COMPARISONS OF LOHSE WING-TIP NUCLEI GENERATORS AND BURN-IN-PLACE PYROTECHNICS IN THE NORTH DAKOTA CLOUD MODIFICATION PROJECT

Bruce A. Boe
North Dakota Atmospheric Resource Board
State Water Commission
Bismarck, North Dakota 58505

Paul J. DeMott
Department of Atmospheric Sciences
Colorado State University
Fort Collins, Colorado 80523

Abstract. The characteristics of the ice nucleating aerosols produced by the Lohse wing-tip generators are compared to those produced by the Weather Modification Group WMG-1 formulation burn-in-place flares. The relative output and operating cost of each device are examined. The circumstances in which each seeding method is likely to be optimal are explored using simple thermodynamic considerations and a microphysical parcel model. On a cost basis, the WMG-1 pyrotechnic is found to offer an order-of-magnitude advantage at temperatures near -6°C, while the Lohse generator offers an similar advantage at temperatures of -10°C. Some implications for operational hail suppression projects are suggested.

1. BACKGROUND

The North Dakota Cloud Modification Project (NDCMP) is a dual-purpose operational cloud seeding program designed to reduce damaging hailfalls and increase rainfall. In this program, cloud-base seeding aircraft generate glaciogenic nuclei in two ways. Nuclei generators in which acetone-based solutions are burned are attached to the aircraft wing tips, and burn-in-place flares are mounted to racks attached to the trailing edges of the wings (Atmospheric Resource Board 1997).

The purpose of this paper is to examine the relative effectiveness and costs of these two methods. This evaluation is based on the ice-forming properties of the cloud seeding aerosol particles as inferred from laboratory studies of their nucleating properties, and from NDCMP operational seeding procedures.

The characteristics of the two seeding agents used in the NDCMP are described, and comparisons made of total nuclei production rates and cost effectiveness. The application of the seeding agents in the NDCMP hail suppression methodology are also discussed. Numerical parcel model microphysical calculations are used in the latter section, which includes a detailed consideration of the roles of ice formation mechanisms.

2. SEEDING AGENTS AND PROCEDURES

2.1 Lohse Wing-Tip Generators

The Lohse wing-tip generator employed in the NDCMP was tested by DeMott (1997) at the Colorado State University Cloud Simulation and Aerosol Laboratory (CSU SimLab) using an acetone-based seeding solution suggested to NDCMP managers by Richard Stone (Desert Research Institute, University of Nevada, Reno, 1997, personal communication), a formulation of the type described by Feng and Finnegan (1989). This testing entailed collection of the aerosol particles produced by combustion of a particular solution and examination of their ice nucleating ability in the CSU isothermal cloud chamber. Nucleation ability was described by the yield of ice crystals produced per mass of seeding agent burned and examination of the rates of formation of the resulting ice crystals. The detail of the standard and specific procedures used in this experimentation are found in DeMott (1997).

The general procedures and configuration of instruments used are equivalent to those described in a number of previous publications (e.g., Garvey, 1975; DeMott et al., 1983). The testing included the attempt to reproduce, as closely as possible, the in-flight airflow conditions surrounding the Lohse generator during nuclei generation. Operational airflow past the generator was achieved by placing it within a 0.58 m diameter flow tube connected to the base of the CSU vertical wind tunnel. The standard entry for air into the tunnel was partially blocked to accelerate flow through the tube containing the Lohse generator. This differs from some historical tests of airborne solution combustion generators that were conducted within the wind tunnel itself. Maximum airspeed is about 55 m s^{-1} in the wind tunnel. Use of the below-tunnel flow tube method permits a variable range of flow speeds, including higher values. The compromise in this arrangement, used for these Lohse burner tests (and many other airborne generators since the early 1980's) is that the smoke produced by the generator immediately enters the high speed tunnel fan, quickly diluting the concentrated plume. This could reduce possible coagulation, but one can imagine this same effect being induced in flight by aircraft wing-tip vortices.

The solution used currently in the Lohse generator combines acetone, silver iodide, ammonium iodide, sodium perchlorate monohydrate, paradichlorobenzene, and water to produce an ice nucleus of a $AgI_{0.8}Cl_{0.2}$-NaCl formulation (see Table 1). The production of this nucleus follows the methods of Feng and Finnegan (1989).

Table 1. Formulation of Acetone-based Seeding Solution Used in Wing-tip Nuclei Generators in the NDCMP

Quantity	Ingredient - Composition
309.10 g	silver iodide - AgI
95.40 g	ammonium iodide - NH_4I
19.35 g	paradichlorobenzene - $C_4H_4Cl_2$
161.85 g	sodium perchlorate monohydrate - $NaClO_4 \cdot H_2O$
< 355 g (12 oz.)	water (added only as needed to get ammonium iodide into solution)

This composition of seeding agent represents a switch from the $AgI_{0.8}Cl_{0.2}$-4NaCl formulation nuclei employed by the NDCMP from 1984-1996. The newer agent is considered to be an improvement over its predecessor because it results in active nuclei at slightly warmer temperatures, while containing 75% less dissolved solids ($NaClO_4 \cdot H_2O$, NH_4ClO_4). This latter trait makes the solution somewhat less corrosive and significantly easier to ignite. The ice formation rates of the new nucleus at a condition of water saturation (standard condition in the isothermal cloud chamber) are slightly slower than the predecessor nuclei, but the mode of ice formation is the same. This mode is condensation-freezing, as found by Feng and Finnegan (1989). This determination is based on a graphical analysis of the ice formation kinetics, as described by DeMott et al. (1983) and Feng and Finnegan (1989).

