INDICATIONS OF RESIDUAL EFFECTS FROM SILVER IODIDE RELEASED INTO THE ATMOSPHERE

By

Lewis O. Grant [1]

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INTRODUCTION

The amounts of silver iodide released into the atmosphere during cloud seeding operations usually range from a few to several hundred grams per hour depending on the type of cloud modification being attempted. This silver iodide may be divided into 10^{15} to 10^{17} separate particles which can act as ice nuclei for at least a short period of time. The purpose of this paper is to consider the movement of silver iodide particles after release and to present analyses of experimental data that suggest residual nucleation effects may be associated with cloud seeding using silver iodide.

Silver iodide particles released into the atmosphere have a negligible fall velocity in terms of atmospheric scale motions, due to their small size, and will move with existing wind currents. If released from aircraft, they can be immediately activated or have a substantial flight period extending for several days. Coagulation with other sub-micron particles then becomes important, and these particles ultimately reach the ground in deposition from air flow and in precipitation. In many cases they will have changed crystal form from ultraviolet decomposition, and are no longer effective as ice nuclei. If released from the ground in the absence of vertical air currents, they can be quickly deposited or collected by nearby obstacles. Even during a seeding operation when good vertical flow does occur, operations are probably not timed exactly to this flow so that a large portion of the silver iodide is deposited or collected relatively near the release point.

If vertical air currents do exist, ground released silver iodide is carried aloft where it can be immediately effective in producing ice crystals or, as in the case of aircraft dispersed materials, have a substantial flight. Probably only a small fraction of the total silver iodide released is effective in producing ice crystals within a relatively short distance of the release point. These ice crystals with the AgI imbedded would in many cases grow rapidly and fall out in the form of snow or rain and could involve an extremely large number of AgI crystals.

Interest in the silver iodide particle usually ceases once it has been deposited directly at the earths' surface in precipitation in the area of interest, or further downwind by the action of coalescence and wind, or in precipitation. Several types of evidence are presented which suggest a residual or carry over effect of ice nuclei from silver iodide directly deposited immediately downwind from seeding sites or by precipitation in the vicinity of the seeded area. A residual effect is suggested from an analysis of Climax, Colorado, ice nuclei observations, from a comparison of Climax and Berthoud Pass, Colorado ice nuclei data for seeded and non-seeded intervals and by Mount Washington data collected during "Operation Overseed".

I. Analysis of Climax, Colorado Ice Nuclei Data for Indications of Residual Effects from Silver Iodide Seeding

Observations of ice nuclei have been made almost continuously at Climax, Colorado, 11,300 feet m.s.l., since November 1954 (2, 3, 4). Observations were made with a diffusion-type cold chamber from November 1954 through March 1960 with an expansion-type chamber from November 1959 to the present. Except during a few special test periods, observations have been made at -20°C. There was no significant difference between the means of observations taken with the two counters during a comparison test interval (2). Cloud seeding operations utilizing ground silver iodide generators have been carried out in the general area for commercial or research purposes during at least five separage periods since 1954. Significant increases of 1-3 orders of magnitude in ice

1/ Colorado State University, Fort Collins, Colorado

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nuclei concentration have been routinely observed at Climax directly following silver iodide releases (3). It is not the purpose of this paper to discuss these direct effects but consider only those of a residual nature. Consequently, data presented in the follow-analyses for seeded intervals considers only data collected on non-seeded days during those intervals when direct effects could not be expected from the seeding operation.

A. Mean Concentrations of Ice Nuclei

Table I shows the mean concentrations of ice nuclei for non-seeded intervals, for non-seeded days during seeded intervals and for the non-seeded six month interval following seeding intervals.

TABLE I Mean Ice Nuclei Concentration at Climax, Colorado, 1954-1963 for Non-Seeded Days during Seeded and Non-Seeded Intervals.

