

## Chapter 4 - Experimental Testing Methods

### **4.1 Purpose of Experimental Testing**

The purpose of experimental testing is to collect data that will aid in the construction of a design methodology to implement efficient snowmaking at a transportation research facility. Testing included the production and characterization of artificial snow, a characterization of natural snow, and wind measurements on the Smart Road.

### **4.2 Snowmaking Tests**

The goal of snowmaking tests was to observe the performance of the HKD Spectrum snowmaking tower under a variety of ambient and operational conditions. Testing procedures and data collection proceeded as described in the following sections.

#### ***4.2.1 Establishing the Test Grid***

Prior to system startup, a test grid was established in front of the tower(s). Stakes (40 in (1.0 m) long, ¾ in (2 cm) diameter) were placed at 10 to 20 ft (3 to 6 m) increments over a test grid measuring 160 ft wide × 80 ft deep (50 m × 25 m). The stakes were made of PVC, a durable, low-cost material. The dimensions and uniformity of the grid varied from test to test depending on the predicted area of deposition and the availability of stakes. The primary field of interest was between 20 and 80 ft from the tower, corresponding to the location of the Smart Road towers with respect to the roadway. On each stake, two measurement references were drawn 12 in (30 cm) apart with a black marker. Each stake was driven into the ground, or snow, until the first measurement reference was flush with the current snow or ground surface (Figure 4.1).



**Figure 4.1 Typical Test Grid**

### ***4.2.2 Tower Preparation***

To install the desired nozzle configuration the tower was lowered to eye level, and the appropriate nozzles were added or replaced. The tower was then raised to the desired vertical angle, and pivoted to the desired horizontal angle. Hoses were fitted between the air and water hydrants and the tower's air and water inlets. If the flowmeter was used, it was attached prior to startup, and required the attachment of extra hosing (Figure 4.2).



**Figure 4.2 Air and Water Flowmeter**

### *4.2.3 Setting the Pumps and Compressors*

With the pumps turned off, the system water pressure supported by gravity flow was around 200 psi (1400 kPa). Additional pumps could be turned on to increase the water pressure to 700 psi, although only 400 psi was available during testing. The system air pressure was maintained by one 25 hp (19 kW) compressor and by one 30 hp (22kW) compressor. Both machines had to be running to maintain an air pressure greater than 100 psi. A view of the pump room is provided in Figure 4.3.



**Figure 4.3 The Pump Room**

(From left to right: 25 hp air compressor, horizontally mounted water pump, pressure gauges)

#### ***4.2.4 System Startup, Observations and Adjustments***

To begin making snow, the water hydrant was slowly opened to full pressure, followed by the air hydrant. As water began ejecting from the head of the tower, the effects of wind on deposition were observed. If the deposition was not occurring inside the test grid, the position of the tower was adjusted to aim the snow toward the grid. This practice ensures that the greatest amount of snow accumulates within the grid, thereby generating more data to describe each test. With the test underway, the starting time, ambient conditions, and operational conditions were recorded on the forms shown in Figures A.6 and A.7.

Temperatures were measured with a thermometer local to the testing site. Wind speed was measured with a hand-held anemometer. During longer tests (more than 3 hours), these conditions were recorded at regular intervals. At the end of testing, final conditions were recorded and the hydrants were turned off. If a flowmeter was used, it was disconnected to prevent freeze-up of the device. This piece of equipment was borrowed from the resort maintenance staff, and was not always available for use.

#### ***4.2.5 Measuring the Depth, Density, and Quality of Snow***

At the end of a test, the depth of snow was measured at each point in the grid. First, the snow next to the stake was brushed away until the measurement reference was visible. The accumulated snow depth was measured using a scale marked at every 1/2 inch. For depths near 12 in, a large divot formed around the stake, making it difficult to take an accurate sight measurement. To assist in measuring the depth at these locations, a stake was placed horizontally across the divot, with both ends of the stake resting on the undisturbed snow surface a few inches away. Then, the distance from the reference line to the horizontal stake was measured and recorded as the true depth at that point (Figure 4.4).

At points in the grid where depth was at least 3 in (8 cm), snow samples were collected to measure density. More accurately, the term density as it is used in this work describes the unit weight of snow. Samples were collected using a standard concrete mixing scoop, shown in Figure 4.4. Although the scoop shape of this device reduced the accuracy of the measurement by compacting snow near the handle, the scoop was sturdy and could push through a dense snowpack for easy sample collection. Five samples taken in the same location revealed a standard error of  $\pm 3.8\%$  (Table A.4). After pushing the scoop into the snow, excess snow was shaved off to obtain an edge that conformed to the shape of the scoop. Samples were placed in freezer storage bags and weighed at a later time. Samples were weighed to the nearest one-tenth gram using a triple beam scale having a 600 g capacity. The scale was calibrated before use.

At various points around the grid, the quality of snow was observed. Quality was rated using the scale developed by Snow Economics, Inc.



**Figure 4.4 Measuring Snow Depth**

#### ***4.2.6 Measuring the Water and Compressed Air Temperature***

During one test, the temperatures of water and compressed air travelling in the hose between the hydrant and snowmaking tower were measured. A digital thermometer was aimed at the desired location on the hose, leaving ½ in of space between the tip of the thermometer and the hose surface. An average of multiple readings at each location was recorded with the results of Test 2 (Table B.2).

#### ***4.2.7 Reporting and Compiling Results***

Results for the snowmaking tests include specific information about each test conducted. The test conditions, characteristics of the manufactured snow, and a contour plot of the manufactured snow are provided in the Appendix (Tables and Figures B.1 through B.17). Components of the result form are explained as follows:

*Location* – Tests were conducted at a total of four tower locations. “Cortina” and “Charlie-1” are located at the top of the Wagner slope at the resort. “Santa’s #10” and “Santa’s #11” are located at the test facility, affectionately called “Santa’s Workshop.”

*Nozzle Configuration* – Lists the nozzle type for the top, middle, and bottom pairs of nozzles on the head of the snowmaking tower. Nozzles range in size from 10 (smallest) to 60 (largest). In most cases new nozzles were used. All nozzles appeared to be free from wear or defect.

*Ave Air & Water Pressures* – The average compressed air and water pressures at the base of the tower. At Cortina and Charlie-1 these pressures were measured using the flowmeter. At Santa’s Workshop, these pressures were read at the pumphouse, as the pressures at the tower matched the system pressures. Pressures were observed at three or four instances during the testing period. Water pressure fluctuated within  $\pm 2$  psi of the

average, except where noted that the pump configuration was altered during the test period. Air pressure fluctuated within  $\pm 13$  psi.

*Dry Bulb Temp* – At Cortina and Charlie-1, this was measured using the thermometer in the control building. At Santa’s Workshop the dry bulb temperature was measured with an outdoor thermometer that was calibrated to the control thermometer.

*Humidity (relative)* – Measured from the control building.

*Wet Bulb Temp* – Derived from a wet/dry bulb conversion table (Table A.5).

*Wind Speed* – Measured with a hand-held anemometer.

*Snomax<sup>TM</sup>* - Snow inducer concentration. This was only used at the resort and not at Santa’s Workshop. The mixture was added at hourly intervals.

*Tower Orientation* - Displayed in two “windows.” The top window shows the vertical angle. The bottom window shows the tower’s direction (bottom arrow) relative to the test grid (rectangle) and wind direction (top arrow).

*% Deposition Area Sampled* – The sample area divided by the total deposition area. The sample area is comprised of each point in the test grid. This includes the area around each point that is represented by the depth measurement at that stake. The total deposition area was estimated using the contour graphics program, Surfer 32.

*Volume Snow Produced* – The total volume of snow deposited near the snowgun. This includes the volume of snow within the estimated deposition area. This fails to include lighter snow that may have deposited a few hundred feet from the sample area.

*Ave Water Flow Rate* – The theoretical flow through the given nozzle configuration at the average pressure (Tables A.1 and A.2).

