

Testing of Cloud Seeding Materials at the Cloud Simulation and Aerosol Laboratory, 1971–1973

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ABSTRACT

Developments in instrumentation at the Cloud Simulation and Aerosol Laboratory at Colorado State University since the Second International Workshop on Condensation and Ice Nuclei are outlined. Emphasis is given to improvements in the isothermal cloud chamber and the current status of a second-generation, controlled slow-expansion cloud chamber in which ascent of an air parcel may be simulated. Work with the aerosol dilution system (wind tunnel) is also described.

Tests conducted during the three years 1971 through 1973 to determine the ice nucleus production of many currently used cloud-seeding devices are summarized. Effectiveness curves for nine ground-based steady-state generators burning various solutions of $\text{AgI-NH}_4\text{I}$ and AgI-NaI in acetone are presented. Test results for three airborne generators are also given and contrasted with the results for the ground generators. Finally, effectiveness values are presented for a number of pyrotechnics manufactured by Olin, Colspan, Sierra Research, and the Naval Weapons Center.

The need for caution in the use of such effectiveness curves in the design of weather modification experiments is stressed. It is believed that optimal "dosages" of artificial nuclei for natural clouds can be determined using cloud chamber measurements. But probable differences in cloud characteristics and aerosol residence times both in cloud and in transit to cloud must be taken into account. Such considerations together with a more accurate simulation of operational conditions of ventilation for different cloud-seeding devices constitute a major thrust of current research effort at the Simulation Laboratory.

1. Introduction

The isothermal cloud chamber (ICC) at the Cloud Simulation and Aerosol Laboratory has been used as a calibration standard for artificial ice nucleus producing devices for more than eight years. During this time a large number of generators and pyrotechnics used in cloud modification experiments have been tested in order to determine their potential efficacy in the field. In particular, since late in 1970, a few months after the Second International Workshop on Condensation and Ice Nuclei, the experimental procedure at the Simulation Laboratory has remained unchanged. Devices tested during this period may thus be usefully compared with one another even if some uncertainty remains as to the applicability of the test results to field conditions.

a. Laboratory objectives and procedures

One objective of the testing is to determine with what efficiency a generator or pyrotechnic produces ice nuclei. The measured efficiency, the *effectiveness*, is the number of ice nuclei active at a given temperature per gram of nucleant burned and is determined in a manner similar to that described by Vonnegut (1949) and by Grant and Steele (1966). Another parameter which results from the calibration procedure is the ice nucleus

production rate, or the output of active ice nuclei per unit time, again as a function of temperature.

A vertical wind tunnel is used to simulate operational conditions of air flow rate and mixing for the generator being tested and to reduce the concentration of aerosol particles to a point such that coagulation is minimal. A sample of this aerosol is then taken from the tunnel downstream of the generator by means of a 4 ℓ syringe. The density of nucleant in the syringe is calculated using the generator burn rate (g min^{-1}) and the tunnel flow rate ($\ell \text{ min}^{-1}$), *assuming uniform mixing of aerosol with wind tunnel air*. The sample is next diluted further by expelling a portion of the sample air from the syringe and replacing it with clean, dry air ($T_D < -30^\circ\text{C}$), thus reducing the number of nuclei to a level which is within the measuring capacity of the ICC and preventing transient supersaturations from occurring should moist air be injected into the cold cloud.

The diluted sample is then injected into the chamber and the number of ice crystals which fall out is determined. The effective volume of the chamber is $\sim 1 \text{ m}^3$ and is controlled such that all points of the supercooled cloud are within $\pm 0.3^\circ\text{C}$ of the desired testing temperature. The liquid water content of the cloud may also be controlled between 0.3 and 3.0 g m^{-3} , the upper

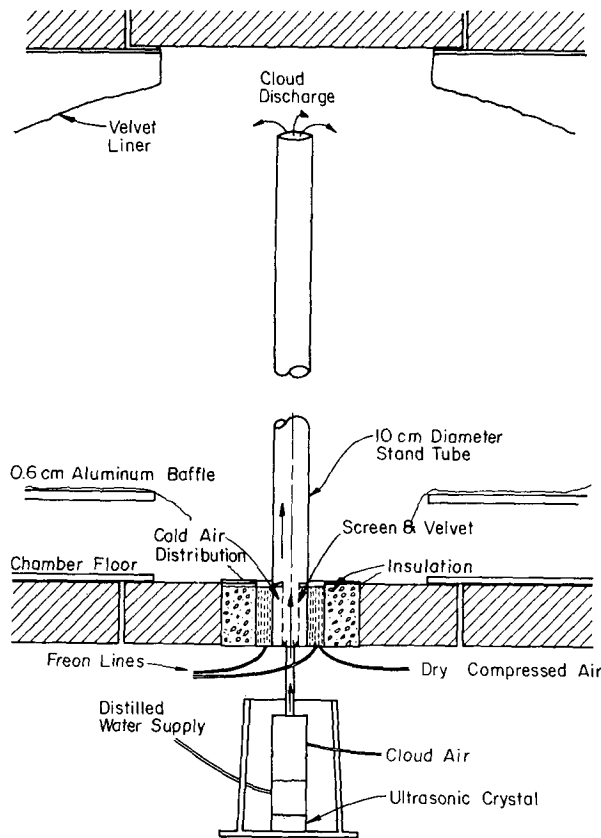


FIG. 1. Schematic of the cloud generation system for the isothermal cloud chamber.

limit depending on the chamber temperature. The crystals are counted on microscope slides which are successively pulled from the bottom of the chamber until all that have been nucleated settle out. The total fallout time varies from 5 to 50 min, depending on the sample and the temperature. Assuming that the fallout is uniform across the chamber, the total number of crystals resulting from the sample can then be determined.

