as ambient air temperature, wet bulb temperature, humidity, and wind speed and direction is collected from as many weather stations on a mountain as needed. The snowmaker can then accurately and more easily modify the snowmaking systems by using computer controls to quickly respond to changing conditions on the slopes. This efficiency decreases overall energy costs related to pumping excess water or compressing excess air, shortcomings that result from lags in response time during manual operations. For internal mix and fan systems, there have been improvements of 30 to 50 percent in efficiency of automatic operations; for external mix systems, the benefit is typically much less since these guns are easy to turn on and off manually and do not require constant adjustment.[13] In addition, weather conditions can change quickly on a mountain, requiring snowmaking operations to move from one area of the mountain to another. Computers facilitate these operations by allowing the snowmaker to focus on snowmaking operations while computers manage equipment operation. Automated systems thus increase efficiency and decrease variability in the snowmaking process.




***System control panel for pumphouse***




***Mountain operation screen for snowmaking***

Computers also monitor system conditions such as water flow rates, water temperature, air flow rates, and air pressure. Computers often control water pressure to accommodate changing water demands during snowmaking operations. Also, automated controls for centrifugal compressor systems can measure the system pressure and control multiple compressors to achieve maximum efficiency by load sharing and by automatically starting and stopping based on system demand.

Starting and shutting down a manual snowmaking system can take from 1 to 4 hours for startup and from 1 to 3 hours for shutdown. Early season snowmaking often is performed in temperature windows as small as 6 to 8 hours. An automated system can start and stop in a 7 to 15 minute period. The automated system is also continually readjusting the snowgun to maintain optimum production and snow quality during the entire period of operation. A manual system must be revisited and readjusted by a snowmaker regularly to adjust for temperature changes and reallocation. According to York Snow, an increase in operating efficiency of up to 60 percent can be achieved.[14]

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13 Scott Barthold, Snomatic.

14 Jay Collins, York Snow.

Safety and reliability of equipment operation are crucial when dealing with high-pressure water and air. A properly installed computer system can manage the overall snowmaking process while monitoring and controlling every machine and device within its operational limits. Real-time alarm reporting and related machine controls are critical elements of an automated snowmaking operation.

Finally, reporting of historical snowmaking operations provided by computer systems can be very useful to management and operational personnel for budgeting and planning purposes. Computer systems are able to generate very accurate reports on all aspects of a snowmaking system, including power usage, water consumption, snow production, and efficiencies.

**CASE STUDY: SNOWMASS MOUNTAIN USES COMPUTER AUTOMATION**[15]

At ASC, the Snowmass Mountain ski area installed a computerized process control system (PCS) to improve the efficiency of its snowmaking system. The primary benefit of the system is its ability to adjust water flow according to ambient air temperature. Depending on the ambient air temperature, water can be lost through evaporation if the water flow rate is too low. ASC estimates that 4.5 to 6.3 million gallons of water is saved each season by using the PCS rather than conventional systems. At an assumed $1.93 per thousand gallons of water, ASC saves from $8,700 to $12,200.

## 11.7 AIR COMPRESSORS

Air compression is a critical component of some snowmaking systems (see Section 11.1). Compressed air, once it is released from a snow gun, works to disperse water into fine droplets that will then freeze and form ice crystals. For internal mix systems, air compression is the main force dispersing the water-air mixture. With these systems, nucleation depends on the length of time the droplets stay in the air and expansive cooling; expansion of the air-water mixture is caused by the pressure release at the nozzle. External mix and air/water/fan systems also rely on these principles to create snow.

***Snow air compressor***

A primary source of energy consumption in snowmaking is air compression. For example, at Buttermilk Mountain, nearly 71 percent of the total amount of energy consumed for snowmaking in November 1999 was expended to compress air.[16] According to the Compressed Air Challenge (CAC) sourcebook "*Improving Compressed Air System Performance*," which was developed for industry by the U.S. Department of Energy Motor Challenge Program at the Lawrence Berkeley National Laboratory, inefficiencies in air compressors can be significant, and system improvements can save as much as 20 to 50 percent in energy consumption.[17]

> Are you planning to install or improve an existing air compressor? Consult "Improving Compressed Air System Performance," a sourcebook for industry (http://www.oit.doe.gov/bestpractices/compressed_air/).

15 ASC. "Efficiency Overview for ASC Snowmaking Facility at Snowmass Ski Area." October 1997.

16 Hal Hartman. "More on Snowmaking." June 2000. Page 13.

17 Lawrence Berkeley National Laboratory for the U.S. Department of Energy Motor Challenge Program. "Improving Compressed Air System Performance." Section 1. April 1998.