The essential behavior of a condensation-freezing nucleus is a dependence of ice formation rate on water vapor saturation ratio at any temperature and not on the characteristics of the cloud droplet distribution, as would be the case for contact-freezing nuclei. The freezing rate as a function of water saturation ratio depends on the chemical composition of condensation-freezing nuclei. The freezing rate may be slower at water saturation and below, while much faster in supersaturated conditions.

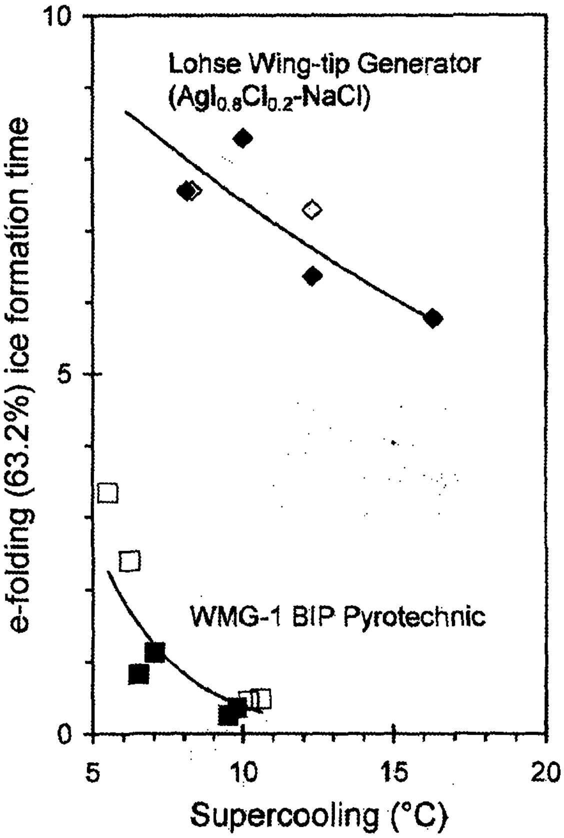

Figure 1. The temperature dependence of e-folding time for ice formation by nuclei from the two generating systems used by cloud-base seeding aircraft in the NDCMP. Values are as measured in the CSU isothermal cloud chamber and represent the negative inverse of the first-order rate constant for ice formation. Closed and open symbols are for clouds with liquid water contents (cloud droplet concentrations) of 1.5 g m^{-3} (~4300 cm^{-3}) and 0.5 g m^{-3} (~2100 cm^{-3}) respectively. The curve fits are simple exponentials.

The dependence of freezing rate on humidity reflects the requirement for diluting excess soluble ions in the condensed phase layers adjacent to the surface of ice nuclei before freezing can occur (Finnegan, 1998). The e-folding times for ice formation (times for 63.2% of ice crystals to form) by $AgI_{0.8}Cl_{0.2}$-NaCl nuclei are plotted as a function of temperature and cloud density in Fig. 1. The raw data are provided in Table 2.The plotted results demonstrate the lack of sensitivity of ice formation times to cloud droplet concentration, thereby confirming the condensation-freezing mechanism. This solution and generator were tested together as described herein early in 1997, to verify that the liquid solution would perform as well or better than its predecessor. The results of the tests conducted with this formulation are compared with the results of the tested flares, described below.

Table 2. Times for formation of 63, 90, and 99% of ice crystal yield as a function of temperature for the nuclei used in the NDCMP

Source	Temp. (°C)	LWC (g m^{-3})	$t_{63\%}$ (min)	$t_{90\%}$ (min)	$t_{99\%}$ (min)
Lohse	-6.0	1.5	5.30	12.2	24.4
	-8.3	1.5	7.55	17.4	34.8
	-10.0	1.5	8.29	19.1	38.2
	-12.3	1.5	6.37	14.7	29.3
	-16.3	1.5	5.77	13.3	26.6
	-8.3	0.5	7.56	17.4	34.8
	-12.3	0.5	7.29	16.8	33.6
WMG-1	-5.5	1.5	3.34	7.69	15.4
	-6.2	1.5	2.39	5.50	11.0
	-6.5	0.5	0.82	1.89	3.78
	-7.1	0.5	1.12	2.56	5.16
	-9.5	0.5	0.25	0.57	1.15
	-9.8	0.5	0.36	0.83	1.66
	-10.2	1.5	0.45	1.04	2.07
	-10.6	1.5	0.48	1.10	2.21

2.2 WMG-1 Burn-in-place Flares

The WMG-1 burn-in-place pyrotechnics, manufactured by the Weather Modification Group of Okotoks, Alberta, Canada, were also tested in the CSU SimLab (DeMott 1995a). The precise formulation of this flare, previously given an SM-1 designation, is proprietary. Though the exact nucleus composition and chemical nature of the soluble salt component of nuclei produced by this flare are unknown to the authors, the behavior of these nuclei in warm cloud can be meaningfully compared to those of the Lohse generator for reasons discussed in section 2.3. As the quantity of seeding agent was known to be 82 g flare, the number of nuclei produced was calculated on the basis of the flare mass consumed. All pyrotechnic flares are tested above the wind tunnel fan following Garvey (1975).

