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Field Performance of a Slimline Turbomist Evaporator under Southeastern U. S. Climate Conditions (U)

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Field Performance of a Slimline Turbomist Evaporator under Southeastern U. S. Climate Conditions

1.0 INTRODUCTION

A recent study of evaporation technologies for treating F- and H-area groundwater contaminated with radionuclides and metals (Flach 2002) suggested that spray evaporation might be a viable alternative or supplemental technique for managing tritiated groundwater at the Mixed Waste Management Facility (MWMF). The particular technology of interest in this study is the Slimline Manufacturing Ltd. Turbo-Mist Evaporator, which uses a powerful blower and high-pressure spray nozzles to propel a fine mist into the air at high air and water flowrates (Figure 1). The evaporator relies on the sensible heat that can be extracted from low (<100%) humidity air to drive evaporation. Incoming "dry" air is brought into contact with the spray field through a combination of the mechanical blower and natural wind, and simultaneously cooled and humidified through evaporative cooling. Because the energy for evaporation comes from a natural source, the overall cost is low compared to evaporation by direct heating.

In general, spray evaporation provides a method for reducing wastewater volume and concentrating contaminants. A concentrated waste stream can usually be treated more economically than a higher volume stream containing the same waste loading. At the MWMF Southwest Plume, a phytoremediation system has been constructed to remediate groundwater contaminated principally with tritium. Contaminated groundwater is collected ahead of a sheet pile dam constructed below natural seeps. The water is then distributed through an extensive spray irrigation system in the surrounding forest. Irrigation rates are adjusted to maximize evapotranspiration while minimizing infiltration past the root zone to the water table. Drought conditions in recent years have been favorable to system performance, and enabled the current irrigation field to meet demand. However, in wetter years and during winter months when evapotranspiration rates are low, the capacity of the irrigation field may not be adequate. In this situation a spray evaporator could potentially provide additional capacity to counter lower irrigation field capacity. The focus of the field evaluation is measuring the performance of the Turbo-Mist evaporator under SRS climate conditions for potential deployment at the MWMF.

Evaporation rate is affected by a number of factors including, the flowrate, temperature and humidity of the air contacting the spray field, and the spatial distribution, residence time, and size of spray droplets. Hot, dry, and windy conditions are most favorable to the spray evaporation, and Turbo-Mist units have been commercially deployed with success at several arid or semi-arid locations in North America (www.turbomist.com/cgi-bin/division.cgi?Wastewater). Quantitative performance or design data for the more humid Southeast United States was not available from Slimline Manufacturing Ltd. during the previous study (Flach 2002). The main objectives of the present study were to 1) develop optimal configurations of the Slimline Turbo-Mist under a variety of SRS field conditions to achieve maximum evaporation and minimal spray fall-back, 2) accurately measure the evaporation and fall-back rates for the optimal configurations and common field conditions, and 3) develop a model capable of predicting Turbo-Mist performance under SRS field conditions with adequate accuracy for design purposes.

Figure 1 Vendor photographs of Slimline Turbo-Mist evaporator.

2.0 EVAPORATION PRINCIPLES

When "dry" (<100% humidity) air is brought into contact with liquid water, with no heat transfer to or from the overall system, liquid evaporates and air is cooled until thermodynamic equilibrium is reached (100% humidity). Such an operation is termed "adiabatic saturation", and is the principle behind "swamp coolers" used for residential cooling in the Southwest US and agricultural cooling (e.g. poultry houses). The energy required to vaporize liquid water (latent heat of vaporization) is extracted from dry air through cooling (sensible heat). The amount of cooling as a function of temperature and relative humidity of the incoming air stream can be determined through application of the first law of thermodynamics, which states that enthalpy is conserved in a open system (cf. Reynolds and Perkins 1977). With minor approximation, the adiabatic saturation process can be described by:

$$h^*_{in} = \left(h_a + \gamma h_w\right)_{in} = \left(h_a + \gamma h_w\right)_{out} = h^*_{out} \qquad (1)$$

where h^* = enthalpy of moist air per unit mass of dry air, h_a = enthalpy of dry air, h_w = enthalpy of water vapor, γ = specific humidity or humidity ratio (Reynolds and Perkins 1977 section 10-4). The thermodynamic properties of moist air can be readily computed from an ASHRAE handbook (e.g. American Society of Heating, Refrigerating and Air-Conditioning Engineers 1985) for equivalent source.

An example calculation is shown in Table 1, where the temperature and humidity of the incoming air stream have been set to the annual averages at the SRS, 65F and 68% (Hunter and Tatum 1997). For these conditions, the evaporative cooling is 6.6 ºF. Figure 2 shows contours of constant evaporative cooling degrees resulting from various combinations of temperature and relative humidity. As illustrated by the plot, higher temperature and lower humidity produce more cooling and corresponding evaporation. Also shown in Figure 2 are seasonal average values of temperature and humidity at the SRS. Table 2 identifies the basis for these values and provides monthly average values as well.

Spray evaporation under atmospheric conditions is expected to be proportional to the cooling and evaporation amounts computed under adiabatic saturation conditions (Figure 2). For evaporation to be sustained, dry air (and water) must be continuously supplied to replenish the system. An energy balance expanding on equation (1) indicates that evaporation of initially dry air and evaporation of liquid water is proportional to the mass flowrate of dry air delivered to the system. For atmospheric spray evaporation, fresh air is delivered to the spray field through natural winds. Thus, the spray evaporation rate is also expected to be proportional to local wind speed. The overall dimensions of the spray field, and the distribution, residence time, and size of spray droplets within, are also expected to affect the evaporation rate. For example, the flowrate of dry air contacting the spray field is proportional to the cross-sectional area perpendicular to wind direction, in addition to wind speed.

In summary, spray evaporation under field conditions is expected to be proportional to the evaporative cooling potential based on adiabatic saturation and wind speed. Characteristics of the spray field will also affect the evaporation rate.

Table 1 Adiabatic saturation calculation for SRS annual average climate conditions.

Adiabatic saturation / swamp cooler calculation using ASHRAE (1985) equations

Constants								*source*
univ. gas const.	*R*	1545.33	ft-lbf/(lbmole-R)					
molecular wt. air	M_a	28.9645	lbm/lbmole					
air gas constant	R_a	53.35	ft-lbf/(lbm-R)					
Incoming air stream								
pressure	p	14.7	psia					
temperature	t	65	F	18.3	C	524.67	R	
relative humidity	ϕ	68%	unitless					
sat. pressure	p_{ws}	0.3097	psia					eqn (4)
water vap. pres.	p_w	0.2106	psia					eqn (22)
humidity ratio	W, γ	0.009040	unitless	63.28	grains/lbm_a			eqn (20)
sat. humidity ratio	W_s	0.013386	unitless					eqn (21)
deg. of saturation	μ	0.6753	unitless					eqn (10)
specific volume	ν	13.42	ft^3/lbm_a					eqn (26)
		13.30	ft^3/lbm					using (1+γ) factor and eqn (26)
		13.22	ft^3/lbm					using ideal gas law
specific enthalpy	h	25.45	BTU/lbm_a					eqn (30)
Outgoing for adiabatic saturation/evaporation								
pressure	p	14.7	psia					
temperature	t	58.35	F	14.6	C	518.02	R	
relative humidity	ϕ	100%	unitless					
sat. pressure	p_{ws}	0.2448	psia					eqn (4)
water vap. pres.	p_w	0.2448	psia					eqn (22)
humidity ratio	W, γ	0.010532	lbm_w/lbm_a	73.72	grains/lbm_a			eqn (20)
sat. humidity ratio	W_s	0.010532	unitless					eqn (21)
deg. of saturation	μ	1.0000	unitless					eqn (10)
specific volume	ν	13.28	ft^3/lbm_a					eqn (26)
		13.14	ft^3/lbm					using (1+γ) factor and eqn (26)
		13.06	ft^3/lbm					using ideal gas law
specific enthalpy	h	25.45	BTU/lbm_a					eqn (30)
Differences								
temperature	Δt	-6.6	F					
relative humidity	$\Delta\phi$	0.32	unitless					
enthalpy	Δh	0.00	BTU/lbm_a					
humidity ratio	ΔW, $\Delta\gamma$	0.001492	lbm_w/lbm_a	10.44	grains/lbm_a			

Table 2 Average climate conditions at the SRS over various time periods.

Period	Temp (ºF) T[1]	Relative Humidity (%) Ø[2]	Wind Speed (mph) V[2]
Annual	64.8	69.8	5.4
Winter	48.4	68.2	5.7
Spring	64.5	66.4	6.1
Summer	80.3	72.4	5.0
Fall	65.9	72.1	4.7
Dec	49.3	72.1	5.5
Jan	46.2	68.2	5.8
Feb	49.7	64.3	5.8
Mar	57	63.8	6.5
Apr	64.5	64.3	6.3
May	72.1	71.0	5.5
Jun	78.7	72.7	5.4
Jul	81.7	70.1	4.8
Aug	80.5	74.3	4.8
Sep	75.6	72.5	5.1
Oct	65.5	71.6	4.6
Nov	56.5	72.2	4.5
Note 1 Average of SRS data 1970-2000			
Note 2 Average of SRS data 1997-2002			

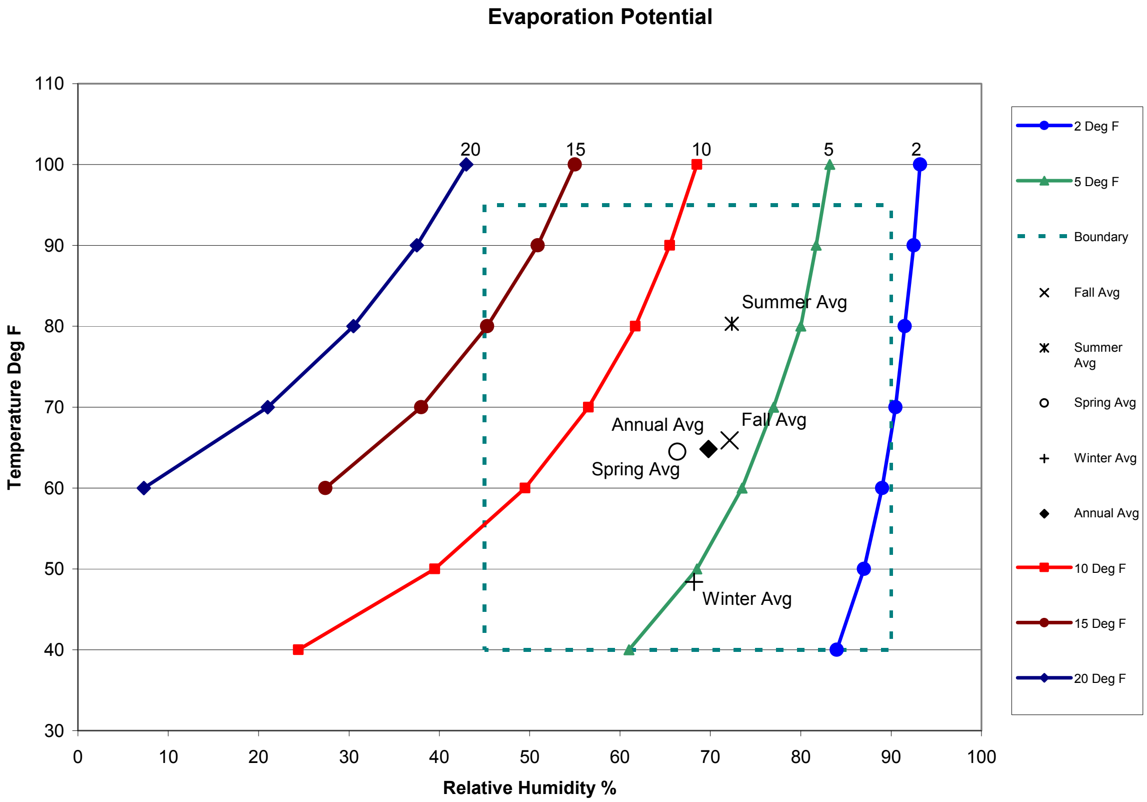

Figure 2 Evaporative cooling potential as a function of temperature and relative humidity.

3.0 EXPERIMENT DESIGN AND SETUP

As stated in the Introduction, one objective of field testing was to identify optimal configurations of the Slimline Turbo-Mist evaporator. For potential deployment at the MWMF over dry land, high evaporation and little or no fallback are considered to be optimal. The unit can be configured with No. 25 or No. 45 nozzle cores, and nozzle orifice plates ranging from D2 through D14 in increasing orifice diameter. An orifice blank can be used if no flow is desired from a nozzle port. The manifold ring accommodates 30 nozzles. Other potential configuration controls are the manifold supply pressure to nozzles, and the inclination of the blower output tube. The air flowrate is fixed by the electric motor speed. Because the number of field tests was limited by budget and schedule considerations, and spray fallback on the F-seepage basin cap was limited by regulators to 25 gpm, not all possible configurations could be tested.

For SRS field testing, the air stream inclination was fixed at the maximum angle of 45 degrees to achieve maximum droplet loft, and the nozzle pressure was fixed at 100 psig. That left nozzle core and orifice plate selection as the attributes open for configuration optimization. Table 3 provides forecasts of the spray rate that will result from various combinations of number of nozzles, nozzle core and orifice plate at 100 psig based on vendor information. Spray rates less than or equal to 25 gpm (but at least 5 gpm) are highlighted as a conservative indicator of evaporator configurations that will avoid fallback exceeding 25 gpm. Turbo-Mist evaporation was roughly estimated from vendor information and engineering judgment to be on the order of 7 gpm for annual average SRS conditions in WSRC-TR-2002-00432. Optimal configurations were assumed to be those producing spray rates of this order of magnitude. From inspection of Table 3, 30 nozzles with orifice sizes D2 through D5 or D7 span the configurations that were anticipated to contain the optimal one for a given temperature and humidity.

To measure evaporator performance for a particular nozzle configuration and weather condition, a grid of collection devices was deployed at the F-seepage basin cap (Figure 3) to measure spray fallback. The evaporation rate was then computed as the measured spray rate minus the fallback rate. The surveyed grid system is depicted in Figure 4. A 20 ft square spacing was used in the center of the grid. Collection devices could be deployed at a variety of grid locations to handle particular weather conditions, primarily wind speed and direction. To handle a wide range of potential fallback amounts over the duration of a field test, both rain gauges and absorbent pads were used (Figure 5). Early testing indicated that rain gauges have a practical detection limit of roughly 0.1”, and perhaps 0.2” is required for reasonable quantification. Absorbent pads can absorb and retain smaller amounts of fallback, approximately 0.2” and lower. Fallback is determined from the area, and dry and wet weights of the pad. Three brands of rain gauges (Figure 6) comprising two types (funnel/graduated cylinder and tipping bucket) were procured for the field testing. The Far View, All-Weather, and Onset gauges are commonly identified as the “Yellow”, “Clear” and “White” gauges, respectively, on procedure, data, and calculation sheets.

Normal deployment of the Slimline Turbo-Mist evaporator allows for up to 15’ of suction head, discharge flows in excess of 66 gpm, and additional water return for the self cleaning filter. To allow full flexibility for the testing, taking in consideration future deployments/test, the unit was purchased from the vendor with the “as supplied water supply pump”. Because of the previously mentioned limitation of 25 gpm fall back limit for testing at this location, and wanting the flexibility to test at low flows, a bypass line was installed. The bypass line allowed for operation at discharge flows down to 5 gpm or less.

Figure 7 schematically illustrates the as-tested configuration of the Slimline Turbo-Mist evaporator at the F-seepage basin cap. Clean water was supplied to the unit via a 4 inch gravity feed PVC pipe. Flowmeters / totalizers were installed on the discharge line and bypass line to determine flows in the entire system. Pressure gauges were located on either side of the strainer and on the discharge line. An adjustable back pressure valve on the bypass line allowed for precise control of the system pressure.

Table 3 Spray rate projected for various nozzle core and orifice plate selections.

Orifice Disc #	Core	PSI	Capacity in GPM at the 100 PSI With xx Nozzles																													
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
D2	25	100	0.250	0.5	0.8	1.0	1.3	1.5	1.8	2.0	2.3	2.5	2.8	3.0	3.3	3.5	3.8	4.0	4.3	4.5	4.8	5.0	5.3	5.5	5.8	6.0	6.3	6.5	6.8	7.0	7.3	7.5
D3	25	100	0.290	0.6	0.9	1.2	1.5	1.7	2.0	2.3	2.6	2.9	3.2	3.5	3.8	4.1	4.4	4.6	4.9	5.2	5.5	5.8	6.1	6.4	6.7	7.0	7.3	7.5	7.8	8.1	8.4	8.7
D4	25	100	0.45	0.9	1.4	1.8	2.3	2.7	3.2	3.6	4.1	4.5	5.0	5.4	5.9	6.3	6.8	7.2	7.7	8.1	8.6	9.0	9.5	9.9	10.4	10.8	11.3	11.7	12.2	12.6	13.1	13.5
D5	25	100	0.54	1.1	1.6	2.2	2.7	3.2	3.8	4.3	4.9	5.4	5.9	6.5	7.0	7.6	8.1	8.6	9.2	9.7	10.3	10.8	11.3	11.9	12.4	13.0	13.5	14.0	14.6	15.1	15.7	16.2
D6	25	100	0.70	1.4	2.1	2.8	3.5	4.2	4.9	5.6	6.3	7.0	7.7	8.4	9.1	9.8	10.5	11.2	11.9	12.6	13.3	14.0	14.7	15.4	16.1	16.8	17.5	18.2	18.9	19.6	20.3	21.0
D7	25	100	0.81	1.6	2.4	3.2	4.1	4.9	5.7	6.5	7.3	8.1	8.9	9.7	10.5	11.3	12.2	13.0	13.8	14.6	15.4	16.2	17.0	17.8	18.6	19.4	20.3	21.1	21.9	22.7	23.5	24.3
D8	25	100	0.97	1.9	2.9	3.9	4.9	5.8	6.8	7.8	8.7	9.7	10.7	11.6	12.6	13.6	14.6	15.5	16.5	17.5	18.4	19.4	20.4	21.3	22.3	23.3	24.3	25.2	26.2	27.2	28.1	29.1
D10	25	100	1.21	2.4	3.6	4.8	6.1	7.3	8.5	9.7	10.9	12.1	13.3	14.5	15.7	16.9	18.2	19.4	20.6	21.8	23.0	24.2	25.4	26.6	27.8	29.0	30.3	31.5	32.7	33.9	35.1	36.3
D12	25	100	1.47	2.9	4.4	5.9	7.4	8.8	10.3	11.8	13.2	14.7	16.2	17.6	19.1	20.6	22.1	23.5	25.0	26.5	27.9	29.4	30.9	32.3	33.8	35.3	36.8	38.2	39.7	41.2	42.6	44.1
D14	25	100	1.65	3.3	5.0	6.6	8.3	9.9	11.6	13.2	14.9	16.5	18.2	19.8	21.5	23.1	24.8	26.4	28.1	29.7	31.4	33.0	34.7	36.3	38.0	39.6	41.3	42.9	44.6	46.2	47.9	49.5
D2	45	100	0.320	0.6	1.0	1.3	1.6	1.9	2.2	2.6	2.9	3.2	3.5	3.8	4.2	4.5	4.8	5.1	5.4	5.8	6.1	6.4	6.7	7.0	7.4	7.7	8.0	8.3	8.6	9.0	9.3	9.6
D3	45	100	0.360	0.7	1.1	1.4	1.8	2.2	2.5	2.9	3.2	3.6	4.0	4.3	4.7	5.0	5.4	5.8	6.1	6.5	6.8	7.2	7.6	7.9	8.3	8.6	9.0	9.4	9.7	10.1	10.4	10.8
D4	45	100	0.56	1.1	1.7	2.2	2.8	3.4	3.9	4.5	5.0	5.6	6.2	6.7	7.3	7.8	8.4	9.0	9.5	10.1	10.6	11.2	11.8	12.3	12.9	13.4	14.0	14.6	15.1	15.7	16.2	16.8
D5	45	100	0.71	1.4	2.1	2.8	3.6	4.3	5.0	5.7	6.4	7.1	7.8	8.5	9.2	9.9	10.7	11.4	12.1	12.8	13.5	14.2	14.9	15.6	16.3	17.0	17.8	18.5	19.2	19.9	20.6	21.3
D6	45	100	0.93	1.9	2.8	3.7	4.7	5.6	6.5	7.4	8.4	9.3	10.2	11.2	12.1	13.0	14.0	14.9	15.8	16.7	17.7	18.6	19.5	20.5	21.4	22.3	23.3	24.2	25.1	26.0	27.0	27.9
D7	45	100	1.11	2.2	3.3	4.4	5.6	6.7	7.8	8.9	10.0	11.1	12.2	13.3	14.4	15.5	16.7	17.8	18.9	20.0	21.1	22.2	23.3	24.4	25.5	26.6	27.8	28.9	30.0	31.1	32.2	33.3
D8	45	100	1.35	2.7	4.1	5.4	6.8	8.1	9.5	10.8	12.2	13.5	14.9	16.2	17.6	18.9	20.3	21.6	23.0	24.3	25.7	27.0	28.4	29.7	31.1	32.4	33.8	35.1	36.5	37.8	39.2	40.5
D10	45	100	1.77	3.5	5.3	7.1	8.9	10.6	12.4	14.2	15.9	17.7	19.5	21.2	23.0	24.8	26.6	28.3	30.1	31.9	33.6	35.4	37.2	38.9	40.7	42.5	44.3	46.0	47.8	49.6	51.3	53.1
D12	45	100	2.20	4.4	6.6	8.8	11.0	13.2	15.4	17.6	19.8	22.0	24.2	26.4	28.6	30.8	33.0	35.2	37.4	39.6	41.8	44.0	46.2	48.4	50.6	52.8	55.0	57.2	59.4	61.6	63.8	66.0
D14	45	100	2.45	4.9	7.4	9.8	12.3	14.7	17.2	19.6	22.1	24.5	27.0	29.4	31.9	34.3	36.8	39.2	41.7	44.1	46.6	49.0	51.5	53.9	56.4	58.8	61.3	63.7	66.2	68.6	71.1	73.5