The effectiveness is calculated as the ratio of the number of crystals to the mass of nucleating material in the diluted air sample. Graphs of effectiveness vs temperature are obtained from successive tests at various chamber temperatures.

b. Isothermal cloud chamber: Improvements

The isothermal chamber, originally constructed by Prof. Roger Steele, was specifically designed to reproduce as accurately as possible conditions existing in a somewhat idealized, quiescent cloud. Temperature and cloud density gradients have been reduced even further by introducing the cloud into the chamber using the system shown in Fig. 1. The cloud is generated continuously by atomizing distilled water with an ultrasonic humidifier (Monaghan 670) and cooling the

droplets with filtered air. By mixing the freshly created cloud with cold air and allowing the mixture to equilibrate with the chamber while rising through a stand tube in its center, it is possible to add new cloud to the old without introducing large temperature gradients.

The cloud density is controlled by varying the rate at which new cloud is brought into the chamber and is continuously monitored by means of a Cambridge dew point hygrometer. The technique employed is to evaporate a cloud sample and measure its dew point; the difference between the saturation mixing ratio corresponding to this dew point and that corresponding to the cloud temperature is taken as the liquid water content. Temperatures throughout the system are measured by thermocouples and are recorded continuously. Supersaturations, if any, are comparable to those for clouds with small temperature gradients. Droplet sizes have been measured using soot-coated slides with a device patterned after that of Squires and Gillespie (1952). Droplet diameters range from 1 to 15 μm , and mean diameters have been found to be between 6.4 and 8.6 μm on all occasions. The cloud can thus be said to simulate a slowly settling fog or stratus cloud, and its quasi-steady-state nature allows nucleation and ice crystal growth to be studied as a function of time.

c. Controlled slow-expansion cloud chamber: Status

The controlled slow-expansion cloud chamber (CSECC) shown schematically in Fig. 2 is to complement the isothermal chamber by more closely reproducing the processes occurring in cumulus clouds. The ascent of an air parcel through the troposphere at rates up to 15 m s^{-1} may be simulated by evacuating the vessel at a predetermined rate and following the temperature drop due to expansion by cooling the walls at a corresponding rate. The outer shell of stainless steel contains the vacuum, while the inner shell of aluminum is cooled by means of refrigerated methanol. Initial temperature, moisture and aerosol content are established by means of a sample conditioning system not shown in the figure. These features of the CSECC are now operational. Work remains to be done in developing the capability of observing the cloud microphysics which results. The procedure we have adopted here is initially to use the somewhat cumbersome but reliable methods of obtaining droplet and crystal replicas, and later to complement these measurements with optical techniques. Droplet sizes are being measured using a device similar to that of Squires and Gillespie (1952). Ice crystals which form are allowed to fall on 35 mm photographic film which moves continuously across the chamber. The film is exposed to light as it passes out of the inner shell, and the resulting "contact" images provide a reliable ice crystal count. Experiments comparing ice crystal counts for various ascent simulations with those in the isothermal chamber using identical artificial aerosol samples are in their initial stage.