Air compression systems used in snowmaking consist of compressors, a distribution network, system controls, and in some cases storage systems and end-use equipment. For a detailed analysis of compressed air systems from machinery and system components to economics and industry standards, consult the CAC sourcebook or visit the Office of Industrial Technologies web site (http://www.oit.doe.gov/bestpractices/compressed_air/) to access the CAC sourcebook on line.

***Centrifugal air compressors***

If an air compression system has not yet been installed at a ski area, the CAC sourcebook or an industrial compressed air systems consultant should be first consulted. The initial expense for analyzing compressed air needs and designing an efficient system can be recovered in future electricity bills because annual energy costs for air compression can almost amount to the cost of the system itself.[18]

For an existing air compression system, if a system analysis reveals inefficiencies that cannot be readily eliminated, the old compression system can be replaced with a newer, more efficient system. The initial capital costs can be quickly recovered through reduced energy consumption, reduced maintenance problems, and increased snowmaking capacity. Older snowmaking systems used single stage rotary screw compressors that typically produced around 4 cubic feet per minute (cfm)/brake horsepower (BHP). Most of these compressors have been replaced with 3 stage centrifugal compressors that produce around 4.8 cfm/BHP.

**CASE STUDY: ASPEN MOUNTAIN REPLACES OLD COMPRESSORS**[19]

In terms of air volume to horsepower ratio, one new 1,100-hp unit = four old 353-hp units

In 1999, Aspen Mountain had six air compressors for its snowmaking operations: one new, 1,100-hp, three-stage, centrifugal unit and five older, 353-hp, rotary screw compressors. Aspen requires about 1,000 hours of air compression per season. The new 1,100-hp unit was the main compressor, and three of the older compressors provided auxiliary support; the remaining two older units had maintenance problems and were rarely used. Aspen Mountain decided to purchase a new air compressor for three reasons. First, two of the rarely used older compressors had defects (a damaged cooler, defective bearings, and overheating) that caused maintenance to be costly and continuous. Second, the older compressors had a dramatically lower air volume to horsepower ratio than the new compressor. Aspen Mountain estimated that it would take about four of the older compressors to produce the same amount of air as one 1,100-hp unit. Third, Aspen Mountain wanted an increase in system capacity.

Electricity and cost savings associated with implementing the new, 1,100-hp air compressor were estimated using the following equations.

Energy Savings (ES) = HP x $C_1$ x H
Energy Cost Savings = ES x (*Avoided Cost of Electricity*)
Noncoincidental Peak Electric Demand Savings (NCDS) = HP x $C_1$ x $NM_{NC}$
Noncoincidental Peak Demand (NCD) Cost Savings = NCDS x (*Avoided Cost of Noncoincident Demand*)
Coincident Peak Electric Demand Savings (CDS) = HP x $C_1$ x $NM_C$
Coincident Peak Demand (CD) Cost Savings = CDS x (*Avoided Cost of Coincident Demand*)

18 Lawrence Berkeley National Laboratory for the U.S. Department of Energy Motor Challenge Program. "Improving Compressed Air System Performance." Section 2. Fact Sheet #9, F9-1. April 1998.

19 Colorado State University. "Energy Efficiency Assessment Report for Aspen Skiing Company Snowmaking Operations." Draft. May 2001. Pages 38 through 40.

where

$HP$ = 312 hp [reduction in power needed by new, 1,100-hp unit to generate same air volume rate, cubic foot per minute (cfm) as four older units]

$C_1$ = Conversion constant, 0.746 kilowatt (kW)/hp

$H$ = 1,000 hours (annual snowmaking hours)

*Avoided Cost of Electricity* = $0.01800/kilowatt-hour (kWh) (for Aspen Mountain)

$NM_{NC}$ = 2 (annual number of months of noncoincident demand savings accrued: November and December at Aspen Mountain)

*Avoided Cost of Noncoincident Demand* = $5.75/kW (for Aspen Mountain)

$NM_C$ = 1 (annual number of months of coincident demand savings accrued: November at Aspen Mountain)

*Avoided Cost of Coincident Demand* = $10.63/kW (for Aspen Mountain)

In addition, Aspen Mountain estimates its cost savings for compressor maintenance to be $5,000 annually and the implementation cost for the new, 1,100-hp compressor to be about $150,000 (including the costs of the compressor unit, cooling unit, air-cooled aftercooler, and installation). These estimates are rough because of unpredictable maintenance events for the older compressors and the varying costs of compressors. Table 11.3 summarizes the individual and total electricity and cost savings.

