Calibration of Snowmaking Equipment for Efficient Use on Virginia's Smart Road

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(ABSTRACT)

Virginia's Smart Road, to be completed by early 2000, is a test bed for numerous research activities including snow and ice control, remote sensor testing, snow removal management, safety and human factors, and vehicle dynamics. An all-weather testing system will feature 75 automated snowmaking towers. In order to provide timely and repeatable weather scenarios, equipment operators will need to understand fully the limitations and capabilities of the snowmaking system.

The research presented herein addresses the hydraulic and hydrologic variables and design methodology to implement efficient snowmaking at a transportation research facility. Design variables include nozzle configuration, water pressure and flowrate, compressed air pressure and flowrate, tower orientation, snow inducer concentration, water and compressed air temperature, and ambient weather conditions. Testing and data collection was performed at the Snow Economics, Inc. research and development site at Seven Springs Mountain Resort in Champion, PA. The results of this work will be used to guide the operators of the Smart Road on the most efficient use of the snowmaking equipment.

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Chapter 1 - Introduction

1.1 All-Weather Testing at a Transportation Research Facility

Virginia Tech, VDOT, and FHWA are currently constructing an instrumented highway that will serve as a test bed for transportation and structures research (Figure 1.1). The Smart Road provides researchers in the transportation industry with a test track that is very different from other testing facilities in the United States. This facility allows for testing under realistic conditions on an actual roadway.

Researchers will be able to control the weather and roadway lighting to a high degree, and observe traffic moving at highway speeds. The all weather testing system will feature 75 automated HKD Spectrum snowmaking towers, manufactured by Snow Economics, Inc. This system is designed to provide a reliable and controlled research environment for the transportation industry.

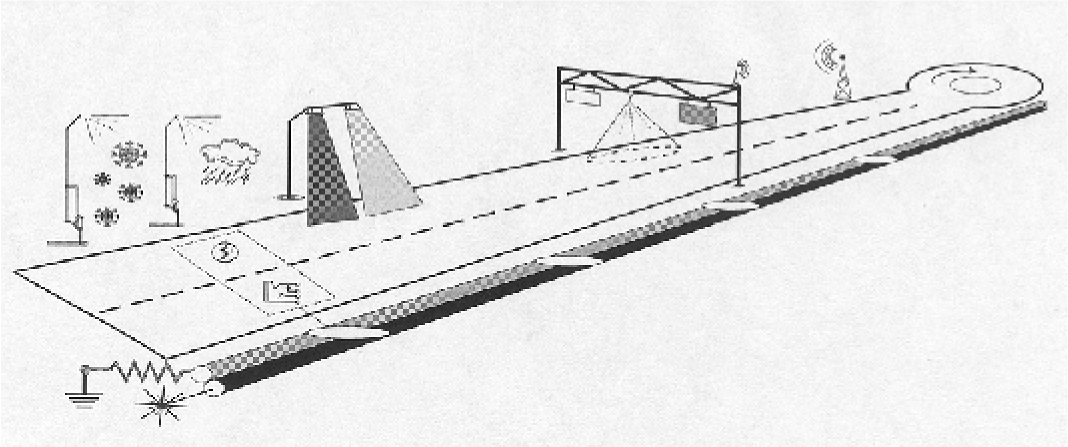

Figure 1.1 Concept Drawing of the Smart Road (Amanna, 1998)

The all-weather testing system is an integral part of this research facility. The system will operate under three weather-generating modes: snow, rain, and fog. During colder periods, the HKD towers will simulate snowfall rates ranging from a mild flurry to blizzard conditions of 4 in/hr (10 cm/hr). The system will be used to create icy road surfaces by spraying water on the roadway in cold conditions. During warmer periods, the towers will produce rainfalls of up to 2 in/hr (5 cm/hr). Smaller nozzles can be attached to the towers to reduce the size of the water droplets for the production of fog.

Numerous research activities will employ the all-weather capabilities of the Smart Road. These activities will include snow and ice control, remote sensor testing, snow removal management, safety and human factors, and vehicle dynamics.

1.2 Snowmaking Research

The Smart Road will be managed and operated by the Center for Transportation Research at Virginia Tech. A major goal of the CTR will be to provide Smart Road research clientele with a reliable and controlled research environment. In order to provide timely and repeatable weather scenarios, equipment operators will need to understand fully the limitations and capabilities of the snowmaking towers. Currently there is a lack of publicly documented knowledge on the operation of snowmaking equipment. Most technical information is proprietary in nature. The results of this study have been compiled and presented to address some of the specific issues which snowmaking operators on the Smart Road will face.