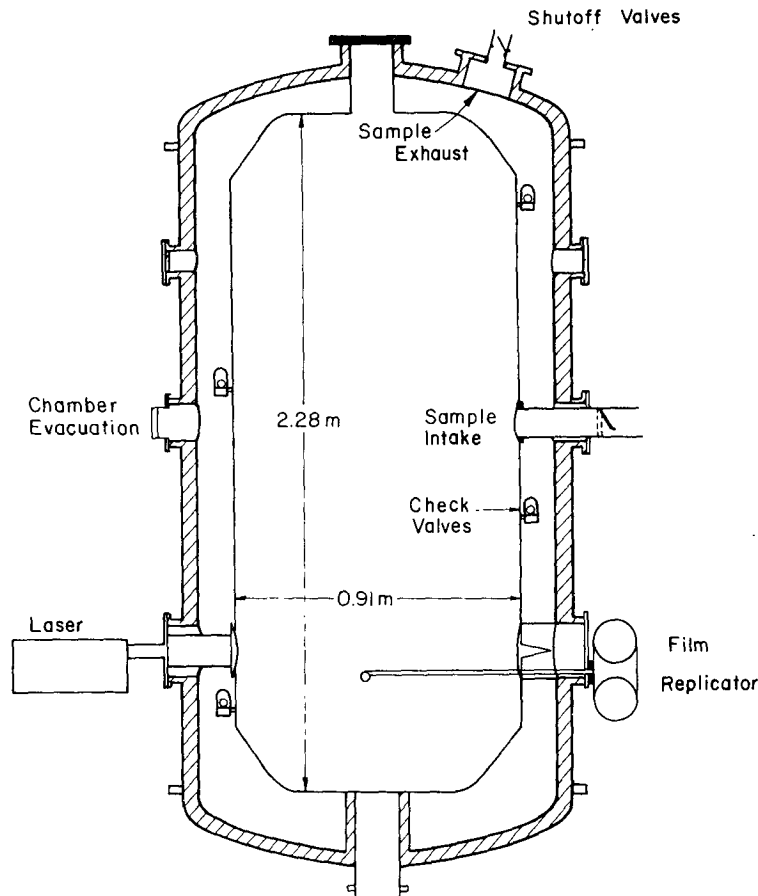


FIG. 2. Schematic of the controlled slow-expansion cloud chamber.

d. Aerosol dilution system: Corrections

For ground-based generators an attempt is made to simulate simultaneously two operational conditions:

- 1) Airflow past the burner head, which influences burn characteristics such as flame temperature and quenching rate.
- 2) Ventilation, or the rate at which effluent from the generator is mixed with uncontaminated air.

Ideally, these operational conditions should be known and the information furnished with the generator to be tested. In the period 1971-73, tests with ground generators were performed using two quite different operational conditions, one employing the fan in the wind tunnel with its maximum displacement rate and the other allowing the natural draft in the wind tunnel to provide the air flow. Generators are placed below the tunnel at a more-or-less fixed distance from the fan. Mixing in the wind tunnel has been found to be fairly uniform under both testing conditions.

For aircraft-mounted devices, attention has principally been given to obtaining a velocity past the device comparable to that of the operational air-speed.

Maximum velocity in the tunnel under present conditions is about 50 m s^{-1} , and the velocity distribution is sufficiently uniform to be assumed constant. The generating device is mounted in the center of the wind tunnel, and it has heretofore been assumed that the mixing of the resulting aerosol took place almost instantaneously. Recent tests in this operational mode, however, have shown this assumption to be grossly inaccurate. Data obtained using two different devices are given in Figs. 3 and 4. Shown here are the radial distributions of ice nuclei in the wind tunnel at the routine testing height (determined using the standard procedure with the ICC). The points were obtained along two radii only, and more points need to be obtained to see whether cylindrical symmetry can be assumed. Curves of the form

$$N = N_0 \exp \left[-\frac{1}{2} \frac{(r-r_0)^2}{\sigma^2} \right] \quad (1)$$

were fit to the resulting points.

These curves provide the information necessary to calculate correction factors for effectiveness values obtained for airborne generators and pyrotechnics during

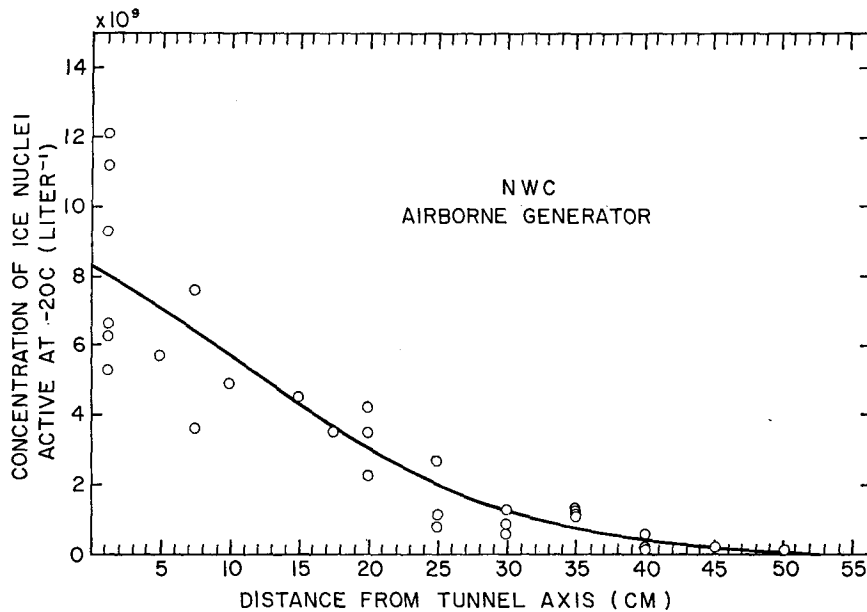


FIG. 3. Radial distribution of the concentration of ice nuclei produced by the Naval Weapons Center airborne generator at the sampling level of the vertical wind tunnel.

the period 1971 to 1973. The curves are certainly dependent upon the cross-sectional area of the ice nucleus source and therefore cannot be said to have any general validity. But since the cross-sectional areas of most airborne generators are roughly the same as that of the Naval Weapons Center airborne generator and since those of pyrotechnics are never much larger than those of the calibration flares, the correction factors obtained using these two curves should be approximately valid for similar devices.