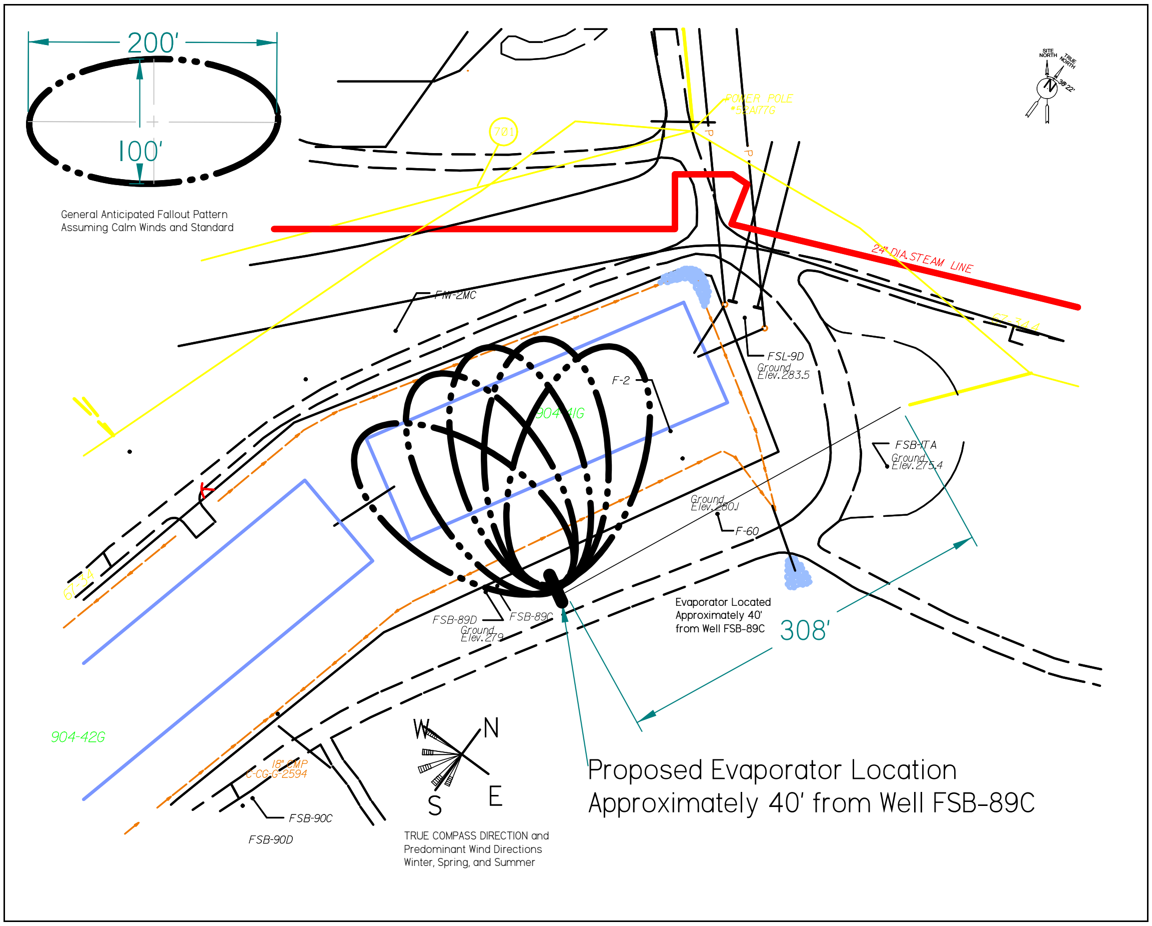

Figure 3 Location of Turbo-Mist field test.

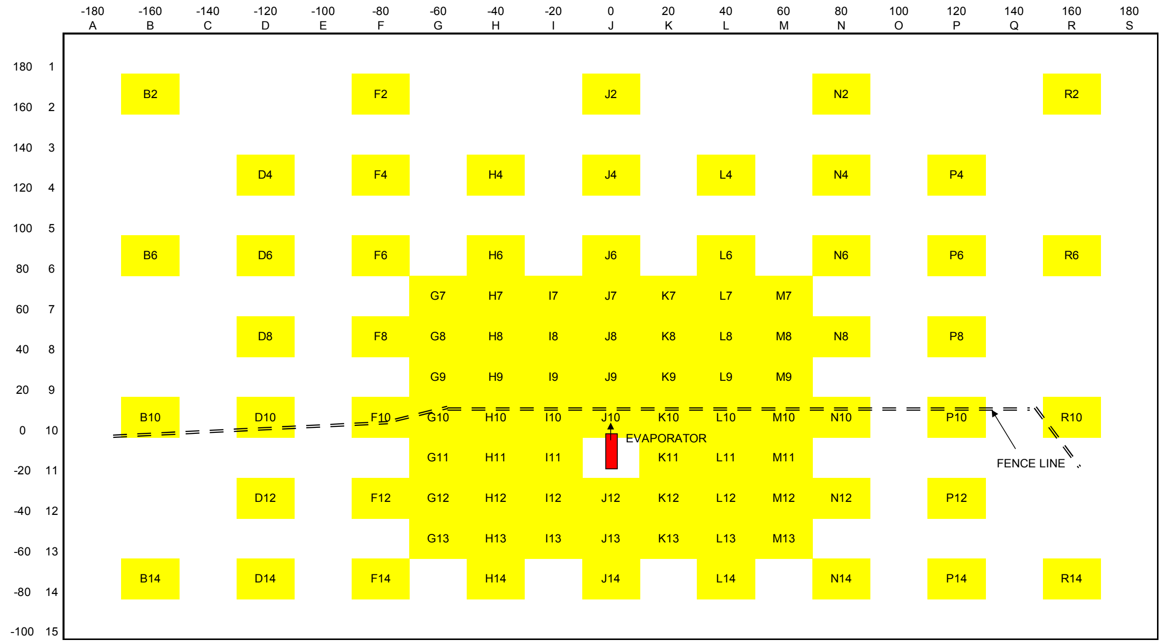

Figure 4 Surveyed grid system for placement of fallback collection devices.

Figure 5 Collection devices selected for measuring spray fallback

(a) Far View (b) All-Weather (c) Onset

Figure 6 Rain gauge brands procured for SRS field testing.

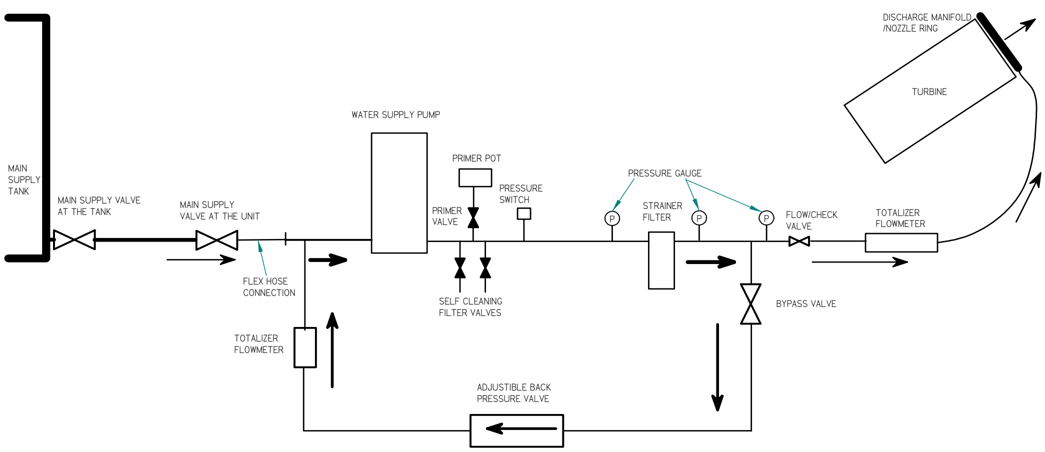

Figure 7 Simplified Piping Configuration

4.0 FIELD TESTING AND DATA

Eight (8) field tests were conducted between March and August of 2003 (Table 4). Prior to the first test on March 31, a number of runs were performed to evaluate test equipment and experimental procedures, adequacy of the surveyed grid system, and performance of rain gauges. Qualitative observation of spray fallback from the initial runs suggested that the detection limit of rain gauges was at least 0.1”. The fine mist produced from the D2 orifices with No. 25 cores during the initial runs would initially adhere to the rain gauge funnel (Far View and All-Weather) or debris screen (Onset). Only after a critical density of droplets had accumulated would droplets coalesce and fall into the graduated cylinder. This observation, and a realization that small amounts of fallback over a large area could be significant, lead to the use of absorbent pads in subsequent tests.

Spray fallback readings from co-located collection devices in the first formal test on March 31 were compared through the series of cross-plots shown in Figures 8-10. The Far-View/Yellow and All-Weather/Clear gauges appeared to be unbiased with respect to each other (Figure 8). The Onset/White gauge appeared to be biased low compared to the Far-View/Yellow (Figure 9) and All-Weather/Clear gauges. This was thought to be a result of the debris screen used in the tipping bucket design, which would retain water in holes through capillary suction. As a result, the Yellow and Clear gauges were used in subsequent tests. Comparison of the absorbent pads and Yellow gauges indicated that the pads are capable of reliably retaining fallback amounts up to 0.2” while at least 0.2” is needed with a rain gauge to avoid readings biased low (Figure 10).

The above observations lead to the following logic for assimilating data from multiple collection devices at individual grid locations:

1. Reading > 0.2” use rain gauge; otherwise use pad

2. Clear preferred over Yellow preferred over White

Readings from the Clear gauge are preferred over the Yellow gauge because the precision of the Clear gauge is 0.01” compared to 0.1” for the Yellow gauge. Figure 11 shows a cross-plot of data from absorbent pads and Yellow gauges across all tests. The plot suggests 0.25” as the optimal cut-off value in retrospect.

For each test a map of spray fallback was created by interpolating the point data from the preferred collection device at each grid location onto a regular 20’ by 20’ grid using a kriging algorithm embedded in Tecplot (Amtec Engineering, Inc.). Numerical integration of the kriged surface produced the total amount of spray fallback for a given test. The fallback rate was computed by dividing the fallback amount by the duration of the test. Detailed calculations for each test are provided in a Controlled Laboratory Notebook (WSRC-NB-2001-00167) and the Appendices.

Table 4 summarizes the evaporator configuration, average weather conditions, and spray fallback for each field test. Because testing was conducted from March through August, periods of rainfall were avoided, and daytime testing was preferred for logistical reasons, most tests were conducted at relatively warm temperatures and moderate humidity. An exception was the 16 hr overnight test beginning at 4:21 PM on March 31 and ending at 8:58 AM on April 1, for which the average conditions were 38.3 ºF, 72% relative humidity, and 1.9 mph wind speed. These conditions are unfavorable for evaporation and the evaporation rate was low.

Figures 12 through 19 shows the spatial distribution of fallback in inches per year for each test. Note that the contour scale varies between plots. For all but the last test using D8 orifice plates, the distribution of fallback was controlled by the prevailing wind direction and heavy fallback was confined to the immediate vicinity of the Turbo-Mist unit. Visual observations suggest this behavior was a result of the small droplet sizes produced by the D2 through D6 orifices. Small droplets have little inertia, and once blown into the atmosphere by the Turbo-Mist, are easily swept along with the natural winds. However, the larger droplets created by the D8 nozzle apparently have sufficient inertia to follow a trajectory in the direction the Turbo-Mist nozzle. In the August 11 test using the D8 orfice plates, the fallback pattern extended out from the unit in the direction of the air nozzle despite a differing prevailing wind direction.

Table 4 Summary of Turbo-Mist field tests.

	Nozzle configuration			Performance		On-site weather			Central Shops 2/4 m tower			Central Shops 18 m tower		
Test date	No.	Cores	Orifices	Spray rate	Evap.	Temp.	Relative humidity	Windspeed	Temp.	Relative humidity	Windspeed	Temp.	Relative humidity	Windspeed
				(gpm)	(gpm)	(F)	(%)	(mph)	(F)	(%)	(mph)	(F)	(%)	(mph)
				Q	E	T	ϕ	V	T	ϕ	V	T	ϕ	V
03/31/03	30	25	D2	6.1	1.81	38.3	72	1.9	39.5	69	2.9	43.1	54	4.4
04/29/03	30	25	D2	6.1	5.31	75.5	60	4.2	77.7	52	4.7	76.0	55	5.7
05/01/03	30	25	D5	15.7	6.49	75.9	67	4.0	78.2	56	7.0	76.7	59	8.8
05/14/03	30	25	D5	16.7	5.71	72.4	46	2.0	NA	NA	NA	NA	NA	NA
06/25/03	30	25	D5	16.2	8.31	87.7	42	2.7	87.9	41	3.7	86.4	41	3.9
06/26/03	27	45	D6	25.5	13.17	87.3	48	4.6	88.0	46	5.0	86.0	46	6.3
07/24/03	27	45	D6	26.1	11.36	82.5	62	3.0	85.0	56	4.4	81.0	59	5.0
08/11/03	30	45	D8	39.2	13.97	85.1	63	2.4	83.5	64	6.5	81.2	66	6.8

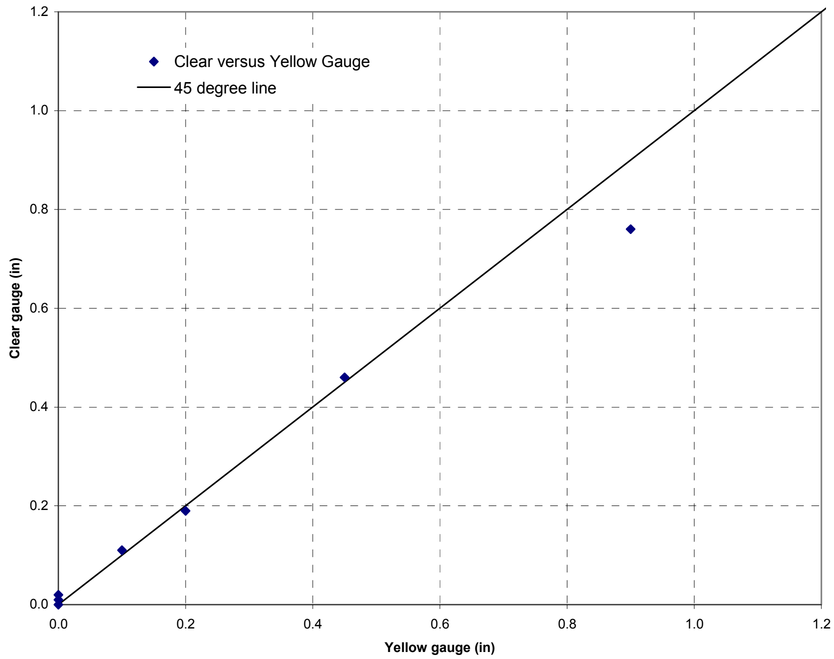

Figure 8 Cross-plot of Clear and Yellow rain gauge data collected during field testing on 3/31/03.

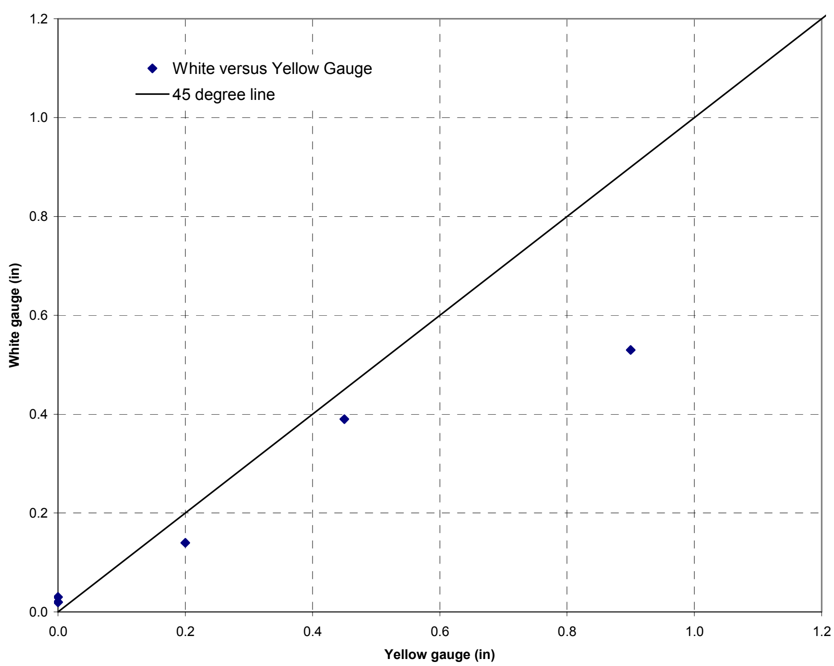

Figure 9 Cross-plot of White and Yellow rain gauge data collected during field testing on 3/31/03.