*Ave Air Flow Rate* – Interpolated from figures supplied from Snow Economics (Figure A.2).

*Range Of Densities* – Reflects the range of densities among the collected samples.

*Max Depth* – The maximum depth recorded in the sample area.

*Snow / Water* – The percentage of water that was converted to snow. This figure compares the weight of snow produced (estimated volume times average density) with the weight of the total amount of water used. The snow to water ratio is essentially a conversion efficiency which helps describe the system's water budget. Snow that drifted beyond the bounds of the estimated total volume of snow was not accounted for. Therefore, the fraction of water that was not "converted" either drifted or evaporated. Error in computing the snow to water ratio derives from the estimation of total snow volume and the averaging of densities from a sample set that did not represent the entire volume of snow. The effects of error are especially apparent in ratios that are greater than 100%.

*Air / Water* – The average air flowrate divided by the average water flowrate (listed in units of cfm/gpm, an industry standard).

*Ave Density* – The average of sampled densities.

*Snow Production Contour Map* – Derived with the Surfer program using the recorded depth data. The tower location is always at grid point (0,0) and points in the direction of tower orientation. The tip of the arrow approximates the position of the tower head and nozzles. The other arrow indicates wind direction and is labeled with the wind speed. Where density samples were taken, the rounded density value is given for that location. In Test 11, density samples were collected from the surface, as well as from a depth of 8 inches below the surface. In Figure B.11, the snow production contour map for this test, the surface density precedes the lower density.

### **4.3 Natural Snow**

A characterization of natural snow can be used to determine how accurately snow can be recreated artificially. Throughout the winter, five samples of snow from natural snowfalls were collected to determine the snow density and quality. Samples varied in the type of surface on which they accumulated and the ambient temperature at the time of sampling. The results are listed in Table B.18 in the Appendix.

### **4.4 Wind Conditions on the Smart Road**

An assessment of wind conditions on the Smart Road will help to describe the future snowmaking environment. On three occasions, wind speed and direction were observed at various locations on the weather simulation section of the road. Measurements were read using a hand-held anemometer. Results are presented in Table B.19.

## Chapter 5 - Theoretical Methods

### **5.1 Purpose of Theoretical Analyses**

Theoretical work will provide valuable information that is not attainable from physical testing. The thermodynamic modeling and analysis of water and compressed air systems will assess the adequacy of certain snowmaking equipment and allow us to make certain assumptions about the capabilities of the snowmaking system. The theoretical study on resultant overlapping snow production from adjacently operating towers will provide a method by which the data collected from the operation of one snowmaking tower can be extrapolated to predict the performance of a system of towers.

### **5.2 Thermodynamic Modeling and Analysis of Water and Compressed Air Systems**

The need to perform a thermodynamic model of the fluid systems arises out of the Smart Road's uncertain decision to purchase compressed air aftercoolers. Snowmakers in the ski industry disagree among one another on the benefits of aftercooling, largely because each snowmaking system is unique. The construction of a thermodynamic model of the Smart Road's system, using the Aspen Plus program, will determine if aftercoolers will benefit snowmaking. The results of the model will also aid in the design methodology to implement snowmaking.

#### ***5.2.1 Water and Compressed Air Systems***

Water system components include a water storage tank with an attached cooling system, pumps, and carbon-steel piping buried underground that delivers the water to the snowmaking hydrants. Compressed air system components include compressors (with intercooling), aftercoolers, a moisture separator and carbon-steel piping buried

underground for delivery to the hydrants. Once the air and water reach the hydrants (above ground), they travel to the base of the tower via two nylon wrapped, high-pressure hoses (similar to fire hoses). The tower is made of aluminum, and consists of three pipes of different diameters that encompass one another (see cross-section - Figure 5.1). The

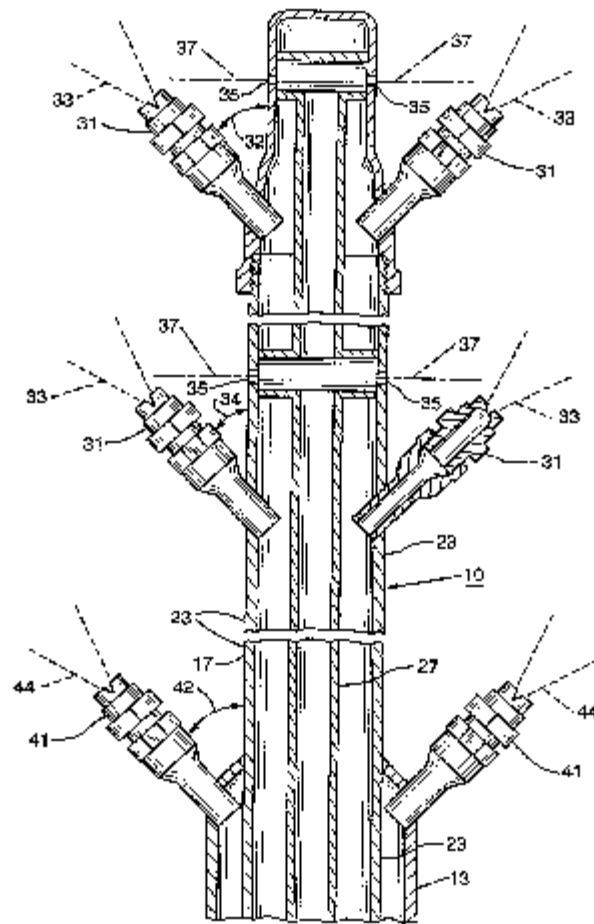


Figure 5.1 Cross Section of the HKD Spectrum (Dupre, 1998)

compressed air travels through the center pipe (smallest diameter) to the top of the tower where it is released through the air nozzles. The water travels through the surrounding middle pipe to the water nozzles at the top of the tower. Water also travels through the outermost pipe (largest diameter) when the auxiliary nozzles are activated.

Efficient snowmaking demands that the water be cold (35° to 40°F) as it exits the nozzles. Compressed air must be cool enough to prevent warming of the water by conduction when isolated in the tower, and cool enough to reach extremely low sub-freezing temperatures (less than -40°F) upon expansion through the nozzles.

Aftercooling of compressed air serves two roles. Primarily, aftercooling cools the high temperature compressor discharge air, which is approximately 190°F. The aftercooler discharge temperature can be set as low as 37°F. Secondly, aftercooling helps to reduce the moisture content of the compressed air. While some concentration of water vapor within the compressed air enhances nucleation upon exiting the tower, excessive amounts may condense within the pipes or the towers. This could pose a corrosion problem in the pipes or freezing of the air line in the tower.

### ***5.2.2 Aspen Plus Simulation***

Aspen Plus is the leading simulation tool in the process industries. The present application of Aspen Plus to the simulation of a snowmaking process may be the first of its kind. Although a few key assumptions are required, the snowmaking process is easily simulated with standard models available within Aspen Plus. The key equations utilized by Aspen Plus are summarized in the following discussion.

## Cooling

Cooling of compressed air in the underground pipeline is simulated through the pipeline model within Aspen Plus. The key assumption within the pipeline is that of a constant overall heat-transfer coefficient,  $U$ . The heat flow,  $Q$ , through the pipe wall is given by:

$$Q = UA\Delta T$$

where  $A$  is the heat-transfer area (i.e., the area of the pipe wall) and  $\Delta T$  is the temperature difference between the compressed air within the pipe and the outside ground temperature. The temperature drop of the compressed air is given by:

$$\Delta T = \frac{Q}{\dot{m}C_p}$$

where  $\dot{m}$  and  $C_p$  are the mass flowrate and heat capacity of the compressed air, respectively. When we assume a constant heat-transfer coefficient, Aspen can quickly solve the above equations for the temperature change within the pipeline. The heat exchanger model within Aspen Plus is based on the same theory presented above, with respect to constant heat-transfer coefficient.