The total number of ice nuclei in a cross section of unit thickness implied by the Gaussian distribution of Eq. (1) is simply $N_0 2\pi\sigma^2$, where N_0 is the concentration at the center of the distribution and σ the standard deviation. It is assumed that the distribution is sufficiently narrow that the limits imposed by the tunnel walls may be neglected; i.e., there is neither reflection nor absorption of particles at the walls, and the error implicit in taking the upper limit of r as infinity when calculating the integral is very small. For both of the

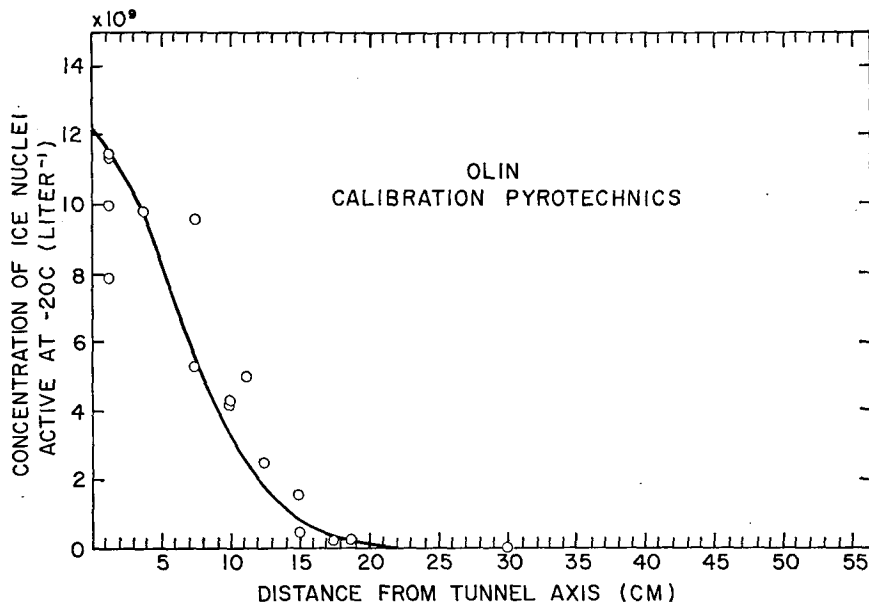


FIG. 4. Radial distribution of the concentration of ice nuclei produced by Olin calibration pyrotechnics (Formulation WM-105) at the sampling level of the vertical wind tunnel.

TABLE 1. Summary of test results for ground generators.*

Generator	AgI (percent)	Burn rate (g min ⁻¹)	Temperature			
			-8°C	-12°C	-16°C	-20°C
NaI solutions: Natural draft						
North American Weather Consultants EG & G	4.0	0.36	3×10 ¹⁰	1.5×10 ¹³	4×10 ¹⁴	6×10 ¹⁴
			1×10 ¹⁰	5×10 ¹²	1.5×10 ¹⁴	2×10 ¹⁴
New Mexico State	4.0	0.35	1×10 ¹¹	1.5×10 ¹³	4×10 ¹⁴	8×10 ¹⁴
			4×10 ¹⁰	5×10 ¹²	1.5×10 ¹⁴	3×10 ¹⁴
New Mexico State	1.7	0.8	3×10 ¹⁰	4×10 ¹²	2×10 ¹⁴	5×10 ¹⁴
			2.5×10 ¹⁰	3×10 ¹²	1.5×10 ¹⁴	4×10 ¹⁴
NaI solutions: Maximum fan						
North [*] American Weather Consultants EG & G	4.0	0.36	1×10 ¹¹	1×10 ¹⁴	1×10 ¹⁶	3×10 ¹⁶
			4×10 ¹⁰	4×10 ¹³	4×10 ¹⁵	1×10 ¹⁶
