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LABORATORY STUDIES OF COMPRESSED AIR SEEDING OF SUPERCOOLED FOG

James R. Hicks and Richard C. Rice, Jr.

May 1977

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Some 400 tests were conducted in the CRREL Cold Cloud Chamber to determine the combination of air pressure and nozzle design that yielded the maximum production of ice crystals in a supercooled fog. It was found that some 0.22 m^3 min^{-1} of air which ~~has been~~ was compressed to 517 kPa is needed to be effective for clearing a supercooled fog.

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PREFACE

This report was prepared by James R. Hicks, Meteorologist, of the Physical Sciences Branch, Research Division, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, NH.

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Laboratory Studies of Compressed-Air Seeding of Supercooled Fog

by

James R. Hicks and Richard C. Rice, Jr.

Introduction and Background

Fog is perhaps the weather phenomenon which most adversely affects all forms of land, sea or air movement of persons and vehicles. Further, fog affects the military use of artillery and the reconnaissance of enemy activities. Hence, fog research within the army has been directed toward developing techniques for improving visibility during periods of fog.

Field and laboratory studies were performed by the U.S. Army Cold Regions Research and Engineering Laboratory to determine the feasibility of using compressed air as an ice-nucleating agent in supercooled fogs. The work of Lukow and Hicks (1974) and Weinstein and Hicks (1975) bore out the feasibility of such an idea. Through their work it was determined that the expansion of air, originally at gage pressures equal to - or greater than - 82.737 kPa can create ice crystals at rates matching those of propane. It was also determined that a nozzle designed for supersonic flow is the most efficient type. The tests described here were made to refine this work. The main objective was to find the nozzle pressure combinations which would yield the most ice crystals for the least amount of air used.

The usefulness of compressed air stems from the adiabatic expansion, and subsequent cooling, of a volume of compressed air that is released

into free air. To be useful the expansion and cooling must lower the air temperature at the mouth of the nozzle below -42°C (231 K). The equation that relates this final nozzle temperature T to the initial nozzle temperature (ambient) T_o and the initial pressure P_o and the final (ambient) pressure P is:

$$T = T_o\left(\frac{P}{P_o}\right)^{0.287}$$

Rewritten this yields:

$$P_o = P\left(\frac{T_o}{T}\right)^{3.48}$$

By using P = 1 atm, T_o = 0°C (273 K), and T = -42°C (237 K) (max), we find that P_o = :

$$P_o = 1\left(\frac{273}{231}\right)^{3.48} = 1.79 \text{ atm (minimum)}.$$

This is why the lowest air pressure tested was 82.7 kPa (1.82 atm) and the lowest design pressure was 82.7 kPa (1.82 atm). At pressures lower than this, sufficient adiabatic-expansion cooling does not occur. The reader should be advised that this formula is accurate only for dry air, but is a close approximation for the ice-saturated air used here.

Table I. Final Nozzle Temperatures
(°C)

	P_o (kPa)			
	82.7	241.3	413.7	517.1
T_o°C				
- 0.5	- 43	- 80	- 101	- 110
- 1.0	- 45	- 80	- 102	- 110
- 2.0	- 45	- 81	- 102	- 110
- 4.0	- 47	- 82	- 104	- 112
- 8.0	- 50	- 85	- 106	- 114

Table I shows the calculated final nozzle temperatures for the temperatures and pressures used in these tests. From this table we expect that the best crystal production would occur in the 517.1-kPa (6.10-atm) range of each series. However, previous tests have shown that this is not always the case. In a recent series of compressed air tests (Weinstein and Hicks 1975), 413.7 kPa was shown to yield a peak of efficiency for supersonic nozzles.

Controlled Environment Tests

Test Facilities and Procedures

The facilities for the controlled environment tests are described by Hicks and Vali (1973). The coldroom-cloud chamber was a walk-in refrigerated room 3.85 m long by 2.3 m wide by 3.63 m high. This yielded an appropriate total room volume of 32.14 m^3. The effective volume of the room however was 29.095 m^3. This takes into account the refrigeration unit located near the room's ceiling and all other objects in the room during the tests, including one person. This number was necessary in extrapolating the total number of crystals produced from the few collected in the samples.