**TABLE 11.3 ANNUAL ELECTRICITY AND COST SAVINGS AT ASPEN MOUNTAIN FROM COMPRESSOR UPGRADE**

| Item | Annual Savings | Annual Cost Savings |
|---|---|---|
| Electricity savings | 232,800 kWh | $4,190 |
| Noncoincident peak electric demand savings | 466 kW | $2,680 |
| Coincident peak electric demand savings | 233 kW | $2,480 |
| Maintenance savings | -- | $5,000 |
| **Total Annual Cost Savings** | | **$14,350** |
| Implementation cost | | $150,000 |
| Simple payback period | | 10.5 years |

## 11.8 AIR LEAK INSPECTIONS

Leaks in any system can be very wasteful of raw materials and energy. Air leaks in air compression systems are especially wasteful of energy because these systems require a good deal of energy to operate. Different air compression systems have different ratings for energy efficiency. Consult the CAC sourcebook for guidance in finding energy efficiency ratings for various air compression systems. A compression system with a leak can waste 20 to 30 percent of the compressor output.[20]

[20] Lawrence Berkeley National Laboratory for the U.S. Department of Energy Motor Challenge Program. "Improving Compressed Air System Performance." Section 2. Fact Sheet #7. April 1998.

Regular inspections should be performed to identify any air leaks in a compression system. Various methods exist to identify leaks, including use of ultrasonic acoustic detectors and pressure gauges at several points in the air distribution system.

Repairing air leaks can be difficult if distribution pipes are buried underground. However, the potential savings in energy consumption can quickly offset the costs of repairs and pipe replacements. The case study presented below provides an example of repairs made for aboveground and underground pipes and the annual cost savings achieved.

## CASE STUDY: COMPRESSED AIR LEAKS[21]

Aspen Mountain was able to quantify the leaks in its compressed air system and estimate the energy and cost savings associated with detecting and repairing the leaks. The compressed air system at Aspen Mountain runs on six compressors operating for about 1,000 hours annually. One compressor is a new, 1,100-hp, three-stage, centrifugal unit, and the remaining five compressors are older, 353-hp, rotary screw compressors. According to Aspen Mountain personnel, the new compressor can bring the system to pressure in about half an hour. When the compressor shuts off, the system returns to zero pressure within 2 hours.

**TABLE 11.4 ASPEN MOUNTAIN COMPRESSED AIR SYSTEM SPECIFICATIONS**

| Variable | Value |
|---|---|
| Air temperature at compressor inlet | 70°F |
| Atmospheric pressure | 10.5 psia |
| System operating pressure | 110 psig |
| Air temperature at the leak | 20°F |
| Line pressure at the leak | 110 psig |
| Compressor motor size | 1,100-hp |
| Compressor motor efficiency | 96.6% |
| Compressor type | Multistage centrifugal |
| Number of stages | 3 |
| Compressor operating hours | 1,000 hours per year |

**Notes:**

psia = Atmospheric pressure in pounds per square inch
psig = Gage pressure in pounds per square inch; positive gage pressure includes atmospheric pressure

Only the new, 1,100-hp compressor was considered in estimating power loss because it is the primary compressor. All compressors feed into the same system.

### How was air loss estimated?

The amount of air lost from a leak in a compressed air system depends on several factors: the line pressure, the compressed air temperature at the point of the leak, the air temperature at the compressor inlet, and the estimated area of the leak. The leak area is usually estimated as a diameter in inches as shown below.

| Hole Size | Hole Diameter (inches) |
|---|---|
| Very small hole | $^{1}/_{64}$ |
| Small hole | $^{1}/_{32}$ |
| Medium-sized hole | $^{1}/_{16}$ |
| Large hole | $^{1}/_{8}$ |
| Enormous hole | ¼ |

21 Colorado State University. "Energy Efficiency Assessment Report for Aspen Skiing Company Snowmaking Operations." Draft. May 2001. Pages 58 through 64.