Israeli B	4.0	0.35	1×10 ¹¹	5×10 ¹³	5×10 ¹⁵	6×10 ¹⁵
			4×10 ¹⁰	2×10 ¹³	2×10 ¹⁵	2×10 ¹⁵
New Mexico State	1.7	0.79	<10 ¹¹	4×10 ¹³	3×10 ¹⁵	7×10 ¹⁵
			<8×10 ¹⁰	3×10 ¹²	2.5×10 ¹⁵	6×10 ¹⁵
Colorado State	1.7	0.8	3×10 ¹¹	5×10 ¹³	9×10 ¹⁵	2×10 ¹⁶
			2.5×10 ¹¹	4×10 ¹³	7×10 ¹⁵	1.5×10 ¹⁶
Colorado State	1.7	0.79	<10 ¹¹	5×10 ¹²	8×10 ¹⁵	2×10 ¹⁶
			<8×10 ¹⁰	4×10 ¹²	6×10 ¹⁵	1.5×10 ¹⁶
NH ₄ I solutions: Natural draft						
Israeli A	1.0	0.18	5×10 ¹¹	6×10 ¹²	1.5×10 ¹⁴	7×10 ¹⁴
			9×10 ¹⁰	1×10 ¹²	2.5×10 ¹³	1.5×10 ¹⁴
New Mexico State	2.0	0.90	1.5×10 ¹²	4×10 ¹³	2×10 ¹⁴	4×10 ¹⁴
			1.5×10 ¹¹	4×10 ¹³	2×10 ¹⁴	4×10 ¹⁴
Montana State	3.4	0.57	2×10 ¹²	3×10 ¹⁴	7×10 ¹⁴	7×10 ¹⁴
			1×10 ¹²	1.5×10 ¹⁴	4×10 ¹⁴	4×10 ¹⁴
Sacramento Municipal Utility District	2.5	0.35	1×10 ¹³	1.5×10 ¹⁴	5×10 ¹⁴	9×10 ¹⁴
			4×10 ¹²	5×10 ¹³	2×10 ¹⁴	3×10 ¹⁴
NH ₄ I solutions: Maximum fan						
Israeli A	1.0	0.18	1.5×10 ¹³	3×10 ¹⁴	1.5×10 ¹⁵	2×10 ¹⁵
			3×10 ¹²	5×10 ¹³	2.5×10 ¹⁴	4×10 ¹⁴
Israeli B	2.0	0.89	4×10 ¹⁰	2.5×10 ¹³	1.5×10 ¹⁵	7×10 ¹⁵
			4×10 ¹⁰	2.5×10 ¹³	1.5×10 ¹⁵	6×10 ¹⁵
New Mexico State	2.0	0.90	2×10 ¹²	6×10 ¹⁴	4×10 ¹⁵	8×10 ¹⁵
			2×10 ¹²	5×10 ¹⁴	4×10 ¹⁵	7×10 ¹⁵
Colorado State	2.0	0.89	1×10 ¹²	1.5×10 ¹⁴	3×10 ¹⁵	7×10 ¹⁵
			9×10 ¹¹	1.5×10 ¹⁴	3×10 ¹⁵	6×10 ¹⁵
Montana State	3.4	0.57	3×10 ¹³	1.5×10 ¹⁵	6×10 ¹⁵	2×10 ¹⁶
			1.5×10 ¹³	9×10 ¹⁴	3×10 ¹⁵	1×10 ¹⁶
Sacramento Municipal Utility District	2.5	0.35	3×10 ¹³	1.5×10 ¹⁵	2.5×10 ¹⁵	5×10 ¹⁵
			1×10 ¹³	5×10 ¹⁴	9×10 ¹⁴	2×10 ¹⁵

