INVESTIGATIONS OF THE TARGETING OF GROUND-RELEASED SILVER IODIDE IN UTAH PART I: GROUND OBSERVATIONS OF SILVER-IN-SNOW AND ICE NUCLEI

Arlin Super
Bureau of Reclamation
Denver CO 80225

and

Arlen W. Huggins
Desert Research Institute
Reno NV 89506

Abstract: During the winter of 1989-90, the Utah Division of Water Resources, the National Oceanic and Atmospheric Administration, and the Bureau of Reclamation cooperated in a limited sampling project to investigate the transport and dispersion of silver iodide (AgI) cloud-seeding aerosol over two target areas in the mountains of Utah. Seeding was done using the ground-based AgI generator network of the Utah operational cloud seeding program. Transport and dispersion over the Wasatch Range and Wasatch Plateau were evaluated using a silver-in-snow sampling technique and the real-time detection of AgI aerosol or sulfur hexafluoride gas.

This report contains an extensive review of past silver-in-snow results from several different regions as a basis for comparison with the current study. The 1989-90 Utah results indicated that a low percentage (< 15 percent) of bulk snow samples from 10 mountain target area locations had silver (Ag) concentrations above background values for periods when seeding had been conducted. Consistently poor targeting and/or low seeding generator output could explain the general lack of detectable Ag in the two Utah target areas.

Seeding generator output also forms the basis for estimates of average ice particle masses required to achieve the greater than 11 percent snowfall increase reported from statistical analyses of the Utah operational program. These estimates are based on very optimistic assumptions (perfect targeting, 100 percent nucleation, 100 percent fallout, etc.). They indicate that snowfall enhancements of 10 percent or greater are unlikely with the current AgI seeding rate of 6 grams per hour used in Utah.

Real-time detection of ground-released AgI showed that seeding material was routinely transported up a particular canyon when releases were made near the bottom of the canyon. Concentrations of AgI at the up-canyon observation site (adjusted for nucleation activity at -10°C) were, however, estimated to average only about one ice nucleus per liter. This relatively low concentration of active AgI nuclei offers a partial explanation of the observed low percentage of silver-in-snow above background at sampling sites above the canyons where AgI was released.

1. INTRODUCTION

An operational cloud seeding program has been conducted in Utah during most winters since 1973-74 (Griffith et al. 1991). The program employs a large network of ground-based silver iodide (AgI) generators, most located in broad valleys such as shown in Fig. 1. The Wasatch Range, shown on Fig. 2, is atypical with several generators in or near the mouths of narrow canyons. The manually operated generators each dispense 6 grams per hour (g h^{-1}) AgI by injecting a 2 percent solution of AgI with ammonium iodide dissolved in acetone into a propane flame.

The National Oceanic and Atmospheric Administration (NOAA) is pursuing a cooperative weather modification research program with Utah's Division of Water Resources. The Bureau of Reclamation is providing scientific expertise and equipment support to this program under a cooperative agreement with NOAA. The goal of all three agencies is to improve weather modification technology by evaluating the effectiveness of current operational seeding practices in Utah and recommending improvements where appropriate.

The transport and dispersion of appropriate concentrations of AgI to supercooled liquid water cloud regions probably pose the area of greatest uncertainty in winter orographic cloud seeding. Rangno (1986), Reynolds et al. (1989), Super (1990) and others have discussed problems associated with targeting of seeding agents.

This paper, and a companion paper by Super and Huggins (1992), discuss results of investigations into the targeting of AgI conducted during the 1989-90 winter. Part I of this two-part series considers: (1) the collection and analysis of snow samples for Ag content, and (2) monitoring of ice nuclei in a particular canyon that had AgI generators near its mouth. The companion paper addresses aircraft tracking of AgI and a tracer gas during near-storm conditions.

2. SILVER-IN-SNOW SAMPLING FOR DETECTION OF AGI

Examining the silver (Ag) content of snowfall in cloud seeding target areas can provide insight into the transport and dispersion of the AgI. Finding enhanced Ag levels in the snowfall does not prove that seeding created additional snowfall. Scavenging primarily by cloud

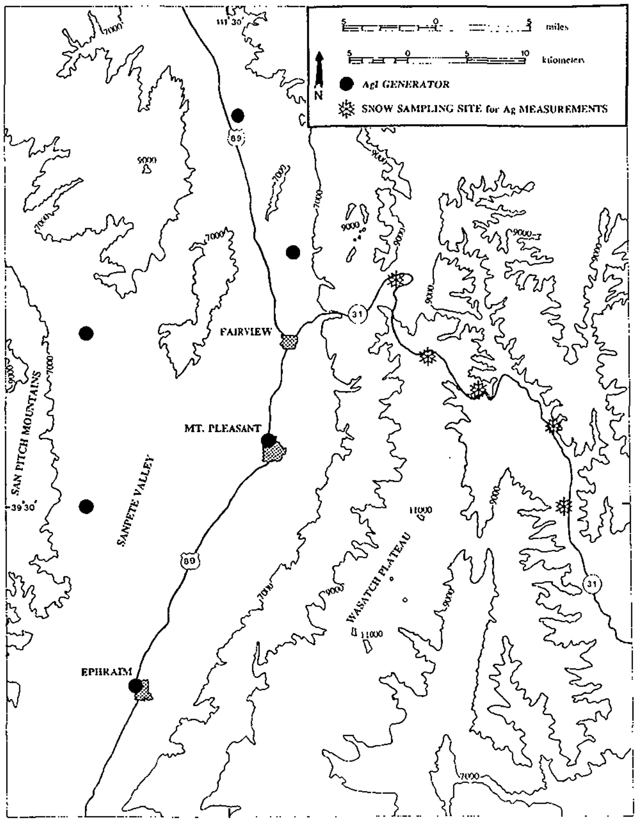

Fig. 1. Map of Wasatch Plateau experimental area showing silver iodide generator and snow sampling sites, selected towns and highways, and elevation contours in 2000 ft intervals.

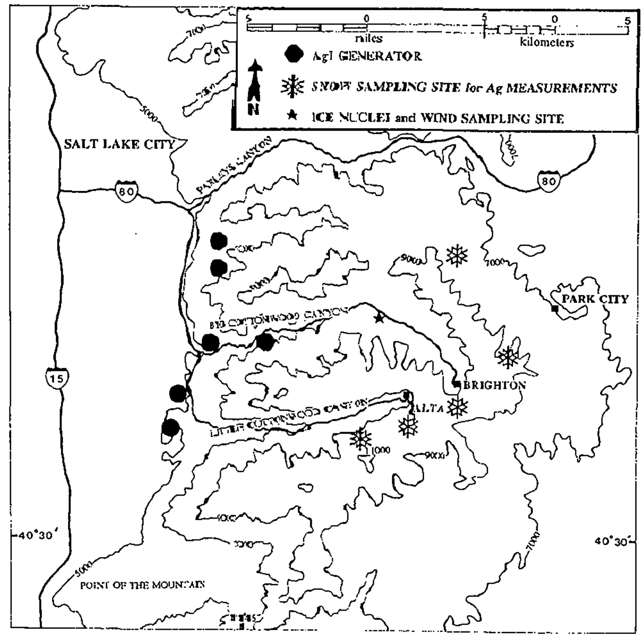

Fig. 2. Map of Wasatch Range experimental area showing silver iodide generator and snow sampling sites, selected towns and highways, and elevation contours in 2000 ft intervals.

droplets and accretion of those droplets by natural snowflakes could account for some or all of an increase in snow Ag content.

Failure to find increased Ag in the snow has generally been assumed to indicate that the AgI was not routinely transported over the sampling site while snow was falling on it (mistargeting occurred). An alternative explanation is that the amount of Ag released was too low to be detectable above natural background levels. As will be discussed, background Ag levels probably indicate that significant snowfall enhancement was not achieved by AgI seeding in Utah.

Analysis of precipitation for Ag content has been possible for over two decades. For example, Warburton and Young (1968a) describe neutron activation procedures for determination of Ag concentrations in precipitation samples. In a companion article, Warburton and Young (1968b) discuss the results of such analysis applied to precipitation samples. The neutron activation technique required about one liter samples of liquid water and had an Ag detection limit near 20×10^{-12} grams per milliliter (g ml^{-1}) of melted water. Snow samples from an unseeded portion of the Sierra Nevada contained less natural Ag than the detection limit.

Warburton (1969) also used atomic absorption spectrophotometry for analysis of Ag concentrations. He showed good agreement between this method and neutron activation. A heavily seeded snow sample, divided into two parts, yielded 11 and 13 parts per billion by the respective techniques.

More recently, flameless atomic absorption has been used to analyze Ag concentrations in snow. Again, results are similar to those obtained with neutron activation, but the atomic absorption technique is more sensitive and shows less variability for subsamples of the same sample (Rick Stone, personal communication). Moreover, atomic absorption requires significantly less precipitation volume for analysis.

Before examining the Utah sampling program and results, evidence will be reviewed from projects demonstrating successful targeting can enhance the Ag content of snowfall to well above background levels. In all cases discussed below, Ag contents were determined by the analyses methods of Warburton and colleagues at the Desert Research Institute (DRI).

Super and Heimbach (1983) reported on snowpit samples from 7 sites obtained from mid- to late March 1971 and 1972. These samples represented entire winter seasons in the Bridger Range Experiment (BRE) target area of Montana. A higher natural Ag background exists in melted Montana snow than found in California or Utah, amounting to approximately 10×10^{-12} g ml^{-1} (neutron activation sensitivity had improved somewhat since the Warburton and Young, 1968b paper). The higher background is presumably because the location is further inland and more wind-borne soil particles containing Ag are scavenged.