DeMott (1995a) found that the nuclei produced by the WMG-1 formulation also function in a condensation-freezing mode. The ice formation rates were found to be much faster at warmer temperatures (-6°C) than the nuclei produced from the wing-tip generators, presumably due to unresolved physical and/or chemical characteristics of the WMG-1 nuclei. This is demonstrated in Fig. 1, which shows the e-folding times for ice formation of the two nuclei types.

2.3 On cloud chamber ice nuclei comparisons

It has long been recognized that results from the CSU isothermal cloud chamber may not be entirely relevant to the behavior of ice nucleus aerosols in real clouds. Consequently, a comparison of different nucleus compositions based on isothermal cloud chamber yield alone may not give a fair comparison of two different systems. This problem was a past motivation for development of the chemical kinetics methodology for analyzing ice formation rates to discern mechanisms of ice formation in cloud chamber studies (e.g., DeMott et al., 1983). Most standard testing performed at the CSU SimLab since the mid-1980's has attempted, when possible, to make a determination of the dominant ice formation mechanism noted at water saturation. With a knowledge of the predominant ice formation processes, extension of the testing results to real cloud conditions becomes a little more meaningful.

More realistic cloud simulations using the CSU dynamic cloud chamber have provided another means for making meaningful recommendations for field application of ice nucleus aerosols (DeMott et al., 1985; DeMott, 1988). This chamber allows for the simulation of an expanding cloud parcel including cloud formation at warm temperature and ice formation in transient or nearly steady-state supersaturated conditions at lower temperatures. Fully evaluating the different ice formation behaviors using this chamber is possible with appropriate experimental techniques (DeMott, 1995), but not in programs of limited scope and resources (such as is most often supported by the weather modification community). Dynamic cloud chamber simulations were not performed for the aerosols that were the subject of this study. We thus point out two facts from tests performed on other nuclei that are quite relevant to this study. First, DeMott et al. (1985) have shown that the activity of ice nucleus aerosols at supercooled cloud temperatures below about -8°C is oftentimes not very dependent upon the amount of time the aerosols spend in cloud at warmer temperatures.

The ice formation mechanism may be altered by the dynamic cloud processing, but once altered, the time nuclei spend in cloud usually only leads to a slight degradation of ice formation yield. The same result has been obtained for aerosols produced by other ground generators, airborne generators, and even a pyrotechnic (unreported data). These studies and those of DeMott (1988) have also shown that the ice nucleus activity of condensation-freezing nuclei versus temperature in a dynamic cloud parcel bears some relationship to the condensation-freezing rate at water saturation.

For nuclei with very slow freezing rates at water saturation (e.g., 2AgI-KI or 2AgI-NaI, due to excess I^- ions at water saturation), ice formation was greatly enhanced in dynamic chamber processing. Nuclei with very fast freezing rates at water saturation (Ag(Cl)I-4NaCl) showed slightly lower yield at supercooled temperatures warmer than about -12°C in dynamic chamber simulations (DeMott, 1988). This latter observation may relate to the effects of dissolution of the less soluble chemical component, particularly the smaller particles, over the long transit times to low temperatures.

These previous observations provide the basis for the simple assumptions made (in section 4 of this paper) in order to address the full range of expected behaviors of these two NDCMP aerosols in real clouds. Though more information would render the conclusions herein less speculative, we nevertheless believe that the comparison methodology presented in this paper is widely applicable and useful for operational planning.

3. YIELD AND TEMPERATURE

In this section the two seeding methods are compared solely on the basis of the total potential number of ice nuclei produced (yield) versus temperature, as measured in the CSU isothermal cloud chamber. Yield data are typically presented as the number of nuclei produced per gram of AgI or, in the case of a pyrotechnic, per gram of flare mass. Yield values are converted here to production rates per minute and per dollar spent.

3.1 Production Rates

The yield of ice crystals per gram of AgI burned by the Lohse generator and per gram of WMG-1 pyrotechnic mass were measured versus temperature by DeMott (1995a,1997). These nucleation activities are listed in Table 3. Provided that the temporal output of AgI and pyrotechnic mass are known, the nuclei production rates can be calculated and compared.