Aspen Mountain developed a relationship between leak diameter and potential annual cost savings achieved through energy savings. First, the volumetric flow rate of the escaping air and the power loss associated with the leaks were estimated. The annual energy savings and annual energy cost savings associated with repairing the leaks were then calculated based on these estimates. The following equations were used in the calculations:

**Volumetric Flow Rate of Escaping Air ($V_f$)**

$$V_f = \frac{NL \times (T_i + 460) \times (P_l/P_i) \times C_l \times C_2 \times C_d \times (pD^2)/4}{C_3 \times v(T_l + 460)}$$

where

$V_f$ = volumetric flow rate of escaping air, cubic feet per minute
NL = number of air leaks
$T_i$ = temperature of air at compressor inlet, °F
$P_l$ = line pressure at leak, psia
$P_i$ = inlet (atmospheric) pressure, psia
$C_l$ = 28.37 feet per second-°$R^{0.5}$ (isentropic sonic volumetric flow constant)
$C_2$ = 60 seconds per minute (conversion constant)
$C_d$ = 0.8 (coefficient of discharge for square-edged orifice)[22]
p = 3.1416 (Pythagorean constant)
D = leak diameter, inches
$C_3$ = 144 square inches per square foot (conversion constant)
$T_l$ = average line temperature, °F

**Power Loss Associated with Leaks (L)[23]**

$$L = \frac{P_i \times C_3 \times V_f \times [k/(k-1)] \times N \times C_4 \times [(P_o/P_i)^{(k-1)/(k \times N)} - 1]}{E_a \times E_m}$$

where

L = power loss associated with air leak, hp
k = 1.4 (specific heat ratio of air)
N = number of stages
$C_4$ = 3.03 x $10^{-5}$ hp-minute per foot-pound (conversion constant)
$P_o$ = compressor operating pressure, psia
$E_a$ = air compressor isentropic (adiabatic) efficiency
$E_a$ = 0.88 for single-stage, reciprocating compressor
$E_a$ = 0.75 for multi-stage, reciprocating compressor
$E_a$ = 0.82 for rotary screw compressor[24]
$E_m$ = compressor motor efficiency

Based on these equations and Aspen Mountain's compressed air system specifications, Table 11.5 shows the energy losses associated with a range of leak diameters and the cost savings associated with leak repair. Figure 11.1 graphically displays the annual cost of the energy lost because of each air leak.

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22 A.H. Shapiro. *The Dynamics and Thermodynamics of Compressible Fluid Flow*. Volume I. Ronald Press. New York. 1953. Page 100.

23 Compressed Air and Gas Institute. *Compressed Air and Gas Handbook*. 5th Edition. Chapters 10 and 11. New Jersey. 1989.

24 Anthony Barber. *Pneumatic Handbook*, 7th Edition. Table 1. Trade and Technical Press. 1989. Page 49.

**TABLE 11.5 DATA ON COMPRESSED AIR LEAKS AT ASPEN MOUNTAIN**

| Leak Diameter (inch) | Flow Rate (cfm) | Power Loss (hp) | NCDS (kW/year) | NCDCS (per year) | Energy Lost (kWh/year) | Energy Cost Savings with Repairs (per year) | Total Cost Savings (per year) |
|---|---|---|---|---|---|---|---|
| 1/64 | 0.5 | 0.1 | 0.1 | $ 1 | 75 | $ 1 | $ 2 |
| 1/32 | 2.0 | 0.4 | 0.6 | $ 3 | 298 | $ 5 | $ 8 |
| 3/64 | 4.5 | 0.8 | 1.2 | $ 7 | 597 | $ 11 | $ 18 |
| 1/16 | 8.1 | 1.5 | 2.2 | $ 13 | 1,119 | $ 20 | $ 33 |
| 3/32 | 18.1 | 3.4 | 5.1 | $ 29 | 2,536 | $ 46 | $ 75 |
| 1/8 | 32.2 | 6.0 | 9.0 | $ 52 | 4,476 | $ 81 | $133 |
| 3/16 | 72.5 | 13.5 | 20.1 | $116 | 10,071 | $181 | $297 |
| 1/4 | 128.9 | 24.0 | 35.8 | $206 | 17,904 | $322 | $528 |

