THE HISTORY AND TECHNOLOGY OF MAN-MADE SNOW IN WINTER RECREATION AREAS

PART I - HISTORY AND TECHNOLOGY

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What is Man-Made Snow

Man-made snow is real snow, produced by:

(1) Atomizing water into a spray or aerosol;

(2) Projecting the droplets into the atmosphere directly over the ground surface to be covered; and

(3) Freezing the droplets before they land by causing them to be intermixed with a large quantity of air having a wet bulb temperature below 32 degrees.

How is this Accomplished

Man-made snow is produced by either of two basically differing techniques, both designed to attain the same end result:

(1) The Compressed Air Method, in which compressed or primary air is expanded to a high velocity to atomize the water, project the droplets and entrain the large quantity of ambient or secondary air needed to complete the freezing process. Compressed air atomization is accomplished by either so-called external or internal mix nozzles.

(2) The Mechanical Method, in which a blower or fan is used to project the droplets produced by liquid pressure or other mechanical means of atomization, and also entrain the secondary ambient air.

Mechanical atomization is accomplished either by pressuring the water to cause break-up through small orifices, or by whirling the water off the tip of the fan. In both cases, high velocity is imparted to the water, rather than to a primary air stream.

Variations of the Mechanical Method include the following:

(a) Introduction of small quantities of air into the water nozzles just prior to atomization. This is the Linde approach (Ref. 1). It is theorized by its developers that the expanding gas bubbles produce tiny ice crystals which later seed the water droplets by a process termed "droplet nucleation." It is also conceivable that the expanding bubbles aid the atomization as in an aerosol can.

(b) Atomizing, separately, in the air stream of the blower, ahead of the main water nozzles, a small amount of water, by a small compressed air atomizer, to produce very fine droplets. The droplets are said to freeze immediately and impact with the larger droplets to produce so-called "droplet nucleation." This is the Hedco approach (Ref. 2).

Characteristics of Man-Made Snow

Man-made snow and natural snow differ, at the time they are produced, in four essential characteristics:

(1) The Mechanism of Formation

(2) The Density

(3) The Particle Size and Shape

(4) The Wetness

Natural snow packs loosely on the ground to a density that is always less than 10 to 15 lbs./cu. ft., and generally around 6 lbs./cu. ft. (Ref. 3).

Man-made snow, except possibly that which blows away from the desired coverage area, appears always to have a density greater than 20 lbs./cu. ft., and generally in the range of 25 to 30 lbs./cu. ft. When very wet, the density goes over 40 lbs./cu. ft. Repeated measurements, made at the time of settling, have shown that good quality man-made snow has a density of 25 to 30 lbs./cu. ft. This has led us to use 27.5 lbs./cu. ft. as convenient standard measure (200 gpm of water produces one cu. ft./second, or one acre-inch hour of snow of this density).

The crystal size appears to be generally proportional to the droplet size. The larger ones, at least, seem to be granular in form.

For production purposes, the percent of unfrozen water may range to over 50% at the time of formation, and is generally in the range of 20 to 40%. The wetness varies greatly with where and when it is measured relative to the position of the nozzle and time of production. The further away from the nozzle, the dryer the snow. The water continues to freeze, evaporate, or drain off after deposition, depending upon the temperature, humidity and wind velocity. In high winds, the snow must be made wet in order to deposit it where desired.

Mechanism of Formation of Man-Made Snow

It is the opinion of this writer that the mechanism generally prescribed for the formation of natural snow does not occur appreciably with man-made snow, because the period of time or falling distance does not permit nucleation to occur. Nucleation is understood to be the mechanism in which particle growth occurs by condensation, or precipitation, of moisture from the vapor state, on to nuclei, to

EXPANSION POTENTIAL

$$\frac{T_1}{T_2} = \left(\frac{P_1}{P_2}\right)^{\frac{K-1}{K}} = \frac{492}{T_2} = \left(\frac{8}{1}\right)^{0.286} = 1.806$$

$T_1 = 32° F$ $P_1 = 117.6$ PSIA $P_2 = 14.7$ PSIA

$T_2 = 273° R = -187° F$

TO HEAT AIR: $15 \text{ FT.}^3/\text{MIN.} \times .075 \#/\text{FT.}^3 \left[32-(-187)\right] \times 0.24 \text{ Btu}/\# \times °\text{F}$

$= 60$ Btu/MIN.

HEAT OF FUSION = 144 × 8.3 = 1200 Btu/MIN.