Room cooling was accomplished by circulating cold brine at -56°C through cores near the chamber ceiling and then circulating the air in the chamber with blowers. The chamber temperature was carefully monitored by a fast-response thermistor located near the center of the chamber at a height of 185 cm. The chamber temperature was kept within 0.5°C of the required testing temperature by thermostats.

The fog was created by releasing low pressure steam into the chamber. Some heating occurred and the room had to be cooled approximately 2°C colder than the desired test temperature. After seeding, the ice crystals were collected from a known volume of air on Formvar-coated slides and examined under a phase contrast microscope.

Seeding air was introduced using the same apparatus described by Lukow and Hicks (1974) and Weinstein and Hicks (1975) (Fig. 1). As shown, the equipment consisted of a compressed air source, a pressure regulator, an ice saturation tank, a solenoid valve controlled by a remote timer, and interchangeable nozzles.

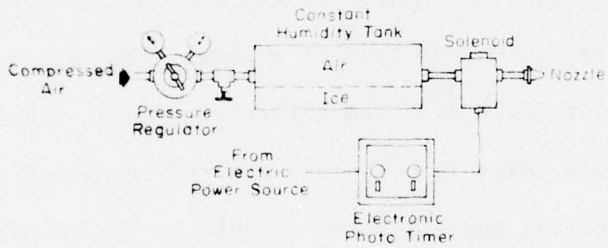
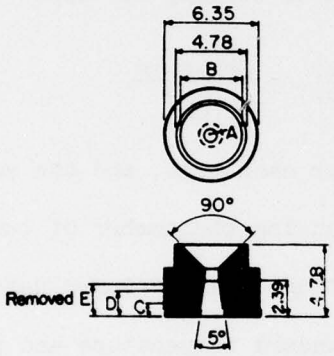


Figure 1. Compressed air apparatus for controlled environment tests. (After Lukow and Hicks 1974)

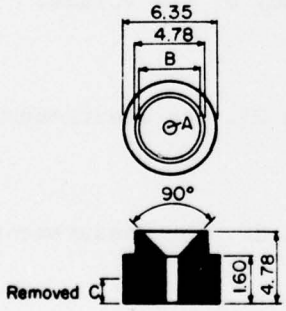
Nozzle Design

Nozzles having throat diameters of 0.5715 mm and 0.8128 were designed and constructed. For each throat diameter, four design gage pressures were used: 82.7, 241.3, 413.7 and 517.1 kPa. Hence, eight nozzles of different designs were fabricated (see Fig. 2).



Nozzle No.	A Drill No.	B mm	C mm / kPa	D mm / kPa	E mm / kPa
1	74	3.76	0.71 / 517.1	1.07 / 413.7	1.80 / 241.3
2	67	3.99	0.00 / 517.1	0.508 / 413.7	1.50 / 241.3

All dimensions are in millimeters



Nozzle No.	A Drill No.	B mm	C mm / kPa
3	74	3.76	0.813 / 82.7
4	67	3.99	0.813 / 82.7

All dimensions are in millimeters

Figure 2. Design specifications for compressed air nozzles.

Each nozzle was scheduled to be tested at gage pressures of 82.7, 241.3, 413.7 and 517.1 kPa and at temperatures of -0.5, -1.0, -2.0, -4.0 and -8.0°C. Of prime concern were the -0.5°C and -1.0°C temperatures, because many fogs occur just below the point of freezing and many seeding agents such as silver iodide are ineffective at these temperatures.