## Vapor-Liquid Equilibrium

Aspen simulates condensation of water vapor within the snow making system through vapor-liquid equilibrium relationships. The governing equation is that the fugacity (or chemical potential) of each component in each phase (i.e., liquid and vapor phases) must be equal at equilibrium (Prausnitz, 1986). In equation form:

$$f_{\text{H}_2\text{O}}^{\text{L}} = f_{\text{H}_2\text{O}}^{\text{V}}$$

where  $f_{\text{H}_2\text{O}}^{\text{L}}$  and  $f_{\text{H}_2\text{O}}^{\text{V}}$  are the fugacity of water in the liquid and vapor phases, respectively. The Aspen Plus user selects appropriate models for the fugacity of each component. At low to moderate pressures in binary (i.e., water/air mixture) systems, ideal solutions are appropriate. Here, the pure component fugacities of water,  $f_{\text{H}_2\text{O,pure}}^{\text{L}}$  and  $f_{\text{H}_2\text{O,pure}}^{\text{V}}$ , are scaled by the composition of water in each phase,  $x_{\text{H}_2\text{O}}$  and  $y_{\text{H}_2\text{O}}$ :

$$f_{\text{H}_2\text{O}}^{\text{L}} = x_{\text{H}_2\text{O}} f_{\text{H}_2\text{O,pure}}^{\text{L}}$$

$$f_{\text{H}_2\text{O}}^{\text{V}} = y_{\text{H}_2\text{O}} f_{\text{H}_2\text{O,pure}}^{\text{V}}$$

where  $x_{\text{H}_2\text{O}}$  and  $y_{\text{H}_2\text{O}}$  are the composition (mole fraction) of liquid and vapor water, respectively, and the pure component fugacities are available within the data banks of Aspen Plus as a function of temperature and pressure. Equating the two fugacity expressions gives:

$$x_{\text{H}_2\text{O}} f_{\text{H}_2\text{O,pure}}^{\text{L}} = y_{\text{H}_2\text{O}} f_{\text{H}_2\text{O,pure}}^{\text{V}}$$

As temperatures decrease through the system, the pure component fugacity of water decreases faster in the liquid phase. This causes  $x_{\text{H}_2\text{O}}$  to increase and water condenses within the system.

### ***5.2.3 Model Formulation, Assumptions and Results***

A model will be constructed to represent the compressed air system in its entirety and the water system within the snowmaking tower. The water system is not modeled prior to the snowmaking towers, due to the assumption that there will be less than a 2°F rise in water temperature between the storage tank and the towers. This assumption is

supported by the results of prior water cooling research (Alford, 1998). The simulation will test three fluid demand situations (low, medium and high) for the case that an aftercooler is not added (compressed air discharge is 190°F). The simulation will also test the model for the case when an aftercooler is added to the system. Results will provide values to describe the profiles of compressed air temperature and water temperature (Table B.20), and will describe the moisture content profile for the system.

The model consists of five key blocks: a compressor, an intercooler, a pipeline, a tower and a nozzle. An aftercooler can be incorporated into the model by adjusting the intercooler parameters. Each component of the model is described as follows:

**Compressor:**

Air enters the compressors at atmospheric pressure (14.7 psia) with a temperature of below 28°F. The air is compressed to 125 psig, increasing its temperature to over 600°F. The compressor is modeled as an isentropic type.

**Intercooler:**

The compressor's intercooler is modeled as a separate unit, cooling the compressed air to 190°F. In actuality, the compressor and intercooler are one unit. During simulation, the outlet temperature of the intercooler can be decreased to 37°F to simulate the performance capability of the aftercooler.

**Pipe:**

The carbon-steel air delivery pipe is buried at a depth of 1.3 m underground (below the frost depth). Dimensions and other properties of the pipe are provided in the following table:

**Table 5.1 Air Delivery Pipe Characteristics**

Length to First Snowmaking Tower	1164 ft
Inside Diameter	1 ft
Roughness	0.00015 ft/ft
Ground Temperature	50°F
Overall Heat-Transfer Coefficient	20 BTU/(hr ft <sup>2</sup> °F)
Fittings	10 x 90° bends

The value for the overall heat-transfer coefficient was selected based on literature (Perry, 1984) values for heat transfer between air and several liquids. Correlations are not available for underground pipelines and solids. This value for overall heat-transfer coefficient was tested in the model simulation with more conservative values (one order of magnitude less) and yielded similar results. Changes in elevation were not included in the simulation, as they have a relatively small effect on pressure and temperature.

**Snowmaking Tower:**

The aluminum snowmaking tower is modeled as a cocurrent (fluids moving in the same direction) heat exchanger. The dimensions and other properties of the tower are provided in the following table:

**Table 5.2 Snowmaking Tower Characteristics**

Heat-Transfer Area (total of all towers)	574 ft <sup>2</sup>
Flow Direction	Cocurrent
Overall Heat-Transfer Coefficient	25 BTU/(hr ft <sup>2</sup> °F)

The heat-transfer area was estimated as the contact area between air and water within the jackets:

$$0.0625 \text{ ft (air pipe dia)} \times \pi \times 39 \text{ ft (pipe length)} = 7.7 \text{ ft}^2 \text{ per tower}$$
$$7.7 \text{ ft}^2 \times 75 \text{ towers} = 574 \text{ ft}^2$$

Later, this approximation was confirmed through rigorous geometric models of heat-exchanger units internal to Aspen Plus.

**Nozzle:**

The nozzle is modeled as a valve with a 1/8 inch diameter that expands compressed air to atmospheric pressure.

**5.3 Theoretical Resultant Snow Production from Adjacent Snowmaking Towers**

Snowmaking towers on the Smart Road are located every 10 m in a relatively straight line (bends slightly at the middle) along the shoulder. Due to the unique spacing of this system (the spacing of ski resort machines is irregular and much farther apart) it is impossible to collect data on adjacently operating towers prior to construction of the facility. Therefore, in order to make assumptions about the combined performance of multiple towers, the creation of a theoretical method to predict the resultant overlapping snow production becomes necessary.

The method proposed here will consider resultant accumulation. This method is dependent on the collection of snow accumulation data from testing with one snowmaking tower. Not enough data was collected in the present study to predict resultant density or quality, although the same method could be applied to resultant density or quality if more data was available.