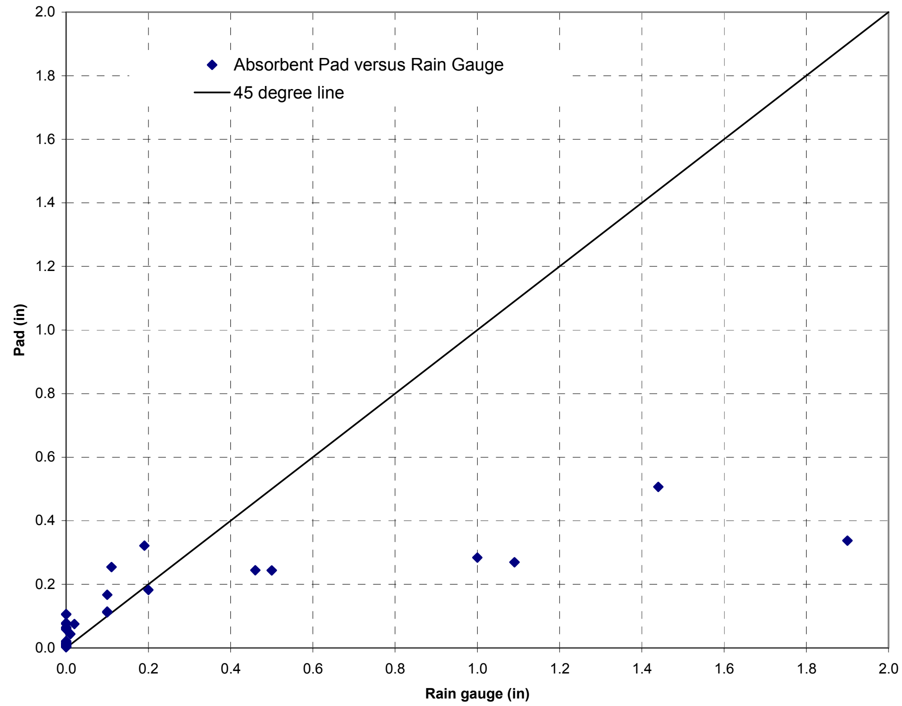

Figure 10 **Cross-plot of absorbent pad and "best" rain gauge fallback data collected during field testing on 3/31/03.**

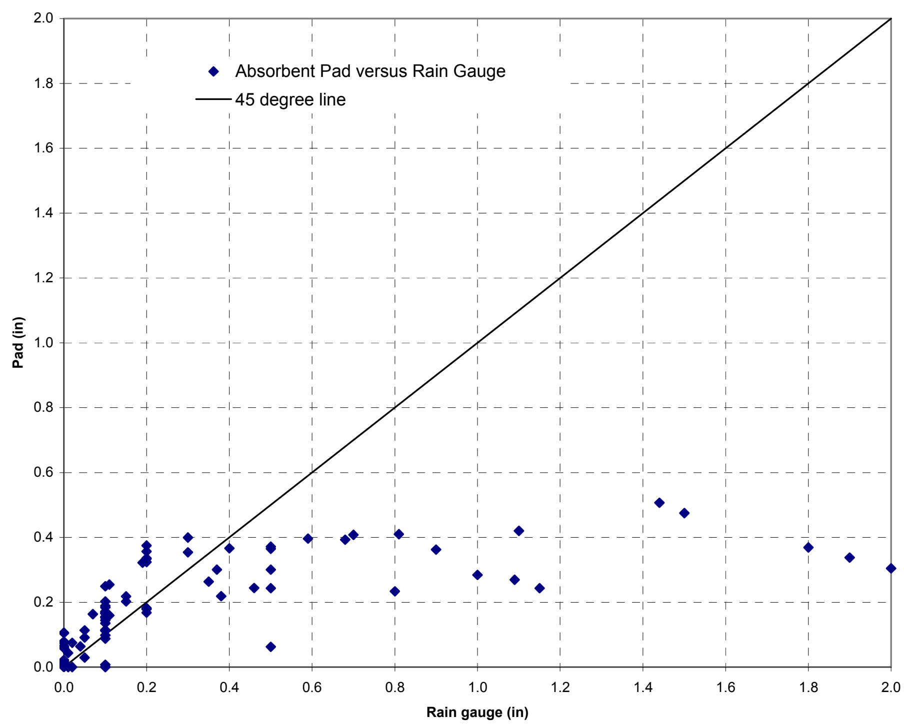

Figure 11 **Cross-plot of absorbent pad and rain gauge data collected from all applicable field tests.**

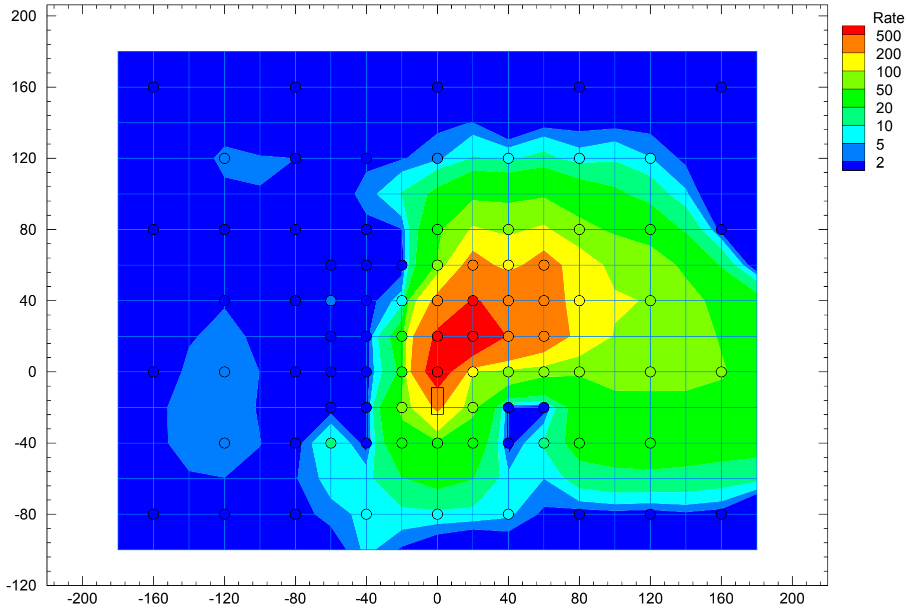

Figure 12 Spray fallback pattern for Turbo-Mist field test on 3/31/03.

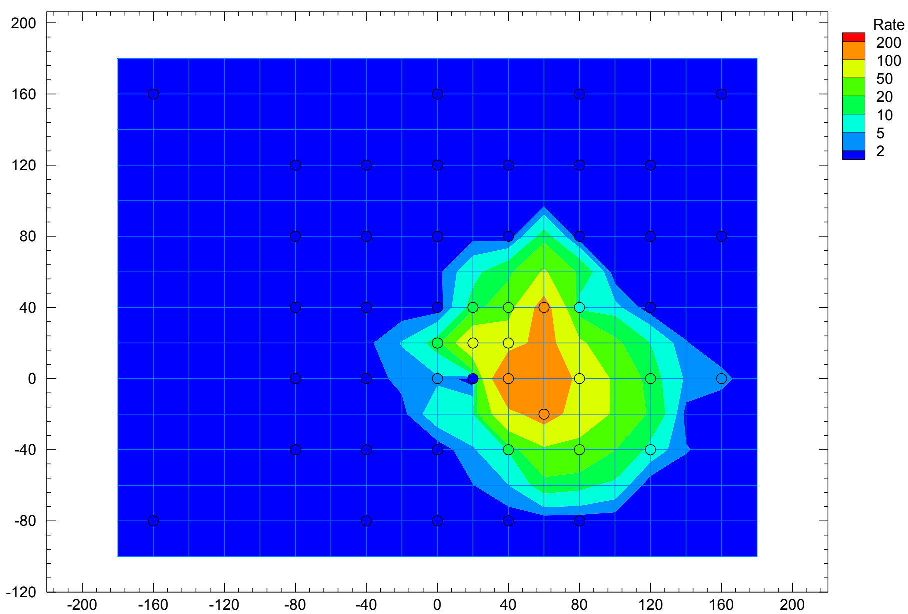

Figure 13 Spray fallback pattern for Turbo-Mist field test on 4/29/03.

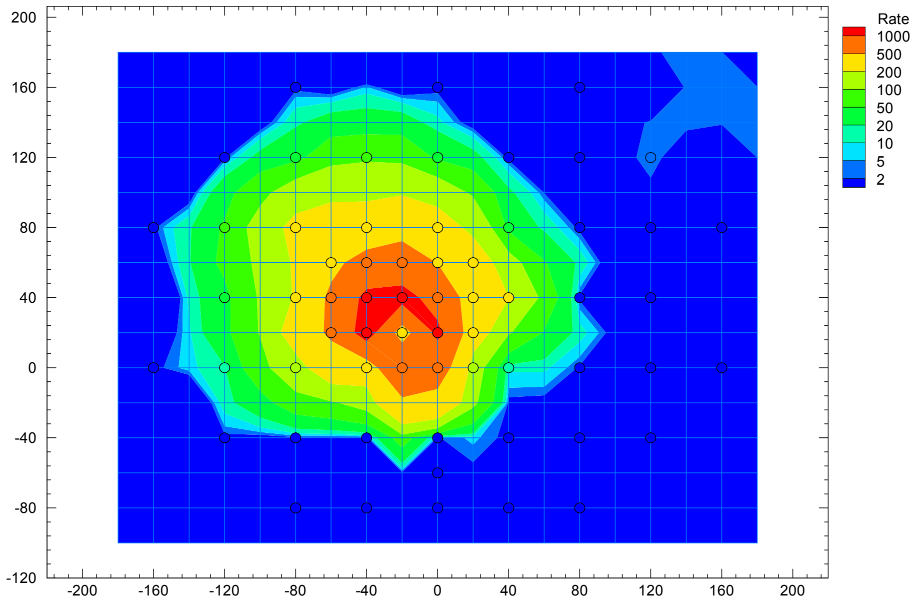

Figure 14 Spray fallback pattern for Turbo-Mist field test on 5/1/03.

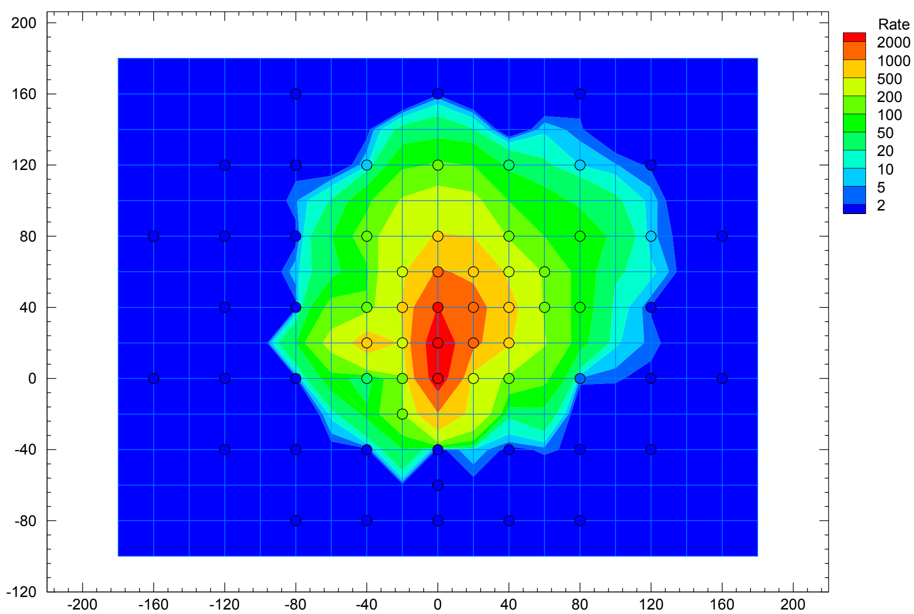

Figure 15 Spray fallback pattern for Turbo-Mist field test on 5/14/03.

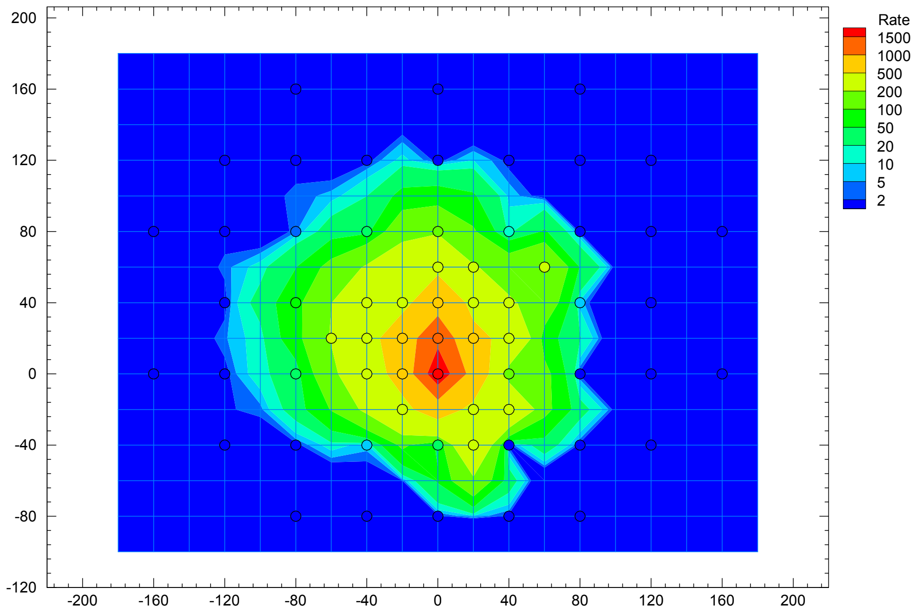

Figure 16 Spray fallback pattern for Turbo-Mist field test on 6/25/03.

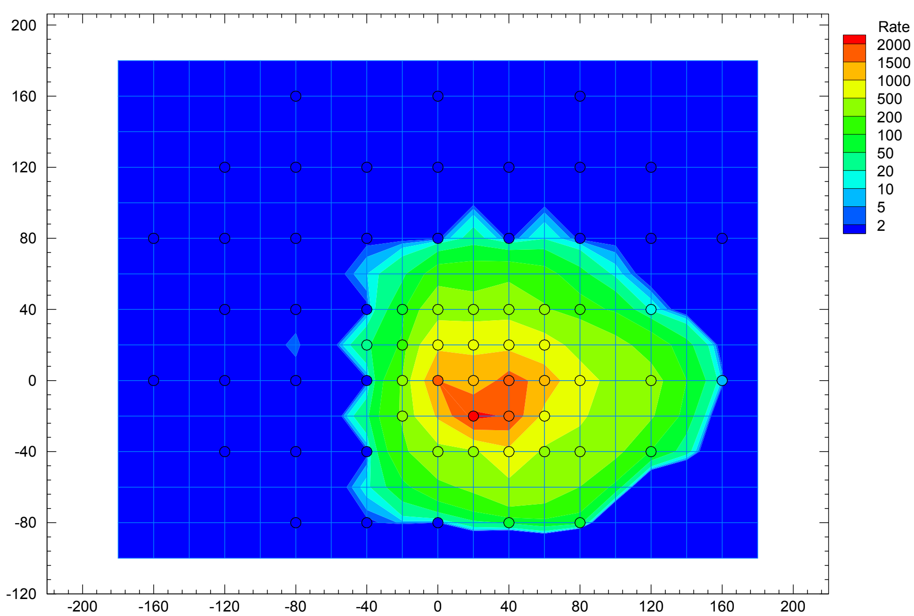

Figure 17 Spray fallback pattern for Turbo-Mist field test on 6/26/03.

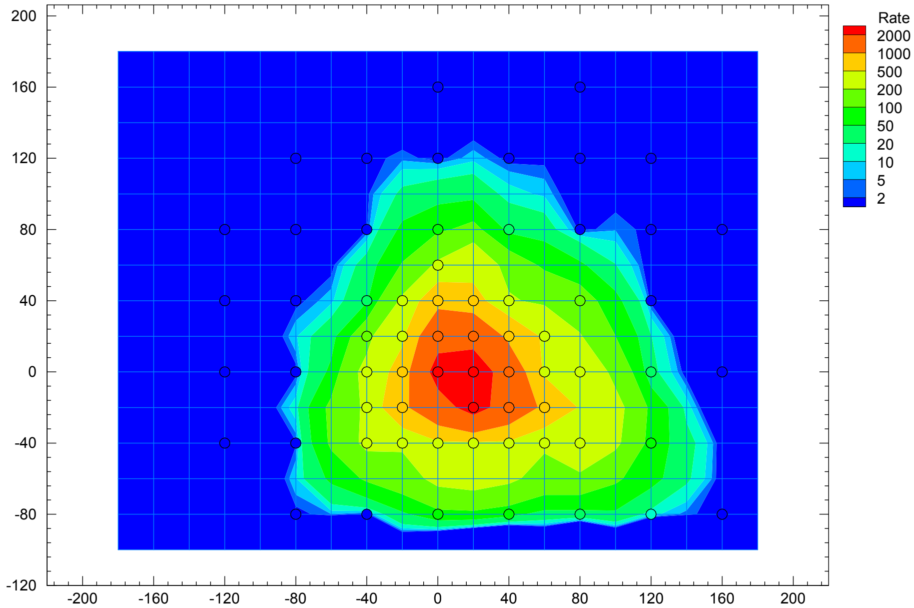

Figure 18 Spray fallback pattern for Turbo-Mist field test on 7/24/03.

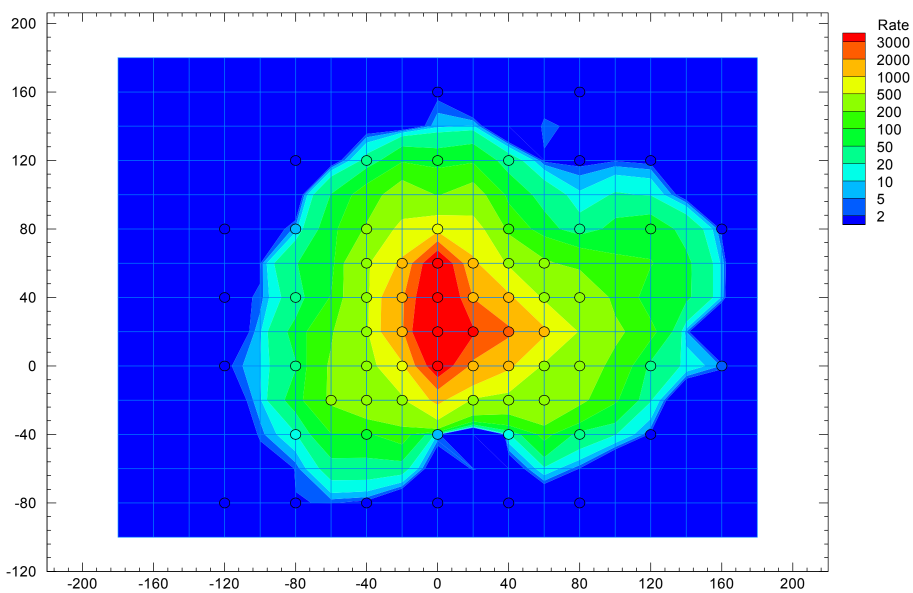

Figure 19 Spray fallback pattern for Turbo-Mist field test on 8/11/03.

5.0 PREDICTIVE MODEL

Because the collection of test data summarized in Table 4 only define Turbo-Mist performance under certain specific conditions, a model capable of predicting performance under arbitrary conditions is desired. Following the previously-stated expectation that the evaporation rate is largely proportional to the evaporative cooling potential based on adiabatic saturation and wind speed, the dimensional evaporation data in Table 4 are first normalized as

$$E' = \frac{E}{a \cdot EP \cdot V} \tag{2}$$

where E' = normalized evaporation rate (unitless), E = evaporation rate (gpm), EP = adiabatic saturation cooling degrees based on temperature and relative humidity (ºF), V = wind speed (mph) and a = empirical constant to be determined (gpm/ºF-mph). Similarly, the spray rate is normalized as

$$Q' = \frac{Q}{a \cdot EP \cdot V} \tag{3}$$

where Q' = normalized spray rate (unitless), Q = spray rate (gpm).