Snowpit samples from the two winters of the BRE ranged between about 30 and 100 X 10^{-12} g ml^{-1} as determined by the neutron activation method, well above background levels. The target area sampling sites were located 9-18 km downwind of the two high altitude AgI generators used during the BRE.

The flameless atomic absorption method was used to analyze seasonal snowpit samples from the 1986-87 operational seeding in the Bridger Range, intended to increase snowfall on a local ski area (Heimbach and Super, 1988). Background levels were again found to be near 10 X 10^{-12} g ml^{-1}. One of the samples came from a site in the earlier BRE target area (site 6 on Fig. 1 of Heimbach and Super, 1988), located about 10 km from the AgI generator. The sample's Ag content was 49 X 10^{-12} g ml^{-1}, in good agreement with the two seasonal values from that site during the BRE, which were 33 and 82 X 10^{-12} g ml^{-1}, respectively. While the BRE used 2 generators, each producing 30 grams of AgI per hour, seeding was conducted during about half the experimental days according to the randomized design. The 1986-87 operational program used one generator of the same type, located at the northern site used during the BRE, which was just upwind of the Bridger Bowl Ski Area. The generator was operated during all storms meeting appropriate wind, temperature and cloud criteria.

Six additional snowpit samples from March 6-12, 1987, were within the Bridger Bowl ski area target, only about 3-4 km downwind of the AgI generator. Ag contents (all X 10^{-12} g ml^{-1}) were 19, 40, 41, 69, 79 and 91. Ski area seasonal snowpit samples from the two winters of the BRE yielded 17 and 64. Thus, values produced by the two DRI techniques, applied to samples taken several years apart, are all in good agreement.

The Bridger Range snow samples clearly demonstrate that seeding can result in markedly enhanced Ag levels if proper targeting is routinely achieved. The two AgI generators used during the BRE were located well up the windward slope of the main ridge. Prevailing westerly flow during storms routinely transported the seeding material toward the next ridge to the east, which was the primary target. Direct evidence that AgI plumes were routinely transported toward and over the BRE target has been presented by Super (1974), Heimbach and Super (1988) and Super and Heimbach (1988).

Super and Heimbach (1983) compared the total silver-in-snow with Ag released during the BRE. About 70 percent of the total winter's Ag, emitted by both generators during periods with measurable target area snowfall, was accounted for in the March 1971 snowpack. The comparable figure for March 1972 was 40 percent. The comparable values for all hours of generator operation were 18 percent and 14 percent for the two winters. A large percentage of seeded hours had no measurable precipitation partially because generators were operated during darkness when it was not feasible to judge whether seedable conditions existed (e.g., whether cloud base was low enough).

Warburton et al. (1979) reported on over 700 snow samples from the Truckee-Tahoe target area in the Sierra Nevada, using flameless atomic absorption. Profile samples were taken each 3 cm in the vertical after each storm. Mean values from 9 sampling sites varied from background values (near 2 X 10^{-12} g ml^{-1}) to 10 X 10^{-12} g ml^{-1}. Peak values sometimes exceeded 70 X 10^{-12} g ml^{-1}, far above background. While this study also demonstrates that "seeding silver" is certainly detectable, it is discouraging that only 10 to 20 percent of all samples had enhanced Ag levels. Further, the "seeding silver" often appeared in narrow time and spatial zones, suggesting routine targeting was not accomplished. Several of the BRE snowpit samples, representing integrated values for the entire winter, were comparable to peak values from the Truckee-Tahoe catchment area. Seeding generator outputs and target area per generator were roughly comparable between the two projects, so one can only speculate why snow Ag contents differed so much. Direct tracking experiments have indicated routine transport of AgI over the BRE target during storms, but comparable observations are not available from the Truckee-Tahoe target.

Stone and Warburton (1989) reported "contamination" of the Truckee-Tahoe watershed by two other projects. Seeding aerosols from different projects were tagged with unique chemicals to track the location of each project's AgI. The results show that AgI transport often did not occur as intended.

Evidence that even high altitude releases of AgI frequently do not go where expected was presented by Reynolds et al. (1989) from observations in the central Sierra Nevada. A combined network of 24 ground-based generators from one experimental project and three operational projects was operated in a coordinated fashion for over two months. A total of 1,681 individual snow samples were collected in profiles divided into 2 cm vertical intervals at 14 sampling sites over the adjoining target areas. Seeding Ag was assumed to exist in snow samples with Ag concentrations greater than 4 X 10^{-12} g ml^{-1} (mean background + 2 standard deviations). Less than 15 percent of the samples indicated seeding Ag. A numerical targeting model, discussed by Rauber et al. (1988), was used to compute nucleation and fallout locations from each generator for each day. The model frequently predicted that AgI released from low elevation generators had trajectories parallel to the barrier; that is, not toward the high altitude targets. From the combined evidence, Reynolds et al. (1989) concluded, "These are disturbing results, even if one considers only scavenging, in that the AgI must not have passed over large regions of the target during precipitation events. Much of the AgI may be transported westward or northwestward at low levels, effectively not passing over the barrier."

Stone and Warburton (1989) showed that targeting was "substantially good" with westerly flow for the Lake Almanor Seeding Project in northern California, but "quite poor" during southerly flow. The percentage of 2-cm vertical snowfall increments that had Ag above 6 X 10^{-12} g

ml^{-1} with westerly flow was between 9 and 60 percent for the 8 sampling sites, with 5 sites above 20 percent. The corresponding range for southerly flow was 0 to 10 percent. Interestingly, the statistical analysis of Mooney and Lunn (1969) for the Lake Almanor Project suggested that seeding resulted in significant precipitation increases with cold westerly flow storms but not with cold southerly flow storms.

The Ag concentrations of 685 samples from the Lake Almanor project, each representing 2 cm depth of snow, were presented by Stone and Warburton (1985). Most obviously seeded samples were in the 10 to 50 X 10^{-12} g ml^{-1} range, but several samples exceeded 100 X 10^{-12} g ml^{-1}, and the highest was 400 X 10^{-12} g ml^{-1}.

Stone and Warburton (1985) also refer to mean ice crystal mass measurements from the Sierra Cooperative Pilot Project that were in the range of 0.002-0.02 mg per crystal. They point out that the average mass of an AgI ice nucleus is approximately 10^{-15} g. Therefore, for ice crystals of about 0.01 mg mass, an Ag concentration of 100 X 10^{-12} g ml^{-1} is equivalent to one AgI particle per ice crystal. Their calculations suggest that Ag concentrations well above background are required if seeding is to have any significant effect on snowfall, assuming that the masses of seeded crystals are similar to those of natural crystals. If anything, seeded crystals from ground generators should tend to have smaller masses because of shorter growth and fallout trajectories. If that is the case, snow caused exclusively by seeding should have even greater Ag concentrations than those in the above example.

Long (1984) reported on the results of applying the DRI flameless atomic absorption method to snow samples from the Tushar Mountains and Sevier Plateau of southern Utah. As typical of the Utah operational seeding program, most of the AgI generators were located at low elevation valley sites. Both AgI and indium oxide were routinely released and snow was analyzed for Ag and indium contents for 4 cm depth increments. Only 11 of 145 snow samples (7.6 percent) had Ag contents greater than background levels at the 5 percent significance level (established as 11.6 X 10^{-12} g ml^{-1} of liquified snow). Only 8 of 289 (2.8 percent) snow samples had indium concentrations which exceeded background at the 5 percent level; that is, fewer than expected by chance.

Long (1984) also reported on results of applying a numerical targeting scheme to seven storms during the same period, using local rawinsonde observations as input. Meteorological conditions were suitable for effective transport of the AgI over the Tushar Mountains only about 36 percent of the time. Downslope flow, entrapment in a stable layer or transport parallel to the mountains were predicted from the majority of soundings. These results, together with lack of enhanced Ag or indium in the snow samples, raised concern about the effectiveness of targeting on the Tushar Mountains and Sevier Plateau.

3. UTAH SAMPLING PROGRAM DURING THE 1989-90 WINTER

It was decided to conduct further silver-in-snow investigations in two different locations, one on the Wasatch Plateau of central Utah and the other in the Wasatch Range of northern Utah, east of Salt Lake City. Both barriers have long north-south extents that might minimize transport around the barrier. An all-weather highway crosses the Plateau, and the Range has several ski areas, allowing routine access to high elevation sites in both mountain areas.

Operational seeding program generators intended to target the Wasatch Plateau are located in a broad mountain valley between the Plateau and the San Pitch Mountains to the west (see Fig. 1). Most seeding generators for the Wasatch Range are located in or near canyon mouths, which provided an opportunity to examine a different mode of seeding. The six seeding generators believed most likely to affect the Wasatch Range region sampled for snow Ag content are shown on Fig. 2. Additional generators exist to the north and south that are not shown on Fig. 2.

Ten sampling sites were established for periodic snow sampling, five in various ski areas in the Wasatch Mountains east of Salt Lake City, and five on the Wasatch Plateau about 70 miles further south. Table 1 contains the latitude, longitude and elevation of each site and the number of samples obtained from each sampling location. Figures 1 and 2 show the snow sample sites.