Table 3.
Yield of ice crystals per gram, per minute, and per dollar, as a function of temperature for the nuclei used in the NDCMP

Source	Temp. (°C)	LWC ($g\ m^{-3}$)	Yield (g^{-1})	Yield (min^{-1})	Yield ($US\$^{-1}$)
Lohse	-6.0	1.5	$2.5x10^{11}$	$7.7x10^{12}$	$9.3x10^{11}$
	-6.0	1.5	$4.8x10^{11}$	$1.5x10^{12}$	$1.8x10^{12}$
	-8.1	1.5	$2.6x10^{13}$	$8.0x10^{13}$	$9.7x10^{13}$
	-8.3	1.5	$2.8x10^{13}$	$8.5x10^{13}$	$1.0x10^{14}$
	-8.3	0.5	$1.9x10^{13}$	$7.7x10^{13}$	$9.4x10^{13}$
	-8.3	0.5	$1.9x10^{13}$	$7.4x10^{13}$	$9.0x10^{13}$
	-10.0	1.5	$1.3x10^{14}$	$4.0x10^{14}$	$4.9x10^{14}$
	-10.0	1.5	$9.9x10^{13}$	$3.1x10^{14}$	$3.7x10^{14}$
	-12.0	0.5	$1.7x10^{14}$	$5.4x10^{14}$	$6.5x10^{14}$
	-12.1	0.5	$1.5x10^{14}$	$4.6x10^{14}$	$5.6x10^{14}$
	-12.3	0.5	$1.7x10^{14}$	$5.4x10^{14}$	$6.5x10^{14}$
	-12.3	1.5	$2.7x10^{14}$	$8.4x10^{14}$	$1.0x10^{15}$
	-12.3	1.5	$4.2x10^{14}$	$1.3x10^{15}$	$1.6x10^{15}$
	-16.3	1.5	$1.4x10^{15}$	$4.3x10^{15}$	$5.2x10^{15}$
	-16.3	1.5	$1.0x10^{15}$	$3.2x10^{15}$	$3.9x10^{15}$
WMG-1	-5.5	1.5	$2.0x10^{12}$	$7.5x10^{13}$	$4.8x10^{12}$
	-6.2	1.5	$6.6x10^{12}$	$2.3x10^{14}$	$1.5x10^{13}$
	-6.5	0.5	$8.9x10^{12}$	$3.2x10^{14}$	$2.0x10^{13}$
	-7.1	0.5	$9.8x10^{12}$	$3.4x10^{14}$	$2.2x10^{13}$
	-9.5	0.5	$1.6x10^{13}$	$5.6x10^{14}$	$3.6x10^{13}$
	-9.8	0.5	$1.1x10^{13}$	$4.1x10^{14}$	$2.6x10^{13}$
	-10.2	1.5	$1.0x10^{13}$	$3.7x10^{14}$	$2.4x10^{13}$
	-10.2	1.5	$1.1x10^{13}$	$3.9x10^{14}$	$2.5x10^{13}$

Since 309.1 g AgI is used in mixing each 5 gallon batch of seeding agent for the NDCMP, and since the consumption rate of seeding solution is 3 gal h^{-1}, the

number of grams of silver iodide, M_{GEN}, consumed per minute of generator burn time is expressed by the formula:

$$M_{GEN} = 309.10\,g\;\frac{3\,gal\;h^{-1}}{5\,gal}\;\frac{1h}{60\,min} = 3.091\,g\;min^{-1}$$

Similarly, each WMG-1 burn-in-place (BIP) flare contains 82 g of reagent, and is characterized by a nominal two-minute burn time. The mass of nucleant output from the BIP flare, M_{BIP}, is thus

$$M_{BIP} = \frac{82\,g}{2\,min} = 41\,g\;min^{-1}$$

A comparison of the production rates of the two seeding generators on a per minute basis is presented in Fig. 2, data are given in Table 3 on the previous page.

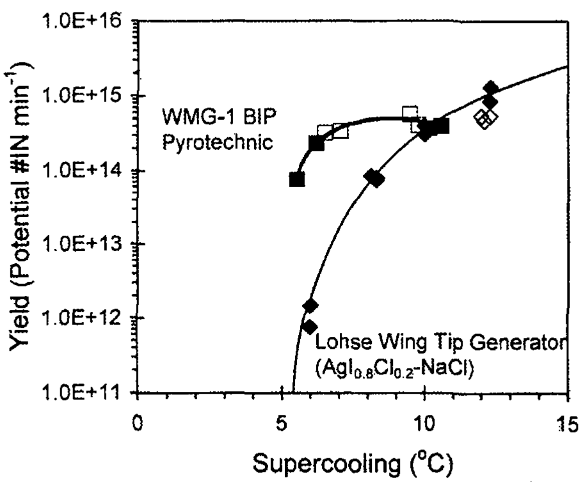

Figure 2. Yield of total potential ice nuclei per minute for $AgI_{0.8}Cl_{0.2}$-NaCl aerosol particles produced by the Lohse generator and the AgI-containing WMG-1 burn-in-place pyrotechnic. Line fits (polynomials) are drawn to distinguish the two series. Open and closed symbols have the same meaning as in Fig. 1.

The WMG-1 BIP flares appear to provide advantageous production rates at all temperatures warmer than about -11°C. The difference in production rates increases with temperature, exceeding a factor of 100 at -6°C. This is because the WMG-1 pyrotechnic nuclei activity is only weakly sensitive to temperatures colder than -6°C, especially when compared to the activity of the nuclei produced by the solution combustion. In hail suppression operations, both wing-tip generators are normally operated, doubling the output of $AgI_{0.8}Cl_{0.2}$-NaCl nuclei. If a single BIP flare is ignited at the same time that both generators are operated, the total output of nuclei from both wing-tip and burn-in-place sources active at -10°C is boosted by 66% to about 1.0×10^{15} min^{-1}. However, if one considers relative performance of the nuclei at warmer (perhaps even warm cloud) temperatures such as would typically encountered earlier, lower in the growing cloud turret, the WMG-1 nuclei have a marked advantage in that they will activate at warmer temperatures. For example, at a temperature of -6°C the number of active WMG-1 nuclei is about 2×10^{14} g^{-1}, exceeding the Lohse generator production by a factor of 100. In any case, this boost in concentration of active nuclei lasts only as long as the flare burns.