Seeding Air Volume Determination

The efficiency of the nozzles E_A is defined as the total number of crystals produced N divided by the volume of seeding air used (V/Burst)

$$E_A = \frac{N}{V/\text{Burst}} \frac{(\text{crystals})}{(\text{cm}^3/\text{burst})} = \frac{\text{Crystals}}{\text{cm}^3}.$$

A 0.1 to 0.2-sec burst of air was used for each test, and the volume of the burst was determined by simply counting the number of bursts it took to inflate a plastic bag of known volume. All volumes determined in this manner were then converted to standard temperature and pressure.

At best, the degree of "inflatedness" of the bag was still subject to human interpretation. For this reason, approximate percentage error figures have been drawn up for the accuracy of the volume. They are as follows:

If the count is high or low by 1 burst in 23, the measurements are off by ± 4.3%

If the count is high or low by 1 burst in 30, the measurements are off by ± 3.3%

If the count is high or low by 1 burst in 50, the measurements are off by ± 2.0%.

Table II. Volume of air released for various temperature - nozzle - pressure combinations.

Temp. (°C) ↓	Throat diameter = 0.5715 mm					Throat diameter = 0.8128 mm				
	Operating Pressure (kPa) ↓ / Design Pressure (kPa) →	82.7	241.3	413.7	517.1	Operating Pressure (kPa) ↓ / Design Pressure (kPa) →	82.7	241.3	413.7	517.1
		Volume/Burst (cm^3)					Volume/Burst (cm^3)			
-0.5 to -1.0	241.3	*57.8	*47.3	*57.6	*47.2	241.3	50.5	*87.4	*79.1	*89.7
	413.7	51.5	49.4	78.8	54.2	413.7	91.2	95.0	87.6	84.6
	517.1	69.5	65.9	67.7	67.5	517.1	94.6	102.6	81.4	102.4
-2.0	241.3	*49.0	*48.5	*52.8	*52.8	241.3	48.5	48.5	48.5	48.5
	413.7	49.3	48.5	47.5	51.6	413.7	72.0	76.7	67.9	69.9
	517.1	62.6	56.6	53.4	59.4	517.1	80.6	79.2	82.0	91.4
-4.0	241.3	*47.9	*51.0	*52.1	*51.0	241.3	48.9	46.0	51.0	47.9
	413.7	47.0	52.1	49.8	52.1	413.7	77.2	74.8	74.8	77.3
	517.1	58.4	57.0	61.4	59.8	517.1	85.5	88.7	87.1	88.7
-8.0	241.3	36.1	33.8	*57.9	*55.9	241.3	49.6	56.5	55.3	52.3
	413.7	54.0	47.7	52.8	52.9	413.7	83.8	83.8	78.4	73.6
	517.1	65.7	57.9	63.1	67.5	517.1	97.2	99.2	97.2	90.0

*0.2 - sec burst, others are 0.1 - sec

These tolerances are considered to be within acceptable limits considering the inherent uncertainty in the actual crystal counts. The smallest seeding air volumes were obtained with the (0.5175-mm)-diam nozzles and the largest from the (0.8128-mm)-diam nozzles (see Table II). Because of the closeness of the -0.5°C and -1.0°C temperature ranges, the volume tests were performed from 0 to -2°C, corrected to standard pressure and used for both ranges.

Table II shows several combinations of nozzles and air pressures that do not appear to fit any pattern. The explanation for these discrepancies may lie in the presence or absence of severe turbulence at the mouth of the nozzles.

Flow Rates

The Flow-Rates (FR) given in Table III are extrapolated from the volume measurements by the following formula:

$$FR = \frac{V/Burst}{Time/Burst} \; \frac{cm^3}{sec} \times \frac{60\ sec}{min} \times \frac{1}{1000} \; \frac{liter}{cm^3}$$

$$= Liters/min \ / \text{ or } FR = 0.06 \; \frac{V/Burst}{Time/Burst} \; \frac{liters}{min} \; .$$

It must be pointed out that these values may not represent the true flow rates for air moving in a continuous stream through these nozzles. For example, the 0.8128-mm - 82.7-kPa nozzle was operated at 241.3 kPa with both 0.1- and 0.2-sec burst times. The volume of air used at the 0.1-sec burst time was 50.5 cm^3/burst, while the amount used at 0.2 sec burst time was 87.4 cm^3/burst at -0.5°C. This represents an increase of only 73.1%, not 100% as would be expected.