$60 \times 100/1200 = 5\%$

RADIATION POTENTIAL

$$q = 0.173\, A\, \epsilon \left[\left(\frac{T_1}{100}\right)^4 - \left(\frac{T_2}{100}\right)^4\right]$$

for $T_1 = 492° R$ $T_2 = 360° R$ ($-100° F$) $\epsilon = 0.94$

$q/A = 68$ Btu/Hr. × FT.^{2}

EVAPORATION POTENTIAL

$$\Delta H_V \cdot X_V = \Delta H_F (1 - X_V) ; \quad X_V = \frac{\Delta H_F}{\Delta H_V - \Delta H_F}$$

$$100\, X_V = \frac{144 \times 100}{1075 - 144} = 11.8\,\%$$

X_V = FRACTION EVAPORATED

$\Delta H_V = 1075$ Btu/#

$\Delta H_F = 144$ Btu/#

Figure I

grow into the crystal patterns of snowflakes. The rising clouds and floating fine crystals, which frequently do occur, however, may be the result of nucleation of a small portion of the spray.

Expansion Potential

It is frequently heard that the expansion and cooling of the compressed air causes or aids the production of snow. This is largely a fallacy as illustrated in the calculation of the expansion potential presented in Figure I, if we assume a typical air-to-water ratio of 15 cu. ft. of free air/gal. water (these are the units commonly employed in the snow-making industry), and if we consider an imaginary case, as a limit, of an adiabatic expansion doing useful work, with all of the heat furnished by the water, the total amount of heat extracted is only 5% of that required to freeze the water. An irreversible expansion results in a far smaller air temperature drop.

Radiation Potential

As also illustrated in Figure I, the radiation potential is estimated to be 68 BTU/hr./sq. ft. A comparison of the heat transfer rate by radiation with the rates by evaporation and convection (presented in Figure III) shows that radiation is insignificant (less than 10% except for large droplets on warm nights).

Evaporation Potential

To illustrate the potential significance of evaporation, we can make a simple heat balance at 32 degrees. In order for a droplet to freeze (as also shown in Figure I), less than 12% of its weight needs to evaporate.

It is, therefore, concluded that the production of man-made snow occurs largely as the result of freezing of the droplets through mass transfer by evaporation and convective heat transfer to the ambient air.

Contributions of Mass and Heat Transfer

The equations presented in Figure II were used to estimate the heat and mass transfer rates, plus the freezing times, for various sized droplets. Heat transfer to the expanding air and radiation was neglected. The procedure is illustrated in Ref. 4 and terminal velocities are from Ref. 5.

The results are shown in Figure III. The following comments are felt to be of interest:

(1) At 5 degree temperature difference and 100% RH, evaporation contributes 48%. At 5 degree temperature difference and 0% RH, evaporation contributes 56%. The relative contributions are independent of droplet size.

(2) At 30 degree temperature difference and 100% RH, evaporation contributes 32%. At 30 degree temperature difference and 0% RH, evaporation contributes 33%. The relative contributions are independent of droplet size.

MASS DIFFUSIVITY, D_{AB} = $CM^2/SEC.$

$$D_{AB} = a \left(\frac{T}{\sqrt{T_{CA} T_{CB}}} \right)^b \frac{(P_{CA} \cdot P_{CB})^{1/3} (T_{CA} \cdot T_{CB})^{5/12} \left(\frac{1}{M_A} + \frac{1}{M_B} \right)^{1/2}}{P}$$

$P = 1$ ATM $\quad T = {}^\circ K \quad a = 3.64\backslash{-4} \quad b = 2.334$

$D_{AB} = 0.20 \pm 5\%$ ($t = 32°$ TO $-8°$), WITHIN 8% OF EXPER. VALUES

MASS TRANSFER COEF., K_{XM}, $g\text{-moles}/sec. \times CM^2$

$$K_{XM} = \frac{C_f D_{AB}}{D} \left[2.0 + 0.6\, Re^{1/2} \cdot Sc^{1/3} \right]$$ - CHILTON-COLBURN ANALOGY

$$Re = \frac{D u_f \rho_f}{\mu_f} \qquad Sc = \frac{\mu_f}{\rho D_{AB}} = 0.615 \text{ @ } 22° F$$