Additional factors related to nucleation rates and mechanisms, cloud dynamics, and microphysical effects must be considered in any meaningful comparison of the different nuclei; these are discussed in section 4.

3.2 Nuclei Production Costs

The use of the Lohse and pyrotechnic generators entail quite different cost factors. During the 1997 NDCMP, a 5-gallons of seeding solution cost $82.00. Computed on a cost per minute basis (again assuming a consumption rate of 3 gal h^{-1}), this works out to $0.82 min^{-1}. Also during the 1997 NDCMP, each WMG-1 BIP flare cost $31.50. With a two minute burn time, this works out to $15.75 min^{-1}. The production rates calculated in section 3.1 are normalized by the production costs, and the costs per dollar are as listed in Table 2 and plotted in Fig. 3. On the basis of a -10°C

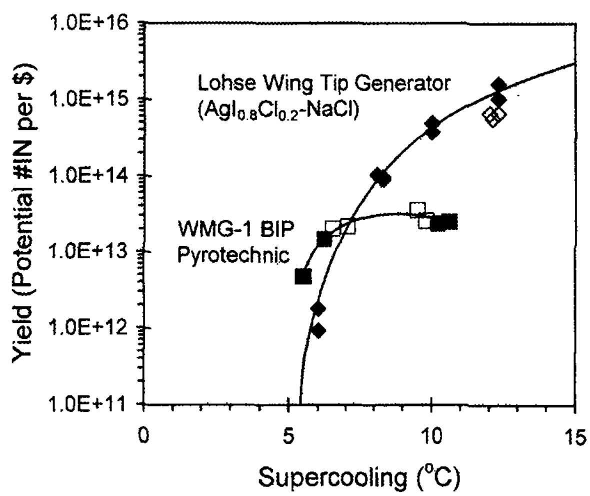

Figure 3. Yield of total potential ice nuclei per dollar expended for $AgI_{0.8}Cl_{0.2}$-NaCl aerosol particles produced by a single Lohse generator versus aerosol particles produced by a single WMG-1 burn-in-place pyrotechnic. Closed and open symbols have the same meaning as in previous figures.

activation temperature, the BIP flare cost 14.5 times more than what a single wing-tip generator cost to operate. However, the -10°C activation temperature is arbitrarily selected for comparing seeding methods because itis a typical cloud temperature at which it is expected that a significant nucleation effect must be achieved in the context of the NDCMP hail suppression conceptual model. Based on Figure 3, the BIP flare is far more cost effective for seeding warmer supercooled cloud regions. This advantage at temperatures warmer than -7°C may be well worth the cost, depending on the microphysical importance of enhanced ice formation at these warmer temperatures. This is further discussed in Sec. 4.

4. HAIL SUPPRESSION AND DYNAMIC NUCLEI RESPONSE CONSIDERATIONS

A rigorous study of the relative merits of wing-tip generators and BIP flares would include a more complete description of nuclei activation characteristics than has yet been obtained, and complete physical descriptions of the processes hypothesized to lead to hail suppression, perhaps integrated with numerical cloud modeling that could resolve some of these effects in different cloud systems on different days. Nevertheless, presently-available information can be used to conduct a simple kinematic analyses of the microphysical seeding effects on air parcels lifted into "typical" clouds, considering NDCMP treatment methods. Resulting insights (see section 5) might improve operational decision-making, especially considering present procedures which are based largely on static nuclei production rates.

The ice formation rates and mechanisms are worthy of additional consideration in the context of the trajectories and seeding aerosol transport times into and within the targeted clouds. It has been noted that the dominant ice formation mechanism in these isothermal cloud chamber studies was found to be condensation-freezing for both nuclei types. However, the activation rates of the Lohse nuclei by this mechanism were found to be significantly slower at water saturation than the WMG-1 BIP nuclei (Fig. 1, Table 2). This could be an additional factor that would moderate the potential nuclei production advantage of the wing-tip generator nuclei in colder cloud regions. However, if freezing rates are limited by the particle solute dilution process, then the time spent by seeded parcels rising in-cloud en route to supercooled regions (where ice can nucleate) could temper the differences in activation times of the two nuclei. Yield might also be altered by the dynamic cloud processing.

Project base-seeding aircraft typically are positioned 500 ft or so below the mean cloud base altitude, in inflow (updraft) speeds on the order of 2.5 m s^{-1} (500 ft min^{-1}), either below rain-free cloud bases, or 3-8 km (2-5 mi) in advance of the leading edge of precipitation (Atmospheric Resource Board 1997). Seeding is conducted in proximity to modest, developing updrafts rather than mature updrafts, as the latter would only serve to rapidly transport the nuclei aloft to the cloud anvil, and would likely not achieve the desired effect. [The interested reader is referred to Smith et al. (1997) for a more detailed description of the NDCMP conceptual model for hail suppression.] Horizontal transport is probably not relevant to ice nuclei activation characteristics, but the vertical transport question can be addressed by some exercises on a thermodynamic diagram. This has been done, and the results again expressed in Table 4.