Table III. Flow rates (approximate) (Liters/minute).

		Throat diameter = 0.5715 mm				Throat diameter = 0.8128 mm			
Temp. (°C)	Operating Pressure (kPa) ↓ / Design Pressure (kPa) →	82.7	241.3	413.7	517.1	82.7	241.3	413.7	517.1
	241.3	17.4	14.2	17.3	14.2	30.3	26.2	23.7	26.9
-0.5	413.7	31.0	29.6	47.3	35.6	54.7	57.0	52.6	50.8
	517.1	41.7	39.6	40.6	40.5	56.8	61.5	48.8	61.4
	241.3	17.4	14.2	17.3	14.2	30.3	26.2	23.7	26.9
-1.0	413.7	31.0	29.6	47.3	35.6	54.7	57.0	52.6	50.8
	517.1	41.7	39.6	40.6	40.5	56.8	61.5	48.8	61.4
	241.3	14.7	14.6	15.8	15.8	29.1	29.1	29.1	29.1
-2.0	413.7	29.6	29.1	28.5	31.0	43.2	46.0	40.7	41.9
	517.1	37.6	33.9	48.1	35.6	48.4	47.5	49.1	54.8
	241.3	14.4	15.3	15.6	15.3	29.3	27.6	30.6	28.7
-4.0	413.7	28.2	31.3	29.9	31.3	46.3	44.9	44.9	27.8
	517.1	35.0	34.2	36.8	35.9	51.3	53.2	52.3	53.2
	241.3	21.7	20.3	17.4	16.8	29.8	33.9	33.2	31.4
-8.0	413.7	32.4	28.6	31.7	31.7	50.3	50.3	47.0	44.2
	517.1	39.4	34.7	37.9	40.5	58.3	59.5	58.3	54.0

Test Results

Total Number of Crystals Produced

The total number of crystals produced (see Table IV) are numbers extrapolated from counts of crystals taken from a known volume. They were collected on Formvar-covered slides and examined under a phase-contrast microscope. By knowing the volume sampled and relating that volume to the total effective volume of the room, a number for total crystals produced is obtained.

Notice from Table IV that the general trend at the higher ambient temperatures, $\geq$-2°C, is for the production of higher numbers of crystals as the pressure increases. At -4°C, and lower, this does not hold true. [Note: Previous studies (Hicks and Vali 1973) showed that crystal production is relatively constant below -4°C. Thus, it appears that the maximum crystal production is a function of the ambient air properties and not necessarily the efficiency of the seeding materials.]

The trend is not consistent though. For example: notice from Table IV that at -0.5°C a nozzle designed for 413.7 kPa optimum pressure produces far fewer crystals than either the 241.3 or 517.1 kPa design pressure nozzles at 413.7 kPa. The same appears true for a 517.1-kPa design pressure operating at 517.1 kPa.

The optimum pressure on the basis of total number of crystals produced appears to be 517.1 kPa. This contrasts with the 413.7-kPa optimum pressure reported in previous work (Weinstein and Hicks 1975). At 517.1 kPa, three nozzles appear to be superior: the 0.5715-mm - 82.7-kPa and 413.7-kPa design pressure nozzles, and the 0.8128-mm - 413.7-kPa design pressure nozzle.

Table IV. Average total number of crystals produced (x 10^8).