Experimental testing and data collection took place at the Snow Economics, Inc. research and development site at Seven Springs Mountain Resort in Champion, PA (Figure 1.2). Testing revealed knowledge about system performance with respect to the following parameters:

1. Nozzle Configuration
Water Pressure and Flowrate
Compressed Air Pressure and Flowrate
Tower Orientation
Snow Inducer Concentration
Water and Compressed Air Temperature
Ambient Conditions

Results and conclusions were compiled in a report to the Center for Transportation Research at Virginia Tech in Blacksburg, VA. The conclusions of this research provide a design methodology to implement efficient snowmaking at a transportation research facility.

Figure 1.2 Snow Economics, Inc Research and Development Site

1.3 The Nature of Snow and the Art of Snowmaking

Snow is a truly unique and complex product of nature. Born from water vapor that sublimates into tiny ice crystals in the upper atmosphere, the flakes grow as they descend to the earth. Depending on the temperature and the duration of descent, the snow may reach the ground in a wet or dry state, and may be light or dense. Snowflakes that form in a relatively cold environment (less than 0°F) tend to be denser, being formed by smaller ice crystals that pack more closely together as they accumulate. Snowflakes that form in warmer environments (around 15°F) are lighter and fluffier, as they are made of larger ice crystals. The air temperature near the ground determines how wet the snow will be. At temperatures near freezing, flakes may melt upon impact with liquid precipitation or the ground.

Snowmakers attempt to recreate nature's doing with a fraction of the available atmosphere and a lot of mechanical energy. From a production standpoint, this task is relatively easy. One snowmaking machine may cover half an acre with a foot of snow in just a few hours. However, from a quality standpoint, no present technology can match the work of nature. While man frequently produces snow having a liquid water content of between 40 and 50 percent, nature's snow accumulates at between 1 and 10 percent.

The process by which snow is created artificially most often involves a high pressure combination of cold water and compressed air (some machines use only water) within a sub-freezing ambient environment. The pressurized water is atomized through a plurality of nozzles. Atomization reduces particle size to increase the ratio of surface area to volume. This action promotes heat transfer, which lowers the temperature of the water to near the ambient air temperature. The addition of compressed air, expanding at a high velocity outside of the air nozzles (some machines release air and water from the same nozzle), atomizes the water further to provide even more rapid cooling. While the water temperature may cool to below it's freezing point, the molecules may exist in a supercooled liquid state until they are introduced to a seed particle that will aid in crystallization. Snowmakers add snow inducing products, made from bacterial proteins, that provide each water droplet with a seed particle or ice nucleation site. The addition of compressed air to the mixture also aids in particle nucleation. Water vapor contained in the compressed air freezes upon expansion from the nozzle, providing additional seed particles around which the larger atomized droplets crystallize.

When the water and air mixture is ejected through a tower at heights of 20 feet or more, the crystals have time to grow before landing on the ground. A long decent aids in the development the man-made "snowflake," just as in nature. The finished product varies greatly according to ambient conditions and the proportion of ingredients used.

This paper will dissect the process described above and examine the relationships that exist between nature and modern snowmaking technology. This paper presents the problem of a new and unique snowmaking application that is dependent on the simulation of a natural snowfall environment.

Chapter 2 - Problem Statement

2.1 Goal of Research

The goal of this work is to produce a design methodology to implement efficient snowmaking at a transportation research facility. This methodology will be presented in the form of a matrix. Optimal operational parameter settings will be matched with a variety of ambient weather scenarios to yield the desired snowmaking demands of the research facility. This will be accomplished through both experimental testing and theoretical analysis. Experimental testing will involve a series of snowmaking tests performed under various operational and ambient conditions, careful observation of the snow produced during these tests, and conclusions describing the influence of parameter settings on the characteristics of manufactured snow. Theoretical work will include a thermodynamic modeling and analysis of the water and compressed air systems, as well as the construction of a method to predict the resultant overlapping snow accumulation from adjacently operating snowmaking towers.