Interval	No. of Months	No. of Obsnl. Units	Mean (b) concentration @-20°C (nuclei/m^3)
Non-seeded intervals (a)	55	4803	$.6 \times 10^3$
Non-seeded days during seeding intervals	18½	3390	5.8×10^3
Non-seeded six month interval following seeded intervals	24	2743	3.6×10^3

(a) This excludes seeded intervals and the six month period following each cloud seeded period.

(b) The value of the mean is biased by the occurrence of some readings below the detection range of the nuclei counters used, $5.5 \times 10^2/m^3$ for the diffusion counter and $1 \times 10^2/m^2$ for the expansion counter.

As can be seen from Table I, mean ice nuclei concentrations have been substantially higher on non-seeded days during seeding periods and following seeding periods than during other non-seeded intervals. The mean concentration has been nearly 10 times greater on non-seeded days during seeded intervals and has remained 6 times greater during the following six month period. The use of only non-seeded days during the seeded intervals while using all days for non-seeded intervals should not introduce any substantial bias since "seed" and "no seed" days were randomly selected for the major portion of the seeded interval data used.

B. Distribution of Ice Nuclei Observations

Concentrations of ice nuclei in excess of $10^3/m^3$ at -20°C. have been observed in from 5% to 46% of the observations during different non-seeded intervals with the mean of all non-seeded intervals being 19% (Figure 1). The mean frequency of $10^3/m$ has been substantially higher for non-seeded days during seeded intervals (67%) and during the six month interval immediately following seeding operations (72%).

Ice nuclei concentrations have rarely exceeded $10^4/m^3$ at -20°C. at Climax. As can be seen, however, in Figure 2 the frequency of concentrations has been substantially greater on the non-seeded days during seeding intervals (15.6%) and the six month interval following seeding (5.8%) than during the non-seeded intervals (0.5%).

C. Changes in Ice Nuclei Concentrations as Seeding Operations Progress

The concentration of ice nuclei on non-seeded days during seeded intervals has not substantially increased as the seeding interval progressed. Since all seeding at Climax has been carried out during the snow accumulation portion of the year, successive seedings are covered by the snow pack which frequently reaches 4 to 8 feet by spring. The later months of the seeded intervals have usually been April and early May when the melt season is first getting underway. These months do show a tendency toward progressively increasing concentrations.

Table II shows the mean percentage of ice nuclei concentrations $\geq 10^3/m^3$ at -20°C. on non seeded days for successive time intervals as seeded intervals have progressed

TABLE II Mean Percentage of Ice Nuclei Concentrations $\geq 10^3/m^3$ at -20°C. on Non-Seeded Days for Successive Time Intervals as Seeded Intervals Have Progressed.

Lapsed Time (per cent)	Ice Nuclei Concentrations ($\geq 10^3/m^3$)
0 - 20	58%
21 - 40	58%
41 - 60	62%
61- 80	77%
81 - 100	79%

II. <u>Comparison of Climax and Berthoud Pass, Colorado Ice Nuclei Data for Indication of Residual Effects from Silver Iodide Seeding</u>

Observations of the concentrations of ice nuclei were made during January, February, March, 1955, 1956, and 1957 at Berthoud Pass, Colorado (11,300 m.s.l.) some 50 miles northeast of Climax, Colorado. Silver iodide was released in certain of these years to affect Berthoud Pass. Berthoud Pass and Climax were both directly affected by seeding operations during 1955. Neither area was seeded during 1956 and only Berthoud Pass was seeded in 1957. A comparison of the ice nuclei concentrations between these two stations has been made for these three years. As with the Climax data comparisons have been for only the non-seeded days to investigate the possibilities of residual rather than direct effects of seeding. Table III summarizes the observations of concentrations at Climax and Berthoud Pass for the 1955-1957 interval.