		Throat diameter = 0.5715 mm				Throat diameter = 0.8128 mm			
Temp. (°C) ↓	Design Pressure (kPa) → / Operating Pressure (kPa)	82.7	241.3	413.7	517.1	82.7	241.3	413.7	517.1
	241.3	0.17	0.12	0.063	0.08	0.14	0.32	0.18	0.51
-0.5	413.7	0.17	0.74	0.23	0.76	0.14	0.81	0.52	0.44
	517.1	0.90	1.88	1.13	0.67	0.48	0.72	1.63	0.68
	241.3	0.38	1.15	2.84	0.995	3.89	0.63	3.47	4.30
-1.0	413.7	6.29	7.14	8.43	6.43	10.27	5.22	6.33	7.31
	517.1	13.56	7.67	9.30	12.91	11.04	4.02	10.26	6.87
	241.3	10.7	15.3	16.2	10.1	14.8	14.2	19.4	13.2
-2.0	413.7	17.7	20.8	16.5	21.7	27.4	25.0	29.9	29.7
	517.1	38.7	32.9	36.6	31.8	37.8	42.5	47.5	30.4
	241.3	13.4	30.5	19.0	22.4	26.6	20.1	25.0	23.8
-4.0	413.7	29.3	37.4	14.0	27.4	16.5	19.0	08.7	44.4
	517.1	31.9	24.3	28.8	24.6	54.5	53.7	23.7	37.2
	241.3	25.1	12.8	12.0	19.8	21.8	14.5	35.2	17.3
-8.0	413.7	23.1	21.5	17.9	29.6	34.4	34.4	28.8	34.1
	517.1	11.5	16.5	31.0	45.8	64.6	39.1	36.7	36.6

Average Nozzle Efficiencies

The efficiency of a nozzle has been defined as the total number of crystals produced per volume of seeding air. Mathematically this is:

$$E_A = \frac{N}{V/\text{Burst}} \left(\frac{\text{crystals}}{\text{cm}^3/\text{burst}}\right)$$

where E_A = Efficiency in crystals/cm^3

N = Total number of crystals produced

V/Burst = Volume of seeding air used (cm^3).

The values are shown in Table V. See also Figure 3. As was expected, the best efficiencies are at 517.1-kPa air pressure. They again belong to the same three nozzles discussed earlier (see Table VI).

Comparison of 1976 Test Results with 1975 Test Results

The work of Weinstein and Hicks (1975) yielded laboratory and field study test results for several supersonic nozzles. Based on their laboratory results, a 1.016-mm - 186.16-kPa design pressure nozzle was recommended for field testing (Fig 4). A comparison of the laboratory results for that nozzle (no. 1) and the most efficient nozzle of this test series (no. 2) is shown in Table VII.

Table V. Nucleation efficiency of various nozzle-pressure combinations.*

Temp. (°C) ↓	Throat diameter = 0.5715 mm					Throat diameter = 0.8128 mm				
	Operating Pressure (kPa) ↓ / Design Pressure (kPa) →	82.7	241.3	413.7	517.1	Operating Pressure (kPa) ↓ / Design Pressure (kPa) →	82.7	241.3	413.7	517.1
		Efficiency(E_A) Crystals $cm^{-3}x10^8$					Efficiency(E_A) Crystals $cm^{3}x10^8$			
	241.3	0.0029	0.0026	0.0011	0.0017	241.3	0.0027	0.0039	0.0023	0.0057
-0.5	413.7	0.0034	0.0150	0.0029	0.0130	413.7	0.0021	0.0085	0.0060	0.0110
	517.1	0.0131	0.0180	0.0170	0.0100	517.1	0.0051	0.0071	0.0200	0.0067
	241.3	0.0065	0.0240	0.0490	0.0210	241.3	0.0770	0.0072	0.0440	0.0480
-1.0	413.7	0.1281	0.1445	0.1070	0.0300	413.7	0.1126	0.0550	0.0723	0.0860
	517.1	0.1956	0.1104	0.1373	0.1914	517.1	0.1168	0.0391	0.1261	0.0671
	241.3	0.2190	0.3100	0.3100	0.1900	241.3	0.3030	0.2900	0.4100	0.2700
-2.0	413.7	0.3600	0.4300	0.3500	0.4200	413.7	0.3800	0.3300	0.4400	0.4200
	517.1	0.6200	0.5800	0.6800	0.5400	517.1	0.4700	0.5400	0.5800	0.3300
	241.3	2.3	3.1	3.2	3.4	241.3	3.4	5.7	4.2	2.8
-4.0	413.7	5.9	5.5	3.5	5.5	413.7	3.3	2.1	3.0	3.6
	517.1	3.9	3.6	5.7	4.5	517.1	4.5	3.7	3.3	4.2
	241.3	4.5	5.0	2.7	3.8	241.3	5.0	3.4	3.9	5.1
-8.0	413.7	3.7	5.5	3.5	4.7	413.7	3.6	2.9	4.3	3.2
	517.1	3.1	4.0	4.9	6.3	517.1	4.5	3.5	3.2	3.3