2.2 Snowmaking Demands

Smart Road clients utilizing the snowmaking capabilities will run experiments under various ranges of snowfall intensity. Three or four such ranges are desirable, and should include a blizzard intensity of around 4 in/hr (10 cm/hr), as well as a mild flurry intensity of around ¼ in/hr (1 cm/hr). The manufactured snowfalls should recreate, as accurately as possible, those of nature. Snow production on the road should be of similar quality to natural snow, and be relatively homogeneous with respect to quality and accumulation. Snowfalls should simulate falling and blowing snow as usually seen in driving conditions (Dingus, 1998).

2.3 System Constraints

There will be 75 HKD Spectrum snowmaking towers, spaced every 33 ft (10.0 m) along the ½ mile weather simulation section of the road. Each tower is 36 ft long, has 90° of freedom in the vertical plane, and 360° of freedom in the horizontal plane. The tower is made of aluminum to promote cooling of the water travelling through the tower to the nozzles, as well as to prevent freezing of the compressed air (details of this design feature will be discussed in 5.2.1).

The HKD Spectrum air/water snowmaking tower (Figure 2.1) is designed for operation in marginal climates, where relatively high winter temperatures make snow production a challenge. The tower has one water inflow connection and one compressed air inflow connection. For each of four water nozzles on the tower head, there exists an air nozzle positioned to promote freezing of the water stream (Figure 2.2). For additional

Figure 2.1 HKD Spectrum Snowmaking Tower

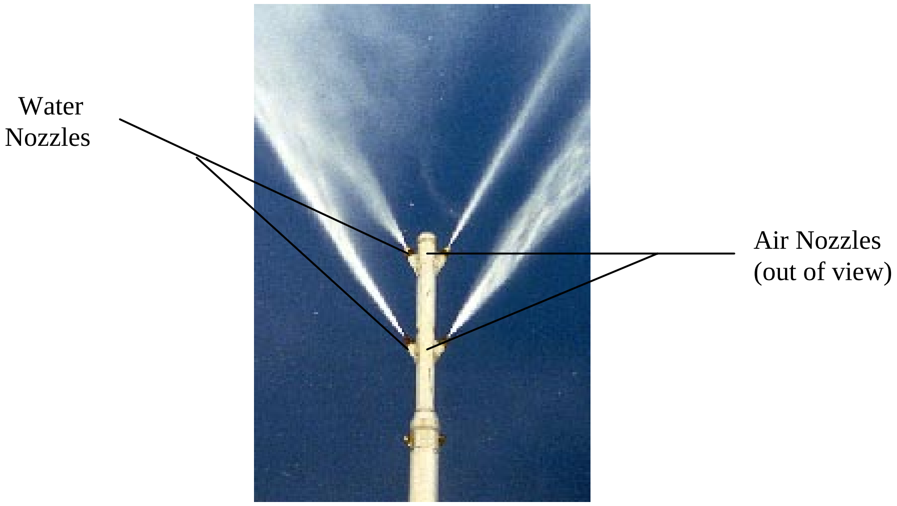

Figure 2.2 Operation of Water and Air Nozzles on the Tower Head

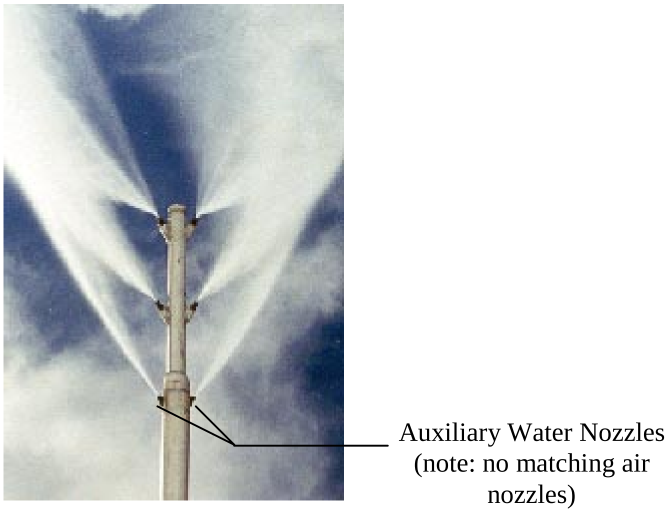

Figure 2.3 Operation of Auxiiary Water Nozzles

water flow during use in colder temperatures, two auxiliary nozzles may be activated (Figure 2.3). The selection of water nozzles available for use ranges (by model number) from 5010 to 5060. Under the available range of water pressures, these nozzles are capable of producing droplet sizes between 300 and 700 microns.