$C_f = g\text{-moles}/CM^3 = 4.55\backslash{-5}$

EVAPORATION RATE, W_A = $g\text{-moles}/Sec.$

$$W_A = K_{XM} \pi D^2 \frac{x_{A0} - x_\infty}{1 - x_{A0}}$$

x_{A0} = VAPOR PRESSURE AT 32° F
x_∞ = AMBIENT VAPOR PRESSURE

HEAT TRANSFER COEF., h_m, $Btu/Hr. \times FT^2 \times {}^\circ F$

$$h_M = \frac{K_f}{D} \left[2.0 + 0.6\, Re^{1/2} \cdot P_r^{1/3} \right]$$

$P_r^{1/3} = 0.875$ @ 22°F $\qquad K_f = .014 \; Btu/Hr \times FT^2 \times {}^\circ F/FT.$

LET h' = HEAT TRANSFER EQUIVALENT OF EVAPORATION

$$h' = W_A \times 1075 \times \frac{18 \times 3600 (30.5 \times 10^4)^2}{454 \pi D^2} = 4.55\backslash{5} \; W_A/D^2$$

$Btu/Hr. \times FT.^2$

FREEZING TIME, θ_F, SEC.

$$\theta_F = \frac{\Delta H_F \times \pi/6\, D^3 \rho}{(h_M \cdot \Delta t + h') \pi D^2} = \frac{(144)(62.4)(3600)\, D}{6 \times 30.34 \times 10^4 (h_M \Delta t + h')} = \frac{17.7\, D}{h_M \Delta t + h'}$$

Figure II- Freezing Rate Equations

DIAMETER, D. MICRONS			50	100	200	400	600	800	1000
TERM. VELOCITY, v_T, FT/SEC			.25	.73	2.2	5.3	8.2	10.9	11.8
REYNOLDS NO., R_e			.31	1.81	10.9	54.6	122	216	292
HEAT TRANSFER COEF. h_M			196	115	80	63	56	52	47
MASS TRANSFER COEF. $K_{xM} \times 10^3$			4.2	2.5	1.70	1.32	1.16	1.09	0.98
Δt	% RH								
5°	100%	$h_M \Delta t$	980	575	400	315	280	260	235
		h'	900	530	363	284	251	234	211
		θ_F, SEC	.47	1.60	4.6	12	20	29	40
5°	0%	$h_M \Delta t$	980	575	400	315	280	260	235
		h'	1225	720	493	385	341	318	286
		θ_F, SEC	.40	1.4	4.0	10	17	24	34
10°	100%	$h_M \Delta t$	1960	1115	800	630	560	520	470
		h'	1225	720	493	385	341	318	286
		θ_F, SEC	0.3	1.0	2.7	7	12	17	23
10°	0%	$h_M \Delta t$	1960	1115	800	630	560	520	470
		h'	1620	952	654	510	451	420	378
		θ_F, SEC	.25	0.85	2.4	6.2	10	15	21
20°	100%	$h_M \Delta t$	3920	2230	1600	1260	1120	1040	940
		h'	2080	1225	840	657	581	540	487
		θ_F, SEC	.15	.51	1.5	3.7	6.2	9	12
20°	0%	$h_M \Delta t$	3920	2230	1600	1260	1120	1040	940
		h'	2440	1335	912	712	631	567	530
		θ_F, SEC	.14	.50	1.4	3.6	6.1	9	12
30°	100%	$h_M \Delta t$	5880	3345	2400	1890	1680	1560	1310
		h'	2760	1625	1110	867	767	714	644
		θ_F, SEC	.10	.36	1.0	2.6	4.3	6.2	9.1
30°	0%	$h_M \Delta t$	5880	3345	2400	1890	1680	1560	1310
		h'	2940	1735	1185	926	820	762	690
		θ_F, SEC	.10	.35	.99	2.5	4.2	6.1	8.9

Figure III
Freezing Time

(3) Freezing time increases eightfold to ninefold over the droplet size range, and fourfold to fivefold from the lowest to the highest temperature.

Mechanism of Atomization

The extensive measurements of droplet sizes produced with small gas-atomizing nozzles performed by Nukiyama and Tanasawa (Ref. 6 and 7), led to the empirical equation presented in Figure IV. While the results cannot be directly extrapolated to the operating conditions of snowmaking, the equation is felt to be of general interest regarding the applicable variables.

For fine droplets, the relative velocity between the air and water streams is the primary factor affecting the degree of atomization. For coarse atomization, the air-to-water ratio is the primary factor. With high air velocity, a wide variation of droplet sizes can be produced by varying the air-to-water ratio.