The evaporation rate is zero when the spray rate is zero. Field data suggest the evaporation rate increases in proportion to spray rate initially, but levels off at higher spray rates. A non-dimensional functional form capturing this qualitative behavior is

$$E' = \frac{1}{1 + \frac{b}{Q'}} \tag{4}$$

where b is an empirical constant (unitless). The limiting behavior of equation (4) is

$$Q' \to 0 \qquad E' \to 0$$
$$Q' \to \infty \qquad E' \to 1$$

In terms of dimensional parameters, equation (4) is equivalent to

$$E = \frac{1}{\frac{1}{a \cdot EP \cdot V} + \frac{b}{Q}} \tag{5}$$

with limits of

$$Q \to 0 \qquad E \to 0$$
$$Q \to \infty \qquad E \to a \cdot EP \cdot V$$

For each set of weather parameters, optimal values for the empirical constants a and b were determined using least-squares parameter fitting, as shown in Table 5. For these settings, the normalized evaporation and spray rates are listed in Table 6.

Normalized evaporation rate is plotted against normalized spray rate in Figure 20 based on weather data from the Central Shops 2/4 meter towers. Also shown in the figure is the predictive model defined by equation (4) and parameters in Table 5. The model fits the data reasonably well.

Table 5 Least-squares parameter estimation results.

	Nozzle configuration			Performance		On-site weather			Central Shops 2/4 m tower			Central Shops 18 m tower		
Test date	No.	Cores	Orifices	Spray rate	Evap.	Model	Residual	Residual^2	Model	Residual	Residual^2	Model	Residual	Residual^2
				(gpm)	(gpm)	(gpm)	(gpm)	(gpm^2)	(gpm)	(gpm)	(gpm^2)	(gpm)	(gpm)	(gpm^2)
				Q	E	E*	E*-E	(E*-E)^2	E*	E*-E	(E*-E)^2	E*	E*-E	(E*-E)^2
03/31/03	30	25	D2	6.1	1.81	2.5	0.7	0.5	2.4	0.6	0.3	3.1	1.3	1.6
04/29/03	30	25	D2	6.1	5.31	3.3	-2.0	4.0	3.7	-1.6	2.7	3.5	-1.8	3.4
05/01/03	30	25	D5	15.7	6.49	7.5	1.0	1.0	8.5	2.0	4.0	8.3	1.8	3.1
05/14/03	30	25	D5	16.7	5.71	7.6	1.9	3.6						
06/25/03	30	25	D5	16.2	8.31	8.1	-0.2	0.0	8.3	0.0	0.0	8.1	-0.2	0.1
06/26/03	27	45	D6	25.5	13.17	12.7	-0.4	0.2	12.3	-0.9	0.8	12.5	-0.7	0.4
07/24/03	27	45	D6	26.1	11.36	11.0	-0.3	0.1	10.7	-0.6	0.4	10.7	-0.6	0.4
08/11/03	30	45	D8	39.2	13.97	13.5	-0.5	0.2	14.4	0.4	0.1	14.3	0.3	0.1
						1.38	**a**	9.6	**0.49**	**a**	8.3	**0.56**	**a**	9.1
						1.74	**b**		**1.45**	**b**		**1.59**	**b**	

Table 6 Normalized evaporation and spray rates.

	Nozzle configuration			Performance		On-site weather			Central Shops 2/4 m tower			Central Shops 18 m tower		
Test date	No.	Cores	Orifices	Spray rate	Evap.	Spray	Evap.	Model	Spray	Evap.	Model	Spray	Evap.	Model
				(gpm)	(gpm)	(unitless)	(unitless)	(unitless)	(unitless)	(unitless)	(unitless)	(unitless)	(unitless)	(unitless)
				Q	E	Q/a*EP*V	E/a*EP*V	E^/a*EP*V	Q/a*EP*V	E/a*EP*V	E^/a*EP*V	Q/a*EP*V	E/a*EP*V	E^/a*EP*V
03/31/03	30	25	D2	6.1	1.81	0.68	0.20	0.28	1.13	0.34	0.44	0.39	0.12	0.20
04/29/03	30	25	D2	6.1	5.31	0.11	0.09	0.06	0.21	0.19	0.13	0.17	0.15	0.10
05/01/03	30	25	D5	15.7	6.49	0.35	0.14	0.17	0.40	0.16	0.22	0.31	0.13	0.16
05/14/03	30	25	D5	16.7	5.71	0.45	0.16	0.21						
06/25/03	30	25	D5	16.2	8.31	0.24	0.13	0.12	0.50	0.26	0.26	0.41	0.21	0.21
06/26/03	27	45	D6	25.5	13.17	0.26	0.13	0.13	0.63	0.33	0.30	0.45	0.23	0.22
07/24/03	27	45	D6	26.1	11.36	0.62	0.27	0.26	0.98	0.43	0.40	0.84	0.37	0.35
08/11/03	30	45	D8	39.2	13.97	1.16	0.41	0.40	1.28	0.46	0.47	1.15	0.41	0.42

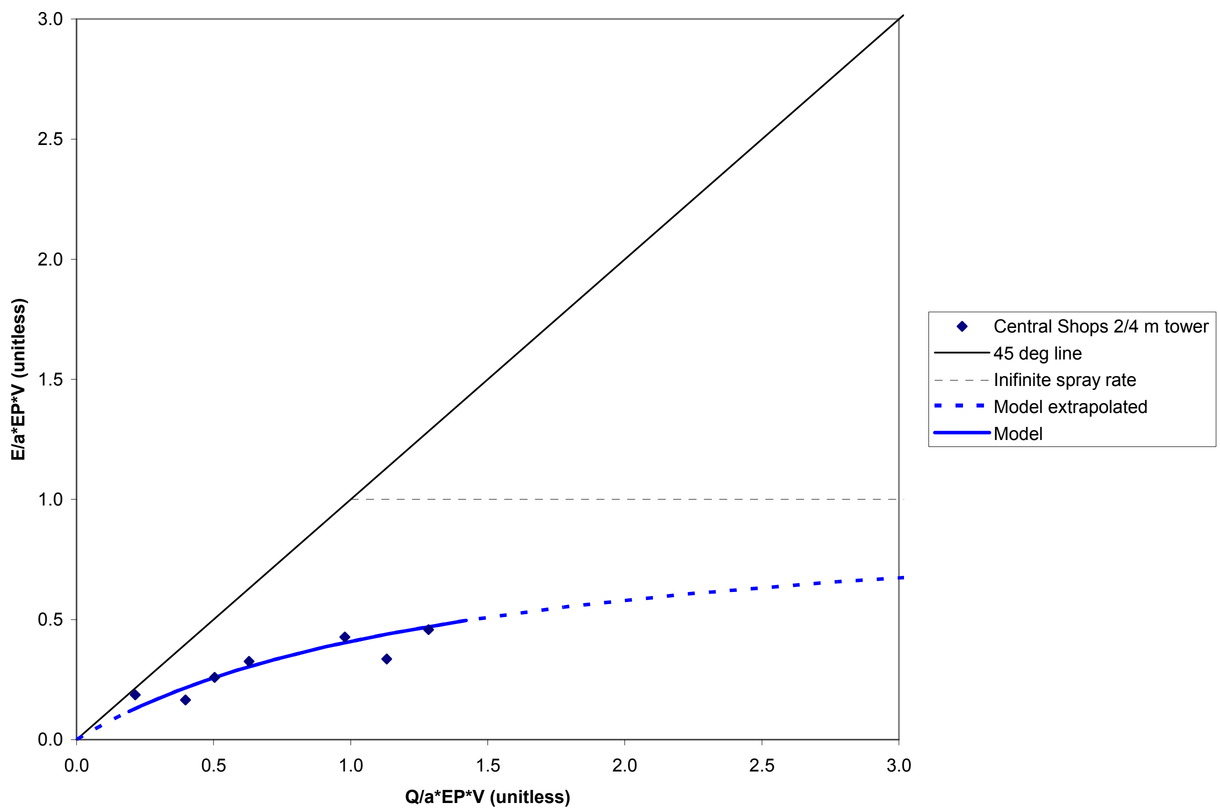

Figure 20 Normalized evaporation and spray rates.

6.0 FORECAST EVAPORATION RATES

The non-dimensional predictive model defined by equation (4) with a = 0.49 gpm/ºF-mph and b = 1.45 (Figure 20) can be translated into equivalent dimensional forms for specific weather conditions. Figure 21 shows predicted evaporation rates in gpm for annual and seasonal average weather conditions at the Savannah River Site and spray rate up to 70 gpm.

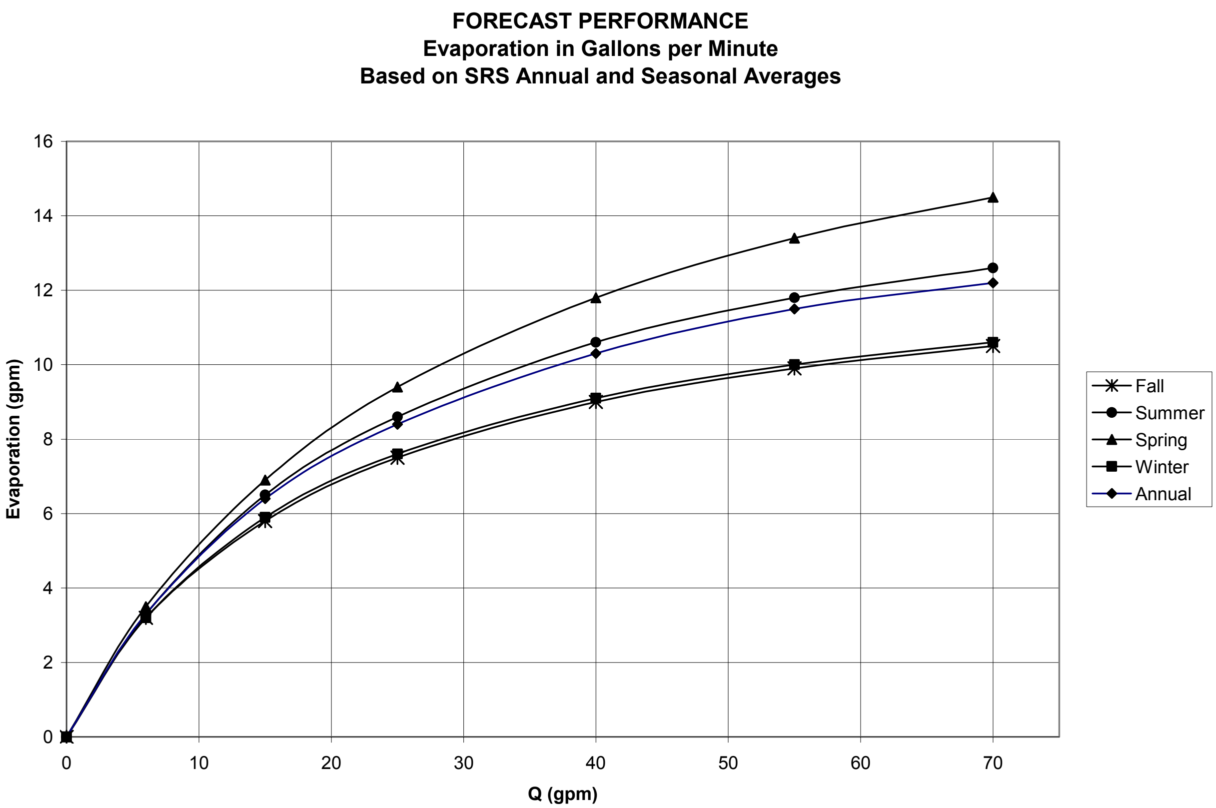

Figure 21 Forecast long-term performance of the Turbo-Mist evaporator for annual and seasonal average weather conditions at the SRS.

7.0 SUMMARY AND CONCLUSIONS

The evaporation rate of spray from a Slimline Turbo-Mist evaporator is approximately proportional to the evaporative cooling potential of "dry" air based on temperature and humidity, and wind speed. As a secondary effort, the evaporation rate was also observed to increase with spray rate, to a point of diminishing increases. A model has been developed for predicting evaporation rate as a function of weather conditions and spray rate. Forecast performance of the Turbo-Mist evaporator under average temperature, humidity and wind speed conditions for the year and each season are plotted in Figure 21 as a function of spray rate (controlled by nozzle orifice selection). The fallback rate is the spray rate less the evaporation rate. If significant fallback is tolerable, an evaporation rate averaging about 12 gpm is estimated for operation at the SRS on a year-round basis.

8.0 REFERENCES

American Society of Heating, Refrigerating and Air-Conditioning Engineers, 1985, ASHRAE Handbook; 1985 Fundamentals, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta GA.

Controlled Laboratory Notebook WSRC-NB-2001-00167, assigned to G. P. Flach.

Hunter, C. H. and C. P. Tatum, 1997, Meteorological annual report for 1996 (U), WSRC-TR-97-0214.

Reynolds, W. C. and H. C. Perkins, 1977, *Engineering Thermodynamics*, McGraw-Hill, New York, 690 p.

Flach, G. P., 2002, Evaluation of Evaporation Technologies for Treating Contaminated Groundwater (U), WSRC-TR-2002-00432.

Appendix A – Data and analysis for Turbo-Mist field test on 3/31/03

30 No. 25 cores with D2 orifice plates **March 31 - April 1, 2003**

30				Number of spray nozzles	0.001897	yr			Duration of test
25				Cores	0.6924	day			
D2				Orifices	16.62	hr			
3/31/03 16:21		37711.6813		Start of test	997	min			
6621	gal		m^3	Nozzle flow totalizer	59820	sec			
5.1	gal/min		m^3/hr	Nozzle flowrate - indicated	6036.5	gal	22.9	m^3	Spray volume
45120	gal		m^3	Bypass flow totalizer	114530	gal	433.5	m^3	Bypass volume
116.1	gal/min		m^3/hr	Bypass flowrate - indicated					
104	psi		Pa	P1	6.1	gal/min	1.38	m^3/hr	Spray flowrate
98	psi		Pa	P2	115	gal/min	26.1	m^3/hr	Bypass flowrate
100	psi		Pa	P3	21	in^2	0.0135	m^2	Pad area
4/1/03 0:11		37712.0076		Midpoint	0.1458	ft^2			
9483.1	gal		m^3	Nozzle flow totalizer	3.35E-06	acre			
5.8	gal/min		m^3/hr	Nozzle flowrate - indicated	480	volts			Voltage
99300	gal		m^3	Bypass flow totalizer	36	amps			Current
114.2	gal/min		m^3/hr	Bypass flowrate - indicated	29.9	kW			Power
100	psi		Pa	P1	38.3	F	3.49	C	Temperature
99	psi		Pa	P2	72%		72%		Relative humidity
100	psi		Pa	P3	1.9	mph	0.84	m/s	Wind speed
4/1/03 8:58		37712.3736		End of test	226.27	deg	226.27	deg	Wind direction
12657.5	gal		m^3	Nozzle flow totalizer	6.05	gpm			Spray
6.1	gal/min		m^3/hr	Nozzle flowrate - indicated	4.24	gpm			Fallback
159650	gal		m^3	Bypass flow totalizer	**1.81**	**gpm**			**Evaporation**
116.1	gal/min		m^3/hr	Bypass flowrate - indicated	30%				
102	psi		Pa	P1	29.9	kW			Power
98	psi		Pa	P2	0.08	\$/kW-hr			Energy cost
100	psi		Pa	P3	**0.022**	**\$/gal**			**Cost**
3	in			Pad width	0.056	\$/gal			Direct heating cost
7	in			Pad length	**39%**				**Relative cost**

Adiabatic saturation / swamp cooler calculation using ASHRAE (1985) equations						
Constants						*source*
univ. gas const.	*R*	1545.33	ft-lbf/(lbmole-R)			
molecular wt. air	M_a	28.9645	lbm/lbmole			from eqn (24)
air gas constant	R_a	53.35	ft-lbf/(lbm-R)			
Incoming air stream						
pressure	p	14.7	psia			
temperature	t	38.282	F	3.5 C	497.952 R	**31Mar03 - 01Apr03 Field Test**
relative humidity	ϕ	0.72	unitless			
sat. pressure	p_{ws}	0.1152	psia			eqn (4)
water vap. pres.	p_w	0.0829	psia			eqn (22)
humidity ratio	W, γ	0.003528	unitless	24.69 grains/lbm_a		eqn (20)
sat. humidity ratio	W_s	0.004913	unitless			eqn (21)
deg. of saturation	μ	0.7180	unitless			eqn (10)
specific volume	ν	12.62	ft^3/lbm_a			eqn (26)
		12.58	ft^3/lbm			using (1+γ) factor and eqn (26)
		12.55	ft^3/lbm			using ideal gas law
specific enthalpy	h	12.99	BTU/lbm_a			eqn (30)
Outgoing for adiabatic saturation/evaporation						
pressure	p	14.7	psia			
temperature	t	34.88	F	1.6 C	494.55 R	
relative humidity	ϕ	1.00	unitless			
sat. pressure	p_{ws}	0.1007	psia			eqn (4)
water vap. pres.	p_w	0.1007	psia			eqn (22)
humidity ratio	W, γ	0.004291	lbm_w/lbm_a	30.03 grains/lbm_a		eqn (20)
sat. humidity ratio	W_s	0.004291	unitless			eqn (21)
deg. of saturation	μ	1.0000	unitless			eqn (10)
specific volume	ν	12.55	ft^3/lbm_a			eqn (26)
		12.50	ft^3/lbm			using (1+γ) factor and eqn (26)
		12.46	ft^3/lbm			using ideal gas law
specific enthalpy	h	12.99	BTU/lbm_a			eqn (30)
Differences						
temperature	Δt	-3.4	F			
relative humidity	$\Delta\phi$	0.28	unitless			
enthalpy	Δh	0.00	BTU/lbm_a			
humidity ratio	ΔW, $\Delta\gamma$	0.000763	lbm_w/lbm_a	5.34 grains/lbm_a		
Evaporation system parameters						
Wind speed	v	1.9	mi/hr	2.76 ft/s		
Height	h	35.0	ft			
Width	w	35.0	ft			
Xsec area	A	1225	ft^2			
Incoming wet air vol. flow	Q	3376	ft^3/s	2.0E+05 ft^3/min (cfm)		
Dry air mass flow	m_a	267	lbm_a/s			
Evaporation rate	m_e	0.20	lbm_w/s	12.25 lbm_w/min		
Liq. water density	ρ	62.3	lbm/ft^3			@ 70F
Evaporation rate	Q_e	0.003	ft^3/s	1.47 gal/min	88 gal/hr	