Each tower connects to the automated hydrant system via two quick-connect nylon wrapped, high pressure hoses (one water and one air). Towers may be activated or deactivated from the Smart Road control room by a single operator. The hydrants respond to signals sent out through the Programmable Logic Control (PLC). When queried, hydrants may react by opening valves or by sending information regarding operating status. Hydrants may be queried in groups or individually.

A system water pressure of 200 to 400 psi (1400 to 2800 kPa) will be maintained by three 400 hp (300 kW) vertical turbine wet well type water pumps. Two of these pumps are static, and the third has variable drive. The maximum combined output of the water pumps is 3000 gpm. The supply of water will be delivered from Montgomery County and contained in a 500,000 gallon steel storage tank. Water in the tank will be circulated and cooled by aeration through a nozzle apparatus mounted atop the tank.

Two 700 hp (525 kW) centrifugal type three-stage air compressors will maintain the system air pressure between 80 and 125 psi (550 and 860 kPa). The maximum combined output of the air compressors is 6400 cfm. Supplemental compressed air capabilities will be achieved through the use of a rental compressor. Two 10 hp aftercoolers will cool the outflowing compressed air to a user-selected temperature as low as 37°F (further discussion of the aftercoolers is provided in 5.2).

Chapter 3 - Literature Review

3.1 History of Snowmaking

In 1949, Walter Schoenknecht, the owner of Mohawk Mountain ski area in Connecticut, applied 700 tons of crushed ice to his slopes in order to save a snow-less Christmas holiday. Later that winter, friends of Schoenknecht who operated an irrigation technologies company called Tey Manufacturing, developed an external mix, air/water spray gun for use at Mohawk Mountain. Schoenknecht was then able to produce up to 15 inches of snow overnight (Collins, 1989).

The snowmaking process has evolved tremendously since the first patent. Many different snowmaking devices have appeared on the market, each one striving to improve snowmaking quality and production, while minimizing the costs of operation and maintenance. In 1985, nearly 80% of ski terrain in the Eastern and Mid-Western U.S. had snowmaking capabilities (Barthold, 1986). Many ski areas are willing to spend over $2 million annually on snowmaking operations, allowing them to open early for Thanksgiving skiers and remain open until late spring (Flynn, 1996). Today, the snowmaking market includes a variety of internal mix and external mix air/water snowguns, airless, fan, and tower snowguns.

3.2 Applications of Snowmaking

In addition to use at ski resorts, snowmaking has been applied successfully to secondary effluent treatment, agricultural irrigation, fertilizers, and arctic construction. In the early 1950's, the U.S. military began research on ice production techniques for the construction of bridges, roads, and aircraft runways in Arctic environments. Traditional methods involved the flooding of seawater onto an area to be frozen in cold temperatures. Freeze spraying systems, similar to that used in snowmaking, were found to improve cooling rates and reduce construction time. Snomax Technologies of Rochester, NY investigated the advantages of using bacterial nucleator additives. These additives lowered the freezing temperature of water, making it possible to produce ice in the highest of sub-freezing temperatures (Collins, 1989).

In 1965, the U.S. Department of Health, Education, and Welfare explored the concept of freezing as a means to isolate contaminants from wastewater. Refrigeration and mechanical methods proved effective, but costly (Gibson, 1996).

In 1973, Wright-McLaughlin Engineers of Denver, CO studied the effectiveness of snowmaking and subsequent land application of secondary wastewater effluent. Results showed that specific pollutants in the meltwater of the manufactured snowpack were reduced to levels acceptable for discharge into natural streams (Wright, 1976).

In 1988, a group led by B. Rabinowitz of Vancouver, B.C. conducted similar studies on snow produced from waste effluent. In addition to confirming the substantial reduction of contaminant concentrations from the freeze/thaw process in the snowpack, this study described the buffering effect of the underlying soil column. Contaminants released from the meltwater provided a nutrient rich layer of soil beneath the snowpack, beneficial to crop production (Rabinowitz, 1989).

Throughout the 1990's, Delta Engineering of Ottawa, Ontario, has been perfecting a two-phase wastewater treatment process that utilizes a unique snowgun technology and the freeze/thaw process. Delta constructed its first large scale treatment facility at Sugarloaf Resort in Maine during the winter of 1994. Conventional wastewater treatment removes solids, and snowguns convert the remaining effluent to snow that is deposited over a 30 acre field (Gibson, 1996).