Table 4.
Nuclei Time from Generation to Activation
Transport from 500 ft below cloud base to the -5°C level by a 500 ft min^{-1} updraft

Surface Temp/ Dew Point (°F)	*Cloud Base Hgt. (kft msl)*	*Mean Cloud Base Temp (°C)*	*Δh, Δt (kft, min)*
61 / 42	5.7	+3.0	4.9, 9.8
77 / 50	7.8	+6.8	7.0, 14.0
86 / 50	9.6	+5.5	6.4, 12.8
95 / 68	7.5	+16.5	14.3, 28.6
86 / 39	12.0	-2.0	2.1, 4.2
68 / 40	8.0	+2.0	3.9, 7.8

The table is based on a fully-mixed subcloud layer, an initial surface pressure of 950 mb, and continuous 500 ft min^{-1} updraft.

A wide range of surface conditions typical of western North Dakota were used to produce Table 4. The shortest transport times (from cloud base to supercooled cloud volume) are most likely with high, colder, cloud bases, which result in atmospheric conditions characterized by less low-level moisture and very warm surface temperatures. While these conditions do occasionally result in high-based thunderstorms, such storms are prone to producing dry microbursts, but not hail.

The numbers in Table 4 are only approximations, however. With a stronger updraft, say 5 m s^{-1} (~1000 ft min^{-1}), the times would be halved. This could easily happen, especially with the higher-dew point conditions, when the convective available potential energy is greater. (The reader is reminded that the clouds of interest are echo-free cumulus congestus, not mature cumulonimbus).

Referring back to Table 2 and Fig. 1, it is seen that compared to the wing-tip generator nuclei the BIP flares have about a 7 min advantage for 63% activation, and up to a 15 min advantage for 90% activation. With reference to Table 3, this rate advantage for the BIP flares should only be realized for colder-based storms with shorter vertical transport times. Shorter transport times are also present in the stronger updrafts associated with more mature cells, but cells at such a stage of maturity are probably not suitable targets for seeding anyway.

There is a possibility that the nucleation mechanism and rates in the atmosphere would be different than in the isothermal cloud chamber studies. It might be expected that water vapor supersaturations in the cloud base region would lead to water uptake (possibly even cloud droplet activation) that speeds the subsequent freezing process at lower temperatures. The ice formation mechanism in such a case would be immersion-freezing, with some fraction of the nuclei activating nearly instantaneously at supercooled temperatures. The active fraction might or might not be the same as measured for condensation-freezing. The process leading to immersion-freezing was not mimicked in the laboratory studies described, although means to do so do exist (e.g., DeMott, 1988 and DeMott et al., 1985).

In the absence of having performed more realistic laboratory cloud simulations, we can only speculate that both nuclei types used for cloud-base treatment in the NDCMP would act as immersion-freezing nuclei with somewhat less efficiency than they do as condensation-freezing nuclei. This would seem most likely to be the case at temperatures warmer than -10°C based on studies of $AgI_{0.8}Cl_{0.2}$-4NaCl nuclei reported by DeMott (1988; 1995b).

To compare the cumulative potential microphysical effects of seeding with the two types of NDCMP nuclei from below cloud base, we use the microphysical parcel model described in Stith et al. (1994). This model has been applied to study natural ice formation processes in North Dakota cumuli. The cloud model requires specification of initial parcel thermodynamic conditions and the parcel trajectory. Liquid and ice particles are nucleated and are allowed to grow and interact. Size distributions are specified within bins and ice crystals are allowed to grow along both *a* and *c* crystal axes. The natural nucleation processes were retained in the seeding simulations, but we consider also ice formation by aerosol particles added by seeding. The model parcel is adiabatic, it never loses water as precipitation, and air is not entrained from nearby cloud parcels.

Two scenarios are modeled to bracket the potential range of seeding effects inside an adiabatic cloud parcel. The best-case scenario is one in which the particles nucleate with the same yield as determined in isothermal cloud chamber tests. This is referred to as the "no rate" simulation. The numbers of ice crystals nucleated as the parcel cools in this case are based on the mass of seeding material per unit volume and a polynomial function fit to the yield data from Table 3. In the worst-case scenario, we assume that the nucleation rates measured in the cloud chamber are also required to form ice at each cloud temperature. This "with rate" case was implemented in the model by fitting a polynomial function to the yield data and applying a temperature dependent rate constant to the yield based on Fig. 1 (where the rate constant is the negative value of the inverse of the e-folding time). The yield and rate constant were adjusted in finite steps at the start of each 1 s model time step. The threshold temperature for any ice formation was taken as -5°C for the $AgI_{0.8}Cl_{0.2}$-NaCl nuclei and -4.5°C for the WMG-1 BIP nuclei.