Station ID	Yellow (in)	Clear (in)	White ID	Pad - Dry (g)	Pad - Wet (g)	White (in)
B2	0	nd	nd	nd	nd	nd
B6	0	nd	nd	nd	nd	nd
B10	0	nd	nd	nd	nd	nd
D4	0	nd	nd	14.3	15.8	nd
D6	0	nd	nd	14.3	15.2	nd
D8	0	nd	nd	14.5	15.7	nd
D10	0	nd	nd	14.4	17.3	nd
F2	0	nd	nd	nd	nd	nd
F4	0	nd	nd	14.0	15.3	nd
F6	0	nd	nd	14.6	15.7	nd
F8	0	nd	nd	nd	nd	nd
F10	0	nd	nd	nd	nd	nd
G7	0	nd	nd	nd	nd	nd
G8	0	nd	nd	14.3	15.7	nd
G9	T	nd	nd	nd	nd	nd
H4	0	nd	nd	14.4	15.4	nd
H6	0	nd	nd	14.3	15.2	nd
H7	0	nd	nd	nd	nd	nd
H8	0	T	TM-2	nd	nd	0.02
H9	T	nd	nd	nd	nd	nd
I7	0	nd	nd	nd	nd	nd
I8	0	nd	nd	14.8	19.4	nd
I9	T	nd	nd	14.4	34.5	nd
J2	0	nd	nd	nd	nd	nd
J4	0	nd	nd	14.3	16.9	nd
J6	T	nd	nd	14.7	41.7	nd
J7	0.1	nd	nd	nd	nd	nd
J8	0.45	0.46	TM-4	14.9	98.9	0.39
J9	1.3	1.09	TM-5	14.8	107.5	1.06
K7	0.5	nd	nd	nd	nd	nd
K8	1.0	nd	nd	14.3	112.0	nd
K9	1.9	nd	nd	14.4	130.6	nd
L4	0	nd	nd	14.4	20.3	nd
L6	0.1	nd	nd	14.9	72.4	nd
L7	0.3	nd	nd	nd	nd	nd
L8	0.9	0.76	TM-7	nd	nd	0.53
L9	0.9	nd	nd	nd	nd	nd
M7	0.5	nd	nd	nd	nd	nd
M8	0.5	nd	nd	14.0	97.8	nd
M9	0.6	nd	nd	nd	nd	nd
N2	0	nd	nd	nd	nd	nd
N4	0	nd	nd	13.8	18.3	nd
N6	0.1	nd	nd	14.3	53.7	nd
N8	0.3	nd	nd	nd	nd	nd
P4	0	nd	nd	14.8	18.2	nd
P6	T	nd	nd	14.3	36.2	nd
P8	0.2	nd	nd	14.4	77.1	nd
R2	0	nd	nd	nd	nd	nd
R6	0	nd	nd	nd	nd	nd
R10	0.1	nd	nd	nd	nd	nd

Station ID	Yellow (in)	Clear (in)	White ID	Pad - Dry (g)	Pad - Wet (g)	White (in)
B14	0	nd	nd	nd	nd	nd
D12	0	nd	nd	14.8	18.0	nd
D14	0	nd	nd	nd	nd	nd
F12	0	nd	nd	nd	nd	nd
F14	0	nd	nd	nd	nd	nd
G10	0	nd	nd	14.7	15.9	nd
G11	0	nd	nd	nd	nd	nd
G12	0	nd	nd	14.6	21.8	nd
G13	nd	nd	nd	nd	nd	nd
H10	0	nd	nd	nd	nd	nd
H11	0	nd	nd	nd	nd	nd
H12	T	nd	nd	nd	nd	nd
H13	nd	nd	nd	nd	nd	nd
H14	0	nd	nd	14.2	18.1	nd
I10	T	0.01	TM-6	14.5	29.6	0.03
I11	T	nd	nd	14.7	50.8	nd
I12	0	nd	nd	14.4	40.4	nd
I13	nd	nd	nd	nd	nd	nd
J10	nd	1.44	nd	14.7	189.0	nd
J11	nd	nd	nd	nd	nd	nd
J12	0	0.02	TM-3	14.5	40.3	0.02
J13	nd	nd	nd	nd	nd	nd
J14	0	nd	nd	14.7	19.8	nd
K10	0.20	0.19	TM-1	14.8	125.6	0.14
K11	T	nd	nd	14.9	51.4	nd
K12	0	nd	nd	14.7	36.9	nd
K13	nd	nd	nd	nd	nd	nd
L10	0.15	nd	nd	nd	nd	nd
L11	T	nd	nd	nd	nd	nd
L12	0	nd	nd	nd	nd	nd
L13	nd	nd	nd	nd	nd	nd
L14	0	nd	nd	14.3	18.1	nd
M10	0.10	0.11	nd	14.5	102.0	nd
M11	T	nd	nd	nd	nd	nd
M12	0	nd	nd	14.6	21.9	nd
M13	nd	nd	nd	nd	nd	nd
N10	0.10	nd	nd	nd	nd	nd
N12	0.05	nd	nd	nd	nd	nd
N14	0	nd	nd	nd	nd	nd
P10	0.10	nd	nd	14.6	53.0	nd
P12	T	nd	nd	14.7	35.3	nd
P14	T	nd	nd	nd	nd	nd
R14	T	nd	nd	nd	nd	nd

Appendix B – Data and analysis for Turbo-Mist field test on 4/29/03

30 No. 25 cores with D2 orifice plates				**April 29, 2003**					
30				Number of spray nozzles	0.000812	yr			Duration of test
25				Cores	0.2965	day			
D2				Orifices	7.12	hr			
4/29/03 8:16		37740.3444		Start of test	427	min			
12681.2	gal		m^3	T1-Nozzle flow totalizer	25620	sec			
5.8	gal/min		m^3/hr	Nozzle flowrate - indicated	2614.8	gal	9.9	m^3	Spray volume
160030	gal		m^3	T2-Bypass flow totalizer	47830	gal	181.1	m^3	Bypass volume
115	gal/min		m^3/hr	Bypass flowrate - indicated					
106	psi		Pa	P1	6.1	gal/min	1.39	m^3/hr	Spray flowrate
100	psi		Pa	P2	112	gal/min	25.4	m^3/hr	Bypass flowrate
102	psi		Pa	P3	21	in^2	0.0135	m^2	Pad area
4/29/03 11:41		37740.4868		Midpoint	0.1458	ft^2			
13934.8	gal		m^3	Nozzle flow totalizer	3.35E-06	acre			
6.5	gal/min		m^3/hr	Nozzle flowrate - indicated		volts			Voltage
183000	gal		m^3	Bypass flow totalizer		amps			Current
114.1	gal/min		m^3/hr	Bypass flowrate - indicated	0.0	kW			Power
102	psi		Pa	P1	75.5	F	24.19	C	Temperature
98	psi		Pa	P2	60%		60%		Relative humidity
100	psi		Pa	P3	4.2	mph	1.86	m/s	Wind speed
4/29/03 15:23		37740.641		End of test	209.056667	deg	209.06	deg	Wind direction
15296	gal		m^3	Nozzle flow totalizer	6.12	gpm			Spray
6.5	gal/min		m^3/hr	Nozzle flowrate - indicated	0.81	gpm			Fallback
207860	gal		m^3	Bypass flow totalizer	**5.31**	**gpm**			**Evaporation**
114.6	gal/min		m^3/hr	Bypass flowrate - indicated	87%				
102	psi		Pa	P1	0.0	kW			Power
98	psi		Pa	P2	0.08	$/kW-hr			Energy cost
100	psi		Pa	P3	**0.000**	**$/gal**			**Cost**
3	in			Pad width	0.056	$/gal			Direct heating cost
7	in			Pad length	**0%**				**Relative cost**

Adiabatic saturation / swamp cooler calculation using ASHRAE (1985) equations							
Constants							*source*
univ. gas const.	*R*	1545.33	ft-lbf/(lbmole-R)				
molecular wt. air	M_a	28.9645	lbm/lbmole				from eqn (24)
air gas constant	R_a	53.35	ft-lbf/(lbm-R)				
Incoming air stream							
pressure	p	14.7	psia				
temperature	t	75.542	F	24.2	C	535.212 R	**29Apr03 Field Test**
relative humidity	ϕ	0.60	unitless				
sat. pressure	p_{ws}	0.4437	psia				eqn (4)
water vap. pres.	p_w	0.2653	psia				eqn (22)
humidity ratio	W, γ	0.011430	unitless	80.01	grains/lbm_a		eqn (20)
sat. humidity ratio	W_s	0.019359	unitless				eqn (21)
deg. of saturation	μ	0.5904	unitless				eqn (10)
specific volume	ν	13.74	ft^3/lbm_a				eqn (26)
		13.58	ft^3/lbm				using (1+γ) factor and eqn (26)
		13.49	ft^3/lbm				using ideal gas law
specific enthalpy	h	30.64	BTU/lbm_a				eqn (30)
Outgoing for adiabatic saturation/evaporation							
pressure	p	14.7	psia				
temperature	t	65.59	F	18.7	C	525.26 R	
relative humidity	ϕ	1.00	unitless				
sat. pressure	p_{ws}	0.3161	psia				eqn (4)
water vap. pres.	p_w	0.3161	psia				eqn (22)
humidity ratio	W, γ	0.013668	lbm_w/lbm_a	95.68	grains/lbm_a		eqn (20)
sat. humidity ratio	W_s	0.013668	unitless				eqn (21)
deg. of saturation	μ	1.0000	unitless				eqn (10)
specific volume	ν	13.53	ft^3/lbm_a				eqn (26)
		13.35	ft^3/lbm				using (1+γ) factor and eqn (26)
		13.24	ft^3/lbm				using ideal gas law
specific enthalpy	h	30.64	BTU/lbm_a				eqn (30)
Differences							
temperature	Δt	-10.0	F				
relative humidity	$\Delta\phi$	0.40	unitless				
enthalpy	Δh	0.00	BTU/lbm_a				
humidity ratio	ΔW, $\Delta\gamma$	0.002238	lbm_w/lbm_a	15.67	grains/lbm_a		
Evaporation system parameters							
Wind speed	v	4.2	mi/hr	6.12	ft/s		
Height	h	35.0	ft				
Width	w	35.0	ft				
Xsec area	A	1225	ft^2				
Incoming wet air vol. flow	Q	7493	ft^3/s	4.5E+05	ft^3/min (cfm)		
Dry air mass flow	m_a	545	lbm_a/s				
Evaporation rate	m_e	1.22	lbm_w/s	73.24	lbm_w/min		
Liq. water density	ρ	62.3	lbm/ft^3				@ 70F
Evaporation rate	Q_e	0.020	ft^3/s	8.79	gal/min	528 gal/hr	

Station ID	Yellow (in)	Clear (in)	White ID	Pad - Dry (g)	Pad - Wet (g)	White (in)
B2	0	nd	nd	14.5	14.5	nd
B6	0	nd	nd	nd	nd	nd
B10	0	nd	nd	nd	nd	nd
D4	0	nd	nd	nd	nd	nd
D6	0	nd	nd	nd	nd	nd
D8	0	nd	nd	nd	nd	nd
D10	0	nd	nd	nd	nd	nd
F2	0	nd	nd	nd	nd	nd
F4	0	nd	nd	14.8	14.8	nd
F6	0	nd	nd	14.2	14.2	nd
F8	T	nd	nd	14.8	14.8	nd
F10	0	nd	nd	14.5	14.5	nd
G7	T	nd	nd	nd	nd	nd
G8	T	nd	nd	nd	nd	nd
G9	0	nd	nd	nd	nd	nd
H4	0.1	nd	nd	14.5	14.5	nd
H6	0	nd	nd	14.5	14.5	nd
H7	T	nd	nd	nd	nd	nd
H8	T	nd	nd	14.8	14.8	0.02
H9	T	nd	nd	nd	nd	nd
I7	T	nd	nd	nd	nd	nd
I8	0	nd	nd	nd	nd	nd
I9	0	nd	nd	nd	nd	nd
J2	0	nd	nd	14.8	14.8	nd
J4	T	nd	nd	14.9	14.9	nd
J6	T	nd	nd	14.1	14.1	nd
J7	0	nd	nd	nd	nd	nd
J8	0	0.01	nd	14.6	14.6	nd
J9	0	0.01	nd	nd	nd	nd
K7	0	nd	nd	nd	nd	nd
K8	0	0.01	nd	nd	nd	nd
K9	T	0.07	nd	nd	nd	nd
L4	0	nd	nd	14.8	14.8	nd
L6	0	nd	nd	14.8	14.8	nd
L7	0	nd	nd	nd	nd	nd
L8	0.1	0.05	nd	14.5	24.5	nd
L9	0.15	0.06	nd	nd	nd	nd
M7	0	nd	nd	nd	nd	nd
M8	0.1	nd	nd	nd	nd	nd
M9	T	nd	nd	nd	nd	nd
N2	0	nd	nd	14.7	14.7	nd
N4	0	nd	nd	14.5	14.5	nd
N6	0	nd	nd	14.3	14.3	nd
N8	0	nd	nd	14.7	16.6	nd
P4	T	nd	nd	14.6	14.6	nd
P6	0	nd	nd	14.7	14.7	nd
P8	0	nd	nd	14.4	14.4	nd
R2	0	nd	nd	14.4	14.4	nd
R6	0	nd	nd	14.6	14.6	nd
R10	T	nd	nd	14.4	15.2	nd

Station ID	Yellow (in)	Clear (in)	White ID	Pad - Dry (g)	Pad - Wet (g)	White (in)
B14	0	nd	nd	14.5	14.5	nd
D12	0	nd	nd	nd	nd	nd
D14	0	nd	nd	nd	nd	nd
F12	0	nd	nd	14	14	nd
F14	0	nd	nd	nd	nd	nd
G10	0	nd	nd	nd	nd	nd
G11	0	nd	nd	nd	nd	nd
G12	0	nd	nd	nd	nd	nd
G13	0	nd	nd	nd	nd	nd
H10	0	nd	nd	14.4	14.6	nd
H11	0	nd	nd	nd	nd	nd
H12	0	nd	nd	14.6	14.6	nd
H13	0	nd	nd	nd	nd	nd
H14	0	nd	nd	14.4	14.4	nd
I10	0	nd	nd	nd	nd	nd
I11	0	nd	nd	nd	nd	nd
I12	0	nd	nd	nd	nd	nd
I13	0	nd	nd	nd	nd	nd
J10	0	nd	nd	14.9	16.1	nd
J11	0	nd	nd	nd	nd	nd
J12	0	nd	nd	15	15	nd
J13	0	nd	nd	nd	nd	nd
J14	0	nd	nd	14.7	14.7	nd
K10	T	T	nd	nd	nd	nd
K11	T	nd	nd	nd	nd	nd
K12	0	nd	nd	nd	nd	nd
K13	0	nd	nd	nd	nd	nd
L10	0.1	nd	nd	15.5	67.9	nd
L11	T	nd	nd	nd	nd	nd
L12	0	nd	nd	14.8	17.7	nd
L13	0	nd	nd	nd	nd	nd
L14	0	nd	nd	14.6	14.6	nd
M10	T	nd	nd	nd	nd	nd
M11	0.1	nd	nd	nd	nd	nd
M12	0	nd	nd	nd	nd	nd
M13	0	nd	nd	nd	nd	nd
N10	T	nd	nd	14.7	40.1	nd
N12	0	nd	nd	14.6	24.3	nd
N14	0	nd	nd	14.8	14.8	nd
P10	0	nd	nd	14.6	18.1	nd
P12	0	nd	nd	14.8	16.9	nd
P14	T	nd	nd	nd	nd	nd
R14	0	nd	nd	nd	nd	nd

Appendix C – Data and analysis for Turbo-Mist field test on 5/1/03

30 No. 25 cores with D5 orifice plates				**1-May-03**					
30				Number of spray nozzles	0.000713	yr			Duration of test
25				Cores	0.2604	day			
D5				Orifices	6.25	hr			
5/1/03 8:35		37742.3576		Start of test	375	min			
15340.6	gal		m^3	T1-Nozzle flow totalizer	22500	sec			
15.9	gal/min		m^3/hr	Nozzle flowrate - indicated	5867.3	gal	22.2	m^3	Spray volume
208207	gal		m^3	T2-Bypass flow totalizer	40423	gal	153.0	m^3	Bypass volume
109.3	gal/min		m^3/hr	Bypass flowrate - indicated					
98	psi		Pa	P1	15.6	gal/min	3.55	m^3/hr	Spray flowrate
94	psi		Pa	P2	108	gal/min	24.5	m^3/hr	Bypass flowrate
94	psi		Pa	P3	21	in^2	0.0135	m^2	Pad area
5/1/03 11:36		37742.4833		Midpoint	0.1458	ft^2			
18189	gal		m^3	Nozzle flow totalizer	3.35E-06	acre			
15.9	gal/min		m^3/hr	Nozzle flowrate - indicated		volts			Voltage
227910	gal		m^3	Bypass flow totalizer		amps			Current
109.2	gal/min		m^3/hr	Bypass flowrate - indicated	0.0	kW			Power
94	psi		Pa	P1	75.9	F	24.38	C	Temperature
90	psi		Pa	P2	67%		67%		Relative humidity
90	psi		Pa	P3	4.0	mph	1.80	m/s	Wind speed
5/1/03 14:50		37742.6181		End of test	86.44	deg	86.44	deg	Wind direction
21207.9	gal		m^3	Nozzle flow totalizer	15.65	gpm			Spray
16.3	gal/min		m^3/hr	Nozzle flowrate - indicated	9.16	gpm			Fallback
248630	gal		m^3	Bypass flow totalizer	**6.49**	**gpm**			**Evaporation**
109.8	gal/min		m^3/hr	Bypass flowrate - indicated	41%				
96	psi		Pa	P1	0.0	kW			Power
92	psi		Pa	P2	0.08	$/kW-hr			Energy cost
92	psi		Pa	P3	**0.000**	**$/gal**			**Cost**
3	in			Pad width	0.056	$/gal			Direct heating cost
7	in			Pad length	**0%**				**Relative cost**

Adiabatic saturation / swamp cooler calculation using ASHRAE (1985) equations								
Constants								*source*
univ. gas const.	*R*	1545.33	ft-lbf/(lbmole-R)					
molecular wt. air	M_a	28.9645	lbm/lbmole					from eqn (24)
air gas constant	R_a	53.35	ft-lbf/(lbm-R)					
Incoming air stream								
pressure	p	14.7	psia					
temperature	t	75.884	F	24.4	C	535.554	R	**01May03 Field Test**
relative humidity	ϕ	0.67	unitless					
sat. pressure	p_{ws}	0.4488	psia					eqn (4)
water vap. pres.	p_w	0.2996	psia					eqn (22)
humidity ratio	W, γ	0.012939	unitless	90.57	grains/lbm_a			eqn (20)
sat. humidity ratio	W_s	0.019588	unitless					eqn (21)
deg. of saturation	μ	0.6606	unitless					eqn (10)
specific volume	ν	13.78	ft^3/lbm_a					eqn (26)
		13.60	ft^3/lbm					using (1+γ) factor and eqn (26)
		13.50	ft^3/lbm					using ideal gas law
specific enthalpy	h	32.38	BTU/lbm_a					eqn (30)
Outgoing for adiabatic saturation/evaporation								
pressure	p	14.7	psia					
temperature	t	67.77	F	19.9	C	527.44	R	
relative humidity	ϕ	1.00	unitless					
sat. pressure	p_{ws}	0.3409	psia					eqn (4)
water vap. pres.	p_w	0.3409	psia					eqn (22)
humidity ratio	W, γ	0.014767	lbm_w/lbm_a	103.37	grains/lbm_a			eqn (20)
sat. humidity ratio	W_s	0.014767	unitless					eqn (21)
deg. of saturation	μ	1.0000	unitless					eqn (10)
specific volume	ν	13.61	ft^3/lbm_a					eqn (26)
		13.41	ft^3/lbm					using (1+γ) factor and eqn (26)
		13.29	ft^3/lbm					using ideal gas law
specific enthalpy	h	32.38	BTU/lbm_a					eqn (30)
Differences								
temperature	Δt	-8.1	F					
relative humidity	$\Delta\phi$	0.33	unitless					
enthalpy	Δh	0.00	BTU/lbm_a					
humidity ratio	ΔW, $\Delta\gamma$	0.001827	lbm_w/lbm_a	12.79	grains/lbm_a			
Evaporation system parameters								
Wind speed	v	4.0	mi/hr	5.91	ft/s			
Height	h	35.0	ft					
Width	w	35.0	ft					
Xsec area	A	1225	ft^2					
Incoming wet air vol. flow	Q	7234	ft^3/s	4.3E+05	ft^3/min (cfm)			
Dry air mass flow	m_a	525	lbm_a/s					
Evaporation rate	m_e	0.96	lbm_w/s	57.56	lbm_w/min			
Liq. water density	ρ	62.3	lbm/ft^3					@ 70F
Evaporation rate	Q_e	0.015	ft^3/s	6.91	gal/min	415	gal/hr	