Currently, the only snowmaking applications that compare to any of those being used on the Smart Road, are conducted at Eglin Air Force Base in Valparaiso, FL. The U.S. Air Force conducts climatic research at Eglin's McKinley Climatic Laboratory within several environment-controlled chambers. The main chamber measures 252 ft ×

260 ft (76.8 m × 79.2 m), and has a 1000 cf/hr (30 m^3/hr) snowmaking capability. Most research pertains to military and commercial aircraft. McKinley's only private sector client is Goodyear, who conducts snow and ice testing in the main chamber on their prototype tires. Testing involves driving the test vehicles around the chamber on a snow or ice track to evaluate vehicle dynamics (Eglin, 1998).

3.3 Testing Methodologies

Throughout the short history of snowmaking, various testing methods have been used to evaluate the performance of snow production. Early measures of snowgun performance include air/water ratio, cost per acre-foot, water flow at a given temperature, and the size of manufactured snow piles. For each of these comparisons, it is important to also measure the quality of snow being produced under the given conditions. Measures of snow quality are quite subjective. A commonly applied method is the sleeve test, where the snowmaker, standing amidst the spray of the snowgun, observes the snow sticking to his coat sleeve for frozen material. Other methods include the snowball test and kick test. Snow Economics, Inc. has developed the following scale to describe quality:

(1) Powder, not capable of making a snowball.
(2) Snow can be compressed into a loose snowball.
(3) Snow can easily be made into a snowball, however no free water can be squeezed from the sample.
(4) Snow is somewhat translucent, free water can be squeezed from the sample.
(5) Very little frozen material.

Snow density is a quantitative measure of snow quality, and at one time was favored as the most accurate account of snow quality (Collins, 1989). Today, the liquid water content of snow is considered as the definitive test of snow quality (York Snow, 1998).

York Snow, Inc, distributor of Snomax™ Snow Inducer, developed a set of guidelines for comparing the performance of different snowguns (York Snow, 1998). These guidelines are summarized as follows:

> “The first step in this procedure is to establish the test criteria that will serve as the basis for evaluation. These criteria may include snow density, particle size, liquid water content, snow distribution, operation under normal weather conditions, and operation under normal system parameters.
>
> “The test area should be flat or at least have a consistent slope. The test grid should be large enough to capture all of the snow being produced. For tower mounted guns, the grid should be at least 70 ft wide by 150 ft deep (20 m × 45 m). Stakes for measuring snow depth should be placed every 10 ft, in a line travelling away from the gun and in the direction of the wind. In the perpendicular direction, stakes should be set every 5 ft (Figure 3.1). For each stake location, measure and record the distance from the ground or snow surface to the top of the stake to establish an initial depth. In order to reduce measurement error, one person should perform all of the measurements.

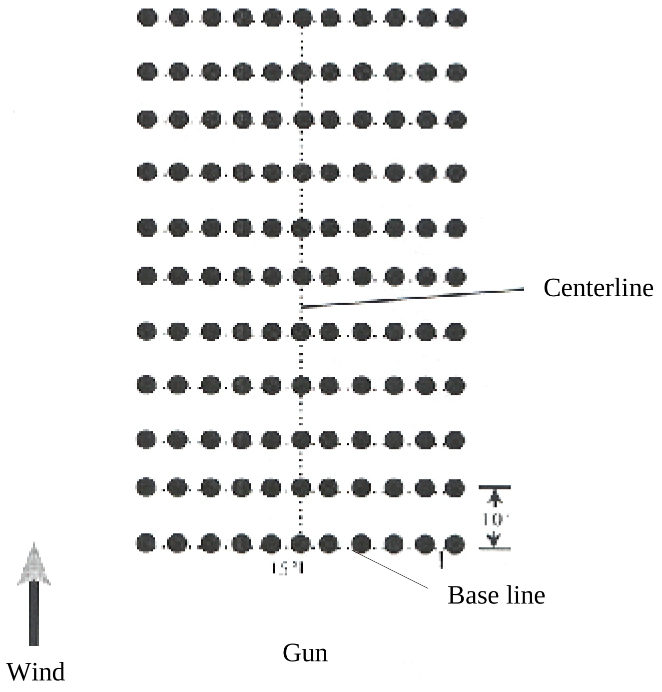

Figure 3.1 Snowmaking Test Grid (York Snow, 1998)