* Two entries are given in each of the last four columns: first, the generator effectiveness value (g⁻¹) and, second, the ice nucleus production rate (min⁻¹).

curves above, this assumption is valid. The total number of ice nuclei in a cross section of unit thickness under the assumption of a uniform concentration is just $N(1.3)\pi R^2$ where $N(1.3)$ is the average concentration at the sampling point (1.3 cm from the tunnel axis) and R is the radius of the tunnel (57.2 cm). The correction factors are therefore given by

$$CF = \frac{N_0 2\sigma^2}{N(1.3)R^2} \quad (2)$$

For the curve of Fig. 3, this value is 0.228. For the curve of Fig. 4, it is 0.0356. These correction factors

were applied to the effectiveness values for airborne generators and pyrotechnics discussed below.

2. Test results

The data presented in Tables 1 and 2 summarize many of the results of the testing program at the Cloud Simulation and Aerosol Laboratory from 1971 through 1973. Effectiveness values and nucleus production rates are tabulated for a large number of nucleating devices. The values given here represent the average of a number of runs (generally three) at a given temperature or are an interpolation from tests at higher and

TABLE 2. Summary of test results for airborne generators and pyrotechnics.*

Device	AgI (percent)	Burn rate (g min ⁻¹)	Temperature				
			-4°C	-8°C	-12°C	-16°C	-20°C
Airborne generators: NH ₄ I solution							
Naval Weapons Center A	10	18.8	7×10 ¹¹ 1.5×10 ¹³	6×10 ¹³ 1×10 ¹⁵	1.5×10 ¹⁴ 3×10 ¹⁵	3×10 ¹⁴ 6×10 ¹⁵	— —
Naval Weapons Center B	10	10.5	—	2×10 ¹² 2×10 ¹³	3×10 ¹³ 3×10 ¹⁴	2.5×10 ¹⁴ 2.5×10 ¹⁵	— —
Naval Weapons Center C	5.4	9.3	7×10 ¹⁰ 6×10 ¹¹	5×10 ¹³ 5×10 ¹⁴	7×10 ¹³ 6×10 ¹⁴	6×10 ¹⁴ 6×10 ¹⁵	— —
Naval Weapons Center D	5.4	5.3	—	2×10 ¹² 1×10 ¹³	1×10 ¹⁴ 5×10 ¹⁴	1×10 ¹⁵ 5×10 ¹⁵	— —
Atmospherics, Inc.	2.0	2.1	—	9×10 ¹⁰ 2×10 ¹¹	2.5×10 ¹³ 5×10 ¹³	1×10 ¹⁴ 2×10 ¹⁴	2.5×10 ¹⁵ 5×10 ¹⁵
NOAA A	5.0	14.1	3×10 ¹⁰ 4×10 ¹¹	9×10 ¹² 1.5×10 ¹⁴	9×10 ¹³ 1.5×10 ¹⁵	6×10 ¹⁴ 8×10 ¹⁵	1.5×10 ¹⁵ 2×10 ¹⁶
NOAA B	2.0	5.8	—	7×10 ¹² 4×10 ¹³	5×10 ¹⁴ 3×10 ¹⁵	9×10 ¹⁴ 5×10 ¹⁵	2×10 ¹⁵ 1×10 ¹⁶
Airborne generator: NaI solution							
NOAA B	2.0	5.8	— —	2×10 ¹¹ 1×10 ¹²	3×10 ¹³ 1.5×10 ¹⁴	7×10 ¹⁴ 4×10 ¹⁵	2.5×10 ¹⁵ 1.5×10 ¹⁶
Pyrotechnics							
Colspan CS033A	60.5	84.3	—	7×10 ⁹ 6×10 ¹¹	5×10 ¹¹ 4×10 ¹³	4×10 ¹² 3×10 ¹⁴	1.5×10 ¹³ 1×10 ¹⁵
Colspan CS036	24.9	21.9	—	1×10 ¹⁰ 2.5×10 ¹¹	7×10 ¹¹ 1.5×10 ¹³	2×10 ¹³ 4×10 ¹⁴	7×10 ¹³ 1.5×10 ¹⁵
Navy TB-1	64.8	172.3	—	4×10 ¹⁰ 6×10 ¹²	1×10 ¹² 2×10 ¹⁴	7×10 ¹² 1×10 ¹⁵	9×10 ¹² 1.5×10 ¹⁵
Navy TB-2	20.0	36.4	—	3×10 ¹⁰ 1×10 ¹²	7×10 ¹¹ 2.5×10 ¹³	1×10 ¹³ 4×10 ¹⁴	4×10 ¹³ 1.5×10 ¹⁵
Sierra Research SR-1	59.6	75.5	—	1.5×10 ¹⁰ 1×10 ¹²	1×10 ¹¹ 9×10 ¹²	6×10 ¹² 5×10 ¹⁴	2×10 ¹³ 1.5×10 ¹⁵
Sierra Research SR-6	41.4	43.9	—	9×10 ⁷ 4×10 ⁹	3×10 ¹⁰ 1.5×10 ¹²	3×10 ¹² 1×10 ¹⁴	1.5×10 ¹³ 7×10 ¹⁴
Sierra Research SR-12	24.9	22.3	—	4×10 ¹⁰ 1×10 ¹²	7×10 ¹² 1.5×10 ¹³	2×10 ¹³ 5×10 ¹⁴	5×10 ¹³ 1×10 ¹⁵
Olin WM-102 Standard	7.0	2.3	—	5×10 ¹⁰ 1×10 ¹¹	7×10 ¹¹ 1.5×10 ¹²	7×10 ¹³ 1.5×10 ¹⁴	4×10 ¹⁴ 8×10 ¹⁴
Olin WM-103 Standard	20.8	5.0	—	1×10 ¹⁰ 5×10 ¹⁰	4×10 ¹¹ 2×10 ¹²	3×10 ¹³ 1.5×10 ¹⁴	2×10 ¹⁴ 9×10 ¹⁴
Olin WM-105 Standard	44.0	14.6	—	4×10 ⁹ 5×10 ¹⁰	1×10 ¹² 1.5×10 ¹³	5×10 ¹³ 8×10 ¹⁴	1×10 ¹⁴ 1.5×10 ¹⁵

* Entries are as described in Table 1.

lower temperatures. Because of such interpolation the values at a particular temperature do not have the same degree of accuracy. They are given here chiefly for completeness. In Figs. 5-8, derived from the data of Tables 1 and 2, the ranges of effectiveness values for four groups of generating devices are plotted for comparison. The figures are self-explanatory, and only some of the salient points to be gained from their study are emphasized here.

1) Ammonium iodide ground generators have a much greater efficiency at warm temperatures than sodium iodide generators. The data at temperatures colder than -16°C support only to some extent the superiority of NaI solutions at colder temperatures.

2) The large differences in effectiveness for the same generator under different conditions of ventilation point out the need to know at just what rate the aerosol is mixed with the atmosphere under operational conditions.

3) Ammonium iodide generators are more variable among themselves and have a greater need of calibration than sodium iodide generators.

4) Airborne generators with high burn rates of ammonium iodide solution are the most efficient devices of all at warm temperatures.