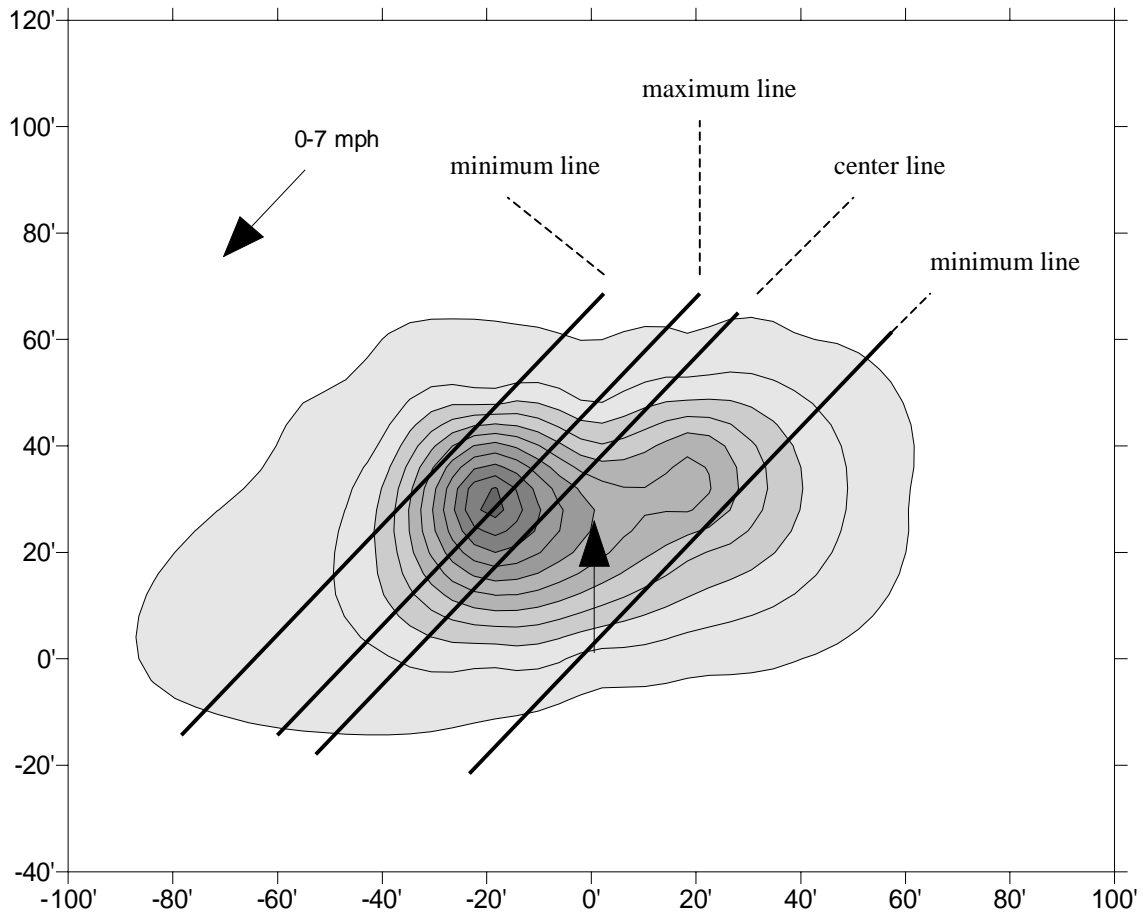
The method will be used to produce a range of factors by which the predicted minimum and maximum overlapping snowfall intensities seen on the roadway are related to the required water flowrate for each individual tower. The following steps are used to develop the range of factors from the data sets generated during the experimental testing of individual towers:

- 1) Construct the Lines of Accumulation on each production contour map.
- 2) Compute the Resultant Accumulation and Intensity for each line.
- 3) Compute the Resultant Accumulation Ratios.
- 4) Develop Resultant Accumulation Factors.

### ***5.3.1 Constructing Lines of Accumulation***

Across the length and width of the roadway there will be a variation in snow accumulation. In predicting the resultant accumulation, it will be helpful to consider the boundaries of this variation so that a confidence interval (loosely defined) can be placed around the targeted value. The resultant accumulation from adjacent towers at any location along the length of the road can be computed by summing the individual accumulations at respective tower locations. This method relies on the same properties of summation that are used in hydrology to lag unit hydrographs. However, instead of summing flowrates of water over a time interval, we will sum snowfall intensities over a distance interval.

The chosen “Line of Accumulation” should be parallel to the roadway (refer to Fig. 5.2). If the accumulation data is from an “off-road” site, as in the case of the present study, the lines should be drawn in a relative manner to the road position with respect to wind direction. The wind direction provides a good reference point, since wind will be the largest factor in determining the placement of the snow.



**Figure 5.2 Drawing the Lines of Accumulation on a Snow Production Contour Map**

There should be a center, minimum and maximum Line of Accumulation to define the range of variation. The center line should be drawn to encompass the bulk of accumulation within the width of the road. Due to irregularities in the snow deposition pattern, this will not always pass through the point of maximum accumulation. The maximum Line of Accumulation should be drawn through the point of maximum accumulation (and intensity). Two more lines should be drawn through points relative to the center line of accumulation that reflect the boundaries of road width (including shoulders). One of these lines will be defined in the next step as the minimum line of accumulation.

### ***5.3.2 Computing the Resultant Accumulation and Intensity For Each Line***

The next step is to calculate the Resultant Accumulation (RA) by summing the snow accumulation at regular intervals along each accumulation line. The interval is defined by the spacing of snowmaking towers. For the maximum line, intervals should begin from the point of maximum intensity. This procedure will almost always produce the greatest possible RA, excepting the case of a largely irregular deposition pattern. For the outer two lines, intervals should begin at the edge of the zero-accumulation contour. This will provide the lowest RA possible. The line with the lower of the two accumulations shall be the minimum line. In addition to computing the sum at every interval, it is helpful to consider alternate operational configurations. On the Smart Road, there will likely be just one alternate pattern, where every other tower is in operation.

Once the minimum and maximum RA's are computed, it is necessary to divide by the duration of the test in hours. This will convert an RA into Relative Intensity (RI).

### ***5.3.3 Computing the Resultant Accumulation Ratios***

With the maximum and minimum resultant accumulations for each tower configuration, it is now desirable to put the numbers in a form that allows an “apples to apples” comparison of results among different tests. The Resultant Accumulation Ratio (RAR) is created by relating the resultant intensities to the maximum intensity created by an individual tower in each test. The RAR is found by dividing the RI by the independent maximum intensity. Thus, for each test and tower configuration, there will be an independent maximum snowfall intensity, and a minimum and maximum RI and RAR

### ***5.3.4 Developing the Resultant Accumulation Factors***

With the resultant intensities and ratios of each snowmaking test, results can be compared to develop Resultant Accumulation Factors (RAF). From the range of RAR's, one may compute an average for both the minimum and maximum cases. This average is helpful in analyzing which results stand out as being high or low outliers. Some tests may be removed from the discussion altogether if it can be justified that the high or low ratios of these tests are due to some anomaly in that testing session. Finally, a range of acceptable values can be chosen that is bound by the adjusted minimum and maximum ratios. This range will provide the Resultant Accumulation Factors by which the target maximum intensity per tower will be multiplied to attain the range of snowfall intensities seen on the roadway with the operation of adjacent towers. The results and calculations of this method are presented in Table B.21 in the Appendix.

## Chapter 6 - Discussion of Results

### 6.1 Experimental Results

Experimental results include snowmaking test results, a characterization of natural snow, and a summary of wind conditions on the Smart Road. Results are recorded in tabular form in the Appendix and are discussed here.

#### 6.1.1 Snowmaking Tests

A total of 92 hours of snowmaking was observed. The results of each test are provided in Figures and Tables B.1 through B.17. The tests are discussed per parameter as follows:

##### *Nozzle Configuration*

The size of a nozzle is the largest factor in determining the size of water droplets exiting the nozzle. Most of the nozzle sizes available to the Smart Road were used in testing, ranging from 5010 to 5060. Ten different nozzle configurations were tested. Due to the symmetrical arrangement of nozzles on the HKD Spectrum tower, nozzles are installed in pairs, where the same nozzle size is used for both orifices in the top, middle or bottom position.

The results of Test 12 (Table B.12) demonstrate the ability of the 5020 and 5010 nozzles to produce high quality, low density snow. The small droplet sizes and low air/water ratios associated with use of these nozzles promote a high percentage of frozen material. However, the extremely low snow/water ratio indicates inefficient production. Much of the precipitation drifted or evaporated because the small droplets did not have enough momentum to reach ground near the tower.

The medium-range water flowrates, attained when 5040 nozzles are included in the configuration, allow for considerable volumes of snow production and medium-range air/water ratios. The 10-40-X nozzle configuration, used in Tests 13 and 15, produced high quality, low density snow, and high snow/water ratios. Presumably, the small drops produced by the 5010 nozzle froze quickly, providing a good nucleator for the larger drops coming out of the 5040 nozzle. The 20-40-X configuration used in Tests 4,5,7, and 9 performed in a similar manner, but produced slightly higher density snow.

Nozzle configurations that included the 5060 nozzles produced wetter, denser snow. The 60-40-20 configuration, used in Test 8, performed the worst. While the tower was positioned at a steep 75°, allowing drops more cooling time, the manufactured snow was very wet and had a high average density. The high flow of water allowed by this configuration restricts the air/water ratio. An additional hindrance to snow quality is the generally poor positioning of the 5060 nozzles on top of the configuration. It is believed that the large drops from these nozzles escape the mixing plume before contacting the smaller nucleating droplets. Also, large drops may melt the smaller nucleating drops that they do come in contact with.