TABLE III Mean Concentration of Ice Nuclei Effective at -20° C. at Climax and Berthoud Pass, Colorado, January - March, 1955-1957 (Non-Seeded Days)

Year	Ice Nuclei Conc. at Climax ($x10^3/m^3$)	Ice Nuclei Conc. at Berthoud Pass ($x10^3/m^3$)
1955	12*	12*
1956	2	5
1957	1	12*

* seeded intervals

The mean concentration of ice nuclei on non-seeded days during 1955 were high ($12 \times 10^3/m^3$) and nearly identical at these two stations where were both under the influence of commercial seeding operations. The mean concentration at both sites dropped appreciably in 1956 when neither station was seeded although the drop was somewhat less at Berthoud Pass. It is possible that commercial seeding operations for an east slope commercial project may have had some effect on the Berthoud Pass counter during this interval. The concentration of ice nuclei at Berthoud Pass in 1957 when seeding was carried out to specifically influence this site, again increased to near ($13 \times 10^3/m^3$) the 1955 seeded interval value. The concentrations at Climax in 1957 remained low ($1 \times 10^3/m^3$) as in 1956 and well below the seeded year value of 1955, indicating that no large increase in background occurred in the general area while the high value of $13 \times 10^3/m^3$ was occurring at Berthoud Pass. The substantially higher concentration associated with seeding years is residual in nature since the data presented is only for days when direct seeding effects could not be expected.

III. Analysis of Mount Washington Data during "Operation Overseed" for Indications of Residual Effects of Silver Iodide Seeding

The only other ice nuclei data known to the author that covers an extended period before, during and after a cloud seeding operation is that presented in the final report of "Operation Overseed". (1) These data have been inspected for indications of residual or indirect effects from seeding operations. Appendix 1 of the final report of "Operation Overseed" reports the maximum ice nuclei concentration observed before each seeded days operation was begun. A relationship between these daily counts before seeding and the seeding operation would be of a residual nature rather than direct since these observations are in all cases more than 12-18 hours subsequent to any previous seeding activities. The days for which data are available were divided into six consecutive groups of 10 days each and a seventh group of the remaining 13 days. Mean concentration of ice nuclei was computed for each group and is shown in Table IV.

TABLE IV Mean "Operation Overseed" Ice Nuclei Concentration for Consecutive Groups of Cloud Seeding Operations

Group	Period	Mean Maximum Concentration Prior to Each Days Seeding-Nuclei/m^3 at -20°C.
1	16 Sept. -22 Nov. 1955	$.4 \times 10^3$
2	25 Nov.-16 Dec. 1955	$.7 \times 10^3$
3	19 Dec. 1955-16 Feb. 1956	6.0×10^3
4	21 Feb.-23 Mar. 1956	11.0×10^3
5	26 Mar.-20 Apr. 1956	4.0×10^3
6	22 Apr.-15 May 1956	$.7 \times 10^3$
7	16 May-15 June 1956	2.0×10^3

A division by months gives a somewhat different grouping but essentially the same trend in the mean concentrations (See Table V.)

TABLE V Calendar Month Mean Ice Nuclei Concentration for "Operation Overseed"

Period	No. Days	Mean Concentration Prior to Seeding-Nuclei/m^3
Sept., Oct., Nov.	15	$.7 \times 10^3$
Dec.-Jan.	8	3.0×10^3
Feb.	12	8.0×10^3
Mar.	8	10.0×10^3
Apr.	13	2.0×10^3
May-June	17	1.5×10^3

It can be seen from both Tables IV and V that concentrations of ice nuclei increased as the seeding period progressed through early spring despite the fact that direct effects from the seeding are not likely in the data considered. A substantial carry over of this trend into the spring months is not noted as has been the case at Climax. This could reasonably result from differences in the snow melt period, atmospheric humidity, rates of melting, and exposure of the mountain peaks.