The significance of first term of the equation may be related, at least qualitatively, to pressure, or other mechanical atomization methods. In these cases, the high velocity is applied to the water stream to effect break-up by its high velocity relative to the still air mass. It has been generally found that very high pressures, or very high centrifugal velocities (whirling disk atomizers) are required to produce the fine atomization that can be obtained with sonic air velocities.

Under the conditions of pressure or rotational speed used to make snow with airless nozzles, it is believed that significantly larger droplet sizes are produced.

Figure V shows some typical droplet size distributions of small pressure nozzles. The data is taken from Ref. 8.

It is of interest to note that, although the average volume or weight diameter ranges from 90 to 150 microns, the median weight diameter ranges from 200 to 400 microns (50% of the mass of liquid falls above the median diameter).

Useful Droplet Sizes

To illustrate the effect of droplet size on snowmaking, we can examine a droplet carried in an air stream of velocity v_w. Neglecting, for simplicity, the time and distance required for the droplet to reach the peak of its trajectory, we can readily compare the settling times and travel distances beyond this point. Figure VI shows the results of this calculation.

The useful size ranges are bracketed on the left side (small diameter) by a maximum allowable travel distance of the order of 200 to 300 ft.

On the righthand side, they are bracketed by the high and low temperature limits for which the freezing time exceeds the settling time.

The following observations may be of interest:

EMPERICAL EQUATION
OF NUKIYAMA AND TANASAWA:

$$D_0 = \frac{1920}{v}\sqrt{\frac{\sigma}{\rho}} + 597\left(\frac{\mu}{\sqrt{\sigma\rho}}\right)^{0.45}\left(\frac{1000\,q_L}{q_G}\right)^{1.5}$$

D_0 = MEAN SURFACE TO VOLUME DIAMETER, MICRONS

v = RELATIVE VELOCITY BETWEEN GAS AND LIQUID
= $v_G - v_L$ - FT./SEC.

σ = SURFACE TENSION - DYNES/CM

ρ = LIQUID DENSITY — GMS/CM^3

μ = VISCOSITY — POISE

q_L/q_C - RATIO OF LIQUID VOLUME
TO GAS VOLUME

EQUATION IS LIMITED TO RANGE OF VALUES
FOR WHICH IT WAS DEVELOPED

Figure IV - Gas Atomization

D	$D^3 \times 10^{-6}$	N	$ND^3 \times 10^{-6}$	CUM % $\Sigma(ND^3)$	N	$ND^3 \times 10^{-6}$	CUM % $\Sigma(ND^3)$	N	$ND^3 \times 10^{-6}$	CUM % $\Sigma(ND^3)$
10	.001	800	.8	.08%	1700	1.7	.17%	100	.1	.01
25	.01562	280	4.4	.52	580	9.1	1.07	50	.78	.09
50	.125	180	22.5	2.77	260	32.5	4.3	45	5.63	.66
100	1.00	60	60	8.77	70	70	11.3	27	27.0	3.37
150	3.375	31	104.6	19.2	35	118	23.1	15	50.9	8.50
200	8.00	23	184	27.6	27	216	44.7	11	88.0	17.3
			MMD →			MMD →				
300	27.0	9	243	61.9	11	297	74.4	6	162	33.6
									MMD →	
400	64.0	4	256	87.5	4	256	100%	3	192	53.0
500	125	1	125	100%	0	–	–	2	250	78.2
600	216	0	–	–	0	–	–	1	216	100%
	$\Sigma =$	1388	1000		2687	1000		260	992	
AVG. VOL. DIA. $= \left[\frac{\Sigma(ND^3)}{\Sigma N}\right]^{1/3}$			90μ			72			156	
MASS MEDIAN DIA: (APPROX.)			250-275			200-225			375-400	
CONDITIONS:			100 PSI 1/16" ORIFICE 1.2 GPM (APPROX.)			200 PSI 1/16" ORIFICE 1.6 GPM (APPROX.)			200 PSI 1/8" ORIFICE 6.0 GPM (APPROX.)	