From the arrangement of snow density data in most tests, it is apparent that the higher density snow deposited closer to the nozzles, while sample points away from the nozzles reflected lower density, fluffier snow. This indicates that larger droplets, which are slower to freeze, deposited closer to the nozzles. The smaller droplets were carried by the wind and deposited farther from the nozzles, creating lower density snow.

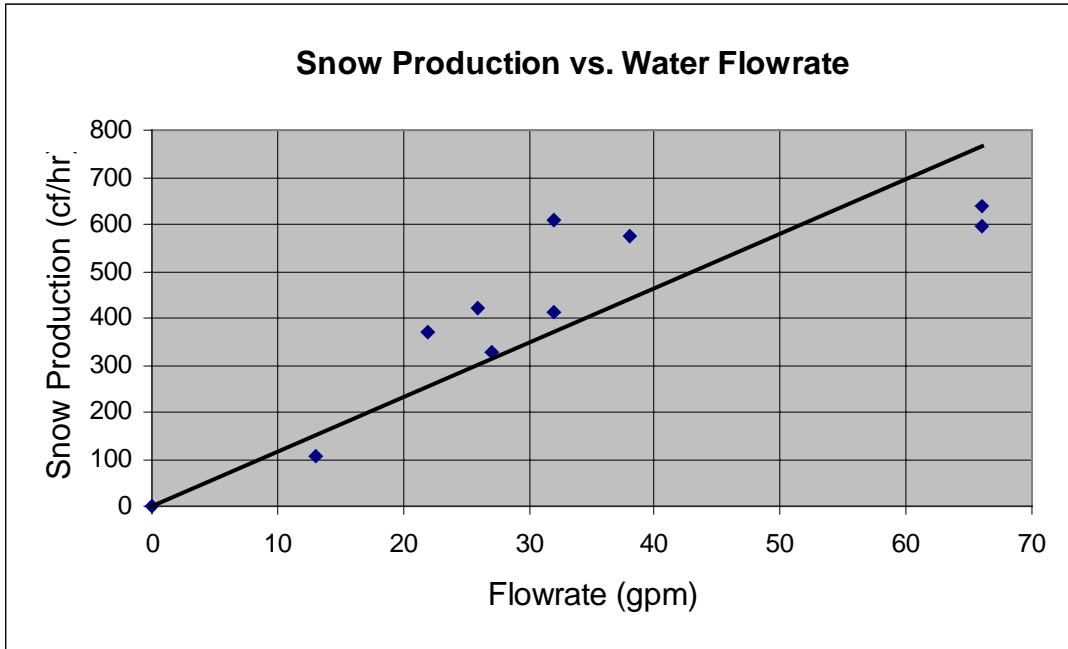
From a maintenance perspective, it is important to note the amount of time and effort required to change the nozzle configuration. The quick-connect coupling on the nozzles allowed easy detachment when the nozzles were dry. However, after snowmaking, the nozzle couplings were frequently coated with ice. This made disconnection difficult and time consuming. The total time required to lower a tower head, change a set of nozzles, and raise the tower head, was about 15 minutes on average.

## *Water Pressure and Flow*

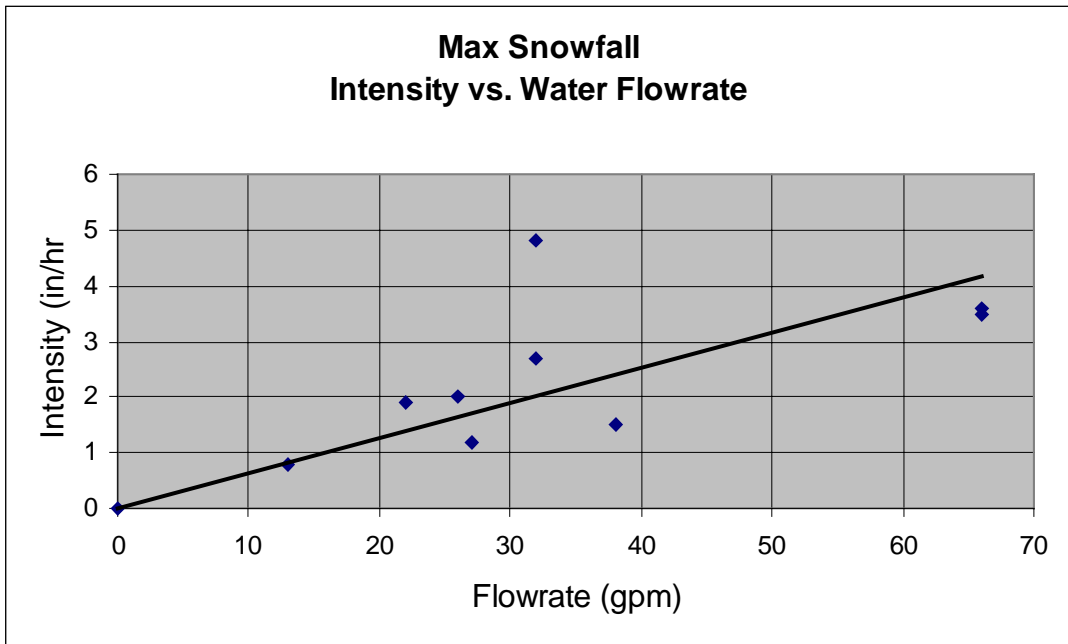
For a given nozzle configuration, the water flowrate is controlled by the water pressure. Test results indicate that an increase in water pressure, and subsequent increase in flowrate, for a given nozzle configuration will increase the volumetric snow production. Results are inconclusive regarding any correlation between water pressure and snow quality.

The relationship between water flowrate and snow production (independent of nozzle configuration) can be observed by comparing the water flowrate to the volumetric snow production rate and the maximum snowfall intensity. Figures 6.1 and 6.2 illustrate these relationships for nine of the tests. These tests have been isolated for observation because each test was conducted with the tower positioned at a 35° vertical angle. While Test 14 was conducted at the same vertical angle, it is removed from the group analysis because the effects of natural accumulation and drift during the test make it impossible to interpret the impacts of individual parameters.

In Figure 6.1, and especially in Figure 6.2, Test 4 is a high outlier. The large maximum intensity in this test is largely due to the position of the tower with respect to the relatively high winds. As observed in the contour map (Fig B.4), the wind had an effect of condensing the deposition into a long, steep formation. The volumetric production for this test is also quite high. This is typical of tests with lower average densities, when for the same mass of water, the snow occupies more volume. The same theory holds true for tests with higher average densities that have a lower production.



**Figure 6.1 Comparison of Volumetric Snow Production to Water Flowrate**



**Figure 6.2 Comparison of Maximum Snowfall Intensity to Water Flowrate**

## Compressed Air Pressure and Flow

The flow of compressed air is controlled by adjustment of the air pressure. The effects of air flow on snow quality are best observed by comparing the air/water ratio to the average density of the manufactured snow. In Figure 6.3, eight (of the previously stated group of nine) tests are compared, as in Section 6.2. It is apparent from the graph that an increased quantity of compressed air relative to the same quantity of water will produce snow with a lower average density.

Test 12 was omitted from the stated group of nine tests, due to the low number of collected samples that represent the average density for this test. Had more samples been collected from points in the grid further from the nozzle, it is believed that the average density would be significantly lower than the reported average of 27.9 lbs/cf. The trendline of Figure 6.3 supports this claim, predicting a density of 24.0 for the air/water ratio of 6.8 reported in Test 12.