*The value of E_A is the average of at least three tests at each of the nozzle-pressure-temperature combinations listed.

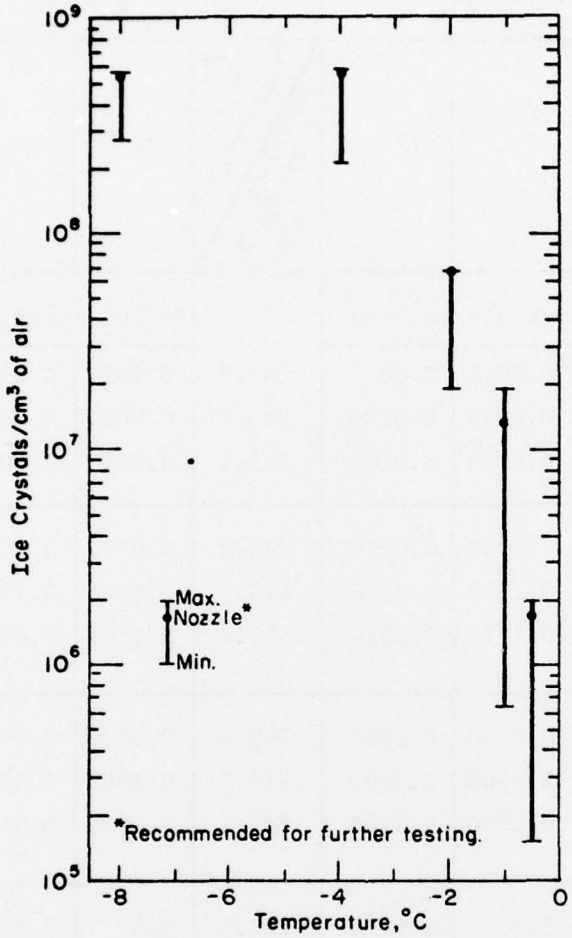


Figure 3. Ice crystal production rates.

TABLE VI. Efficiency data for the three most efficient nozzles.

All nozzles operated at 517.1 kPa

Nozzle Type				
Diameter (mm)	Design Pressure (kPa)	Temperature (°C)	Average # crystals produced	Average efficiency (E_A) $\frac{\text{crystals}}{\text{cm}^3 \text{ seeding air}}$ 0.10^8
0.5715	413.7	- 0.5	1.13	0.0170
		- 1.0	9.30	0.1373
		- 2.0	36.6	0.6800
		- 4.0	28.8	5.700
		- 8.0	31.0	4.900
0.5715	82.7	- 0.5	0.90	0.0131
		- 1.0	13.56	0.1956
		- 2.0	38.7	0.6200
		- 4.0	31.9	3.900
		- 8.0	11.5	3.100
0.8128	413.7	- 0.5	1.63	0.0200
		- 1.0	10.26	0.1261
		- 2.0	47.5	0.5800
		- 4.0	36.7	3.300
		- 8.0	23.7	3.200