(Note: Total grid dimensions would be larger than that shown here when testing a tower mounted gun)

> “After starting the snowgun, record the time, temperature, and humidity. Then adjust the gun to achieve the desired snow quality. Once this is accomplished, observe and record the air and water flowrates. The ambient conditions and flowrates should be recorded at regular intervals throughout the test duration. In addition, the snow density and liquid water content should be measured at these time intervals to ensure that the quality of snow produced by each gun being tested is the same. The test should be run long enough to deposit 1 ft (30cm) of snow in the center of the grid. A longer test duration will provide results with a higher degree of accuracy. After the gun is shut down, measure and record the height at each stake.

Wright-McLaughlin Engineers designed a test for their 1973 study of secondary waste effluent treatment. On six occasions over the course of a month, snow was made for about two hours. Samples of the snowpack were collected, and measurements of snow and air temperatures, water content, and snow depth were recorded. Additionally, observations about snow type, color, and odor were recorded. Samples were sent to the Colorado Dept. of Health Water Quality Control Laboratory for analysis of biochemical properties. Several weeks after snowmaking operations concluded, samples of the remaining snowpack and meltwater were collected and analyzed for comparison with the initial snowpack conditions.

In Rabinowitz’s 1988 study on the treatment of effluent, snow depth was recorded at the end of snowmaking. Snow density was monitored continuously by placing plastic tubes of known volume at a specific location in the accumulating snowpile, and weighing them when full.

3.4 Snowmaking Parameters

Most of the documented knowledge about parameters in an air/water snowmaking system pertains to internal mix snowguns. Many of the theories hold true for external mix tower systems, with a few minor exceptions that will be noted.

Nozzle Configuration

In tower snowmaking, the droplet size is mostly controlled by the size of nozzle being used. Smaller droplets are an advantage during warmer snowmaking ambient temperatures (23°F to 30°F, -5.0°C to –1.1°C), as the higher surface/volume ratios promote rapid cooling. However, these smaller particles will have less momentum when leaving the snow nozzle and will not be distributed as far (Barthold, 1986).

Normally, a recirculation zone created by the 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 some smaller droplets tend to collect towards the end of the pile. However, Barthold notes that this classic distribution is not always the case with some nozzle types. With swirling or wide-angle cone nozzles, the heavy, high momentum particles often deposit closest to the nozzle exit.

Different nozzle types will also have an effect on the height of trajectory and the break up of the water stream. The break up of the water stream will produce smaller water droplets, having a decreased trajectory. Therefore, a compromise between the droplet's freezability and trajectory is necessary (Collins, 1989).

Water Pressure

Snow Economics, Inc. (1994) recommends operation of the HKD Tower with between 180 and 750 psi (1200 and 5200 kPa) of water pressure. Greater water pressures allow greater mass flowrates through the nozzles, increasing the volume of snow produced. Table A.1 in the Appendix lists the flowrates for different nozzles at various water pressures. Table A.2 lists the flowrates for different nozzle configurations on the HKD Spectrum.

Higher flowrates, and subsequently higher outlet velocities, will increase the height and distance of the spray stream trajectory, which provide more cooling time for water droplets to freeze (Collins, 1989). Higher flow rates also reduce droplet size. Figure A.1 in the Appendix shows the relationship between water pressure and median droplet size for various snowmaking nozzles.

Air Pressure

Air/water snow nozzles atomize the flow of water by introducing a high velocity differential between the water and compressed air phases. This velocity differential induces surface perturbations in the water jet, which provides energy to overcome surface tension and effectively shatters the fluid. By increasing or decreasing the flow of compressed air, the velocity differential between air and water can be adjusted, creating a method by which droplet sizes can be altered. Most ski resorts supply their snowmaking equipment with a compressed air pressure of 80 to 100 psi (550 to 700 kPa). In recent years, a few resorts have elevated this compressed air pressure to 150 psi (1000 kPa). 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 air to 150 psi is increased by 40%. There is disagreement within the ski industry whether this added expense pays off (Barthold, 1986).

Air flow through the HKD Spectrum varies logarithmically with changes in air pressure. Three data points were supplied by the manufacturer to describe this relationship. Figure A.2 in the Appendix shows the interpolated pressure versus flow curve.