Figure V
Droplet Sizes – Pressure Nozzles

DIAMETER, D, MICRONS		50	100	200	400	600	800	1000
TERM. VEL, v_T - FT/SEC (32°F)		.25	.73	2.2	5.3	8.2	10.9	11.8
FREEZING TIME, SEC	27°/100%	.47	1.62	4.6	12	20	29	40
(t_B MAX. = 27°) (t_B MIN. = −2°)	−2°/0%	.10	.35	1.0	2.5	4.2	6.1	8.9
SETTLING TIME, FT.	$y = 20$	80	27	9	3.7	2.4	1.8	1.7
$(= y/v_T)$	$y = 40$	160	54	18	7.4	4.8	3.6	3.4
	$y = 80$	320	108	36	15	9.6	7.2	6.8
TRAVEL DISTANCES, FT.:								
v_W = 3 MPH = 4.4' SEC								
$(= v_W \cdot y/V_T)$	$y = 20$	350	120	40	16	11	8	7.5
	$y = 40$	700	240	80	32	22	16	15
	$y = 80$		480	160	64	44	32	30
v_W = 6 MPH = 8.8'/SEC								
	$y = 20$	700	240	80	32	22	16	15
	$y = 40$		480	160	64	44	32	30
	$y = 80$		960	320	128	88	64	60
v_W = 12 MPH = 17.6'/SEC								
	$y = 20$		480	160	64	44	32	30
	$y = 40$		960	320	128	88	64	60
	$y = 80$			640	256	176	128	120
v_W = 24 MPH = 35.2'/SEC								
	$y = 20$		960	320	128	88	64	60
	$y = 40$			640	256	176	128	120
	$y = 80$				512	352	256	240

Figure VI
Useful Droplet Sizes

(1) Under mild conditions and low wind velocities, the range is 100 to 200 microns.

(2) High winds narrow the useful range to zero under warm conditions.

(3) The upper size limit of the useful range is extended to 400 microns with a very high trajectory (80 ft.). High wind defeats this, however.

(4) Low temperatures and high trajectories extend the upper limits.

(5) Airless nozzles, because of their generally larger droplet size, and more limited control of droplet size, are most useful under cold ambient conditions, and require high trajectories to utilize the large droplet sizes best.

Total Air Requirement

A heat balance can be made to obtain the minimum amount of total air that must be intermixed with the water to complete the freezing process. By total air is meant the sum of the primary (compressed or blown) air, and the secondary, or entrained air. The gain in heat content of a volume of air going to equilibrium with the water, at 32 degrees, is the difference between its enthalpy at 32 degrees and the enthalpy at its adiabatic saturation, or wet bulb temperature. As a convenient means of calculation, a power equation was assumed. The constants were solved at two intermediate temperatures, 0 degree and 20 degrees. The results are shown in Figure VII. The power equation error is less than 3% over the useful temperature range. By equating with the heat of fusion, the expression relating the total air to the quantity of water converted is obtained.

Entrainment Ratio

It has been determined experimentally (Ref. 9) that the ratio of total air to released air issuing from a nozzle as an isothermal free jet is related to the nozzle diameter and distance downstream from the nozzle (except in the immediate vicinity of the nozzle), as also shown in Figure VII. Assuming, for the purpose of illustration, a ratio of total air to primary air = 200, at the point of freezing of the water, the primary air to converted water ratios (gp/gc) of the nozzle would be as shown. While these values are generally in the ball park of actual ratios reported, they are not intended as such. The reported values vary quite widely. The true values are probably higher at warm temperatures and may be lower at low temperatures.

Droplet Nucleation

Droplet nucleation is a phenomenon which has been given increasing attention in the snow-making industry in recent years, particularly among the manufacturers of airless snow generators. It appears to have first come to light in the German publication by Linde (Ref. 1). As described by Linde, the initial experiments with airless nozzles produced only water. This was assumed to be the result of the water droplets being sub- (or super-) cooled to equilibrium at the wet bulb temperature, without the formation of ice crystals. As the result of

t_B	ENTHALPY $-h_s$	$h_s(32)-h_s(t_B)$	CALC ΔH_s	% ERROR	q_A/q_C	q_P/q_C @ $q_A/q_P=200$
32	11.758	0	–			
30	10.915	.843	.974	+15		
25	8.934	2.824	2.90	+3	5500	28
* 20	7.106	4.62	4.64	+.5	3400	17
15	5.403	6.35	6.30	-1	2530	12.6
10	3.803	7.95	7.87	-1	2030	10.1
5	2.826	9.54	9.43	-1	1690	8.5
* 0	0.835	10.9	10.9	0	1460	7.3
-5	-0.562	12.3	12.4	+.5	1350	6.7
-10	-1.915	13.7	13.8	+.5	1150	5.7
-15	-3.235	15.0	15.2	+2	1050	5.2
-20	-4.527	16.3	16.7	+2	920	4.6