5) The very narrow plume produced by pyrotechnics has led to a large overestimate of their effectiveness. Even the nucleus production rate of these devices is less than that of the airborne generators at warmer temperatures. The values given in Fig. 8 are in agree-

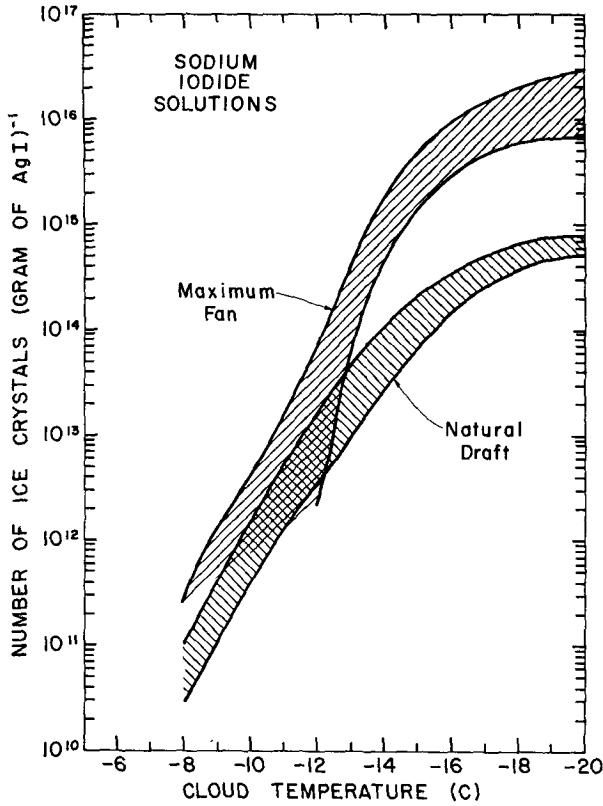


FIG. 5. Ranges of effectiveness values for the aerosols produced by five ground generators burning solutions of AgI-NaI in acetone for two conditions of ventilation.

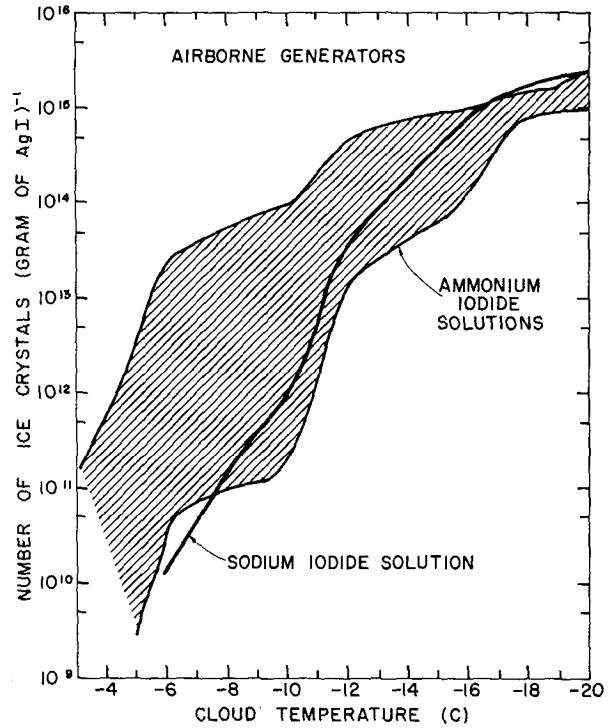


FIG. 7. Range of effectiveness values for the aerosols produced by three airborne generators burning various solutions of AgI-NH₄I and one solution of AgI-NaI.

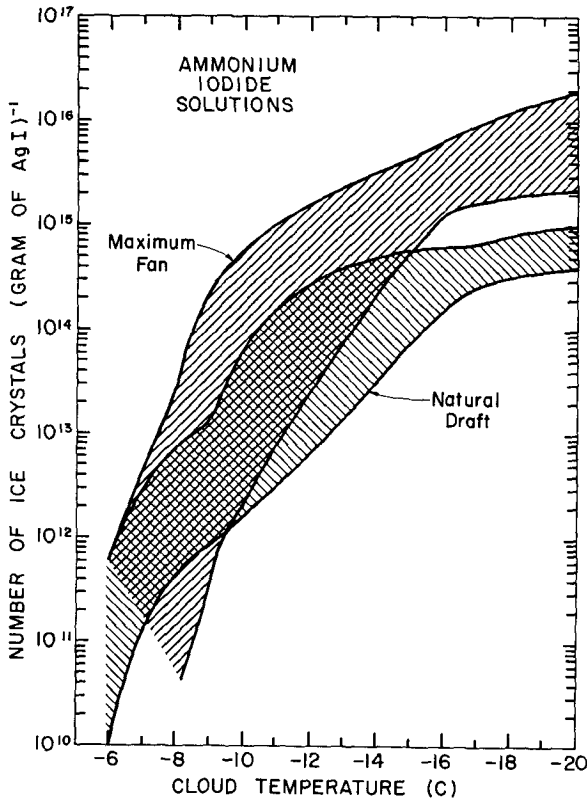


FIG. 6. Ranges of effectiveness values for the aerosols produced by six ground generators burning solutions of AgI-NH₄I in acetone for two conditions of ventilation.