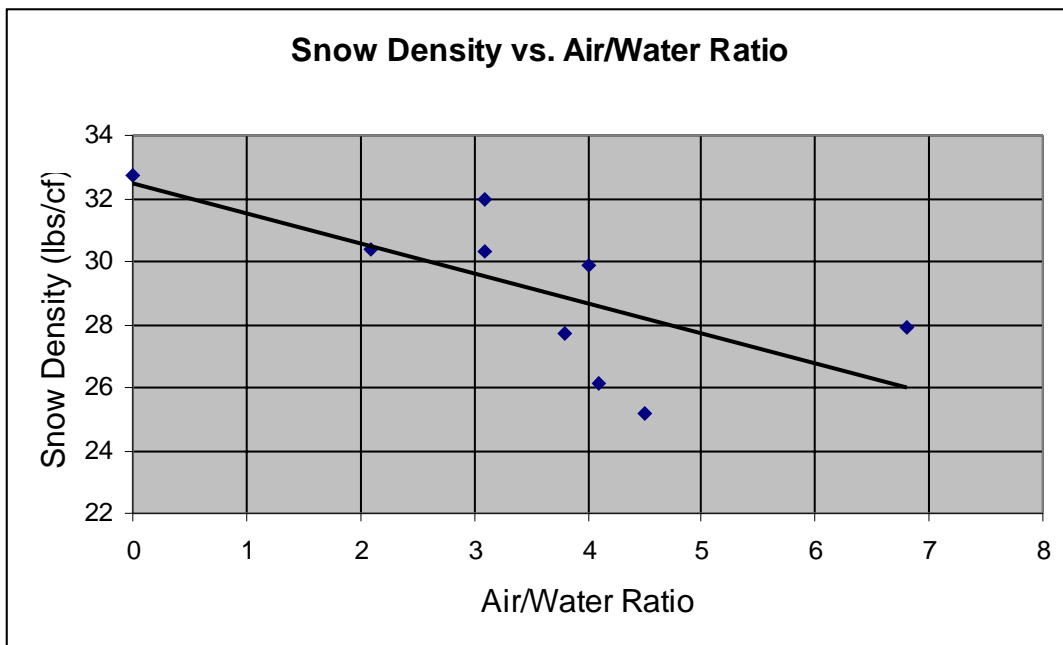


Figure 6.3 Comparison of Average Snow Density to the Air/Water Ratio

There is no evidence to support the idea that increases in the air/water ratio beyond these tested values would subsequently continue to reduce the average snow density. It is more likely that an asymptote is reached where the density cannot be reduced by a further increase in the air/water ratio.

In addition to improving snow quality, an increase in the air/water ratio generally increases the volumetric snow production. A comparison between Tests 4 and 5, where the nozzle configuration and water flowrates are identical, demonstrates this idea. It is apparent that the 23% increase in air/water ratio of Test 4 over Test 5 contributed to the 47% increase in volumetric production. Colder temperatures in Test 4 also contributed to the increased production, so it is difficult to quantify the exact impact of the increased air flow. When more water droplets freeze, either from an increased quantity of compressed air or colder temperatures, the density of the manufactured snow decreases. For the same quantity of water, a higher volume of low density snow can be produced than of high density snow.

### *Tower Orientation*

The HKD Spectrum pivots horizontally with 360° of freedom, and pivots vertically with 90° of freedom. Testing revealed a lack of deposition control, and subsequent decrease in volumetric snow production, when the tower was positioned at higher vertical angles. Figure 6.4 is a photograph of Test 3, with the tower at a vertical angle of 80°, and winds of 7 to 9 mph in the direction of the nozzle spray. There is virtually no deposition within 60 ft of the tower. The low snow/water ratio, estimated to be 0.6, supports the conclusion that most of the manufactured snow drifted over the test grid and deposited over a vast area.

Tests conducted with the tower at a vertical angle of 35° demonstrate a higher degree of control over deposition. A higher percentage of the estimated total deposition area was contained within the test grid, and snow/water ratios near 2.0 were common.

Test 16 was conducted with the tower at a vertical angle of 20°. While deposition was highly controllable, the resulting position of the tower head at a negative angle (the tower head bends downward at a 35° angle from the stem of the tower) led to freezing of the tower head and nozzles following the test. When the tower head is positioned at a negative angle, water remaining in the head after shutdown drains slowly through the nozzles and freezes in cold temperatures (Figure 6.5). This can damage the tower head and nozzles.

The horizontal position of the tower with respect to the wind plays a large role in determining where the maximum snowfall will occur. Even the slightest wind will quickly overtake the comparatively small momentum of the nozzle spray. Without being able to control droplets once the wind has taken over, it is only possible to determine where the water droplets will begin their journey.

For tests where the tower was generally aimed into the wind, the maximum snowfall intensity occurred reasonably close to the nozzles. When the vertical angle was 35°, the maximum intensity occurred within 20 ft of the nozzles. At the same vertical angle, the maximum intensity from towers aiming with the wind occurred between 40 and 60 ft from the nozzles.



**Figure 6.4 Snowmaking In High Winds With the Tower at a Steep Vertical Angle**



**Figure 6.5 Frozen Tower Head and Nozzles**

### *Snow Inducer Concentration*

Snomax™ Snow Inducer was used in four of the tests. The Snomax™ injection system is only available at the mountain top testing site. Therefore, the product could be used in only four tests. The results of these tests do not provide insight to the effectiveness of the product. However, conversations with the snowmaking staff during testing, as well as conversations with other industry professionals, confirm the usefulness of the product. While the manufacturer recommends a dosage of 1 liter per 1,000 gallons of water, snowmakers at Seven Springs prefer a concentration of 1 liter per 100,000 gallons (ice nucleating activity per bag of this mixture is unknown). This quantity of Snomax™ has been proven to significantly enhance their ability to make snow in marginal temperatures.

### *Water and Compressed Air Temperature*

The test results for Test 2 include temperature data for the air and water travelling between the hydrant and the tower. Temperatures were measured near the connection at the ends of both hoses. Results prove that significant cooling occurs in both fluids once exiting the hydrants from underground. While the water cooled to the ambient temperature of 14°F (-10°C), the air cooled to 7°F (-14°C). This could be a result of minor expansions within the air passage at this location.

### *Ambient Conditions*

The ambient conditions observed during snowmaking tests include dry and wet bulb temperature, humidity, wind speed and direction, and weather (i.e. sunny, flurries, etc.). These conditions often determined the appropriate operational settings for testing. Each of the ambient parameters exhibited a large variance during each test, and among

the group of tests. Therefore, conclusions regarding the effects of ambient conditions on snowmaking are general in nature.

Snowmaking tests were conducted in ambient dry bulb temperatures ranging from -5°F to 33°F (-21 C to 1°C). If all other parameters had been held constant, a better quality of snow would have been achieved for decreases in temperature. However, other parameters, including air/water ratio, water flowrate, and tower orientation, fluctuated among tests.

During Test 11, the dry bulb temperature ranged from -5°F to 17°F. Humidity was generally low, providing a maximum wet bulb temperature of 13°F. The average density for this test ranked the highest among all tests at 32.7 lbs/cf. This is largely due to the fact that no compressed air was used during the test. Had wet bulb temperatures not climbed above 10°F (near the static freezing point of water), it is presumed that the average density would have been much lower.

In Test 6, the dry and wet bulb temperatures were 30°F. The test was cancelled after 10 minutes when it was observed that virtually none of the water was freezing. Had Snomax™ been used in this test, it is believed that some of the material would have frozen. As mentioned in the literature review, Snomax™ has been proven to raise the static freezing point of water to 28°F.

Weather conditions affected the accuracy of test results on a few occasions. In Tests 1, 5 and 14, a significant amount of natural snowfall was observed. During the last few hours of Test 14, 15 to 20 mph winds were observed. The high winds and reported 2 in of natural snowfall rendered the results of Test 14 useless. Negative depths were measured at some locations in the test grid due to the effects of drifting snow. The high winds also made it difficult to observe how much of the snow at each location could be attributed to snowmaking.

### ***6.1.2 Natural Snow***

Five natural snow samples were taken through the winter. The results are presented in Table B.18. Temperatures at the time of accumulation ranged between 13° and 33°F (dry bulb). Accumulation surfaces included grass, gravel, and pavement. Four of the samples were naturally accumulated snow, while one sample was plowed snow.