Snowboards were positioned at relatively protected sites and visited periodically. The field technician lived in Big Cottonwood Canyon in the Wasatch Range and thus was able to monitor the local weather. She sampled snowboards on the Range shortly after each storm or series of storms so sampling intervals ranged from a few to several days. The technician visited the more distant Wasatch Plateau at approximately 2-week intervals, accounting for the fewer samples shown in Table 1.

The entire depth of snow on each board was combined into one sample for each visit. It might have been desirable to sample vertical increments as done in some of the studies noted above. However, the approach used cost much less, and was expected to provide evidence of enhanced Ag provided AgI plumes frequently passed over the sampling sites during snowfall periods.

All presumably unseeded snow samples were examined to check the natural background levels of Ag. Thirteen samples existed from snowboards not initially exposed until at least 12 hours had elapsed after all seeding was terminated (11 samples were first exposed more than 30 hours after seeding termination), and seeding was not restarted until after these samples were collected. All 13 samples came from the Wasatch Range as no Plateau samples met the unseeded criteria. The distribution of Ag contents from these samples appears on Fig. 3.

Table 1. Locations of snow sampling sites during the 1989-90 winter

Location	Longitude (Deg-Min)	Latitude (Deg-Min)	Elevation (Feet-MSL)	No. of samples
(Wasatch Range - all in ski areas)				
Alta	111-37.0	40-34.5	9600	14
Brighton	111-34.5	40-35.5	9500	16
Park City	111-32.0	40-37.5	9400	12
Park West	111-35.0	40-41.0	8100	12
Snowbird	111-39.5	40-34.0	9100	13
(Wasatch Plateau)				
Cleveland Reserv.	111-14.5	39-35.5	8900	5
Engineer Canyon	111-10.5	39-33.5	8200	6
Huntington Campgnd.	111-09.5	39-30.0	7600	2
7.4 mile Site	111-20.0	39-40.5	8500	6
Skyline Drive	111-17.5	39.37.0	9700	6

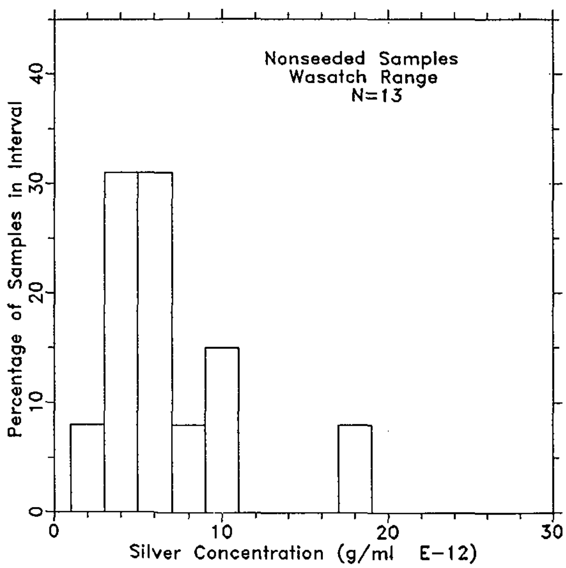

Fig. 3. Frequency distribution of silver concentration for 13 nonseeded snow samples from the Wasatch Range.

All but one sample in Fig. 3 (1/13=8 percent) had concentrations less than 11 X 10^{-12} g ml^{-1}. This concentration is similar to the distribution shown by Long (1984) for 1982 nonseeded samples from the Tushar Mountains, except that the peak of Long's distribution was about 1.5 X 10^{-12} and Fig. 3 peaks near 5 X 10^{-12} g ml^{-1}. Long also presented a small percentage of outlying values greater than 15 X 10^{-12} g ml^{-1}. From both the data of Fig. 3 and the data presented by Long, presumably natural snowfall in Utah often has Ag contents up to about 10 X 10^{-12} g ml^{-1}, and occasionally has values two to three times that high. Residual Ag from earlier seeding might have contaminated some of the "natural" snowfall samples, but no direct evidence exists to support that speculation.

The distribution of all 54 samples from the Wasatch Range which had seeding conducted during the snowboard exposure periods appears on Fig. 4. Only 8 samples (15 percent) exceeded 11 X 10^{-12} g ml^{-1}, just 7 percent more than for the nonseeded population of Fig. 3. The 4 samples (7 percent) exceeding 15 X 10^{-12} g ml^{-1} were examined in terms of location, snowfall amounts and duration of AgI generator operation. No obvious similarities were found except that 2 of the samples came from the same site (Park City) and all 4 represented significant snowfall amounts.

An attempt was made to select "well-seeded" samples from the Wasatch Range. A detailed graph was constructed (not shown) which showed the time history for the entire December through March period. It indicated when each seeding generator was operated, when each snowboard was exposed and sampled, and 12 hour precipitation totals from Alta. Well-seeded snow samples were subjectively chosen with the aid of this graph whenever a large fraction of Alta's snowfall, during the period of snowboard exposure, fell during a seeded period(s). A total of 22 snow samples were selected as well-seeded and the distribution of their Ag concentrations appears on Fig. 5. The highest value observed was 12 X 10^{-12} g ml^{-1}. Neither Fig. 4 nor 5 offers much evidence that the AgI intended to target the Wasatch Range is routinely transported over the Range during snowfall events, except possibly in low concentrations.

Finally, the 25 samples from the Wasatch Plateau were examined as illustrated on Fig. 6. Forty-four percent of all samples had less than 3 X 10^{-12} g ml^{-1} as compared with only 8 percent of the nonseeded samples from the Wasatch Range. Only 3 samples (12 percent) exceeded 7 X 10^{-12} g ml^{-1}. These observations suggest (1) natural snowfall has less Ag on the Plateau as compared with the Range, possibly because of less local contamination, and

(2) the seeding material released west of the Plateau has little impact on the Ag content of the snowfall on the Plateau.

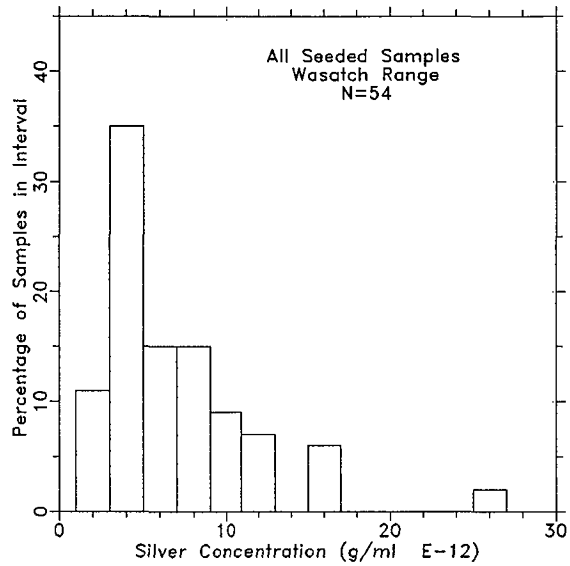

Fig. 4. Frequency distribution of silver concentration for 54 seeded snow samples from the Wasatch Range.

The findings from the silver-in-snow analysis from the Wasatch Range and Wasatch Plateau for the 1989-90 winter are in good agreement with the earlier findings reported by Long (1984) for the Tushar Mountains and Sevier Plateau. There is little evidence of the seeding material in the mountain precipitation in any of the areas. One might choose to ignore the highest nonseeded sample in Fig. 3 as an "outlier" (although there is no known reason to do so and the field technician's thorough notes do not suggest possible contamination or any other problems). Then one might conclude that some of the samples in Figs. 4 and 6 had Ag concentrations noticeably above background, but the number would still be limited.

4. POSSIBLE REASONS FOR LOW AG CONCENTRATIONS

Two possibilities come to mind in attempting to explain the low Ag levels found in the Utah target areas. Either the AgI was seldom transported over the targets during cloud and precipitation periods, or it was transported over the targets but the AgI amounts deposited on the surface were too low for detection above the natural background levels of silver-in-snow.

It has been shown that some mountain target areas, using higher AgI release rates than Utah, exhibited substantially higher Ag levels during some seeding events. But one could argue that lower AgI concentrations than used in those seeding projects will significantly affect the snowfall. We will now examine that possibility as well as some differences in AgI release methods.

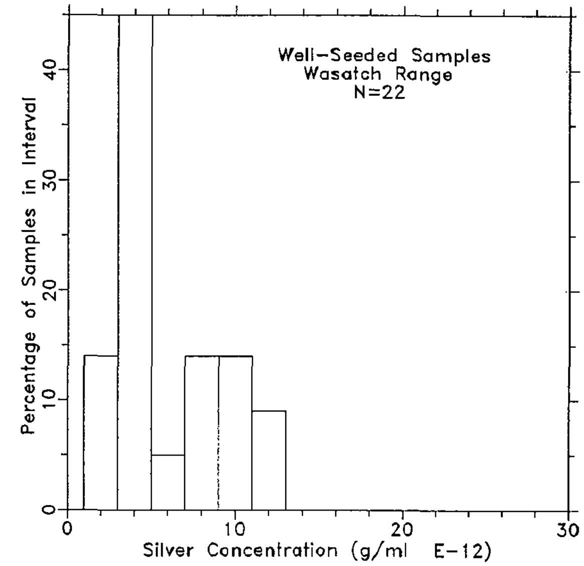

Fig. 5. Frequency distribution of silver concentration for 22 presumably "well-seeded" snow samples from the Wasatch Range.