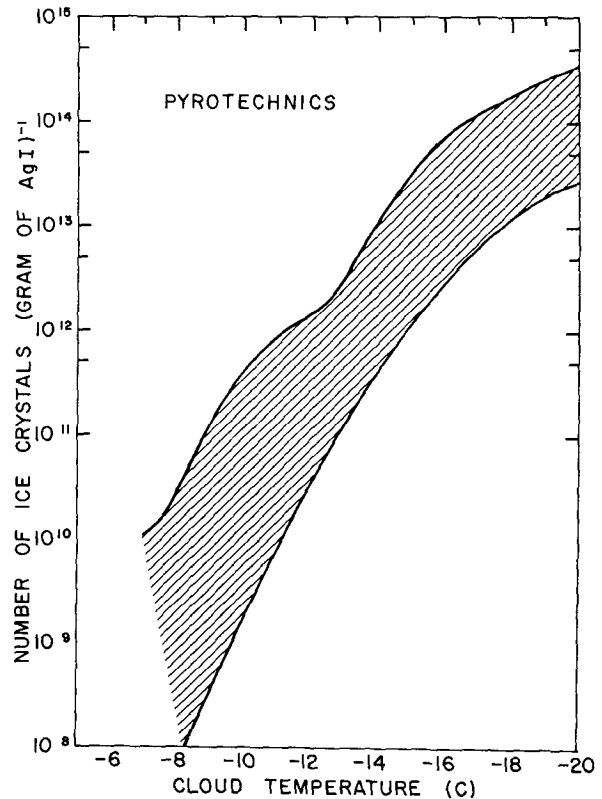


FIG. 8. Range of effectiveness values for the aerosols produced by ten kinds of pyrotechnics.

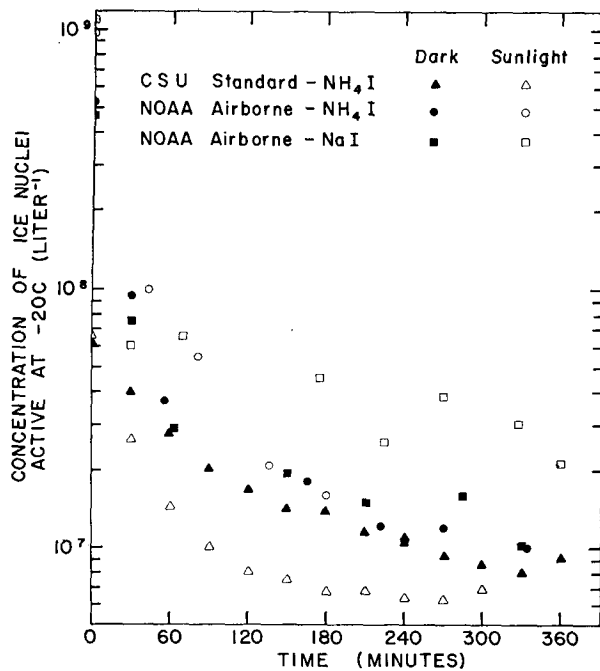


FIG. 9. Decay of the ice-nucleating activity of three aerosols stored in a 760 ℓ holding tank, both in the dark and exposed to sunlight.

ment with those of other pyrotechnics tested at the laboratory before 1970.

3. Research related to generator calibration

In order to properly calibrate an ice nucleus generator, the operational conditions of ventilation need to be known and simulated. Work on this problem was discussed in Section 1. Even assuming proper airflow past the generators, however, the effectiveness values given above may not be relevant to weather modification experiments if due consideration is not given to factors which might influence the aerosol in transit to the cloud volume to be treated. For example, it was pointed out above that concentrations of nuclei in the wind tunnel for airborne generators and pyrotechnics are of the order of $10^{10} \ell^{-1}$. Unless such concentrations are diluted very quickly as the plume disperses in the atmosphere, coagulation of the particles will rapidly reduce the total number of ice nuclei. Other potential

effects are the decay (or enhancement) of the ice nucleating properties of the aerosol because of environmental factors such as radiation and moisture.

Results of tests in which three aerosols were stored in an aluminum holding tank of roughly the same size as the isothermal chamber and samples taken periodically to determine the resulting changes in ice-nucleating activity are shown in Fig. 9. For initial concentrations greater than $10^8 \ell^{-1}$, coagulation was rapid, so that after approximately 30 min all concentrations of ice nuclei active at -20°C were between 2×10^7 and $10^8 \ell^{-1}$, regardless of initial activity. Thereafter, the activity of the contained aerosols decayed more slowly so that after 5 h all three aerosols stored in the dark had an activity of about $10^7 \ell^{-1}$. Exposing the aerosols to sunlight did not give the same result in each case, but in no case was the effect very large. The decay in activity for all the experiments from 30 to 300 min represents a combined effect of coagulation among the particles, loss to the container walls, and decay in the nucleating properties of the particles themselves. The relative magnitudes of the first and third of these effects should be known for field conditions if seeding dosages are to be intelligently estimated.

Finally, the interaction of the artificial aerosol with the cloud itself needs to be examined and compared with field conditions. Initial steps in this direction have been taken for the isothermal cloud chamber and an orographic cap cloud. Work of a similar nature needs to be done with the controlled slow-expansion cloud chamber and prototype cumulus clouds.

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