Natural snow, accumulated on the grass, had densities near 6 lbs/cf. Plowed snow exhibited a higher density (10.7 lbs/cf), as it had been compacted by plowing equipment. Accumulation on the pavement in the warmer temperatures had the highest densities (16.4 and 19.9 lbs/cf). Pavement has the ability to prevent any significant amount of drainage from melting snow. Therefore, a slushy layer developed at the base of accumulation when near-freezing temperatures allowed some of the snow to melt. These samples, which included the slush, were the heaviest and had the poorest quality.

### ***6.1.3 Wind Conditions on the Smart Road***

On three non-consecutive days, wind conditions were observed on the Smart Road. Results are presented in Table B.19. On the first day, wind speed was the highest, gusting to 40 mph in the middle of the snowmaking section of the road. Wind was less intense at the beginning and end of the half-mile section, blowing at 5 to 20 mph. At all locations the wind direction was steady, blowing out of the west and down the road.

A bell-shaped curve describing wind speed over the distance of the road became apparent through the second day of testing, although the winds were less intense (8 to 10 mph in the middle). The massive “cut” through the mountain in which the road lies is deepest at the center of the snowmaking section, and trails off somewhat at the ends of the section on both sides. This topographic feature provides a suction effect, lifting air out of the valley and forcing it up the road on some days, or blowing it straight down the

road towards the east on other days. As the air squeezes through the deepest part of the cut, it picks up speed, and then slows down again as the cut becomes shallow.

On the third and final day of testing, winds were calm at all locations of the road and maintained a westerly flow.

## **6.2 Theoretical Results**

Theoretical results include the output of the Aspen Plus thermodynamic simulation and the resultant snow production from adjacent towers estimated by the method proposed in 5.3. Results are presented in the Appendix and discussed here.

### ***6.2.1 Thermodynamic Modeling and Analysis of Water and Compressed Air Systems***

The goal of thermodynamic modeling and analysis was to assess the benefits of compressed air aftercooling with respect to cooling and moisture removal. The Aspen Plus simulation tested the model at low, medium and high flow demands. The results of the simulation are presented in Table B.20. The results of the simulation show:

- For all flows, and when the aftercooler is not modeled, the compressed air cools to ground temperature (50°F) in the pipeline prior to reaching the first snowmaking tower. Subsequently, the addition of an aftercooler would have no effect on the final temperature of the compressed air. The air would cool to ground temperature within the pipe for any initial temperature at or below 190°F.
- For all flows, with or without the aftercooler, the temperature increases of the water in the tower due to conduction through the slightly warmer compressed air are negligible.

- For all flows, with or without the aftercooler, the compressed air, as it expands through the air nozzle, reaches extremely low temperatures (less than -300°F) in the region surrounding the orifice.
- For all flows, and without the addition of an aftercooler, condensed moisture is present throughout the system.

### ***6.2.2 Theoretical Resultant Snow Production from Adjacent Towers***

A method was created to predict the resultant overlapping snow production from adjacently operating towers. The results of this analysis are presented in Table B.21. The method was used to compute a range of factors with which a minimum and maximum resultant accumulation could be assigned to a target snowfall intensity for an individual tower. Using the snowfall intensity data from snowmaking tests, the range of factors for the operation of every tower was found to be 0.5 to 2.0. This means that if the water flowrate travelling through one tower is set to produce 1 inch per hour of snow, the accumulation on the road from adjacently operating towers will be at least 0.5 inches and at most 2.0 inches. The range of factors for the operation of every other tower was found to be 0.2 to 1.2.

As expected, a narrower range of accumulation values is obtained when every consecutive tower is used. This is because the operation of consecutive towers ensures complete coverage across the roadway. The operation of every other tower leaves gaps in snowfall where almost no snow accumulates. This expands the range of intensities by ensuring that there is zero accumulation at some points.

The results of this work were used in the development of the parameter matrix (Section 7.2). The range of accumulation factors aids in determining the flowrate needed for each tower to produce the desired range of snowfall intensities.

## Chapter 7 - Conclusions

### 7.1 Goals Accomplished

The research presented in this work aided in the construction of a design methodology to implement efficient snowmaking at a transportation research facility. The conclusions of this research are supported by experimental and theoretical tests. Experimental testing included a series of snowmaking tests, a characterization of natural snow, and observation of wind conditions at the site of the transportation research facility. Theoretical testing included the modeling and analysis of the snowmaking system and the construction of a method to predict the resultant snow production from adjacently operating snowmaking towers. The results of these tests were used to produce a set of matrices that describe the optimal operational parameter settings for the Smart Road snowmaking system to meet the required snowmaking demands in various ambient environments.

All of the snowfall intensity demands can be satisfied within the constraints of the snowmaking system. Artificially created snowfalls will be homogeneous with respect to quality and accumulation, within certain limits. A method was created to define these limits (Section 5.3). The manufactured snowfalls will recreate the appearance of natural snowfalls with limited success. While a driver passing through the man-made storm will experience realistic visibility impairment, the form and shape of the falling precipitation does not accurately represent nature's snowflakes. Accumulation on the roadway will resemble that of the wet, dense snow that accumulates on roadways in near-freezing (or near-melting) temperatures.

A goal of snowmaking at a transportation research facility is to produce the highest quality and lowest density snow. Quality 1 or 2 snow with a density between 20 and 25 lbs/cf shall be considered fulfillment of this goal, as a higher quality is virtually unattainable and a lower quality will be considered undesirable in most cases.

## **7.2 Optimized Parameter Matrices**

The optimized parameter matrices, to be used by operators on the Smart Road for efficient snowmaking, are presented in this section. A separate matrix has been created for each demand of snowfall intensity. A general discussion in 7.2.1 provides conclusions and recommendations for snowmaking with regards to each operational and ambient parameter.

### ***7.2.1 General Discussion***

An optimized parameter matrix has been defined for each range of snowmaking intensities. This range is bounded by the minimum and maximum snowfall intensities expected on the road under the specified operational and ambient conditions. The matrices address each of the parameters identified in 1.2, with the exception of water and compressed air temperature, horizontal tower orientation, and wind speed and direction. These parameters were left out of the matrices because their optimization does not vary with each snowmaking demand intensity or ambient temperature. Optimization of these parameters, as well as those included in the matrices are discussed as follows:

#### **Water Temperature**

Water will enter the Smart Road storage tank at ground temperature (50°F). The water is then cooled by aeration in the cold ambient air. Optimally, water will be cooled to near freezing temperatures. However, timing of the demands placed on the snowmaking system may inhibit complete cooling of the water. Efficient snowmaking dictates that the water temperature should be less than 40°F. Warmer water temperatures (at or above 40°F) will require that concentrations of snow inducer approach the high end of the range provided in the matrices. Additionally, snowmaking with warm water necessitates a high air/water ratio to provide additional atomization and heat transfer.

The high water flowrates required for a blizzard snowfall intensity limit the air/water ratio to below acceptable values for producing high quality snow. Therefore, snow production of this intensity should not take place when the water can not be cooled to below 40°F.

### **Compressed Air Temperature**

On the Smart Road, compressed air temperature will be controlled at the aftercooler. The present research has demonstrated that compressed air cools to ground temperature regardless of the discharge temperature at the aftercooler. Therefore, cooling the compressed air only serves to reduce the moisture content of the air. There is no prescribed formula for determining the most effective concentration of water vapor for snowmaking. Therefore, the operator should use judgement in determining the effects of compressed air moisture content on the quality and production of snow. If the air hoses or air lines in the towers show signs of freezing, then the moisture content is too high, and the compressed air should be cooled more to remove moisture.