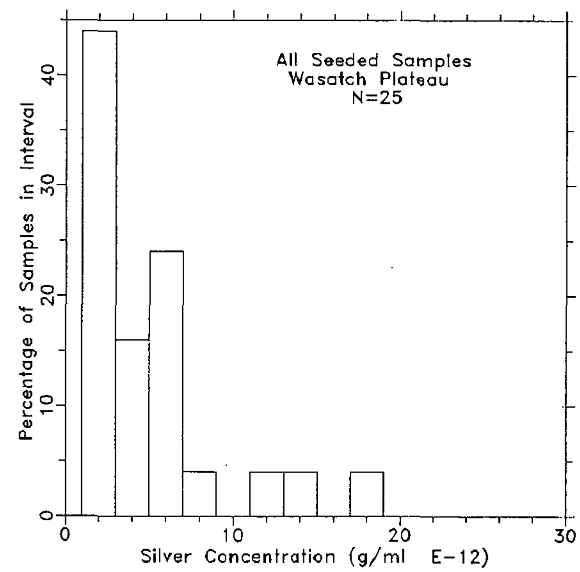

Fig. 6. Frequency distribution of silver concentration for 25 seeded snow samples from the Wasatch Plateau.

The highest silver-in-snow levels reviewed were from the BRE in Montana (Super and Heimbach, 1983), the later Bridger Range snowpack augmentation program (Heimbach and Super, 1988), and the Lake Almanor Project (Stone and Warburton, 1985). The earlier Bridger program used 2 AgI generators, each with 30 g h^{-1} output, at high altitude locations 4 miles crosswind of each other. The BRE appeared to affect an area in excess of 100 mi^2. The latter Bridger project used the same type of generator at one of the original BRE sites to target a small ski area, although Ag was found downwind as well. The Lake Almanor Project used 7 high altitude generators west and south of the 500 mi^2 watershed. Generator output was 25 g h^{-1}, and 3-4 generators were used at a time, depending upon wind direction. Spacing between generators was 5-8 miles. Both the Lake Almanor and Bridger projects used generators on upwind ridges to target high terrain further downwind.

Table 2 compares some of the differences in seeding approach between the BRE during the winters of 1970-71 and 1971-72 and the Utah operational program during the winter of 1989-90.

Three major differences in seeding exist between the BRE and the Utah programs. First, the BRE generators were located well up the windward slope of a relatively uniform north-south barrier, only about 1300 ft below the mean crestline elevation. The Wasatch Plateau is also a relative uniform north-south barrier, but generators were located at widely separated valley locations (see Fig. 1). The Wasatch Range had 2 generators near the mouths of each of 3 major canyons as shown on Fig. 2. Second, the BRE used generators with 5 times the hourly AgI output of the Utah generators. Third, the BRE generators operated about four times as many hours per month on average (even though the BRE was randomized).

Spacing between generators was roughly similar. The BRE generators were spaced between the average distances for the Wasatch Range and the Wasatch Plateau. The Plateau generator spacing is more typical of the entire Utah seeding generator network than is the Wasatch Range spacing.

The average monthly AgI output per generator during the BRE was approximately 20 times higher than that in the two Utah areas. Ignoring all other factors such as transport and dispersion, these differences alone could result in the much lower Ag observed in Utah snow samples <u>on average</u>. The BRE seasonal snowpack samples were in the range 30-100 X 10^{-12} g ml^{-1}. Reducing those values by a factor of 20 would bring them into general agreement with the observations shown on Figs. 4, 5 and 6. The Ag in Utah might often be undetectable because Ag concentrations deposited during seeding operations were similar to or below natural background levels.

The above comparisons deal with long-term average conditions. Only seasonal integrated values were analyzed during the BRE, and again during the operational program for the Bridger Bowl Ski Area (Heimbach and Super, 1988). Moreover, the BRE was randomized, with only about half the storm days seeded. However, the Utah samples were taken at much shorter intervals, ranging from a few to several days in the Wasatch Range and about bi-weekly in the Wasatch Plateau. The Range samples corresponded to periods ranging from a single storm up to a few storms passing in a series. Accordingly, one might expect some of the Utah snow samples to exhibit Ag levels well above average conditions, especially if seeding was conducted during a period with abundant supercooled liquid water (SLW) when both nucleation by AgI and scavenging could bring Ag to the surface. But, as discussed earlier, only a limited number of samples showed any suggestion of above-background Ag concentrations. This low concentration raises concern about whether routine targeting is being achieved in the Utah operational program.

Physical evidence from 20 separate aircraft passes through AgI plumes over the Bridger Range indicated that, on average, about 10-20 ice crystals per liter were created over the target when temperatures were about -10°C, with typical liquid water contents near 0.1 g m^{-3} (see Table 2 of Super and Heimbach, 1988). The Bridger Range generator produced 30 g h^{-1} AgI, five times the rate used in Utah, and the natural draft effectiveness at -10°C was 6 X 10^{13} ice crystals per gram of AgI (Super and Heimbach, 1983), almost seven times higher than that of the Utah generators (see Table 3). Nevertheless, seeded precipitation rates at aircraft levels over the Bridger Range were estimated at only 0.03 to 0.09 mm h^{-1}. Even though additional growth likely occurred between the aircraft and ground, it is difficult to imagine that significant snowfall rates could be achieved with much lower ice particle concentrations. The statistical analysis presented by Super and Heimbach (1983) suggested no noticeable seeding effects when ridge-top temperatures were warmer than -9°C, presumably because AgI activation was too limited.

Table 2. Comparison of AgI generators and siting between the Bridger Range Experiment and the Utah operational seeding program

	BRE	Utah
Generator sites	High altitude, about 1300 ft below crestline	Mostly valley sites, some near canyon mouths
Approx. north-south spacing between generators (miles)	4.0	Wasatch Range: 2.2 Wasatch Plateau: 6.7
Mean hours of AgI generator operation per month	1970-71: 190 1971-72: 210	Wasatch Range: 52 Wasatch Plateau: 47
Generator AgI output	30 g h^{-1}	6 g h^{-1}

Reynolds (1988) reviewed several direct observations of seeding effects on precipitation rate. None exceeded 1.0 mm h^{-1} and most were less than 0.5 mm h^{-1}, even though a number of the experiments incorporated direct injection of seeding agents. Reynolds (1988) cites typical values of 10 to 25 ice particles per liter due to seeding. Hobbs (1975), in his discussion of winter clouds over the Cascade Mountains, noted that, "However, for seeding to have a significant effect in these regions the concentrations of artificial ice nuclei must clearly reach values of the order of 10 $liter^{-1}$ and probably much higher". It seems unlikely that the Utah ground releases of AgI can routinely result in ice particle concentrations approaching the values suggested by Hobbs or observed by Super and Heimbach (1988) or Reynolds (1988).

5. CONSIDERATION OF MAXIMUM ACHIEVABLE SNOWFALL AMOUNTS WITH UTAH SEEDING

It is interesting to consider whether the snowfall increases suggested by statistical analyses of the Utah operational program are physically reasonable in view of the low seeding rates. This analysis will involve, first, estimation of the amount of additional water produced if the suggested increases are correct; second, estimation of the amount of effective ice nuclei released; and, third, consideration of the mean masses of ice particles required to produce that much water with that many ice nuclei. Are the resulting ice particle masses within reason? Estimates will be based on mean monthly values for convenience.

In estimating the number of available ice nuclei, several unrealistically favorable assumptions for snowfall enhancement will be made. The approach to this estimate will consider what might occur under optimum conditions; that is, set an optimistic upper limit. An estimate of available ice nuclei that is too low to produce ice particles of reasonable mass indicates a serious problem for more realistic assumptions.

Griffith et al. (1991) presented a post hoc statistical analysis suggesting a mean seasonal increase of 11.4 percent for the operational seeding program in central and southern Utah over 13 seeded winters. An earlier analysis by Thompson and Griffith (1981) suggested increases of 13-20 percent. The suggested 11.4 percent increase corresponded to an average precipitation enhancement of 1.23 inches at target area gauges for the December-March period, or 0.31 inches per month. This enhancement is likely an underestimate because precipitation gauges undercatch snowfall significantly in even light winds. Equivalent 11.4 percent increases in the Wasatch Range would provide greater monthly precipitation amounts at high elevation snowcourses. For example, the April 1 normal snow water equivalent is 39.4 inches at Alta (8800 ft - all elevations are above mean sea level (MSL) unless otherwise noted) and 30.6 inches at Brighton (8750 ft). Assuming snowpack accumulation begins near mid-November, 11.4 percent increases would produce mean monthly values of 1.0 and 0.8 inches, respectively.

Similar calculations for the average of four high elevation snowcourses (8700 to 10,000 ft) on the Wasatch Plateau, near the silver-in-snow sampling sites, yields a mean monthly figure of 0.6 inches. It appears reasonable to assume that an 11.4 percent increase in snowfall would represent at least 0.5 inches (1.3 cm) during an average month on the Wasatch Range of northern Utah and 0.4 inches (1.0 cm) on the Wasatch Plateau of central Utah.

The intended targets for the generators shown in Figs. 1 and 2 are approximately the areas east of the generators above about 7000 feet. The six generators of the Wasatch Range have a target area of about 450 km^2. The six generators west of the Wasatch Plateau have a target area of approximately 2,100 km^2. Mean monthly precipitation increases due to seeding, using the 1.3 and 1.0 cm estimates, would be 6 and 21 X 10^{12} cm^3 (or grams) for the respective target areas.