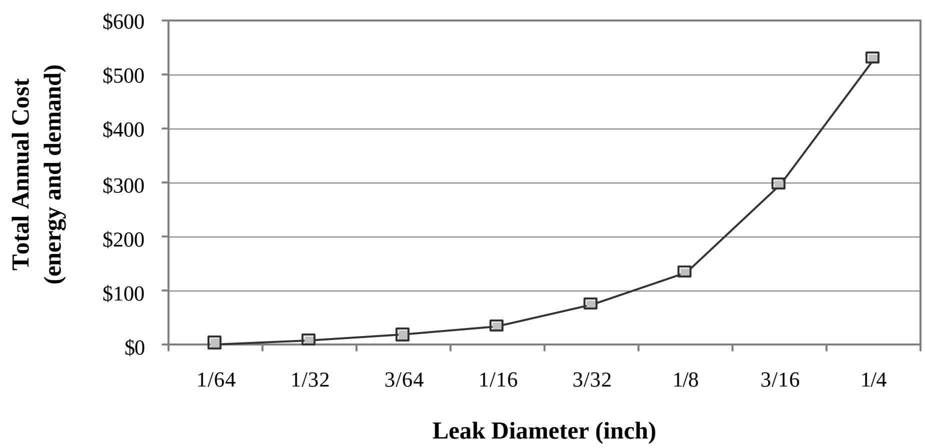
**Notes:**

cfm = cubic feet per minute
NCDS = noncoincident demand savings
NCDCS = noncoincident demand cost savings

The NCDS values reflect the savings associated with 2 months of electric demand.

Because of the restrictive nature of the compressed air system and the fact that the system was not in operation during the site visit by Industrial Assessment Center (IAC of Colorado State University) staff, the actual number and sizes of the leaks were difficult to quantify. Thus, based on the time required to pressurize the system and the time required for the leaks to bleed the system empty, a conservative estimate of 275 hp was made for the power loss associated with the air leaks.

**Figure 11.1 Annual Cost of Energy Lost Associated with Compressed Air Leaks by Hole Size at Aspen Mountain**



Energy and cost savings were calculated as follows.

**Annual Energy Savings (ES)**

*ES = HP x $C_1$ x H = (275) x (0.746 kW/hp) x (1,000 hours/year) =* ***205,200 kWh/year***

where

HP = 275 hp (power loss associated with air leaks; estimated using equations presented above)

$C_1$ = 0.746 kW/hp (conversion constant)

H = 1,000 hours per year (annual hours of compressor operation)

**Energy Cost Savings (ECS)**

*ECS = ES x (Avoided Cost of Electricity) = (205,200 kWh/year) x ($0.01800/kWh) =* ***$3,690/year***

where

ES = 205,200 kWh/year (annual energy savings)

Avoided Cost of Electricity = $0.01800 per kWh at Aspen Mountain Snow Central control center

**Annual Noncoincident Peak Electric Demand Savings (NCDS)**

*NCDS = HP x $C_1$ x $NM_{NC}$ = (275) x (0.746 kW/hp) x (2) =* ***410 kW/year***

where

HP = 275 hp (power loss associated with air leaks; estimated using equations presented above)

$C_1$ = 0.746 kW/hp (conversion constant)

$NM_{NC}$ = 2 (annual number of months during which noncoincident demand savings would accrue)

**Annual Noncoincident Peak Electric Demand Cost Savings (NCDCS)**

*NCDCS = NCDS x (Avoided Cost of Noncoincident Demand) = (410 kW/year)x($5.75/kW) =* ***$2,360/year***

where

NCDS = 410 kW/year (annual NCDS)

Avoided Cost of Noncoincident Demand = $5.75 per kW at Aspen Mountain Snow Central control center

**Annual Coincident Peak Electric Demand Savings (CDS)**

*CDS = HP x $C_1$ x $NM_C$ = (275) x (0.746 kW/hp) x (1) =* ***205 kW/year***

where

HP = 275 hp (power loss associated with air leaks; estimated using equations presented above)

$C_1$ = 0.746 kW/hp (conversion constant)

$NM_C$ = 1 (annual number of months during which coincident demand savings would accrue)

**Annual Coincident Peak Electric Demand Cost Savings (CDCS)**

*CDCS = CDS x (Avoided Cost of Coincident Demand) = (205 kW/year) x ($10.63/kW) =* ***$2,180/year***

where

CDS = 205 kW/year (annual CDS)

Avoided Cost of Coincident Demand = $10.63 per kW at Aspen Mountain Snow Central control center

**Implementation costs for leak detection and repair**

The following practices are recommended to maintain the integrity of the compressed air pipelines:

- Shut all unused valves to prevent loss of air
- Repair all aboveground leaks at the hydrants
- Repair leaks in snowmaking equipment, including valves and fittings
- Target and replace corroded underground pipelines

Assumptions
Pipe installation = $50/foot, including costs of
- Materials
- Trenching
- Labor

Length of new pipe = 500 feet (estimated length that would eliminate most air leaks associated with damaged pipe)

Aspen Mountain already had much of the software and monitoring equipment needed to detect and isolate water leaks. It was assumed that detection of air leaks could be done similarly at minimal cost.