### **Horizontal Tower Orientation**

The snowmaking towers pivot 360° in the horizontal axis. The position of the tower in this axis should be located to target the snow within the shoulders of the roadway. The speed and direction of the wind will dictate the best horizontal orientation for the towers. The spray from the nozzles should always travel at an acute angle with the prevailing winds. This ensures maximum hang time for droplets to freeze.

## **Wind Speed and Direction**

The wind direction on the Smart Road is consistently parallel to the road. This is to the benefit of the snowmaking operator, who would have no chance of landing snow on the road if the wind was at an angle more perpendicular to the road. For winds up to 10 mph, efficient snowmaking can satisfy all demand intensities. For winds greater than 10 mph, more output is required from each tower to counteract the loss of snow due to drift. Widespread snow accumulation under high wind conditions may be undesirable. In the case of the Smart Road, where the nearby east-bound lane of traffic is open to the public, snowmaking may prove hazardous under these circumstances.

## **Nozzle Configuration**

Two proposed nozzle configurations are listed in the matrices (20-20-30 and 30-30-30). Both of these nozzle configurations can be used to create each of the demand snowmaking intensities. The operator adjusts water flow through the tower by changing the pressure or by opening the auxiliary nozzles (an “x” is noted in the configuration where the auxiliary nozzles are not activated).

The flexibility to achieve all of the demand intensities with one nozzle configuration saves the operator from having to change the nozzle configuration between tests of different intensity (a process that could take 20 man-hours). The medium-sized droplets produced with the 5020 and 5030 nozzles are conducive to freezing and will not drift or evaporate as readily as smaller droplets will.

## **Water Pressure and Flow**

In each matrix, a water pressure is listed that will provide adequate flow through the nozzles to meet the desired snowmaking demand intensity. In the case where two

pressures are listed, the first pressure should be used with the first nozzle configuration listed, and the second pressure used with the second nozzle configuration listed. The minimum water pressure needed to produce quality snow with the HKD Spectrum snowmaking tower is 180 psi. The maximum pressure that can be provided by the Smart Road snowmaking system is 440 psi. The maximum water flowrate is 3000 gpm. The flowrate is the limiting factor in the highest intensity parameter matrix.

### **Compressed Air Pressure and Flow**

The design pressure of the air compressors on the Smart Road is 125 psi. The only case in which the pressure will not be maintained at this point is when the volumetric flow demand exceeds the design point of 6400 cfm. After this point, the compressors will attempt to meet the flow demand while sustaining a loss in pressure. When all 75 towers are in operation, the compressors will not be able to meet the demand, and the pressure will drop to between 85 and 100 psi.

When the wet bulb temperature drops below 10°F the air can be turned off.

### **Snow Inducer Concentration**

Snow inducer will improve snow quality in temperatures above 15°F, raising the spontaneous nucleation temperature of the water from around 15°F to near 28°F. In warmer temperatures, the concentration of snow inducer should be designed to provide at least one nucleation site for every hundred water droplets. When the supply water is warm (greater than 40°F), or the quality of snow already being produced is otherwise insufficient, this concentration should be increased to provide one nucleation site for every water droplet. Table A.3 in the Appendix will help the operator to match the required mixture of snow inducer with the droplet size being produced. Figure A.1 can be used to find the droplet size produced for a given nozzle and water pressure.

## **Vertical Tower Orientation**

For the lightest snowmaking intensity, the tower is oriented at the highest possible angle. This procedure effectively “wastes” the excess snow being created by the towers by allowing it to drift or evaporate. The idea of wasting a product in an efficient operation seems like a paradox. However, this procedure is necessary because even with the water pressure at a minimum, too much snowfall would result on the roadway if the tower were positioned at a lower angle. For higher snowfall intensities, the tower is lowered, as less snow has to be wasted. The tower should never be positioned at an angle less than  $35^{\circ}$  because of the freeze-up problem associated with drainage following operation.

## 7.2.2 Matrices

**Table 7.1 Optimized Parameter Matrix for 0 to ¼ in/hr Snowfall Intensity**

Intensity (IN / HR)	0 - 1/4				
Wet Bulb Temp (F)	< 10	10 - 15	15 - 20	20 - 25	25 - 28
Towers	every other	every other	every other	every other	every other
Nozzles (TOP-MID-BOTTOM)	20-20-X 30-30-X	20-20-X 30-30-X	20-20-X 30-30-X	20-20-X 30-30-X	20-20-X 30-30-X
Water Pressure (PSI)	180	180	180	180	180
Air Pressure (PSI)	0	125	125	125	125
Snow Inducer (nucl. sites / drops H2O)	0	0	1:1 to 1:100	1:1 to 1:100	1:1 to 1:100
Vert Tower Angle	70 - 80	70 - 80	70 - 80	70 - 80	70 - 80

**Table 7.2 Optimized Parameter Matrix for ¼ to ½ in/hr Snowfall Intensity**

Intensity (IN / HR)	1/4 - 1/2				
Wet Bulb Temp (F)	< 10	10 - 15	15 - 20	20 - 25	25 - 28
Towers	every other	every other	every other	every other	every other
Nozzles (TOP-MID-BOTTOM)	20-20-X 30-30-X	20-20-X 30-30-X	20-20-X 30-30-X	20-20-X 30-30-X	20-20-X 30-30-X
Water Pressure (PSI)	180	180	180	180	180
Air Pressure (PSI)	0	125	125	125	125
Snow Inducer (sites / drops H2O)	0	0	1:1 to 1:100	1:1 to 1:100	1:1 to 1:100
Vert Tower Angle	50 - 70	50 - 70	50 - 70	50 - 70	50 - 70

**Table 7.3 Optimized Parameter Matrix for ½ to 2 in/hr Snowfall Intensity**

Intensity (IN / HR)	1/2 - 2				
Wet Bulb Temp (F)	< 10	10 - 15	15 - 20	20 - 25	25 - 28
Towers	every	every	every	every	every
Nozzles (TOP-MID-BOTTOM)	20-20-X 30-30-X	20-20-X 30-30-X	20-20-X 30-30-X	20-20-X 30-30-X	20-20-X 30-30-X
Water Pressure (PSI)	180	180	180	180	180
Air Pressure (PSI)	0	89 - 100	89 - 100	89 - 100	89 - 100
Snow Inducer (sites / drops H2O)	0	0	1:1 to 1:100	1:1 to 1:100	1:1 to 1:100
Vert Tower Angle	35 - 50	35 - 50	35 - 50	35 - 50	35 - 50

**Table 7.4 Optimized Parameter Matrix for 1½ to 5 in/hr Snowfall Intensity**

Intensity (IN / HR)	1 1/2 - 5				
Wet Bulb Temp (F)	< 10	10 - 15	15 - 20	20 - 25	25 - 28
Towers	every	every	every	every	every
Nozzles (TOP-MID-BOTTOM)	20-20-30 30-30-30	20-20-30 30-30-30	20-20-30 30-30-30	20-20-30 30-30-30	20-20-30 30-30-30
Water Pressure (PSI)	330 200	330 200	330 200	330 200	330 200
Air Pressure (PSI)	0	89 - 100	89 - 100	89 - 100	89 - 100
Snow Inducer (sites / drops H2O)	0	0	1:1 to 1:100	1:1 to 1:100	1:1 to 1:100
Vert Tower Angle	35	35	35	35	35

### **7.3 Future Calibration and Research**

Once the Smart Road's All-Weather Testing system becomes operational, additional testing should be conducted to confirm or adapt these recommendations. Each parameter should be isolated and tested under a range of ambient and operational conditions. The subject of aftercooling should be studied further to determine the optimal compressed air moisture content for snowmaking. Specific cost figures were unavailable at the time of this report, therefore operation may be optimized further to account for cost variables such as electrical energy and snow inducer.

Additional research based on the present study could study ways to implement the simulation of various other forms of precipitation on a transportation research facility. The production of rain, fog and sleet each demand their own methodology. There may also be a need in the future, pending the success of the Smart Road, to develop weather generating equipment that is specific to weather simulation on a transportation research facility.