The increase in concentration does not appear to result from a seasonal trend in ice nuclei concentration. Based on ice nuclei data for Mount Washington collected by Schaefer (6) for the period 1948 through 1953, a seasonal variation that would account for the increased concentrations did not occur. Figure 2 of the Schaefer report shows that about 70% of the Mount Washington concentrations were $1 \times 10^3/m^3$ during October, November and December, while about the same percentage, 75%, were $1 \times 10^3/m^3$ for January, February and March. A somewhat lower percentage, around 55%, were $1 \times 10^3/m^3$ during April, May and June. There were two years during the 1948-1953 period when the fall season ice nuclei concentrations were higher than the winter season and three seasons when this was reversed. Ten to twenty per cent of Schaefer's observations were in the range $5 \times 10^5/m^3$. A considerably higher percentage fell during the fall than during the winter months. A seasonal increase on non-seeded days that would account for the increase noted during "Operation Overseed" is not apparent and some other effect related to the seeding is suggested.

IV. Physical Evidence

The physical process by which a residual effect from silver iodide crystals might occur is not obvious. The questions of storage, reactivation and redistribution of effective ice nuclei offer serious problems in any consideration of a residual effect. Laboratory and field investigations are in progress to explore processes by which this effect might occur. The occurrence of a residual effect related to atmospheric storage under temperature inversions and to the redistribution of snowfall from intercepted and dry powdered snow is suggested. A more extensive redistribution process is also suggested.

The nucleation characteristics of water collected in the Climax area are being investigated. In addition to distilled water, water samples from Fort Collins, Denver, and Twin Lakes, and several Climax area sources have been checked for silver iodide using the Isono technique. (5). The samples collected in the vicinity of Climax--all show the presence of silver iodide. It is not detectable in any of the other water samples tested.

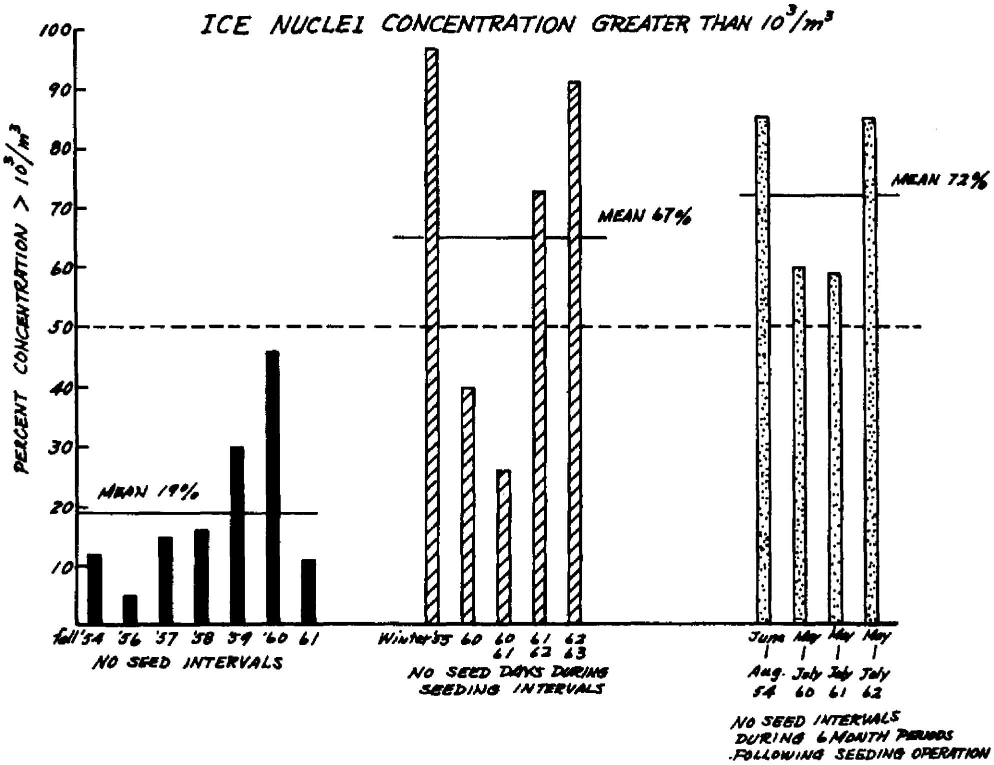
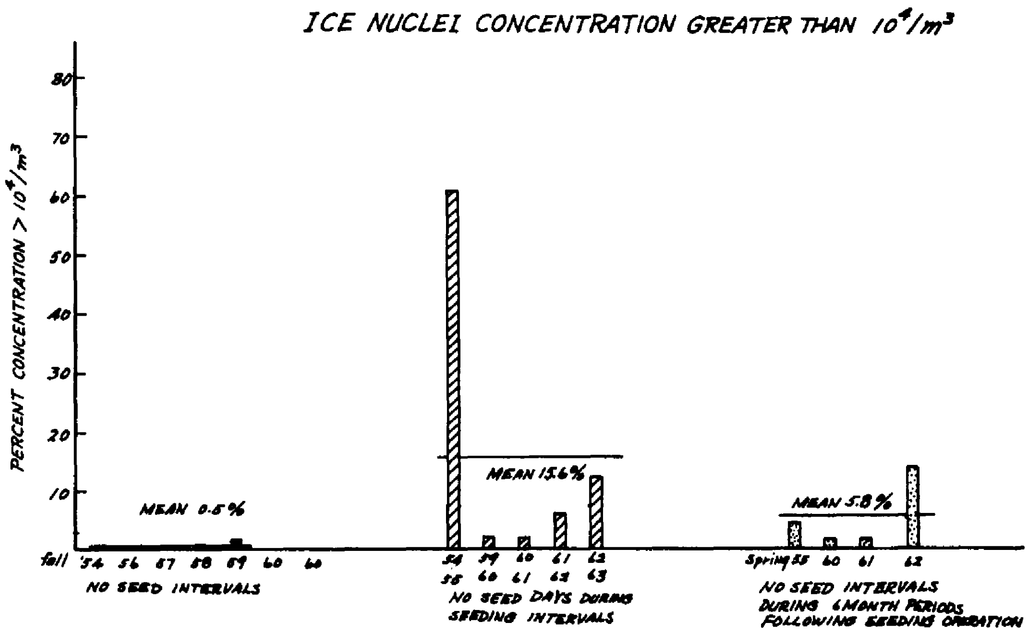