LET $\Delta H_s = a\,\Delta t_s^{\,b}$ $a = 0.533$ $b = .871$

$\Delta H_s = h_s(32) - h_s(t_B)$ $\Delta t_s = 32 - t_B$ * - VALUES USED

SINCE: $(144)(8.33)\,q_C = .075\,\Delta H_s \cdot q_A$; $q_C = 3.33^{-5}\,q_A\,(32-t_B)^{.871}$

q_C = GMP, CONVERTED
q_P = PRIMARY AIR
q_A = CFM, TOTAL AIR

ENTRAINMENT RATIO – ISOTHERMAL FREE JET

q_A/q_P =	3	30	300
DIST. – DIAMETERS =	10	100	1000
DIST., FT. (NOZZLE DIA. = 1.2")	1	10	100

Figure VII
Total Air Requirement

atomization experiments in a cooled nitrogen chamber, they concluded that snow formed only at temperatures below -15 degrees C. (+5 degrees F.). They tried silver iodide and lowering the surface tension, but finally achieved success by mixing small amounts of gas to the water before atomizing. "As long as the water temperature was below 32 degrees F. at the time of seeding, they produced snow."

The Hedco (Ref. 2) method of "seeding the droplets with a separate air atomizer" claims significant improvement in their snow-making capability.

As the result of snow-making experiments performed at Ingersoll-Rand (Ref. 10), the authors concluded that nucleation plays a significant role in the snow-making process.

The importance of droplet nucleation seems to be a rather moot question at the present time. It appears to this writer that further research is required. Several disturbing questions arise:

(1) How do compressed air nozzles produce snow without "nucleators," unless one assumes that the air itself causes nucleation?

(2) Can one assume that small droplets freeze without nucleation, while large ones do not?

(3) Isn't it rather difficult to supercool water in the laboratory? It has always been the belief of this writer that it required pure distilled water, having no dust particles, etc. The water commonly used in snow production does not usually meet this requirement.

Even if nucleation occurs after cooling the water droplet to the wet bulb temperature, the percentage of freezing upon its spontaneous warming to 32 degrees is generally small (10% per 14.4 degrees of subcooling). Once nucleation has started, the balance must still freeze by a time dependent process (which says nothing if the freezing doesn't start in the first place).

The question of the importance of "droplet nucleation" is one which the Eastern Snow Conference might examine and answer.

Nozzle Testing

Figure VIII lists the data required to evaluate nozzles.

Figure IX shows some equations that are suggested for use in test data in a form usable for nozzle evaluation.

It is a difficult, cold, and often wet operation to obtain reliable nozzle data at several conditions of temperature, humidity and wind velocity. Valid values for wetness and density are a particular problem.

Data Correlation

Figure X lists the equations employed by this writer in an effort to obtain a general temperature-humidity correlation of data obtained at two ambient conditions. The approach is admittedly only an

A. WATER: q_W - GPM ; t_W - °F ; P_W - PSI

B. AIR: q_P - CFM ; t_P - °F ; P_P - PSI

C. AMBIENT: t_A - °F ; % RH ; WIND VELOCITY

D. SNOW CONDITIONS:

F_C - FRACTION CONVERTED
d_M - DENSITY - lbs./FT.^{3}
QUALITATIVE OBSERVATIONS
    SPRAY DISTANCE
    BLOW OFF
    AREA COVERED
    DEPTH
    QUANTITY - SKIABILITY