The implementation cost for air leak detection and repair therefore included only the cost of replacing damaged pipes. An estimate of 500 feet was made for the length of pipe that needed to be replaced. Based on a unit cost of $50 per foot for pipe replacement, the total implementation cost was $25,000.

Table 11.6 summarizes the estimated annual savings realized by repairing the air leaks.

**TABLE 11.6 ESTIMATED ANNUAL SAVINGS**

| Item | Estimated Annual Savings |
|---|---|
| Electricity savings | 205,200 kWh |
| Noncoincident peak demand savings | 410 kW |
| Coincident peak demand savings | 205 kW |
| | |
| Electricity cost savings | $3,690 |
| Noncoincident peak demand cost savings | $2,360 |
| Coincident Peak Demand Cost Savings | $2,180 |
| **Total Annual Cost Savings** | **$8,230** |
| Implementation cost | $25,000 |
| Simple payback period | 3.0 years |

## 11.9 WATER LEAK INSPECTIONS

Water leaks can be caused by corroded underground pipes, faulty piping, or faulty pipe installation. Leaks in the water distribution lines that feed snowmaking systems can have several negative impacts on the overall snowmaking operation. In addition to the wasted water, energy is also wasted when water is pumped through a leaking pipeline to the snowmaking system. In some cases, leaking water can also come into contact with and melt snow on the slopes; this is especially wasteful if the snow has been manmade. Quantifying the amount of energy wasted and the volume of manmade snow melted by a water leak is difficult and depends on the severity of the leak, the pumping system in use, and the topography of the affected slopes.

## CASE STUDY: REPAIRING A SNOWMAKING SYSTEM WATER LEAK[25]

During a closed-loop test of the water distribution system at Aspen Mountain, a large leak was discovered between the primary and booster pumphouses. The system was losing about 100 gallons of water per minute. Aspen Mountain operates its snowmaking system about 1,100 hours annually.

Aspen Mountain estimated its annual water and energy usage for the water distribution system and the savings associated with water leak repair. Aspen Mountain roughly estimated the energy losses associated with the leak. Water savings, water cost savings, and energy cost savings are calculated as shown below.

**Water Savings (WS)**
*WS = H x* $C_1$ *x Q = (1,100 hours/year) x (60 minutes/hour) x (100 gpm) =* ***6,600,000 gallons/year***

where

H = 1,100 hours/year (annual hours that water is being pumped through system)
$C_1$ = 60 minutes/hour (conversion constant)
Q = 100 gpm (volumetric flow rate of water lost)

**Water Cost Savings (WCS)**
*WCS = WS x WC = (6,600,000 gallons/year) x (\$1,93/1,000 gallons) =* ***\$12,740/year***

where

WC = \$1.93/1,000 gallons (cost of water at Aspen Mountain)

**Energy Cost Savings (ECS)**
*ECS = ES x (Avoided Cost of Electricity) = (44,300 kWh/year) x (\$0.01854/kWh) =* ***\$820/year***

where

ES = 44,300 kWh/year (annual energy savings; for further details, see the Colorado State University "Energy Efficiency Assessment Report for Aspen Skiing Company Snowmaking Operations")
Avoided Cost of Electricity = \$0.01854/kWh (at Aspen Mountain)

Aspen Mountain estimates the total implementation cost for water leak repair to be about \$12,000. This cost includes the costs of materials, excavation, and revegetation. It is conservatively estimated that 200 feet of pipe will have to be replaced. Table 11.7 summarizes the annual savings that will be realized by repairing the leak.

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[25] Colorado State University. "Energy Efficiency Assessment Report for Aspen Skiing Company Snowmaking Operations." Draft. May 2000. Pages 41 through 43.

## TABLE 11.7 ANNUAL SAVINGS

| Item | Annual Savings |
|---|---|
| Estimated water savings | 6,600,000 gal |
| | |
| Estimated water cost savings | $12,740 |
| Estimated electricity cost savings | $820 |
| **Total Annual Cost Savings** | **$13,560** |
| Implementation Cost | $12,000 |
| Simple Payback Period | 0.9 year |

**Assumptions:**

Pipe installation = $60/foot, including costs of materials, excavation, and revegetation
Length of new pipe = 200 feet (conservative estimate)