Initial conditions for simulations were selected in the following manner. Initial concentrations of nuclei entering cloud base were based on a simplified analysis of generator effluent dilution following generation. If particles dilute into a (wing-tip) vortex 30 m in diameter at an aircraft speed of 55 m s^{-1}, then they fill a volume of 3.9×10^4 m^3 in 1 s. If this initial volume expanded at lateral and vertical rates of 1 m s^{-1} for one minute during transport to cloud base, the volume entering cloud base would be about 9.7×10^5 m^3. This volume was taken as that into which the number of grams generated per second was dispersed. It suggests cloud base total nuclei (e.g., yield at -25°C) concentrations of about 5.3 x 10^5 L^{-1} for the nuclei from a single Lohse burner and 9.4 x 10^3 L^{-1} for the pyrotechnic nuclei. A constant updraft rate of ~2.5 m s^{-1} (500 ft/min) carried parcels from cloud base (+5°C) to the -15°C cloud level.

Some basic results of the model simulations for each nucleant are summarized in Table 5. Ice crystal concentrations, maximum ice crystal dimensions, and ice water content (IWC) are included.

The full ice crystal size distributions at the -10°C level in the four simulations are shown in Figure 4. Several results stand out. First, greater numbers of larger ice crystals are predicted to form in all scenarios when seeding is done with the WMG-1 BIP nuclei. The presence of these larger crystals is clearly due to the maximization of the BIP flare yield at warmer cloud temperatures. The particles have longer times to grow. A consequence is that higher IWC is produced in the parcel in BIP flare seeding. This advantage for the BIP flare is particularly evident at the -10°C level. Such conversion of cloud water to ice at a warmer temperature is a desirable trait for a nucleant used for hail suppression. The Lohse nuclei are predicted to form more ice crystals in the parcel in the best-case "no rate" scenario of instantaneous nucleation at each cloud temperature. Since the ice formation rates in the worst-case are slower for the Lohse nuclei, the ice crystal concentrations are lowered more (two to three orders of magnitude) for these aerosols, as compared to the WMG-1 BIP flare nuclei, which are lowered by one order of magnitude in comparison to the best-case scenario for a rising cloud parcel. Nevertheless, as the "no rate" scenario seems

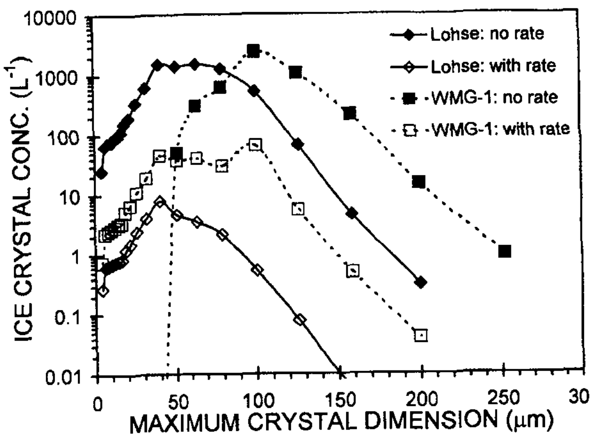

Figure 4. Ice crystal size distributions at -10°C in parcel simulations using Lohse and WMG-1 nuclei, with assumptions on the spontaneity of the ice formation. Simulation conditions and further description are given in the text. Data points are plotted at the midpoints of bins (not shown) of variable size. As shown herein, size is the maximum dimension (a or c-axis) of the ice crystals.

more parcel. realistic, based on past laboratory studies (see section 2.3), and since most target clouds probably penetrate the -10°C level, the improvements suggested for the BIP flare may not justify the additional costs.

On the other hand, the cost of the BIP flares may be justified as a better assurance of warmer temperature cloud effects for clouds with a wide range of base/top temperatures and updraft speeds. To guarantee success regardless of cost, the simulations would seem to support the case for the use of a BIP flare in combination with solution combustion generators.

Table 4.
Simulated Ice Crystal Concentrations, Diameters, and Ice Water Contents

Source	Simulation Type	Temp. (°C)	Conc. (L^{-1})	D_{avg} (μm)	IWC ($g\ m^{-3}$)
Lohse	"with rate"	-10	9.7	51	.001
WMG-1	"with rate"	-10	86.7	69	.017
Lohse	"no rate"	-10	4,120	52	0.25
WMG-1	"no rate"	-10	2,100	94	1.05
Lohse	"with rate"	-15	13.1	152	1.00
WMG-1	"with rate"	-15	384	139	2.45
Lohse	"no rate"	-15	26,600	72	3.25
WMG-1	"no rate"	-15	1,900	150	3.26

5. SUMMARY

The following points summarize this paper.

a. The production rates of nuclei (min^{-1}) of the WMG-1 BIP flares exceed those of a single Lohse wing-tip generator (producing $AgI_{0.8}Cl_{0.2}$-NaCl nuclei) at isothermal cloud chamber test temperatures warmer than -10°C. The difference exceeds a factor of 100 at -6°C in water saturated conditions.

b. On a per dollar basis (1997 costs), the BIP flare outperforms a single wing-tip generator by an order of magnitude at -6°C. A wing-tip generator outperforms the BIP flares by an order of magnitude on a cost basis at -10°C. The two generation methods have equal cost factors for producing ice nuclei effective at about -7°C on the basis of CSU isothermal cloud chamber results.