Tower Orientation

A critical requirement in snowmaking is to propel the droplets in a trajectory that allows them to freeze before hitting the ground. By tilting a nozzle at a steep angle, orienting it with or against the wind, and placing it at the top of knolls in the terrain, an operator can adjust the cooling time of the droplets and the location of the depositing snow pile (Barthold, 1986).

Snow Inducer Concentration

In order for a water droplet to nucleate, it must cool to its spontaneous nucleation temperature or be introduced to a seed particle. A few products on the market, called “snow inducers,” provide seed particles that actually induce freezing of water droplets as they leave the snowgun. One such product is Snomax™ Snow Inducer. Snomax™ is an active protein used to catalyze the conversion of water to ice. It is grown by Eastman Kodak’s Bio-Products Division, and processed into freeze dried pellets.

When Snomax™ concentrated slurry is injected into the water supply at the prescribed rate of 1 liter per 1000 gallons, there will be, on average, one nucleating site per water droplet. When a droplet of water is seeded with a nucleator, it will start to freeze quickly after leaving the gun. The use of Snomax™ has been found to increase the amount of water converted to snow by 20-200% over the same water without Snomax™. Ski areas have been able to raise the static freezing temperature of their water from the 15°F to 20°F (-9.4°C to –6.7°C) range to as much as 28°F (-2.2°C) (Collins, 1989). Figure A.3 in the Appendix, shows the nucleation temperatures of water samples from six New England ski resorts, with and without Snomax™ (Barthold, 1986). Table A.3 compares the number of ice nucleation sites for different quantities of Snomax™ and water droplet sizes (Collins, 1999). A variety of ice nucleating activity levels (IN) are available. Each IN provides a different quantity of ice nucleating sites.

Water Temperature

The temperature of the water droplets leaving the nozzle must not only be cold enough to undergo spontaneous nucleation, but also cold enough to prevent melting of previously nucleated drops. Water tests at six New England ski areas show a remarkable difference in spontaneous nucleation temperatures ranging from 10°F to 21°F (–12°C to –6°C) (Figure A.3).

The Alford Design Group of Englewood, CO has studied the performance of snowguns operating with various inflow water temperatures (Alford, 1998). Research shows that significant reductions in the air flow requirement are achieved (to produce the same quality of snow) when water flowing into the snowguns is near 35°F (Figure A.4).

Compressed Air Temperature

Particle nucleation is markedly enhanced by the presence of compressed air. The compressed air temperature as it accelerates through a nozzle reaches approximately –40°F (-40°C) due to the expansion of the fluid. Herman Dupre, inventor of the HKD Spectrum tower, claims that compressed air exits the tower at –140°F. At temperatures this cold, the small water particles contained in the compressed air freeze instantly. These small particles form nuclei to promote freezing of the water droplets in the spray of a snow nozzle (Barthold, 1986).

Ambient Conditions

At temperatures below 21°F (–6.1°C), convective heat transfer is the dominant heat transfer mechanism, while above 21°F, evaporation is the dominant mechanism. It is very difficult and expensive to produce snow during periods of high ambient temperatures and relative humidities due to the low heat transfer rates associated with these conditions (Figure A.5). Energy consumption of snowmaking in ambient temperatures of 10°F (–12°C) more than doubles for that in temperatures of 25°F (–3.9°C) (Barthold, 1986). Conversations with Snow Economics revealed that when wet bulb temperatures drop below 10°F, effective snowmaking can take place without the benefit of compressed air.

The wet bulb temperature is a measure frequently used by snowmakers to determine if and with what proportion of ingredients they can make snow. The wet bulb can be derived from a measure of the dry bulb temperature and relative humidity (conversion chart provided in the Appendix, Table A.5). When the relative humidity is 100%, the dry bulb and wet bulb temperatures are equal. As the humidity decreases, the wet bulb temperature decreases with respect to the dry bulb. This is called the wet bulb "depression." The depression is greater at higher temperatures. At temperatures near 0°F the depression becomes negligible.

At relatively similar wet bulb temperatures, even though the dry bulb and humidity may vary, it is believed that the energy requirements to make a consistent quality of snow are also similar. This means that a lower dry bulb, high humidity environment is as conducive to snowmaking as a higher dry bulb, lower humidity environment. There is no formal documentation within the ski industry that proves this claim. Therefore, it is helpful to understand that this theory holds true only within certain, somewhat obvious limits. Regardless of the relative humidity and wet bulb temperature, it is impossible to freeze water when the dry bulb temperature is above 32°F.