ICE NUCLEI CONCENTRATION GREATER THAN $10^3/m^3$
PERCENT CONCENTRATION > $10^3/m^3$
MEAN 19%
MEAN 67%
MEAN 72%
fall '54 '56 '57 '58 '59 '60 61
NO SEED INTERVALS
NO SEED DAYS DURING SEEDING INTERVALS
NO SEED INTERVALS DURING 6 MONTH PERIODS FOLLOWING SEEDING OPERATION

FIG. 1


ICE NUCLEI CONCENTRATION GREATER THAN $10^4/m^3$
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MEAN 0.5%
MEAN 15.6%
MEAN 5.8%
NO SEED INTERVALS
NO SEED DAYS DURING SEEDING INTERVALS
NO SEED INTERVALS DURING 6 MONTH PERIODS FOLLOWING SEEDING OPERATION

FIG. 2

CONCLUSION

An inspection of the Climax, Berthoud Pass and Mount Washington ice nuclei data shows that ice nuclei concentrations on non-seeded days during seeded intervals have been substantially higher than those during non-seeded intervals. This suggests a carry over or residual effect from seeding with silver iodide. The uncertainties in many of the charcertistics of ice nuclei, the inadequacies of procedures for observing them, limited information on natural and artificial nuclei sources, and lack of understanding of a process by which a carry over effect might work, precludes a final assessment of its reality at this time. Investigations in progress are expected to provide an improved understanding of the indicated residual effect. A residual effect of the nature suggested above would have considerable bearing on the design of weather modification experiments, especially if randomization is to be employed, and on the planning, operation, and analysis of commercial seeding efforts.

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