E. MISCELLANEOUS

NOZZLE WEIGHT, SIZE, MOBILITY

NOZZLE FREEZE-UP

ADJUSTMENTS REQUIRED

POWER OR FUEL CONSUMPTION

Figure VIII - Data Requirements

1.	$R_p = Q_P/Q_W$ - FT^3 AIR/GAL. WATER
2.	$R_p' = Q_P/Q_C = R_P/F_c$ WHERE $F_c = 1 - F_W = Q_c/Q_W$ = FRACTION CONVERTED
3.	$V_M = 0.14\ Q_W/d_M$, A-I/Hr. or FT^3/SEC, Snow Mixture of density, d_M, lbs./ft.^{3} (1 AI/Hr. = 1.01 FT^3/SEC)
4.	$V_s = 0.14\ Q_W\left[1/d_M - .0175(1-F_c)\right]$ - A-I/Hr. Where V_s is the actual volume of dry snow in mixture
5.	$V_s^* = .005\ Q_W$, when $F_c = 1.0$ and $d_M = 27.5$ #/FT.^{3} * = dry snow condition OR 200 GPM = 1 AI/Hr. = 1 FT.^{3}/SEC.
6.	$V_I = V_M - V_s = .0024\ Q_W(1-F_c)$, FT.^{3}/SEC - ICE VOLUME $\rho_{ICE} = 57$ #/FT.^{3}
7.	$V_e = 0.14\ Q_W/d_n = .022\ Q_W$, AI/Hr., EQUIV. NATURAL SNOW @ $d_n = 6.2$ #/FT.^{3}
8.	$V_{es} = .022\ F_c \cdot Q_W$, A-I/Hr., VOL. NAT. SNOW EQUIVALENT TO DRY SNOW PRODUCED
9.	$V_e^* = .022\ Q_W$ OR 45 GPM = 1 AI/Hr., NAT. SNOW @ $F_c = 1.0$
10.	$V_{eM} = V_{es} + V_I = .022\ Q_W\ (0.89\ F_c + 0.11)$, AI/Hr. - allows for contribution of ice
11.	$U_s = \frac{140}{R_p}\left[1/d_M - .0175(1-F_c)\right] = \frac{1000\ V_s}{Q_P}$, AI/Hr./1000 cfm - NOZZLE EFF.
12.	$U_s^* = 5.0/R_p^*$ @ $d_M = 27.5$ #/FT.^{3} (AVG.) AI/Hr./1000 CFM
13.	$U_{es} = 22\ F_c/R_p = 22/R_p^* = U_e^*$

Figure IX - Nozzle Performance

1. $Q_A = Q_E + Q_P$

2. $R_P^* = Q_P^*/Q_W^* = Q_P/Q_c = R_P/F_c = R_P'$

3. $Q_P = K_1 \; R_P^{a}$ — NOT FULLY ESTABLISHED AS VALID

4. $Q_P = Q_P^* \cdot F_c^{a}$

5. $Q_W^* = Q_W \cdot F_c^{1-a}$

6. $Q_c = Q_W^* \cdot F_c^{a}$

7. $Q_W = K_1 \cdot R_P^{a-1}$

8. $Q_W = K_1 \cdot Q_A^{\frac{a-1}{a}}$

9. $V_e^* = .022\, Q_W^* = .022\, Q_W \cdot F_c^{1-a}$

10. $U_e^* = 22.2\, F_c \cdot Q_W/Q_P$ (INDEPENDENT OF a)

11. $V_e^* = K_2 \left(32 - t_B\right)^{n}$ constants, n and K_2 determined from 2 data points.

12. $U_e^* = K_3 \left(32 - t_B\right)^{g}$ g and K_3 determined from 2 data points.