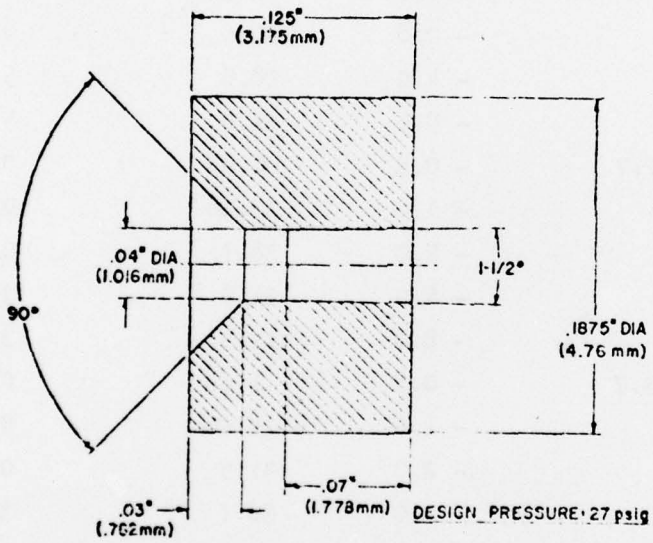


Figure 4. Geometry of the supersonic nozzle used in the free environment tests. [From Weinstein and Hicks (1975).]

TABLE VII. Test results for nos. 1 and 2 nozzles.

Test temperature (°C)	Nozzle no. 1 1.016 mm - 186.16 kPa design pressure nozzle operated at 413.7 kPa	Nozzle no. 2 0.5715 mm - 413.7 kPa design pressure nozzle operated at 517.1 kPa
- 0.5	0.024×10^8 xtals/cm^3	0.017×10^8 xtals/cm^3
- 1.0	0.051×10^8 xtals/cm^3	0.140×10^8 xtals/cm^3
- 2.0	0.220×10^8 xtals/cm^3	0.680×10^8 xtals/cm^3
- 4.0	1.400×10^8 xtals/cm^3	5.700×10^8 xtals/cm^3
- 8.0	1.500×10^8 xtals/cm^3	4.900×10^8 xtals/cm^3

Nozzle no. 1 Flow rate = 42.2 liter/min

Nozzle no. 2 Flow rate = 40.6 liter/min at -0.5, -1.0°C

= 48.1 liter/min at -2.0°C

Nozzle no. 1 V/burst (approx) ≅ 70.3 cm^3/0.1-sec burst

Nozzle no. 2 V/burst (approx) ≅ 67.7 cm^3/0.1-sec burst at -0.5, -1.0°C

≅ 80.2 cm^3/0.1-sec burst at -2.0°C

A comparison of flow rates and volumes/0.1-sec burst of air do not show a significant difference. There is obviously a difference in efficiency in that at the -1.0 and -2.0°C ranges the 0.5715-mm nozzle was 2 to 3 times as efficient in producing ice crystals. It is interesting to note that the 0.5715-mm nozzle has approximately 1/3 as much nozzle area as the previous nozzle did. Consequently, the 0.5715-mm nozzle yields an air flow velocity 3 times faster than the previous (1.016-mm) nozzle did (laboratory studies bear this out).

Another comparison is that of compressed air versus propane's ice crystal production rates. According to Weinstein and Hicks (1975), the best previous comparison (at -2.0°C) was that about 4500 cm^3 of compressed air would yield the same number of crystals as 1 cm^3 of propane. The present laboratory findings indicate that only 1500 cm^3 of air are now needed to produce the same number of crystals as 1 cm^3 of propane. Again the efficiency obtained in these tests is about 3 times as much as that previously obtained.

Conclusions and Recommendations

Conclusions

Based upon the known effective rate of release for propane, i.e., 10 gallons (37.85 liters) hr^{-1}, it can now be concluded that 0.22 m^3 min^{-1} of air which has been compressed to 517 kPa is needed to be effective for clearing a supercooled fog.

Recommendations

It is therefore recommended that field tests of the nozzle having a throat diameter of 0.5715 mm, a design pressure of 413.7 kPa, and an operating pressure of 517.1 kPa be conducted to determine the feasibility of using compressed air to disperse supercooled fog.

Literature Cited

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