We will now estimate the mean monthly production of effective ice nuclei, using 50 hours of operation per generator per month (Table 2). Table 3 shows effectiveness values from the Colorado State University (CSU) Cloud Simulation Laboratory for the North American Weather Consultants (NAWC) AgI generator used in Utah (Griffith et al. 1991 plot the same data in their Fig. 3). Data for "natural draft" is equivalent to a light wind of about 2-3 m s^{-1} by the generator (Paul DeMott, personal communication), while "maximum fan" provides about 10 m s^{-1} wind past the burner head, greatly reducing coagulation losses.

Data from the early 1991 field program on the Wasatch Plateau (yet to be reported) suggests that the upwind valley typically experiences light and variable winds during snowfall periods on the Plateau. One storm did produce strong valley winds that caused problems with generator operation. The canyon mouth generators west of the Wasatch Range are generally located in protected locations and also should experience strong winds only occasionally. Accordingly, effectiveness values nearer natural draft than maximum fan are appropriate for most storm periods. Effectiveness values increase markedly as cloud temperature decreases as shown in Table 3.

The typical temperature range of the SLW zone over Utah barriers will be estimated to consider appropriate generator effectiveness values. Most SLW has been found in the lowest kilometer above barrier crests in a number of studies in the West. In Utah, Hill (1986) showed that SLW had a median height between 500 and 1000 m above the crest of the northern Wasatch Mountains. Sassen (1985) indicated the liquid cloud base was usually from 1 km above to 1 km below the crest of the Tushar Mountains. Cloud base temperatures were usually between 0 to -5°C when vertically-integrated SLW amounts exceeded 0.05 mm according to microwave radiometer observations. Similar results were obtained on top the Wasatch Plateau during the first half of March 1991. Surface temperatures ranged between +2 and -5°C when SLW was present during passage of several storms. Temperatures 1 km above the barrier would be about 6°C colder, or from -4 to -11°C.

Table 3. Effectiveness values for NAWC AgI generators (ice crystals per gram of AgI) reported by the CSU Cloud Simulation Lab - April 1982.

Chamber Temp. (°C)	Natural Draft	Maximum Fan
-6	2×10^{10}	N.A.
-8	1×10^{12}	9×10^{12}
-10	9×10^{12}	9×10^{12}*
-12	4×10^{13}	4×10^{14}
-16	5×10^{14}	3×10^{15}
-20	1×10^{15}	1×10^{16}

* this reported value appears to be an order of magnitude low

Even if SLW existed at higher elevations, plume tracing investigations have shown ground-released AgI plumes generally are not transported higher than 1 km above barrier crests in the absence of convection (Holroyd et al. 1988; Super and Heimbach, 1988; Super et al. 1989). Admittedly, these plume tracking studies all used high altitude releases. Valley releases might be transported higher under some conditions, in locations providing greater time and distance for vertical dispersion. However, observations were made over the Wasatch Plateau in March 1991, with embedded convection present which should enhance vertical mixing. These measurements, yet to be reported, suggested that the bulk of valley-released seeding material was still within 1 km of the Plateau top.

Huggins (1990) discussed sounding temperatures at 3.6 km MSL when liquid water cloud existed over the Tushar Mountains. The temperature at that altitude was considered representative of the bulk of cloud liquid water over the barrier. The larger liquid values (above 0.1 mm) predominantly occurred at temperatures warmer than -10°C. Thirty-seven percent of these cases occurred at temperatures warmer than -5°C, which is too warm for significant nucleation with AgI.

The cited measurements indicate that SLW will usually be found in the range 0 to -10°C. The values in Table 3 make it highly optimistic to assume that, on average, 5×10^{13} ice nuclei per gram of AgI would be produced by the Utah seeding generators, effective at SLW cloud temperatures. That optimistic assumption will be made for the sake of discussion. Six generators per target area, each operated for 50 hours, would produce a total of 9×10^{16} ice nuclei in an average month.

We will make the additional optimistic assumptions that every ice nucleus produced by the generators having the potential to create an ice crystal does so, and that each resulting ice particle passes through a favorable growth environment and eventually falls to the surface of the target area. These assumptions imply:

1. the seeding material is always transported over the target,
2. always encounters SLW,
3. the SLW is always cold enough for significant ice nucleation (-10 to -12°C for the generator effectiveness value used, depending on the windspeed),
4. each of the resulting 9×10^{16} ice crystals always falls to the surface within the target (no "blowover" and sublimation to the lee of the barrier).

We can examine the above assumptions with the available data by considering the average silver-in-snow concentrations that would have to result. Average monthly precipitation increases, if seeding enhanced the snowfall by 11.4 percent on the Wasatch Range and Wasatch Plateau target areas, were estimated as 6 and 21×10^{12} g, respectively. Equivalent total precipitation values per month (seeded + natural snow) are 6 and 20×10^{13} g (or ml of water). Six generators per target, each operated for 50 hours per month at a rate of 6 g AgI h^{-1}, produce a total of 1800 g of AgI. The Ag portion of approximately 826 g per month, if uniformly distributed throughout each target area's average monthly snowfall, would be equivalent to 14 and 4×10^{-12} g ml^{-1} for the Range and Plateau, respectively. Only 4 of 54 seeded samples in the Wasatch Range exceeded the expected average value of 14×10^{-12} g ml^{-1}, while 12 of 26 Wasatch Plateau samples exceeded the expected average of 4×10^{-12} g ml^{-1}.

These calculations suggest that the amount of Ag released west of the Wasatch Plateau might be difficult to detect above background levels, even if all the Ag was deposited on the target. Some snow samples might be well above the estimated average depending upon variations in targeting, airflow patterns, snowfall rates, etc.; however, the resulting Ag distribution might be similar to that shown on Fig. 6.

Approximately the same amount of Ag was released west of the much smaller Wasatch Range target area. In this case, the estimated average Ag concentration was well above that shown on Fig. 4, as only 7 percent of the seeded snow samples exceeded 14 X 10^{-12} g ml^{-1}. Unless all 5 sampling sites were somehow unrepresentative of the overall target area, much of the AgI released west of the Wasatch Range must have been transported and deposited in areas other than the target. Thus, the assumption that all AgI ended up in the target's snowfall is very questionable for the Range on the basis of the silver-in-snow data. However, we will make that assumption for the sake of discussion.

We estimated earlier that 11.4 percent snowfall enhancement was equivalent to roughly 6 and 21 X 10^{12} g of water per month over the Wasatch Range and Wasatch Plateau targets, respectively. Dividing those amounts of water uniformly amongst the 9 X 10^{16} ice nuclei estimated using the optimistic assumptions stated above, the average mass of crystals settling onto each target would be 0.07 and 0.23 mg, respectively.

We will now consider the masses of individual ice crystals observed in or below winter orographic clouds. Redder and Fukuta (1989) presented empirical growth equations from several published sources. Few individual crystals exceeded 0.01 mg after 1000 seconds growth time (equivalent to 10 km horizontal travel at 10 m s^{-1}). Stone and Warburton (1985) refer to crystal masses between 0.002-0.02 mg in the Sierra Nevada. Mitchell et al. (1990) carefully examined masses, dimensions and habits of over 2800 ice particles precipitating in the Sierra Nevada. The masses of individual crystals were usually between 0.001 and 0.1 mg. Crystals rarely exceeded 0.1 mg, even when rimed, except for heavily rimed dendritic crystals (the largest sampled was about 0.7 mg). Fukuta et al. (1988) presented average particle mass data from 3 sampling sites in the Tushar Mountains of Utah during 3 storms. All crystal types observed, both rimed and unrimed, were considered. The large majority of ice particles had average masses between 0.01-0.1 mg, with distributions heavily skewed to the smaller masses. Average masses greater than 0.2 mg were infrequently observed. The comprehensive study by Locatelli and Hobbs (1974) measured the masses of many rimed and unrimed particles falling on the Cascade Mountains of Washington during winter. Masses for several types of densely rimed precipitation particles generally ranged from 0.01 to 0.6 mg. Even graupel (snow pellets) and graupel-like snow particles seldom exceeded 1 mg mass and median values were typically 0.2 mg.

These many observations show that the average crystal masses calculated above (0.07 and 0.23 mg) would be substantially greater than measured masses of most ice crystals falling on western mountains in winter. In fact, the calculated masses are high into the range of crystal masses for heavily rimed particles or mid-range for graupel. These masses suggest that to even approach a 11.4 percent snowfall enhancement in an average month, we would have to make yet another unrealistic assumption: each ice nucleus resulted in a heavily rimed particle or graupel.

The snowfall increases suggested by the statistical analysis of Griffith et al. (1991), and that of Thompson and Griffith (1981) which suggested even larger increases, do not agree with the physical realities of available ice nucleus production according to current understanding. Even using favorable assumptions, noted above as unrealistic, each ice nucleus would have to result in a massive ice particle. In reality, the seeding material will not always be transported over the target, and when it is, the AgI will not always encounter SLW. When SLW is present, it frequently will be too warm for effective nucleation, especially in lower portions of the liquid cloud. Even when the AgI reaches sufficiently cold SLW cloud, it is unlikely that each potential ice nucleus will create an ice crystal. Some ice crystals created by seeding will not grow large enough to reach the surface before sublimating to the lee of the barrier. These realities all argue for significantly fewer available ice nuclei than estimated.