Station ID	Yellow (in)	Clear (in)	White ID	Pad - Dry (g)	Pad - Wet (g)	White (in)
B2	0	nd	nd	nd	nd	nd
B6	0	nd	nd	14.5	14.6	nd
B10	0	nd	nd	14.5	14.5	nd
D4	0	nd	nd	14.5	14.7	nd
D6	0	nd	nd	14	27.4	nd
D8	T	nd	nd	14	23.6	nd
D10	0	nd	nd	14.5	19.2	nd
F2	0	nd	nd	14	14.1	nd
F4	0	nd	nd	14.5	24.1	nd
F6	0.1	nd	nd	14.5	73.4	nd
F8	0.15	nd	nd	15.5	85	nd
F10	T	nd	nd	14.5	52.3	nd
G7	0.3	nd	nd	nd	nd	nd
G8	0.4	nd	nd	nd	nd	nd
G9	0.4	nd	nd	nd	nd	nd
H4	nd	nd	nd	14.5	36.6	nd
H6	0.2	nd	nd	14.5	130.1	nd
H7	0.45	nd	nd	nd	nd	nd
H8	0.8	nd	nd	15	95.4	nd
H9	0.9	0.88	nd	nd	nd	nd
I7	0.5	nd	nd	nd	nd	nd
I8	1	0.83	nd	nd	nd	nd
I9	0.2	0.22	nd	nd	nd	nd
J2	0	nd	nd	14.5	14.5	nd
J4	0	nd	nd	14.5	25.3	nd
J6	0.2	nd	nd	14	125.4	nd
J7	0.35	nd	nd	nd	nd	nd
J8	0.7	0.59	nd	14.5	150.9	nd
J9	0.8	0.78	nd	nd	nd	nd
K7	0.15	0.21	nd	nd	nd	nd
K8	0.2	0.22	nd	nd	nd	nd
K9	0.2	nd	nd	nd	nd	nd
L4	0	nd	nd	14.5	14.5	nd
L6	0	nd	nd	14.5	24.4	nd
L7	0	nd	nd	nd	nd	nd
L8	0.1	nd	nd	14.5	64.2	nd
L9	T	nd	nd	nd	nd	nd
M7	0	nd	nd	nd	nd	nd
M8	0	nd	nd	nd	nd	nd
M9	0	nd	nd	nd	nd	nd
N2	0	nd	nd	14.5	14.5	nd
N4	0	nd	nd	14.5	14.6	nd
N6	0	nd	nd	15	15	nd
N8	0	nd	nd	14	14.2	nd
P4	0	nd	nd	14	14.7	nd
P6	0	nd	nd	14.5	14.5	nd
P8	0	nd	nd	14.5	14.6	nd
R2	0	nd	nd	nd	nd	nd
R6	0	nd	nd	14	14.1	nd
R10	0	nd	nd	14.5	14.5	nd

Station ID	Yellow (in)	Clear (in)	White ID	Pad - Dry (g)	Pad - Wet (g)	White (in)
B14	0	nd	nd	nd	nd	nd
D12	0	nd	nd	14.5	14.6	nd
D14	0	nd	nd	nd	nd	nd
F12	0	nd	nd	14	14.1	nd
F14	0	nd	nd	14.5	14.6	nd
G10	0	nd	nd	nd	nd	nd
G11	0	nd	nd	nd	nd	nd
G12	0	nd	nd	nd	nd	nd
G13	nd	nd	nd	nd	nd	nd
H10	0.2	nd	nd	14.5	137.1	nd
H11	0	nd	nd	nd	nd	nd
H12	0	nd	nd	14	14.1	nd
H13	nd	nd	nd	nd	nd	nd
H14	0	nd	nd	15	15	nd
I10	0.7	nd	nd	nd	nd	nd
I11	0	nd	nd	nd	nd	nd
I12	0	nd	nd	nd	nd	nd
I13	nd	nd	nd	nd	nd	nd
J10	0.5	nd	nd	14.5	140	nd
J11	nd	nd	nd	nd	nd	nd
J12	0	nd	nd	14	14.4	nd
J13	nd	nd	nd	14.5	14.5	nd
J14	0	nd	nd	14.5	14.5	nd
K10	0.1	nd	nd	nd	nd	nd
K11	0	nd	nd	nd	nd	nd
K12	0	nd	nd	nd	nd	nd
K13	nd	nd	nd	nd	nd	nd
L10	0	nd	nd	14.5	17.3	nd
L11	0	nd	nd	nd	nd	nd
L12	0	nd	nd	14.5	14.5	nd
L13	nd	nd	nd	nd	nd	nd
L14	0	nd	nd	14.5	14.5	nd
M10	0	nd	nd	nd	nd	nd
M11	0	nd	nd	nd	nd	nd
M12	0	nd	nd	nd	nd	nd
M13	nd	nd	nd	nd	nd	nd
N10	0	nd	nd	14	14.3	nd
N12	0	nd	nd	14.5	14.6	nd
N14	0	nd	nd	14.5	14.5	nd
P10	0	nd	nd	14.5	14.7	nd
P12	0	nd	nd	15	15	nd
P14	0	nd	nd	nd	nd	nd
R14	0	nd	nd	nd	nd	nd

Appendix D – Data and analysis for Turbo-Mist field test on 5/14/03

30 No. 25 cores with D5 orifice plates				**14-May-03**					
30				Number of spray nozzles	0.000557	yr			Duration of test
25				Cores	0.2035	day			
D5				Orifices	4.88	hr			
5/14/03 10:07		37755.4215		Start of test	293	min			
21258.9	gal		m^3	T1-Nozzle flow totalizer	17580	sec			
16.3	gal/min		m^3/hr	Nozzle flowrate - indicated	4895.3	gal	18.5	m^3	Spray volume
248970	gal		m^3	T2-Bypass flow totalizer	30480	gal	115.4	m^3	Bypass volume
109.8	gal/min		m^3/hr	Bypass flowrate - indicated					
96	psi		Pa	P1	16.7	gal/min	3.79	m^3/hr	Spray flowrate
92	psi		Pa	P2	104	gal/min	23.6	m^3/hr	Bypass flowrate
92	psi		Pa	P3	21	in^2	0.0135	m^2	Pad area
5/14/03 12:01		37755.5007		Midpoint	0.1458	ft^2			
23186.5	gal		m^3	Nozzle flow totalizer	3.35E-06	acre			
17	gal/min		m^3/hr	Nozzle flowrate - indicated	490	volts			Voltage
260960	gal		m^3	Bypass flow totalizer	35	amps			Current
104.2	gal/min		m^3/hr	Bypass flowrate - indicated	29.7	kW			Power
102	psi		Pa	P1	72.4	F	22.47	C	Temperature
98	psi		Pa	P2	46%		46%		Relative humidity
98	psi		Pa	P3	2.0	mph	0.91	m/s	Wind speed
5/14/03 15:00		37755.625		End of test	136.20	deg	136.20	deg	Wind direction
26154.2	gal		m^3	Nozzle flow totalizer	16.71	gpm			Spray
16.6	gal/min		m^3/hr	Nozzle flowrate - indicated	11.00	gpm			Fallback
279450	gal		m^3	Bypass flow totalizer	**5.71**	**gpm**			**Evaporation**
103.8	gal/min		m^3/hr	Bypass flowrate - indicated	34%				
100	psi		Pa	P1	29.7	kW			Power
96	psi		Pa	P2	0.08	$/kW-hr			Energy cost
96	psi		Pa	P3	**0.007**	**$/gal**			**Cost**
3	in			Pad width	0.056	$/gal			Direct heating cost
7	in			Pad length	**12%**				**Relative cost**

Adiabatic saturation / swamp cooler calculation using ASHRAE (1985) equations						
Constants						*source*
univ. gas const.	*R*	1545.33	ft-lbf/(lbmole-R)			
molecular wt. air	M_a	28.9645	lbm/lbmole			from eqn (24)
air gas constant	R_a	53.35	ft-lbf/(lbm-R)			
Incoming air stream						
pressure	p	14.7	psia			
temperature	t	72.446	F	22.5 C	532.116 R	**14May03 Field Test**
relative humidity	ϕ	0.46	unitless			
sat. pressure	p_{ws}	0.3999	psia			eqn (4)
water vap. pres.	p_w	0.1839	psia			eqn (22)
humidity ratio	W, γ	0.007881	unitless	55.16 grains/lbm_a		eqn (20)
sat. humidity ratio	W_s	0.017394	unitless			eqn (21)
deg. of saturation	μ	0.4531	unitless			eqn (10)
specific volume	ν	13.58	ft^3/lbm_a			eqn (26)
		13.48	ft^3/lbm			using (1+γ) factor and eqn (26)
		13.41	ft^3/lbm			using ideal gas law
specific enthalpy	h	26.00	BTU/lbm_a			eqn (30)
Outgoing for adiabatic saturation/evaporation						
pressure	p	14.7	psia			
temperature	t	59.18	F	15.1 C	518.85 R	
relative humidity	ϕ	1.00	unitless			
sat. pressure	p_{ws}	0.2521	psia			eqn (4)
water vap. pres.	p_w	0.2521	psia			eqn (22)
humidity ratio	W, γ	0.010853	lbm_w/lbm_a	75.97 grains/lbm_a		eqn (20)
sat. humidity ratio	W_s	0.010853	unitless			eqn (21)
deg. of saturation	μ	1.0000	unitless			eqn (10)
specific volume	ν	13.31	ft^3/lbm_a			eqn (26)
		13.16	ft^3/lbm			using (1+γ) factor and eqn (26)
		13.08	ft^3/lbm			using ideal gas law
specific enthalpy	h	26.00	BTU/lbm_a			eqn (30)
Differences						
temperature	Δt	-13.3	F			
relative humidity	$\Delta\phi$	0.54	unitless			
enthalpy	Δh	0.00	BTU/lbm_a			
humidity ratio	ΔW, $\Delta\gamma$	0.002972	lbm_w/lbm_a	20.81 grains/lbm_a		
Evaporation system parameters						
Wind speed	v	2.0	mi/hr	2.99 ft/s		
Height	h	35.0	ft			
Width	w	35.0	ft			
Xsec area	A	1225	ft^2			
Incoming wet air vol. flow	Q	3657	ft^3/s	2.2E+05 ft^3/min (cfm)		
Dry air mass flow	m_a	269	lbm_a/s			
Evaporation rate	m_e	0.80	lbm_w/s	48.03 lbm_w/min		
Liq. water density	ρ	62.3	lbm/ft^3			@ 70F
Evaporation rate	Q_e	0.013	ft^3/s	5.77 gal/min	346 gal/hr	

Station ID	Yellow (in)	Clear (in)	White ID	Pad - Dry (g)	Pad - Wet (g)	White (in)
B2	T	nd	nd	nd	nd	nd
B6	0	nd	nd	14.3	14.3	nd
B10	0	nd	nd	14.6	14.7	nd
D4	0	nd	nd	14.9	14.9	nd
D6	T	nd	nd	14.2	14.2	nd
D8	0	nd	nd	14.2	14.2	nd
D10	0	nd	nd	14.3	14.3	nd
F2	0	nd	nd	14.3	14.4	nd
F4	0	nd	nd	15	15	nd
F6	0	nd	nd	15.1	15.1	nd
F8	0	nd	nd	14.7	14.8	nd
F10	0	nd	nd	14.5	14.5	nd
G7	T	nd	nd	nd	nd	nd
G8	0	nd	nd	nd	nd	nd
G9	0	nd	nd	nd	nd	nd
H4	0	nd	nd	14.4	16	nd
H6	0	nd	nd	14.4	40.7	nd
H7	T	nd	nd	nd	nd	nd
H8	0.5	nd	nd	14.7	36.1	nd
H9	T	0.4	nd	nd	nd	nd
I7	0.25	nd	nd	nd	nd	nd
I8	0.35	0.3	nd	nd	nd	nd
I9	0.3	0.27	nd	nd	nd	nd
J2	0.1	nd	nd	14.8	15	nd
J4	0	nd	nd	14.2	35.1	nd
J6	0.3	nd	nd	14.6	136.3	nd
J7	0.6	nd	nd	nd	nd	nd
J8	1.3	1.15	nd	14.6	98.4	nd
J9	2	1.6	nd	nd	nd	nd
K7	0.5	nd	nd	nd	nd	nd
K8	0.75	0.7	nd	nd	nd	nd
K9	0.8	0.65	nd	nd	nd	nd
L4	0	nd	nd	14.4	22.4	nd
L6	0.1	nd	nd	14.4	84	nd
L7	0.25	nd	nd	nd	nd	nd
L8	0.35	nd	nd	14.1	104.7	nd
L9	0.3	nd	nd	nd	nd	nd
M7	0.1	nd	nd	nd	nd	nd
M8	0.1	nd	nd	nd	nd	nd
M9	T	nd	nd	nd	nd	nd
N2	0	nd	nd	14.8	14.9	nd
N4	T	nd	nd	14.6	16.5	nd
N6	T	nd	nd	14.2	30.6	nd
N8	0	nd	nd	14.5	28.5	nd
P4	0	nd	nd	14.4	14.6	nd
P6	0	nd	nd	14.7	15.9	nd
P8	0	nd	nd	14.8	15.1	nd
R2	0	nd	nd	nd	nd	nd
R6	0	nd	nd	14.5	14.5	nd
R10	0	nd	nd	14.3	14.3	nd

Station ID	Yellow (in)	Clear (in)	White ID	Pad - Dry (g)	Pad - Wet (g)	White (in)
B14	0	nd	nd	nd	nd	nd
D12	0	nd	nd	14.6	14.6	nd
D14	0	nd	nd	nd	nd	nd
F12	0	nd	nd	14.3	14.3	nd
F14	0	nd	nd	14.5	14.5	nd
G10	0	nd	nd	nd	nd	nd
G11	0	nd	nd	nd	nd	nd
G12	0	nd	nd	nd	nd	nd
G13	nd	nd	nd	nd	nd	nd
H10	T	T	nd	14.7	20	nd
H11	0	nd	nd	nd	nd	nd
H12	0	nd	nd	14.4	14.4	nd
H13	nd	nd	nd	nd	nd	nd
H14	0	nd	nd	14.4	14.4	nd
I10	0.1	nd	nd	nd	nd	nd
I11	0.1	nd	nd	nd	nd	nd
I12	0	nd	nd	nd	nd	nd
I13	nd	nd	nd	nd	nd	nd
J10	1.5	nd	nd	14.4	177.7	nd
J11	nd	nd	nd	nd	nd	nd
J12	0	nd	nd	14.5	14.5	nd
J13	nd	nd	nd	14.5	14.5	nd
J14	0	nd	nd	14.5	14.5	nd
K10	0.2	nd	nd	nd	nd	nd
K11	T	nd	nd	nd	nd	nd
K12	0	nd	nd	nd	nd	nd
K13	nd	nd	nd	nd	nd	nd
L10	0.1	0.05	nd	14.2	45.5	nd
L11	0	nd	nd	nd	nd	nd
L12	0	nd	nd	13.9	13.9	nd
L13	nd	nd	nd	nd	nd	nd
L14	0	nd	nd	14.4	14.4	nd
M10	T	nd	nd	nd	nd	nd
M11	0	nd	nd	nd	nd	nd
M12	0	nd	nd	nd	nd	nd
M13	nd	nd	nd	nd	nd	nd
N10	T	nd	nd	14.7	15.6	nd
N12	0	nd	nd	14.4	14.5	nd
N14	0	nd	nd	15	15	nd
P10	0	nd	nd	14.3	14.4	nd
P12	0	nd	nd	14.5	14.5	nd
P14	0	nd	nd	nd	nd	nd
R14	0	nd	nd	nd	nd	nd

Appendix E – Data and analysis for Turbo-Mist field test on 6/25/03

30 No. 25 cores with D5 orifice plates **25-Jun-03**

30				Number of spray nozzles	0.000479	yr			Duration of test
25				Cores	0.1750	day			
D5				Orifices	4.20	hr			
6/25/03 10:43		37797.4465		Start of test	252	min			
26238	gal		m^3	T1-Nozzle flow totalizer	15120	sec			
16.6	gal/min		m^3/hr	Nozzle flowrate - indicated	4071.4	gal	15.4	m^3	Spray volume
279850	gal		m^3	T2-Bypass flow totalizer	25660	gal	97.1	m^3	Bypass volume
106.8	gal/min		m^3/hr	Bypass flowrate - indicated					
102	psi		Pa	P1	16.2	gal/min	3.67	m^3/hr	Spray flowrate
98	psi		Pa	P2	102	gal/min	23.1	m^3/hr	Bypass flowrate
100	psi		Pa	P3	21	in^2	0.0135	m^2	Pad area
6/25/03 12:55		37797.5382		Midpoint	0.1458	ft^2			
28413.8	gal		m^3	Nozzle flow totalizer	3.35E-06	acre			
16.6	gal/min		m^3/hr	Nozzle flowrate - indicated	480	volts			Voltage
293560	gal		m^3	Bypass flow totalizer	35	amps			Current
104.9	gal/min		m^3/hr	Bypass flowrate - indicated	29.1	kW			Power
100	psi		Pa	P1	87.7	F	30.95	C	Temperature
96	psi		Pa	P2	42%		42%		Relative humidity
98	psi		Pa	P3	2.7	mph	1.20	m/s	Wind speed
6/25/03 14:55		37797.6215		End of test	188.61	deg	188.61	deg	Wind direction
30309.4	gal		m^3	Nozzle flow totalizer	16.16	gpm			Spray
16.3	gal/min		m^3/hr	Nozzle flowrate - indicated	7.85	gpm			Fallback
305510	gal		m^3	Bypass flow totalizer	**8.31**	**gpm**			**Evaporation**
104.7	gal/min		m^3/hr	Bypass flowrate - indicated	51%				
100	psi		Pa	P1	29.1	kW			Power
96	psi		Pa	P2	0.08	$/kW-hr			Energy cost
98	psi		Pa	P3	**0.005**	**$/gal**			**Cost**
3	in			Pad width	0.056	$/gal			Direct heating cost
7	in			Pad length	**8%**				**Relative cost**