c. The base costs of flight operations per minute were $1.22 for reconnaissance (flight without any seeding), $2.04 for single-generator seeding, $2.86 for dual-generator seeding, and $18.61 for dual-generator seeding while burning a single BIP flare. Thus, the use of flares adds significantly to the operational costs.

d. Both nuclei types activate ice formation by a condensation freezing mechanism. At water saturation, the BIP nuclei are faster-acting. This difference may not exist in seeded cumulus updrafts since exposure to water vapor supersaturation would tend to increase water uptake and indirectly speed the rate-determining freezing process for both nuclei.

e. Microphysical model simulations to bracket best- and worst-case expected seeding effects using the two types of nuclei suggest that the use of the BIP nuclei may be warranted as a means of most effectively converting cloud water into larger ice crystals at the earliest stage of cloud development. A combination of the two generator types may offer the best, if not the most cost-effective strategy.

It must be reiterated that the laboratory studies did not exactly mimic the operational seeding. In particular, the possible enhancement or degradation of ice nuclei yield under dynamic cloud conditions was not investigated. Also, the cloud model used only simulated an "idealized" cloud parcel, and did not project the ultimate effects on precipitation and hail production. Nevertheless, this study offers a basis for comparing seeding techniques and making operational decisions that should be applicable to any program and for any generators and flares that have been tested in the laboratory.

In the context of NDCMP base seeding operations, two wing-tip generators are always operated when seeding for hail suppression purposes. In addition, multiple aircraft are frequently employed in treating a single convective storm complex. Given the cost per minute of seeding time reported herein, six cloud base seeding aircraft can be flown with both Lohse generators running for about the same price as a burning a single WMG-1 BIP flare. Nevertheless, the faster (and warmer) activation of the WMG-1 BIP nuclei makes it an attractive addition to the seeding arsenal. In part due to the exploratory investigations reported herein, seeding rates employed in the NDCMP are presently being re-examined. Changes in policy and procedure are probable.

ACKNOWLEDGMENTS

The authors wish to thank the reviewers, whose suggestions were very helpful. We also acknowledge Troy Seidel of Weather Modification, Inc. who provided information regarding the specifics of the Lohse airborne ice nuclei generator. Testing of the Lohse generator at the CSU SimLab was conducted at the joint expense of the North Dakota Atmospheric Resource Board and Weather Modification, Inc., Fargo.

REFERENCES

Atmospheric Resource Board, 1997: *North Dakota Cloud Modification Project Operations Manual*, 1997 revision. North Dakota Atmospheric Resource Board, State of North Dakota, 62 p.

DeMott, P.J., W.G. Finnegan and L.O. Grant, 1983: An application of chemical kinetic theory and methodology to characterize the ice nucleating properties of aerosols used in weather modification. *J. Clim. Appl. Meteor.*, **22**, 1190-1203.

DeMott, P.J., W.G. Finnegan and L.O. Grant, 1985: On the effectiveness of artificial seeding from below cumulus cloud base. *4th WMO Scientific Conference on Weather Modification, World Meteor. Org. Tech. Doc. No. 53,* **1**, 225-228.

DeMott, P.J., 1988: Comparisons of the behavior of AgI-type ice nucleating aerosols in laboratory-simulated clouds. *J. Weather Modif.*, **20**, 44-50.

DeMott, P.J., 1995a: *Report to the North Dakota Atmospheric Resource Board on Tests of the Ice Nucleating Ability of Aerosols Produced by the WMG "SM-1" Pyrotechnic.* Cloud Simulation and Aerosol Laboratory, Department of Atmospheric Science, Colorado State University, Fort Collins, CO. 24 p.

DeMott, P.J., 1995b: Quantitative descriptions of ice formation mechanisms of silver iodide-type aerosols. *Atmos. Res.*, **38**, 63-99.

DeMott, P.J., 1997: *Report to the North Dakota Atmospheric Resource Board and Weather Modification, Incorporated on Tests of the Ice Nucleating Ability of Aerosols Produced by the Lohse Airborne Generator - 1997.* Cloud Simulation and Aerosol Laboratory, Department of Atmospheric Science, Colorado State University, Fort Collins, CO. 29 p.

Feng D. and W.G. Finnegan, 1989: An efficient, fast functioning nucleating agent - AgI-AgCl-4NaCl. *J. Weather Modif.*, **21**, 41-45.

Finnegan, W.G, 1998: Rates and mechanisms of heterogeneous ice nucleation on silver iodide and silver chloroiodide particulate substrates. *J. Colloid Interface Sci.*, **202**, 518-526.

Garvey, D.M., 1975: Testing of cloud seeding materials at the Cloud Simulation and Aerosol Laboratory, 1971-1973, *J. Appl. Meteor.*, **14**, 883-390.

Smith, P.L., L.R. Johnson, D.L. Priegnitz, B.A. Boe, and P.W. Mielke, Jr., 1997: An exploratory analysis of crop-hail insurance data for evidence of cloud seeding effects in North Dakota. *J. Appl. Meteor.*, **36**, 463-473.

Stith, J.L., D.A. Burrows, and P.J. DeMott, 1994: Initiation of ice: comparison of numerical model results with observations of ice development in a cumulus cloud. *Atmos. Res.*, **32**, 13-30.