When considering whether factors other than those discussed could invalidate the above calculations, at least two possibilities come to mind:

1) The ice nucleus effectiveness values may be incorrect. Typical winter orographic clouds have lower liquid water contents and less homogeneity than found in the CSU Simulation Laboratory. Natural clouds likely have more turbulence. We do not know the net result of these and other differences. Field observations reported by Deshler and Reynolds (1990) suggest somewhat greater effectiveness at -10°C than indicated by the CSU Laboratory, but DeMott (1991) questioned their interpretation. At any rate, ice nucleus effectiveness in natural clouds would have to be substantially greater than that found in laboratory results to invalidate the above discussion.

2) Ice crystal multiplication may result in seeded crystals creating additional crystals without further intervention from AgI. Fragmentation of delicate ice crystals can produce additional particles, but Hobbs and Rangno (1985) note that fragments increase the ice particle concentrations by only a factor of about 5 in stratiform clouds. Ice splinter production during heavy crystal riming has been demonstrated in the laboratory when supercooled droplets greater than about 23 μm diameter are present in significant concentrations at temperatures between -3 and -8°C (Hallett and Mossop, 1974). Ice needles are common at these temperatures. Later work indicated droplets smaller than 13 μm had to be present in concentrations exceeding 100 cm^{-3} for this ice multiplication mechanism to be effective (Mossop, 1978). It is suspected that all these conditions exist infrequently in Utah winter clouds, although observations are limited. The surface microphysical measurements reported by Fukuta et al. (1988) suggest that multiplication sometimes occurs. For example, the storm of February 13, 1987, had rimed needle showers. Graupel and other evidence of heavy crystal riming are common during portions of some Utah winter storms, but are often absent during other periods. Thus, while ice multiplication occurs in Utah, it is not believed to be a major factor in snowfall production; however, further investigation is warranted.

In light of current physical understanding, it appears unlikely that the seeding rates used in the Utah operational program can produce snowfall enhancements on the order of 10 percent, even if the valley-released AgI were routinely transported into SLW cloud regions. The transport of AgI is examined in the next section, and in the companion paper by Super and Huggins (1992).

6. ICE NUCLEUS SAMPLING IN BIG COTTONWOOD CANYON

Most seeding generators in the Utah operational seeding program have been located in valleys as shown on Fig. 1. A limited number of generators have been placed in or near canyon mouths, primarily for the Wasatch Range, as shown on Fig. 2. Big Cottonwood Canyon is atypical in that one AgI generator is located near the mouth of the Canyon at 5000 ft elevation, while a second generator is located 2.5 miles further up the canyon at an elevation of 5810 ft. Only a few other canyons in Utah have generators located that far above their entrances.

The field technician who collected snow samples for Ag analysis lived well up Big Cottonwood Canyon. The location of her home, at 7330 ft elevation, is shown on Fig. 2. It was decided to take advantage of the opportunity and have the technician operate an acoustical counter (Langer, 1973) to measure ice nuclei (IN). The collection of IN observations in the Canyon was analogous to the collection of snow samples for Ag analysis. Finding enhanced Ag amounts in the snow does not prove that seeding modified the snowfall. However, failure to find enhanced Ag raises the strong possibility of mistargeting. In like manner, detection of enhanced IN at the particular Canyon site does not prove the AgI was transported miles further downwind, and thousands of feet higher, into the SLW cloud above the windward slope and crest of the Wasatch Range. However, failure to find AgI at the sampling site well up the canyon would raise doubts about the efficacy of canyon seeding.

The NAWC forecaster phoned the technician whenever operational seeding was about to be conducted in the Canyon. The technician would then operate the acoustical counter, obtaining continuous measurements of IN throughout several seeded storms during the 1989-90 winter. In addition, she also operated the counter during several nonseeded days to monitor background IN concentrations. Five-minute mean IN concentrations during the nonseeded periods, measured at a cloud chamber temperature near -20°C, were consistently between 0-4 per liter, and were usually below 2 per liter. As will be shown, seeded periods had IN levels far in excess of background (natural) levels.

The technician visited the counter periodically during each storm and made notes on various gauge readings and any problems. Some problems encountered during the course of the winter included pump and microphone failures, and exceedingly high false count rates due to glycol or contaminating frost buildup in the sensor (the system was located in an unheated garage and space heaters could not always prevent frost). In spite of these problems, most periods had good quality data as attested to by the technician's careful notes regarding equipment checkout and testing. The data discussed came from such periods. Ice nucleus measurements were made for portions of, or throughout, 34 separate days between December 21, 1989, and March 29, 1990.

An automatic weather station at the technician's home provided 10 minute mean observations of air temperature and windspeed and direction. Forest cover near her home prevented wind measurement in an open site. Consequently, the commonly measured light and variable winds may not represent winds well above the canyon floor.

A typical time history during a seeding period appears on Fig. 7. Both Canyon AgI generators were started between 1000-1015. The upper generator was turned off at 2000 but the lower unit ran till 2330. Data are shown till 2800 (actually 0400 on February 2). Data collection from the acoustical counter did not begin until shortly after 1100. About 1145 (1.5 h after generator startup), the IN concentration began to rise from background levels and stayed above 50 l^{-1} most of the time till after generator turnoff. During the 3 periods noted by "filter," the acoustical counter had a filter that was capable of extracting almost all AgI particles hooked to the intake line for 20-40 minutes. The filter served to test that the system was actually measuring IN and not experiencing spurious counts caused by the instrument itself, and that the system did not have serious leaks (the count rate would not approach zero if unfiltered outside air was entering the cloud chamber). The temporal variability of IN concentration shown on Fig. 7 was characteristic of other seeded periods.

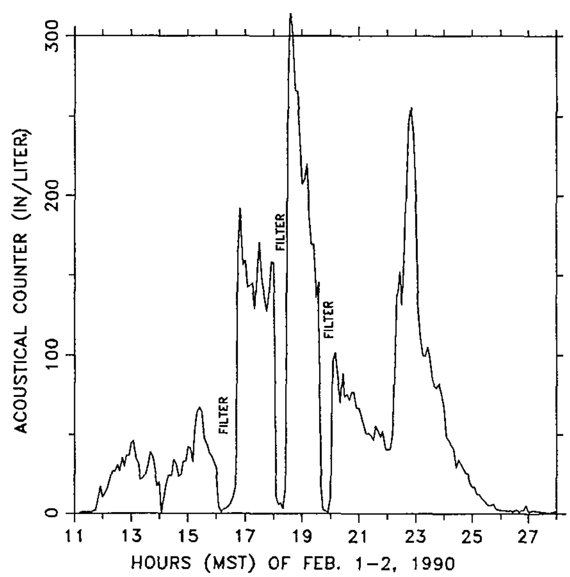

Fig. 7. Time history of ice nuclei per liter as measured by an acoustical counter at -20°C at the 7330 ft sampling site in Big Cottonwood Canyon on February 1-2, 1990.

Table 4 summarizes the dates of AgI generator operation in Big Cottonwood Canyon and associated acoustical counter measurements. All IN per liter are actually measured counts per minute (5 minute means) multiplied by 10 to compensate for known chamber losses (Langer, 1973). The acoustical counter sample rate was near 10 liters per minute. Measurements by an acoustical ice nucleus counter are considered semi-quantitative (as are most IN observational methods). The cloud in the refrigerated chamber was deliberately much more dense than natural clouds to hasten contact nucleation in the minute or two that sample air was in the chamber. In spite of this and other differences from natural clouds, a properly operated acoustical counter has shown good agreement with a cloud simulation chamber for the type of AgI used in Utah (Langer and Garvey, 1980).

The mean AgI concentration listed in Table 4 is only an approximate "eyeball average" of daily plots of IN vs time. The means apply only to periods when AgI was well above background most of the time. The beginning or ending portions of some periods of seeding generator operation, when AgI concentrations were only a few times background, were ignored in averaging.

One noteworthy finding from Table 4 is that AgI was detected each day that the generators were operated 6.9 and 9.6 miles (road distance) down-canyon from the IN sampling site, respectively. Mean IN concentrations ranged between 50-250 per liter with a typical value of 125 per liter, effective at -20°C. Maximum values of about 800 per liter were achieved on 3 different days. According to the AgI generator calibration given in Table 3, corresponding average values at -10°C would be about two orders of magnitude less or 1 IN per liter (8 per liter for maximum values). As discussed in Sec. 5, the SLW zone over Utah's mountain barriers often exists at temperatures between 0 to -10°C. Thus, even the 1 IN per liter estimate is optimistic for most winter storms. These low IN concentrations, found in the canyon bottom 5 miles down-canyon of the barrier crest, do not suggest that seeding will create significant ice crystal concentrations in the SLW-cloud at higher elevations.

It is encouraging that a mechanism exists to transport seeding material well up into the Canyon on a routine basis. Canyon seeding might be effective using higher AgI release rates and AgI types with better warm temperature effectiveness. It is discouraging that the 14 snow samples from the Brighton site, exposed during seeding in Big Cottonwood Canyon, had an average Ag concentration less than 6×10^{-12} g ml^{-1}. The highest and second highest values observed were 17 and 9×10^{-12} g ml^{-1}. The Brighton site values are typical of the distribution shown in Fig. 4. Since this site was only 800 ft above the town of Brighton at the head of the Canyon (Fig. 2), high Ag levels might frequently be expected there, but high Ag concentrations were not found.