Figure I - Data Correlation

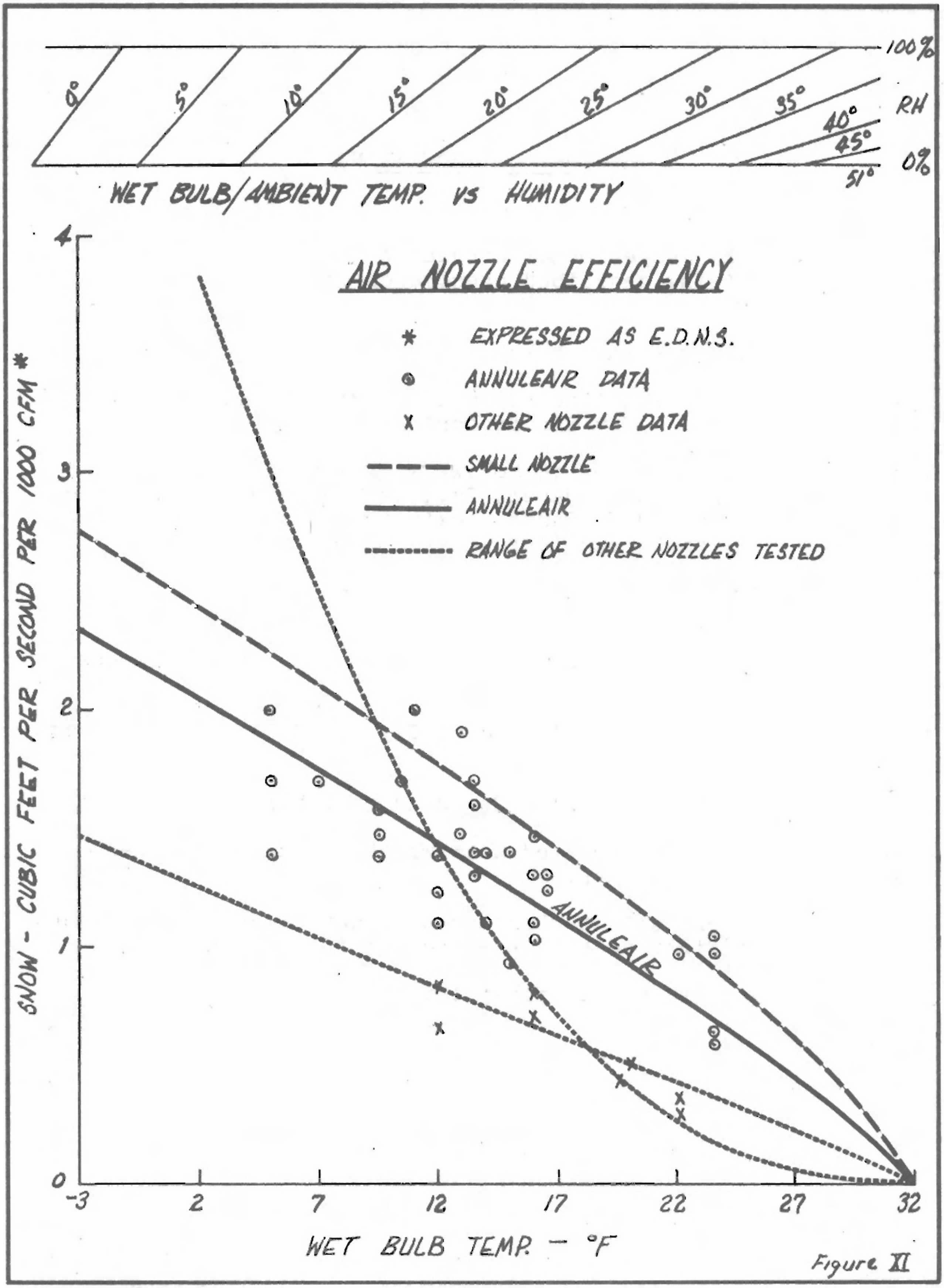
0°
5°
10°
15°
20°
25°
30°
35°
40°
45°
51°
100%
RH
0%
WET BULB/AMBIENT TEMP. VS HUMIDITY
AIR NOZZLE EFFICIENCY
* EXPRESSED AS E.D.N.S.
ANNULEAIR DATA
X OTHER NOZZLE DATA
SMALL NOZZLE
ANNULEAIR
RANGE OF OTHER NOZZLES TESTED
ANNULEAIR
SNOW - CUBIC FEET PER SECOND PER 1000 CFM *
0
1
2
3
4
-3
2
7
12
17
22
27
32
WET BULB TEMP. — °F

Figure XI

HISTORY OF SNOWMAKING

1945 (approx.) - Spray experiments conducted in Canada on aircraft deicing described phenomenon of nozzles producing snow.

1949 - Ice crushing at Mohawk Mountain, Cornwall, Conn.

1949 (Dec.) - First experiements on snowmaking - Paint spray nozzle - Tey Manufacturing Co., Milford, Conn.

1950 - Installations at Mohawk Mountain, and Split Rock Lodge, White Haven, Pa., by Tey -- Pipe furnished by Larchmont Farms, Lexington, Mass. (Irrigation equipment supplier).

1950 (Dec.) - Patent application filed by Tey.

1952 - First permanent installation - Tey - Grossingers Hotel.

1954 (Apr.) - Method patent issued to Tey - U.S. + (Later) Canada.

1956 - Tey Manufacturing Co. sold to Emhart Corp.

1957 (May) - Emhart contracted with Walsh as exclusive agent under patents.

1959 - Patent sold to Larchmont in out of court settlement of first test case of patent filed by Emhart.

1968 - Airless nozzle first introduced - Linde.

FIGURE XII

approximation. Considerable further study is needed to confirm and refine the approach taken.

Figure XI presents some results of nozzle tests. The curves were produced by applying the above method of analysis to test data for two conditions. Most of the data was obtained at Waterville Valley during the NSAA test program, January 1972. The superimposed points are from other tests performed by the writer. The greatest factor of uncertainty concerned the snow wetness, which varied widely.

Figure XII presents a brief outline of the history of snowmaking.

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