Adiabatic saturation / swamp cooler calculation using ASHRAE (1985) equations							
Constants							*source*
univ. gas const.	*R*	1545.33	ft-lbf/(lbmole-R)				
molecular wt. air	M_a	28.9645	lbm/lbmole				from eqn (24)
air gas constant	R_a	53.35	ft-lbf/(lbm-R)				
Incoming air stream							
pressure	p	14.7	psia				
temperature	t	87.71	F	31.0	C	547.38 R	**25Jun03 Field Test**
relative humidity	ϕ	0.42	unitless				
sat. pressure	p_{ws}	0.6591	psia				eqn (4)
water vap. pres.	p_w	0.2775	psia				eqn (22)
humidity ratio	W, γ	0.011966	unitless	83.76	grains/lbm_a		eqn (20)
sat. humidity ratio	W_s	0.029195	unitless				eqn (21)
deg. of saturation	μ	0.4099	unitless				eqn (10)
specific volume	ν	14.06	ft^3/lbm_a				eqn (26)
		13.90	ft^3/lbm				using (1+γ) factor and eqn (26)
		13.80	ft^3/lbm				using ideal gas law
specific enthalpy	h	34.21	BTU/lbm_a				eqn (30)
Outgoing for adiabatic saturation/evaporation							
pressure	p	14.7	psia				
temperature	t	69.96	F	21.1	C	529.63 R	
relative humidity	ϕ	1.00	unitless				
sat. pressure	p_{ws}	0.3676	psia				eqn (4)
water vap. pres.	p_w	0.3676	psia				eqn (22)
humidity ratio	W, γ	0.015952	lbm_w/lbm_a	111.66	grains/lbm_a		eqn (20)
sat. humidity ratio	W_s	0.015952	unitless				eqn (21)
deg. of saturation	μ	1.0000	unitless				eqn (10)
specific volume	ν	13.69	ft^3/lbm_a				eqn (26)
		13.48	ft^3/lbm				using (1+γ) factor and eqn (26)
		13.35	ft^3/lbm				using ideal gas law
specific enthalpy	h	34.21	BTU/lbm_a				eqn (30)
Differences							
temperature	Δt	-17.7	F				
relative humidity	$\Delta\phi$	0.58	unitless				
enthalpy	Δh	0.00	BTU/lbm_a				
humidity ratio	ΔW, $\Delta\gamma$	0.003986	lbm_w/lbm_a	27.90	grains/lbm_a		
Evaporation system parameters							
Wind speed	v	2.7	mi/hr	3.94	ft/s		
Height	h	35.0	ft				
Width	w	35.0	ft				
Xsec area	A	1225	ft^2				
Incoming wet air vol. flow	Q	4823	ft^3/s	2.9E+05	ft^3/min (cfm)		
Dry air mass flow	m_a	343	lbm_a/s				
Evaporation rate	m_e	1.37	lbm_w/s	82.03	lbm_w/min		
Liq. water density	ρ	62.3	lbm/ft^3				@ 70F
Evaporation rate	Q_e	0.022	ft^3/s	9.85	gal/min	591 gal/hr	

Station ID	Yellow (in)	Clear (in)	White ID	Pad - Dry (g)	Pad - Wet (g)	White (in)
B2	nd	nd	nd	nd	nd	nd
B6	nd	nd	nd	14.2	14.2	nd
B10	nd	nd	nd	13.7	13.7	nd
D4	nd	nd	nd	14.4	14.4	nd
D6	nd	nd	nd	14.2	14.2	nd
D8	nd	nd	nd	14.1	14.1	nd
D10	nd	nd	nd	13.9	13.9	nd
F2	nd	nd	nd	14.4	14.4	nd
F4	nd	nd	nd	14.2	14.2	nd
F6	nd	nd	nd	14.3	15	nd
F8	0	nd	nd	15.1	28	nd
F10	0	nd	nd	14.1	19.6	nd
G7	0	nd	nd	nd	nd	nd
G8	0	nd	nd	nd	nd	nd
G9	0.1	nd	nd	nd	nd	nd
H4	0	nd	nd	14.2	14.2	nd
H6	T	nd	nd	14.6	20.9	nd
H7	T	nd	nd	nd	nd	nd
H8	0.1	nd	nd	13.8	78.6	nd
H9	0.2	0.17	nd	nd	nd	nd
I7	nd	nd	nd	nd	nd	nd
I8	0.2	0.19	nd	nd	nd	nd
I9	0.3	0.36	nd	nd	nd	nd
J2	nd	nd	nd	14	14	nd
J4	0	nd	nd	14.1	14.1	nd
J6	0.1	nd	nd	13.9	44.2	nd
J7	0.2	nd	nd	nd	nd	nd
J8	0.4	0.38	nd	14.6	89.9	nd
J9	0.7	0.65	nd	nd	nd	nd
K7	0.1	nd	nd	nd	nd	nd
K8	0.2	0.2	nd	nd	nd	nd
K9	0.4	0.28	nd	nd	nd	nd
L4	0	nd	nd	14.2	14.2	nd
L6	0.1	nd	nd	13.6	16.1	nd
L7	T	nd	nd	nd	nd	nd
L8	T	nd	nd	14.5	49.6	nd
L9	0.2	nd	nd	nd	nd	nd
M7	0.1	nd	nd	nd	nd	nd
M8	T	nd	nd	nd	nd	nd
M9	T	nd	nd	nd	nd	nd
N2	nd	nd	nd	14.4	14.4	nd
N4	nd	nd	nd	14.4	14.4	nd
N6	0	nd	nd	14.5	14.5	nd
N8	T	nd	nd	14.3	15.5	nd
P4	nd	nd	nd	14.5	14.5	nd
P6	nd	nd	nd	14.6	14.6	nd
P8	nd	nd	nd	14.2	14.2	nd
R2	nd	nd	nd	nd	nd	nd
R6	nd	nd	nd	13.9	13.9	nd
R10	nd	nd	nd	13.8	13.8	nd

Station ID	Yellow (in)	Clear (in)	White ID	Pad - Dry (g)	Pad - Wet (g)	White (in)
B14	T	nd	nd	nd	nd	nd
D12	nd	nd	nd	14.2	14.2	nd
D14	T	nd	nd	nd	nd	nd
F12	0	nd	nd	14	14	nd
F14	0	nd	nd	14.2	14.2	nd
G10	0	nd	nd	nd	nd	nd
G11	T	nd	nd	nd	nd	nd
G12	0	nd	nd	nd	nd	nd
G13	nd	nd	nd	nd	nd	nd
H10	0.1	0.07	nd	14.4	70.5	nd
H11	nd	nd	nd	nd	nd	nd
H12	0	nd	nd	14.4	15.5	nd
H13	nd	nd	nd	nd	nd	nd
H14	0	nd	nd	14.2	14.2	nd
I10	0.3	nd	nd	nd	nd	nd
I11	0.2	nd	nd	nd	nd	nd
I12	nd	nd	nd	nd	nd	nd
I13	nd	nd	nd	nd	nd	nd
J10	0.9	nd	nd	14.2	138.8	nd
J11	nd	nd	nd	nd	nd	nd
J12	nd	nd	nd	14	21.2	nd
J13	nd	nd	nd	nd	nd	nd
J14	0	nd	nd	14.4	14.4	nd
K10	nd	nd	nd	nd	nd	nd
K11	0.2	nd	nd	nd	nd	nd
K12	0.2	nd	nd	nd	nd	nd
K13	nd	nd	nd	nd	nd	nd
L10	T	0.04	nd	14.1	36.1	nd
L11	0.2	nd	nd	nd	nd	nd
L12	0	nd	nd	14	14	nd
L13	nd	nd	nd	nd	nd	nd
L14	0	nd	nd	14.1	14.1	nd
M10	0	nd	nd	nd	nd	nd
M11	0	nd	nd	nd	nd	nd
M12	0	nd	nd	nd	nd	nd
M13	nd	nd	nd	nd	nd	nd
N10	0	nd	nd	14	14.1	nd
N12	0	nd	nd	14.1	14.1	nd
N14	nd	nd	nd	14.3	14.3	nd
P10	0	nd	nd	14.2	14.2	nd
P12	nd	nd	nd	14.2	14.2	nd
P14	nd	nd	nd	nd	nd	nd
R14	nd	nd	nd	nd	nd	nd

Appendix F – Data and analysis for Turbo-Mist field test on 6/26/03

27 No. 45 cores with D6 orifice plates **26-Jun-03**

27				Number of spray nozzles	0.000464	yr			Duration of test
45				Cores	0.1694	day			
D6				Orifices	4.07	hr			
6/26/03 10:50		37798.4514		Start of test	244	min			
30418.4	gal		m^3	T1-Nozzle flow totalizer	14640	sec			
26.1	gal/min		m^3/hr	Nozzle flowrate - indicated	6211.4	gal	23.5	m^3	Spray volume
305990	gal		m^3	T2-Bypass flow totalizer	22500	gal	85.2	m^3	Bypass volume
94.1	gal/min		m^3/hr	Bypass flowrate - indicated					
104	psi		Pa	P1	25.5	gal/min	5.78	m^3/hr	Spray flowrate
100	psi		Pa	P2	92	gal/min	20.9	m^3/hr	Bypass flowrate
100	psi		Pa	P3	21	in^2	0.0135	m^2	Pad area
6/26/03 13:00		37798.5417		Midpoint	0.1458	ft^2			
33783.1	gal		m^3	Nozzle flow totalizer	3.35E-06	acre			
26.1	gal/min		m^3/hr	Nozzle flowrate - indicated	480	volts			Voltage
318180	gal		m^3	Bypass flow totalizer	35	amps			Current
94.2	gal/min		m^3/hr	Bypass flowrate - indicated	29.1	kW			Power
104	psi		Pa	P1	87.3	F	30.70	C	Temperature
100	psi		Pa	P2	48%		48%		Relative humidity
100	psi		Pa	P3	4.6	mph	2.04	m/s	Wind speed
6/26/03 14:54		37798.6208		End of test	245.89	deg	245.89	deg	Wind direction
36629.8	gal		m^3	Nozzle flow totalizer	25.46	gpm			Spray
26.1	gal/min		m^3/hr	Nozzle flowrate - indicated	12.28	gpm			Fallback
328490	gal		m^3	Bypass flow totalizer	**13.17**	**gpm**			**Evaporation**
93.8	gal/min		m^3/hr	Bypass flowrate - indicated	52%				
102	psi		Pa	P1	29.1	kW			Power
100	psi		Pa	P2	0.08	$/kW-hr			Energy cost
100	psi		Pa	P3	**0.003**	**$/gal**			**Cost**
3	in			Pad width	0.056	$/gal			Direct heating cost
7	in			Pad length	**5%**				**Relative cost**

Adiabatic saturation / swamp cooler calculation using ASHRAE (1985) equations								
Constants								*source*
univ. gas const.	*R*	1545.33	ft-lbf/(lbmole-R)					
molecular wt. air	M_a	28.9645	lbm/lbmole					from eqn (24)
air gas constant	R_a	53.35	ft-lbf/(lbm-R)					
Incoming air stream								
pressure	p	14.7	psia					
temperature	t	87.259	F	30.7	C	546.929	R	**26Jun03 Field Test**
relative humidity	ϕ	0.48	unitless					
sat. pressure	p_{ws}	0.6497	psia					eqn (4)
water vap. pres.	p_w	0.3102	psia					eqn (22)
humidity ratio	W, γ	0.013409	unitless	93.87	grains/lbm_a			eqn (20)
sat. humidity ratio	W_s	0.028761	unitless					eqn (21)
deg. of saturation	μ	0.4662	unitless					eqn (10)
specific volume	ν	14.08	ft^3/lbm_a					eqn (26)
		13.90	ft^3/lbm					using (1+γ) factor and eqn (26)
		13.78	ft^3/lbm					using ideal gas law
specific enthalpy	h	35.69	BTU/lbm_a					eqn (30)
Outgoing for adiabatic saturation/evaporation								
pressure	p	14.7	psia					
temperature	t	71.65	F	22.0	C	531.32	R	
relative humidity	ϕ	1.00	unitless					
sat. pressure	p_{ws}	0.3893	psia					eqn (4)
water vap. pres.	p_w	0.3893	psia					eqn (22)
humidity ratio	W, γ	0.016921	lbm_w/lbm_a	118.45	grains/lbm_a			eqn (20)
sat. humidity ratio	W_s	0.016921	unitless					eqn (21)
deg. of saturation	μ	1.0000	unitless					eqn (10)
specific volume	ν	13.76	ft^3/lbm_a					eqn (26)
		13.53	ft^3/lbm					using (1+γ) factor and eqn (26)
		13.39	ft^3/lbm					using ideal gas law
specific enthalpy	h	35.69	BTU/lbm_a					eqn (30)
Differences								
temperature	Δt	-15.6	F					
relative humidity	$\Delta\phi$	0.52	unitless					
enthalpy	Δh	0.00	BTU/lbm_a					
humidity ratio	ΔW, $\Delta\gamma$	0.003512	lbm_w/lbm_a	24.58	grains/lbm_a			
Evaporation system parameters								
Wind speed	v	4.6	mi/hr	6.69	ft/s			
Height	h	35.0	ft					
Width	w	35.0	ft					
Xsec area	A	1225	ft^2					
Incoming wet air vol. flow	Q	8192	ft^3/s	4.9E+05	ft^3/min (cfm)			
Dry air mass flow	m_a	582	lbm_a/s					
Evaporation rate	m_e	2.04	lbm_w/s	122.57	lbm_w/min			
Liq. water density	ρ	62.3	lbm/ft^3					@ 70F
Evaporation rate	Q_e	0.033	ft^3/s	14.72	gal/min	883	gal/hr	

Station ID	Yellow (in)	Clear (in)	White ID	Pad - Dry (g)	Pad - Wet (g)	White (in)
B2	nd	nd	nd	nd	nd	nd
B6	nd	nd	nd	14.3	14.3	nd
B10	nd	nd	nd	13.9	13.9	nd
D4	nd	nd	nd	14.1	14.1	nd
D6	nd	nd	nd	14.2	14.2	nd
D8	nd	nd	nd	14.2	14.2	nd
D10	nd	nd	nd	14.4	14.4	nd
F2	nd	nd	nd	14.3	14.3	nd
F4	0	nd	nd	14	14	nd
F6	0	nd	nd	14	14	nd
F8	0	nd	nd	14.2	14.2	nd
F10	0	nd	nd	14.4	14.4	nd
G7	0	nd	nd	nd	nd	nd
G8	nd	nd	nd	nd	nd	nd
G9	0	nd	nd	nd	nd	nd
H4	0	nd	nd	14.1	14.1	nd
H6	0	nd	nd	14	14	nd
H7	0	nd	nd	nd	nd	nd
H8	0	nd	nd	14.2	14.2	nd
H9	0	0.02	nd	nd	nd	nd
I7	0	nd	nd	nd	nd	nd
I8	0	0.04	nd	nd	nd	nd
I9	0	0.05	nd	nd	nd	nd
J2	0	nd	nd	14.1	14.1	nd
J4	0	nd	nd	13.7	13.7	nd
J6	0	nd	nd	14.1	14.1	nd
J7	0	nd	nd	nd	nd	nd
J8	0.1	0.15	nd	14	88.9	nd
J9	0.4	0.42	nd	nd	nd	nd
K7	0	nd	nd	nd	nd	nd
K8	0.1	0.12	nd	nd	nd	nd
K9	0.4	0.45	nd	nd	nd	nd
L4	0	nd	nd	14.3	14.3	nd
L6	0	nd	nd	14	14	nd
L7	0	nd	nd	nd	nd	nd
L8	0.1	nd	nd	14.4	71.2	nd
L9	0.4	nd	nd	nd	nd	nd
M7	0	nd	nd	nd	nd	nd
M8	0.1	nd	nd	nd	nd	nd
M9	0.3	nd	nd	nd	nd	nd
N2	nd	nd	nd	14	14	nd
N4	0	nd	nd	13.9	13.9	nd
N6	0	nd	nd	14.1	14.1	nd
N8	T	nd	nd	14	34.7	nd
P4	nd	nd	nd	13.7	13.7	nd
P6	nd	nd	nd	14	14	nd
P8	nd	nd	nd	13.6	16.3	nd
R2	nd	nd	nd	nd	nd	nd
R6	nd	nd	nd	14.1	14.1	nd
R10	nd	nd	nd	14.4	15.7	nd

Station ID	Yellow (in)	Clear (in)	White ID	Pad - Dry (g)	Pad - Wet (g)	White (in)
B14	nd	nd	nd	nd	nd	nd
D12	nd	nd	nd	14.3	14.3	nd
D14	nd	nd	nd	nd	nd	nd
F12	0	nd	nd	14.4	14.4	nd
F14	nd	nd	nd	14.5	14.5	nd
G10	0	nd	nd	nd	nd	nd
G11	0	nd	nd	nd	nd	nd
G12	0	nd	nd	nd	nd	nd
G13	nd	nd	nd	nd	nd	nd
H10	0	T	nd	13.8	13.8	nd
H11	0	nd	nd	nd	nd	nd
H12	0	nd	nd	14.4	14.4	nd
H13	nd	nd	nd	nd	nd	nd
H14	nd	nd	nd	14.3	14.3	nd
I10	0.1	nd	nd	nd	nd	nd
I11	0.1	nd	nd	nd	nd	nd
I12	0	nd	nd	nd	nd	nd
I13	nd	nd	nd	nd	nd	nd
J10	0.7	nd	nd	14.1	154.4	nd
J11	nd	nd	nd	nd	nd	nd
J12	0.1	nd	nd	14.2	67.8	nd
J13	nd	nd	nd	nd	nd	nd
J14	nd	nd	nd	14	14.3	nd
K10	0.5	nd	nd	nd	nd	nd
K11	1	nd	nd	nd	nd	nd
K12	0.2	nd	nd	nd	nd	nd
K13	nd	nd	nd	nd	nd	nd
L10	1	0.81	nd	14.4	155.4	nd
L11	0.9	nd	nd	nd	nd	nd
L12	0.4	nd	nd	14.3	140.3	nd
L13	nd	nd	nd	nd	nd	nd
L14	nd	nd	nd	14.1	22.7	nd
M10	0.6	nd	nd	nd	nd	nd
M11	0.4	nd	nd	nd	nd	nd
M12	0.2	nd	nd	nd	nd	nd
M13	nd	nd	nd	nd	nd	nd
N10	0.3	nd	nd	14.1	151.6	nd
N12	0.2	nd	nd	13.7	75.3	nd
N14	nd	nd	nd	14	23.7	nd
P10	nd	nd	nd	14.1	54.2	nd
P12	nd	nd	nd	14.3	29.5	nd
P14	nd	nd	nd	nd	nd	nd
R14	nd	nd	nd	nd	nd	nd

Appendix G – Data and analysis for Turbo-Mist field test on 7/24/03

27 No. 45 cores with D6 orifice plates				**24-Jul-03**					
27				Number of spray nozzles	0.000457	yr			Duration of test
45				Cores	0.1667	day			
D6				Orifices	4.00	hr			
7/24/03 11:00		37826.4583		Start of test	240	min			
36736.2	gal		m^3	T1-Nozzle flow totalizer	14400	sec			
26.1	gal/min		m^3/hr	Nozzle flowrate - indicated	6253	gal	23.7	m^3	Spray volume
328910	gal		m^3	T2-Bypass flow totalizer	22590	gal	85.5	m^3	Bypass volume
94.6	gal/min		m^3/hr	Bypass flowrate - indicated					
106	psi		Pa	P1	26.1	gal/min	5.92	m^3/hr	Spray flowrate
102	psi		Pa	P2	94	gal/min	21.4	m^3/hr	Bypass flowrate
102	psi		Pa	P3	21	in^2	0.0135	m^2	Pad area
7/24/03 13:00		37826.5417		Midpoint	0.1458	ft^2			
39820.1	gal		m^3	Nozzle flow totalizer	3.35E-06	acre			
25.7	gal/min		m^3/hr	Nozzle flowrate - indicated	480	volts			Voltage
340020	gal		m^3	Bypass flow totalizer	35	amps			Current
94.7	gal/min		m^3/hr	Bypass flowrate - indicated	29.1	kW			Power
103	psi		Pa	P1	82.5	F	28.0	C	Temperature
103	psi		Pa	P2	62%		62%		Relative humidity
101	psi		Pa	P3	3.0	mph	1.35	m/s	Wind speed
7/24/03 15:00		37826.625		End of test	264.06	deg	264.06	deg	Wind direction
42989.2	gal		m^3	Nozzle flow totalizer	26.05	gpm			Spray
25.7	gal/min		m^3/hr	Nozzle flowrate - indicated	14.70	gpm			Fallback
351500	gal		m^3	Bypass flow totalizer	**11.36**	**gpm**			**Evaporation**
94.6	gal/min		m^3/hr	Bypass flowrate - indicated	44%				
103	psi		Pa	P1	29.1	kW			Power
101	psi		Pa	P2	0.08	$/kW-hr			Energy cost
101	psi		Pa	P3	**0.003**	**$/gal**			**Cost**
3	in			Pad width	0.056	$/gal			Direct heating cost
7	in			Pad length	**6%**				**Relative cost**