7. SPECIAL EXPERIMENT OF MARCH 12, 1990

A special experiment was conducted on March 12 using a NAWC van equipped with a fast-response sulfur hexafluoride (SF_6) detector. The van was driven up Big Cottonwood Canyon while AgI and SF_6 were released from the lower (5000 ft) site near the Canyon mouth. Surface winds at the release site, estimated by the field technician every 15 minutes, were westerly at about 5 mph during the SF_6 release period. The AgI generator was started at 1330 and the tracer gas was released at 80 lbs h^{-1} beginning at 1430. The release rate of tracer gas rapidly decreased after 1535 as the tanks emptied and went to zero before 1600. The AgI generator was shut down at 1615.

The van entered the Canyon at 1430 and proceeded to the acoustical counter sampling site at 7330 ft elevation, 9.6 miles by road from the release site. Snowfall was

Table 4. Summary of AgI generator operations and associated acoustical counter IN measurements in Big Cottonwood Canyon: Dec. 21, 1989 - Mar. 29, 1990.

Date of AgI Gen. Operation	mean IN per liter	maximum IN per liter
Jan. 02	125	250
Jan. 08	100	260
Jan. 13	70	125
Jan. 14	180	800
Jan. 26	50	120
Jan. 29	75	225
Jan. 31	250	800
Feb. 01	100	300
Feb. 07	200	800
Feb. 17	75	275
Mar. 05	175	550
Mar. 11	175	550
Mar. 28	100	325

reaching the surface 2.5 miles into the canyon, and was moderate while the tracer gas detector was operated near the acoustical counter from 1503-1640. Clean air was injected into the gas detector at 5-minute intervals to monitor the baseline.

The first detectable gas was observed at 1533, 63 minutes after release began. The concentration increased, stabilized at about 1600, and remained stable until the van left the site 40 minutes later. The mean value was 350 ppt from 1600-1640. The acoustical counter first detected IN above background about 1445, some 75 minutes after the AgI generator was started. The 63-75 minute times between start of release and first detection of SF_6 and AgI, respectively, indicates a mean transport speed of 8 mph up the Canyon. Mean speed measured at the protected IN and wind monitoring site was 4 mph from 1330-1530 with a steady upcanyon direction.

The SF_6 detector on the van was of the type described by Benner and Lamb (1985). It can be shown that 350 ppt (by volume) of the tracer gas has a density of 1.8×10^{-9} g l^{-1} at the sampling site temperature of -5°C and pressure of 794 mb. The source strengths of the tracer gas and AgI were 10 g s^{-1} and 1.7×10^{-3} g s^{-1}, respectively. The mass of AgI per unit volume (density) equivalent to 350 ppt SF_6 is given by:

$$\text{AgI density} = [(1.8 \times 10^{-9})(1.7 \times 10^{-3})]/10 = 3.1 \times 10^{-13} \text{ g l}^{-1}.$$

Table 3 shows the effectiveness values for the NAWC generator at -20°C vary between 10^{15} to 10^{16} ice crystals per liter, depending on windspeed. For the fairly light winds observed near the generator during this period a value of 1×10^{15} appears reasonable. That value multiplied by the AgI density yields an estimate of about 300 IN (or crystals) per liter. From the data of Table 3, 350 ppt tracer gas leads to an estimate of about 3 IN l^{-1}, effective at -10°C, and less at warmer temperatures.

After leaving the acoustical counter site at 1640, the van was driven to the top of the road at the town of Brighton, 9.5 miles further up the Canyon. Tracer gas sampling was done there, at an elevation of 8730 ft, from 1652-1703. The SF_6 concentration was again fairly constant with time, averaging 190 ppt. The van then sampled at 8200 ft at Solitude Ski Area, about 1.8 miles downcanyon from Brighton, from 1710-1733. The mean tracer gas concentration was constant near 460 ppt till 1715 but then gradually decreased to 190 ppt by 1733. The decrease was likely due to the gradual ending of gas release near 1545. By about 1745, the van had entirely exited the tracer gas plume as it was driven down the Canyon.

Calculations similar to those above suggest an average AgI density of 2×10^{-13} g l^{-1} at Brighton and 4×10^{-13} g l^{-1} at Solitude for the NAWC generator operated at 6 g h^{-1}. For the prevailing temperature near -6°C at both locations the corresponding IN concentrations would be negligible. The AgI would need to be transported up to about the -12°C level, about 1000 ft above the crestline east of Brighton, before IN concentrations exceeding 10 l^{-1} could result. Any ice crystals created above that crestline would be in the lee subsidence zone of the Wasatch Range, unlikely to be a favorable growth environment. Moreover, these estimates ignore the probable significant losses of AgI due to scavenging in cloud and in the "fairly heavy" to "very heavy" snowfall rates noted at the Brighton and Solitude locations during tracer gas sampling.

It was intended to compare the acoustical counter measurements of IN with the estimated IN concentration based on the tracer gas. However, examination of the operator's log indicated the acoustical counter vacuum pump was failing during this experiment, with the pressure drop across the sensor approximately half the intended value. This would result in a sample flow reduction. Far more important, counter sensitivity would be significantly reduced due to the decreased sounds made by crystals passing through the acoustical sensor. In addition, flow within the cloud chamber could become laminar, with a much higher crystal loss rate to the bottom cone (Gerhard Langer, personal communication). It is believed that these known problems explain the acoustical counter concentration of only 8 IN l^{-1} during the period 1600-1640. Reference to Table 4 shows that mean concentrations on other days ranged from 50-250 IN l^{-1} (with two generators operating).

The estimate of 300 IN l^{-1} from the tracer gas is above all mean values in Table 4 but less than half of the maximum values. There are several possible explanations for these differences. The acoustical counter could have undercounted for a variety of reasons. While Langer and Garvey (1980) showed good agreement between an acoustical counter and a cloud simulation chamber, those tests were done in laboratory conditions with the acoustical counter's inventor present. The field measurements presented here are likely somewhat degraded from what is possible with optimum counter operation.

Another factor is that AgI is subject to significant scavenging losses while the SF_6 gas is not. A crude estimate of possible scavenging losses of AgI was made by using a rate constant for aerosol removal presented by Pruppacher and Klett (1980). Assuming an in-cloud travel time of 2000 s, and various reasonable sizes and concentrations for cloud droplets and AgI aerosol, estimates of AgI removal were between 7-17 percent. Removal by mechanisms other than Brownian coagulation were not considered, such as direct capture by snow and by conifer forest. It is conceivable that roughly half the AgI might have been lost before reaching the acoustical counter site during some storm periods.

The special experiment of March 12 provided encouragement in that tracer gas was observed far up the Canyon to the end of the highway. However, estimates of available IN suggest limited ice nucleation would have occurred until the AgI plume reached altitudes above the crestline east of the Canyon. It is not known if the gas and AgI plumes were transported over the Wasatch Range crestline, and, if so, in what concentrations.

8. SUMMARY

Silver-in-snow analyses and detection of ice nuclei during the Utah/NOAA winter field program in 1989-90 have produced some insights into the transport and dispersion of AgI aerosols over two of Utah's operational cloud seeding target areas. Because of the lack of accompanying detailed meteorological and cloud microphysical data, a complete explanation of the results found during this limited field effort will require further study.

The results of the silver-in-snow investigation at sites in the Wasatch Range and Wasatch Plateau revealed that background (nonseeded) Ag concentrations were similar to those found by Long (1984) in the Tushar Mountains of southern Utah. In addition, as Long found in Ag samples from 1983, there was little evidence of enhanced Ag concentration in snow samples from seeded periods.

Possible explanations for the low frequency of above-background Ag are:

1. consistently poor targeting of the AgI occurred from the predominantly valley-based generators to the high altitude target areas located east (presumably downwind) of the generators,
2. the 6 g h^{-1} AgI output of the Utah operational generators was not sufficient to produce enhanced Ag concentrations, even if targeting was good.

A comparison with the results of the Bridger Range experiments, where seeded snow samples consistently contained enhanced Ag and where good targeting existed, supports the explanation that generator output could account for the different Ag concentration in seeded samples. The mean monthly Bridger AgI generator output exceeded Utah generator output by a factor of 20, while the Ag concentration in seeded snow samples in the Montana experiment exceeded Utah samples by factors of 10-30. However, given the relatively short periods represented by Utah samples (1-14 days compared to Bridger seasonal data), one would expect a larger percentage of "hits" than was observed in the Utah target areas. The low frequency of above-background Ag concentrations brings into question whether routine targeting was accomplished. Part II of this paper will address this question in more detail as will the more comprehensive transport and dispersion studies performed in the 1991 Utah/NOAA program, yet to be fully analyzed.

The question of seeding generator output was also addressed in the context of 11.4 percent precipitation increases for the Utah operational program suggested by statistical analysis of precipitation data (Griffith et al. 1991). A number of optimistic assumptions were employed such as a generator effectiveness of 5×10^{13} ice nuclei per gram of AgI for the SLW zone, perfect targeting by the valley-based generators, nucleation by all potentially active AgI particles, and growth and fallout of all nucleated ice crystals onto the targets. Using these assumptions, an estimate was made of the average ice particle mass required to produce the reported precipitation increases. The average computed masses of 0.07 to 0.23 mg were much larger than typical average masses of natural snow particles documented in several locations in the western United States. It is possible (but believed unlikely) that generator ice nucleus effectiveness in natural clouds is substantially greater than that found in cloud chambers. It is also possible (but believed unlikely) that some form of ice multiplication routinely creates an order of magnitude or more additional ice particles without further nucleation by AgI. Unless such mechanisms are involved, the calculations strongly suggest that the current network of Utah generators cannot produce snowfall enhancements approaching 10 percent with the type of seeding solution used and an AgI release rate of 6 g h^{-1}.