Adiabatic saturation / swamp cooler calculation using ASHRAE (1985) equations								
Constants								*source*
univ. gas const.	*R*	1545.33	ft-lbf/(lbmole-R)					
molecular wt. air	M_a	28.9645	lbm/lbmole					from eqn (24)
air gas constant	R_a	53.35	ft-lbf/(lbm-R)					
Incoming air stream								
pressure	p	14.7	psia					
temperature	t	82.454	F	28.0	C	542.124	R	**24Jul03 Test**
relative humidity	ϕ	0.62	unitless					
sat. pressure	p_{ws}	0.5569	psia					eqn (4)
water vap. pres.	p_w	0.3464	psia					eqn (22)
humidity ratio	W, γ	0.015010	unitless	105.07	grains/lbm_a			eqn (20)
sat. humidity ratio	W_s	0.024491	unitless					eqn (21)
deg. of saturation	μ	0.6129	unitless					eqn (10)
specific volume	ν	13.99	ft^3/lbm_a					eqn (26)
		13.79	ft^3/lbm					using (1+γ) factor and eqn (26)
		13.66	ft^3/lbm					using ideal gas law
specific enthalpy	h	36.26	BTU/lbm_a					eqn (30)
Outgoing for adiabatic saturation/evaporation								
pressure	p	14.7	psia					
temperature	t	72.29	F	22.4	C	531.96	R	
relative humidity	ϕ	1.00	unitless					
sat. pressure	p_{ws}	0.3979	psia					eqn (4)
water vap. pres.	p_w	0.3979	psia					eqn (22)
humidity ratio	W, γ	0.017302	lbm_w/lbm_a	121.12	grains/lbm_a			eqn (20)
sat. humidity ratio	W_s	0.017302	unitless					eqn (21)
deg. of saturation	μ	1.0000	unitless					eqn (10)
specific volume	ν	13.78	ft^3/lbm_a					eqn (26)
		13.55	ft^3/lbm					using (1+γ) factor and eqn (26)
		13.41	ft^3/lbm					using ideal gas law
specific enthalpy	h	36.26	BTU/lbm_a					eqn (30)
Differences								
temperature	Δt	-10.2	F					
relative humidity	$\Delta\phi$	0.38	unitless					
enthalpy	Δh	0.00	BTU/lbm_a					
humidity ratio	ΔW, $\Delta\gamma$	0.002292	lbm_w/lbm_a	16.04	grains/lbm_a			
Evaporation system parameters								
Wind speed	v	3.0	mi/hr	4.43	ft/s			
Height	h	35.0	ft					
Width	w	35.0	ft					
Xsec area	A	1225	ft^2					
Incoming wet air vol. flow	Q	5426	ft^3/s	3.3E+05	ft^3/min (cfm)			
Dry air mass flow	m_a	388	lbm_a/s					
Evaporation rate	m_e	0.89	lbm_w/s	53.32	lbm_w/min			
Liq. water density	ρ	62.3	lbm/ft^3					@ 70F
Evaporation rate	Q_e	0.014	ft^3/s	6.40	gal/min	384	gal/hr	

Station ID	Yellow (in)	Clear (in)	White ID	Pad - Dry (g)	Pad - Wet (g)	White (in)
B2	nd	nd	nd	nd	nd	nd
B6	nd	nd	nd	nd	nd	nd
B10	nd	nd	nd	nd	nd	nd
D4	nd	nd	nd	nd	nd	nd
D6	nd	nd	nd	14.3	14.3	nd
D8	nd	nd	nd	14.7	14.7	nd
D10	nd	nd	nd	14.2	14.2	nd
F2	nd	nd	nd	nd	nd	nd
F4	nd	nd	nd	14.2	14.2	nd
F6	nd	nd	nd	14.5	14.5	nd
F8	0	nd	nd	14.0	14.0	nd
F10	0	nd	nd	14.4	14.4	nd
G7	0	nd	nd	nd	nd	nd
G8	0	nd	nd	nd	nd	nd
G9	0	nd	nd	nd	nd	nd
H4	nd	nd	nd	14.1	14.1	nd
H6	0	nd	nd	14.1	14.3	nd
H7	0	nd	nd	nd	nd	nd
H8	0	nd	nd	14.2	21.2	nd
H9	0	0.07	nd	nd	nd	nd
I7	0	nd	nd	nd	nd	nd
I8	0	0.1	nd	nd	nd	nd
I9	0.2	0.20	nd	nd	nd	nd
J2	nd	nd	nd	15.0	15.0	nd
J4	0	nd	nd	14.3	14.3	nd
J6	0	nd	nd	14.3	28.3	nd
J7	0.1	nd	nd	nd	nd	nd
J8	0.3	0.37	nd	13.4	116.8	nd
J9	0.8	0.74	nd	nd	nd	nd
K7	0	nd	nd	nd	nd	nd
K8	0.3	0.3	nd	nd	nd	nd
K9	0.8	0.75	nd	nd	nd	nd
L4	0	nd	nd	14.1	14.1	nd
L6	0	nd	nd	14.2	20.4	nd
L7	0	nd	nd	nd	nd	nd
L8	0.1	nd	nd	14.7	100.4	nd
L9	0.4	nd	nd	nd	nd	nd
M7	0	nd	nd	nd	nd	nd
M8	0	nd	nd	nd	nd	nd
M9	0.2	nd	nd	nd	nd	nd
N2	nd	nd	nd	14.3	14.3	nd
N4	0	nd	nd	14.4	14.4	nd
N6	0	nd	nd	14.4	14.4	nd
N8	0	nd	nd	14.3	35.7	nd
P4	nd	nd	nd	13.7	14.0	nd
P6	nd	nd	nd	14.4	14.4	nd
P8	nd	nd	nd	14.4	14.4	nd
R2	nd	nd	nd	nd	nd	nd
R6	nd	nd	nd	14.1	14.1	nd
R10	nd	nd	nd	14.0	14.0	nd

Station ID	Yellow (in)	Clear (in)	White ID	Pad - Dry (g)	Pad - Wet (g)	White (in)
B14	nd	nd	nd	nd	nd	nd
D12	nd	nd	nd	14.5	14.5	nd
D14	nd	nd	nd	nd	nd	nd
F12	0	nd	nd	14.0	14.2	nd
F14	nd	nd	nd	14.5	14.5	nd
G10	0	nd	nd	nd	nd	nd
G11	0	nd	nd	nd	nd	nd
G12	0	nd	nd	nd	nd	nd
G13	nd	nd	nd	nd	nd	nd
H10	0	0.05	nd	14.4	53.3	nd
H11	0.1	nd	nd	nd	nd	nd
H12	0	nd	nd	14.3	50.0	nd
H13	nd	nd	nd	nd	nd	nd
H14	nd	nd	nd	14.6	14.6	nd
I10	0.3	nd	nd	nd	nd	nd
I11	0.4	nd	nd	nd	nd	nd
I12	0.1	nd	nd	nd	nd	nd
I13	nd	nd	nd	nd	nd	nd
J10	1.1	nd	nd	14.4	158.9	nd
J11	nd	nd	nd	nd	nd	nd
J12	0.2	nd	nd	14.5	143.5	nd
J13	nd	nd	nd	nd	nd	nd
J14	0	nd	nd	14.6	27.0	nd
K10	1.2	nd	nd	nd	nd	nd
K11	1.1	nd	nd	nd	nd	nd
K12	0.2	nd	nd	nd	nd	nd
K13	nd	nd	nd	nd	nd	nd
L10	0.6	0.68	nd	14.5	149.7	nd
L11	0.7	nd	nd	nd	nd	nd
L12	0.2	nd	nd	14.6	129.5	nd
L13	nd	nd	nd	nd	nd	nd
L14	0	nd	nd	14.4	24.1	nd
M10	0.2	nd	nd	nd	nd	nd
M11	0.4	nd	nd	nd	nd	nd
M12	0.1	nd	nd	nd	nd	nd
M13	nd	nd	nd	nd	nd	nd
N10	0	nd	nd	14.6	65.2	nd
N12	0.1	nd	nd	14.6	77.9	nd
N14	0	nd	nd	14.5	20.1	nd
P10	nd	nd	nd	14.2	18.2	nd
P12	nd	nd	nd	14.4	26.1	nd
P14	nd	nd	nd	14.2	16.2	nd
R14	nd	nd	nd	14.3	14.3	nd

Appendix H – Data and analysis for Turbo-Mist field test on 8/11/03

30 No. 45 cores with D8 orifice plates				**11-Aug-03**					
30				Number of spray nozzles	0.000327	yr			Duration of test
45				Cores	0.1194	day			
D8				Orifices	2.87	hr			
8/11/03 12:08		37844.5056		Start of test	172	min			
43236.4	gal		m^3	T1-Nozzle flow totalizer	10320	sec			
40.1	gal/min		m^3/hr	Nozzle flowrate - indicated	6738.2	gal	25.5	m^3	Spray volume
352000	gal		m^3	T2-Bypass flow totalizer	-351917.3	gal	-1332.2	m^3	Bypass volume
82.4	gal/min		m^3/hr	Bypass flowrate - indicated					
102	psi		Pa	P1	39.2	gal/min	8.90	m^3/hr	Spray flowrate
96	psi		Pa	P2	-2046	gal/min	-464.7	m^3/hr	Bypass flowrate
100	psi		Pa	P3	21	in^2	0.0135	m^2	Pad area
8/11/03 13:25		37844.559		Midpoint	0.1458	ft^2			
46245.1	gal		m^3	Nozzle flow totalizer	3.35E-06	acre			
39.7	gal/min		m^3/hr	Nozzle flowrate - indicated	480	volts			Voltage
358380	gal		m^3	Bypass flow totalizer	35	amps			Current
82.7	gal/min		m^3/hr	Bypass flowrate - indicated	29.1	kW			Power
100	psi		Pa	P1	85.1	F	29.5	C	Temperature
96	psi		Pa	P2	63%		63%		Relative humidity
98	psi		Pa	P3	2.4	mph	1.09	m/s	Wind speed
8/11/03 15:00		37844.625		End of test	181.50	deg	181.50	deg	Wind direction
49974.6	gal		m^3	Nozzle flow totalizer	39.18	gpm			Spray
39.3	gal/min		m^3/hr	Nozzle flowrate - indicated	25.21	gpm			Fallback
366080	gal		m^3	Bypass flow totalizer	**13.97**	**gpm**			**Evaporation**
82.7	gal/min		m^3/hr	Bypass flowrate - indicated	36%				
100	psi		Pa	P1	29.1	kW			Power
94	psi		Pa	P2	0.08	$/kW-hr			Energy cost
96	psi		Pa	P3	**0.003**	**$/gal**			**Cost**
3	in			Pad width	0.056	$/gal			Direct heating cost
7	in			Pad length	**5%**				**Relative cost**

Adiabatic saturation / swamp cooler calculation using ASHRAE (1985) equations							
Constants							*source*
univ. gas const.	*R*	1545.33	ft-lbf/(lbmole-R)				
molecular wt. air	M_a	28.9645	lbm/lbmole				from eqn (24)
air gas constant	R_a	53.35	ft-lbf/(lbm-R)				
Incoming air stream							
pressure	p	14.7	psia				
temperature	t	85.1	F	29.5	C	544.77 R	**11Aug03 Test**
relative humidity	ϕ	0.63	unitless				
sat. pressure	p_{ws}	0.6065	psia				eqn (4)
water vap. pres.	p_w	0.3829	psia				eqn (22)
humidity ratio	W, γ	0.016635	unitless	116.45	grains/lbm_a		eqn (20)
sat. humidity ratio	W_s	0.026765	unitless				eqn (21)
deg. of saturation	μ	0.6215	unitless				eqn (10)
specific volume	ν	14.10	ft^3/lbm_a				eqn (26)
		13.87	ft^3/lbm				using (1+γ) factor and eqn (26)
		13.73	ft^3/lbm				using ideal gas law
specific enthalpy	h	38.70	BTU/lbm_a				eqn (30)
Outgoing for adiabatic saturation/evaporation							
pressure	p	14.7	psia				
temperature	t	74.91	F	23.8	C	534.58 R	
relative humidity	ϕ	1.00	unitless				
sat. pressure	p_{ws}	0.4344	psia				eqn (4)
water vap. pres.	p_w	0.4344	psia				eqn (22)
humidity ratio	W, γ	0.018940	lbm_w/lbm_a	132.58	grains/lbm_a		eqn (20)
sat. humidity ratio	W_s	0.018940	unitless				eqn (21)
deg. of saturation	μ	1.0000	unitless				eqn (10)
specific volume	ν	13.88	ft^3/lbm_a				eqn (26)
		13.63	ft^3/lbm				using (1+γ) factor and eqn (26)
		13.47	ft^3/lbm				using ideal gas law
specific enthalpy	h	38.70	BTU/lbm_a				eqn (30)
Differences							
temperature	Δt	-10.2	F				
relative humidity	$\Delta\phi$	0.37	unitless				
enthalpy	Δh	0.00	BTU/lbm_a				
humidity ratio	ΔW, $\Delta\gamma$	0.002304	lbm_w/lbm_a	16.13	grains/lbm_a		
Evaporation system parameters							
Wind speed	v	2.4	mi/hr	3.58	ft/s		
Height	h	35.0	ft				
Width	w	35.0	ft				
Xsec area	A	1225	ft^2				
Incoming wet air vol. flow	Q	4381	ft^3/s	2.6E+05	ft^3/min (cfm)		
Dry air mass flow	m_a	311	lbm_a/s				
Evaporation rate	m_e	0.72	lbm_w/s	42.96	lbm_w/min		
Liq. water density	ρ	62.3	lbm/ft^3				@ 70F
Evaporation rate	Q_e	0.011	ft^3/s	5.16	gal/min	310 gal/hr	

Station ID	Yellow (in)	Clear (in)	White ID	Pad - Dry (g)	Pad - Wet (g)	White (in)
B2	nd	nd	nd	nd	nd	nd
B6	nd	nd	nd	nd	nd	nd
B10	nd	nd	nd	nd	nd	nd
D4	nd	nd	nd	nd	nd	nd
D6	nd	nd	nd	14.7	14.7	nd
D8	nd	nd	nd	14.3	14.3	nd
D10	nd	nd	nd	14.4	14.4	nd
F2	nd	nd	nd	nd	nd	nd
F4	0	nd	nd	14.7	14.9	nd
F6	0	nd	nd	14.5	15.5	nd
F8	0	nd	nd	14.3	19.3	nd
F10	0	nd	nd	13.8	21.3	nd
G7	0	nd	nd	nd	nd	nd
G8	T	nd	nd	nd	nd	nd
G9	T	nd	nd	nd	nd	nd
H4	0	nd	nd	14.1	18.2	nd
H6	0.1	nd	nd	13.6	47.3	nd
H7	0.2	nd	nd	nd	nd	nd
H8	0.2	nd	nd	14	75.6	nd
H9	0.2	0.2	nd	nd	nd	nd
I7	0.5	nd	nd	nd	nd	nd
I8	0.9	0.85	nd	nd	nd	nd
I9	1	0.85	nd	nd	nd	nd
J2	nd	nd	nd	14.8	14.8	nd
J4	nd	nd	nd	14.3	25.8	nd
J6	nd	nd	nd	14	125.7	nd
J7	1.2	2	nd	14.3	119.1	nd
J8	2.2	nd	nd	nd	nd	nd
J9	3	2.7	nd	nd	nd	nd
K7	0.5	nd	nd	nd	nd	nd
K8	1	0.9	nd	nd	nd	nd
K9	1.5	1.45	nd	nd	nd	nd
L4	0	nd	nd	14.3	19.4	nd
L6	T	nd	nd	14.2	38.9	nd
L7	0.2	nd	nd	nd	nd	nd
L8	0.5	nd	nd	14.5	117.9	nd
L9	1	nd	nd	nd	nd	nd
M7	0.1	nd	nd	nd	nd	nd
M8	0.2	nd	nd	nd	nd	nd
M9	0.5	nd	nd	nd	nd	nd
N2	nd	nd	nd	14.1	14.1	nd
N4	0	nd	nd	14.1	14.1	nd
N6	0	nd	nd	14.4	18.8	nd
N8	0.2	nd	nd	14.3	72.1	nd
P4	nd	nd	nd	14.4	14.4	nd
P6	nd	nd	nd	14.1	25.6	nd
P8	nd	nd	nd	nd	nd	nd
R2	nd	nd	nd	nd	nd	nd
R6	nd	nd	nd	14	14	nd
R10	nd	nd	nd	14.2	14.9	nd

Station ID	Yellow (in)	Clear (in)	White ID	Pad - Dry (g)	Pad - Wet (g)	White (in)
B14	nd	nd	nd	nd	nd	nd
D12	nd	nd	nd	nd	nd	nd
D14	nd	nd	nd	14.5	14.5	nd
F12	nd	nd	nd	14.6	17.4	nd
F14	nd	nd	nd	14	14.3	nd
G10	T	nd	nd	nd	nd	nd
G11	0.1	nd	nd	nd	nd	nd
G12	T	nd	nd	nd	nd	nd
G13	nd	nd	nd	nd	nd	nd
H10	0.15	0.11	nd	14.8	69.6	nd
H11	0.15	nd	nd	nd	nd	nd
H12	T	nd	nd	14.7	29.4	nd
H13	nd	nd	nd	nd	nd	nd
H14	nd	nd	nd	13.9	13.9	nd
I10	0.4	nd	nd	nd	nd	nd
I11	0.2	nd	nd	nd	nd	nd
I12	T	nd	nd	nd	nd	nd
I13	nd	nd	nd	nd	nd	nd
J10	1.8	nd	nd	14.1	141	nd
J11	nd	nd	nd	nd	nd	nd
J12	0	nd	nd	14.5	15.9	nd
J13	nd	nd	nd	nd	nd	nd
J14	nd	nd	nd	14.6	14.6	nd
K10	0.8	nd	nd	nd	nd	nd
K11	0.2	nd	nd	nd	nd	nd
K12	0	nd	nd	nd	nd	nd
K13	nd	nd	nd	nd	nd	nd
L10	0.5	0.5	nd	13.9	141.6	nd
L11	0.15	nd	nd	nd	nd	nd
L12	T	nd	nd	14.1	16.7	nd
L13	nd	nd	nd	nd	nd	nd
L14	nd	nd	nd	14.4	14.4	nd
M10	0.2	nd	nd	nd	nd	nd
M11	0.2	nd	nd	nd	nd	nd
M12	0	nd	nd	nd	nd	nd
M13	nd	nd	nd	nd	nd	nd
N10	0.1	nd	nd	14.4	60.9	nd
N12	0	nd	nd	14.4	19.7	nd
N14	nd	nd	nd	14	14	nd
P10	nd	nd	nd	14.3	20.3	nd
P12	0	nd	nd	14.3	14.4	nd
P14	nd	nd	nd	nd	nd	nd
R14	nd	nd	nd	nd	nd	nd