The real-time sampling of AgI and SF_6 in one canyon several miles above two seeding generators produced puzzling results. AgI was detected in every instance when generators were operated near the bottom of the canyon, yet snow samples immediately above the head of this canyon rarely yielded enhanced Ag concentrations. This result might be partially due to low AgI concentrations. When the mean IN concentration from the acoustical counter (operated at -20°C) was reduced to account for decreased effectiveness at a more typical liquid water temperature of 10°C, the IN concentration dropped to near 1 IN per liter. At this low concentration, seeding would probably not significantly increase snowfall, nor would enhanced Ag be detected in the snow downwind. One special experiment using a fast response SF_6 detector in the canyon supported this low concentration explanation. At the altitudes and temperatures where the gas was detected the corresponding AgI concentrations (estimated from SF_6 concentration) would have been very low. Nucleation at concentrations of about 10 IN l^{-1} would likely have occurred only at higher (colder) above crestline altitudes. If these canyon conditions were typical of most storms, the lack of Ag in snow just above the canyon head is not surprising.

Most winter cloud seeding projects have only assumed, but not tested, the adequacy of their targeting. Physical evidence continues to accumulate that routine targeting of adequate IN concentrations to SLW regions may be the exception and not the rule. It is strongly recommended that projects which have not done so, carefully scrutinize their targeting. We cannot claim to have a credible technology unless we demonstrate that our seeding methods actually treat the clouds.

Acknowledgements:

Evelyn Lees is to be commended for her careful collection of snow samples for Ag analysis, her many long hours tending the acoustical ice nucleus counter, and her extensive field notes, which have been valuable to the data analysis process. Rick Stone's guidance for the silver-in-snow data collection and analysis is appreciated. Gerhard Langer provided expert advice on operation and maintenance of the acoustical counter on several occasions. North American Weather Consultants was most cooperative in supporting the program. Don Griffith, Bill Hauze, George Wilkerson, Dan Risch, John Thompson and others from NAWC contributed to the field efforts, as did Jack McPartland and Glenn Cascino from the Bureau of Reclamation. Jim Heimbach deserves thanks for many helpful discussions. Thanks also to Bruce Boe and to the reviewers for providing suggestions to improve this paper. Barry Saunders and Clark Ogden of the Utah Division of Water Resources provided overall management for the research efforts and Clark gave considerable support to the field program. John Lease provided overall management of Reclamation efforts.

This research was primarily supported by NOAA's Atmospheric Modification Program, directed by Roger Reinking, with additional support from the Bureau of Reclamation.

9. REFERENCES

Benner, R.L. and B. Lamb, 1985: A fast response continuous analyzer for halogenated atmospheric tracers. J. Atmos. Oceanic Technol., **2**, 582-589.

DeMott, P.J., 1991: Comments on "The persistence of seeding effects in a winter orographic cloud seeded with silver iodide in acetone." J. Appl. Meteor., **30**, 1376-1380.

Deshler, T. and D.W. Reynolds, 1990: The persistence of seeding effects in a winter orographic cloud seeded with silver iodide burned in acetone. J. Appl. Meteor., **29**, 477-488.

Fukuta, N., E. Lees, M. Murakami and D.C. Tomten, 1988: Ground microphysical observations, 1987. Final Report to the Utah Div. of Water Resources by the Dept. of Meteorology, Univ. of Utah, Contract No. 88-0262, 89 pp.

Griffith, D.A., J.R. Thompson and D.A. Risch, 1991: A winter cloud seeding program in Utah. J. Weather Mod., **23**, 27-34.

Hallett, J. and S.C. Mossop, 1974: Production of secondary particles during the riming process. Nature, **249**, 26-28.

Heimbach, J.A. and A.B. Super, 1988: The Bridger Range, Montana, 1986-1987 snowpack augmentation program. J. Weather Mod., **20**, 19-25.

Hill, G.E., 1986: Seedability of winter orographic clouds. "Precipitation Enhancement - A Scientific Challenge," (R. Braham, Ed.), Meteor. Monogr. **21**, No. 43, Amer. Meteor. Soc., Boston, 127-137.

Hobbs, P.V., 1975: The nature of winter clouds and precipitation in the Cascade Mountains and their modification by artificial seeding. Part I: Natural conditions. J. Appl. Meteor., **14**, 783-804.

Hobbs, P.V. and A.L. Rangno, 1985: Ice particle concentrations in clouds. J. Atmos. Sci., **42**, 2523-2549.

Holroyd, E.W., J.T. McPartland and A.B. Super, 1988: Observations of silver iodide plumes over the Grand Mesa of Colorado. J. Appl. Meteor., **27**, 1125-1144.

Huggins, A.W., 1990: Investigations of winter mountain storms in Utah during the 1987 Utah/NOAA field program. Final Report to the Utah Dept. of Natural Resources, under NOAA Cooperative Agreements NA87RAH07081 and NA88RAH08128. Desert Research Institute, Reno, NV, 212 pp.

Langer, G., 1973: Evaluation of NCAR ice nucleus counter. Part I: Basic operations. J Appl. Meteor., **12**, 1000-1011.

Langer, G. and D. Garvey, 1980: Intercomparison of MEE and NCAR ice nucleus counters and CSU isothermal chamber. J. Weather Mod., **12**, 24-33.

Locatelli, J.D. and P.V. Hobbs, 1974: Fall speeds and masses of solid precipitation particles. J. Geophysical Res., **79**, 2185-2197.

Long, A.B., 1984: Physical investigations of winter orographic clouds in Utah. Final Report to the Utah Dept. of Natural Resources under NOAA Cooperative Agreement NA82RAH00001. Desert Research Institute, Reno, NV, 286 pp.

Mitchell, D.L., R. Zhang and R.L. Pitter, 1990: Mass-dimensional relationships for ice particles and the influence of riming on snowfall rates. J. Appl. Meteor., **29**, 153-163.

Mooney, M.L. and G.W. Lunn, 1969: The area of maximum effect resulting from the Lake Almanor randomized cloud seeding experiment, J. Appl. Meteor., **8**, 68-74.

Mossop, S.C., 1978: The influence of drop size distribution on the production of secondary ice particles during graupel growth. Quart. J. Roy. Meteor. Soc., **104**, 323-330.

Pruppacher, H.R. and J.D. Klett, 1980: "Microphysics of Cloud and Precipitation." D. Reidel Publishing Co., Dordrecht, Holland, 714 pp.

Rangno, A.L., 1986: How good are our conceptual models of orographic cloud seeding? in "Precipitation Enhancement - a Scientific Challenge," (R. Braham, Ed.), Meteor. Monogr. **21**, No. 43, Amer. Meteor. Soc., 115-126.

Rauber, R.M., R.D. Elliott, J.O. Rhea, A.W. Huggins and D.W. Reynolds, 1988: A diagnostic technique for targeting during airborne seeding experiments in wintertime storms over the Sierra Nevada. J. Appl. Meteor., **27**, 811-828.

Redder, C.R. and N. Fukuta, 1989: Empirical equations of ice crystal growth microphysics for modeling and analysis, I. Mass and dimensions. Atmos. Research, **24**, 247-272.

Reynolds, D.A., 1988: A report on winter snowpack-augmentation. Bull. Amer. Meteor. Soc., **69**, 1290-1300.

Reynolds, D.A., J.A. Humphries and R.H. Stone, 1989: Evaluation of a 2-month cooperative ground-based silver iodide seeding program. J. Weather Mod., **21**, 14-28.

Sassen, K., 1985: Supercooled liquid water in winter storms: A preliminary climatology from remote sensing observations. J. Weather Mod., **17**, 30-35.

Stone, R.H. and J.A. Warburton, 1985: Phase II - The use of trace chemistry for assessment of seeding effects in the Lake Almanor watershed. Final Report to the Pacific Gas and Electric Co., Desert Research Institute, Reno, Nevada, Vol. I, Dec. 1985, 102 pp.

Stone, R.H. and J.A. Warburton, 1989: The dispersion of silver iodide in mountainous target areas on the western United States. Preprints, Fifth WMO Scientific Conf. on Weather Modification and Applied Cloud Physics, Beijing, China, May 8-12, pp. 167-169.

Super, A.B., 1974: Silver iodide plume characteristics over the Bridger Mountain Range, Montana. J. Appl. Meteor., **13**, 62-70.

Super, A.B., 1990: Winter orographic cloud seeding status in the intermountain West. J. Weather Mod., **22**, 106-116.

Super, A.B. and J.A. Heimbach, 1983: Evaluation of the Bridger Range winter cloud seeding experiment using control gages. J. Climate Appl. Meteor., **22**, 1989-2011.

Super, A.B. and J.A. Heimbach, 1988: Microphysical effects of wintertime cloud seeding with silver iodide over the Rocky Mountains. Part II: Observations over the Bridger Range, Montana. J. Appl. Meteor., **27**, 1152-1165.

Super, A.B. and A.W. Huggins, 1992: Investigations of the Targeting of Ground-released Silver Iodide in Utah. Part II: Aircraft Observations, J. Weather Mod., **24**, accepted.

Super A.B., E.W. Holroyd and J.T. McPartland,1989: Winter cloud seeding potential on the Mogollon Rim. Final Report to the Arizona Dept. of Water Resources under IGA-88-6189-000-0051. Bureau of Reclamation Report R-89-02, Denver Federal Center, D-3720, P.O. Box 25007, Denver CO, 173 pp.

Thompson, J.R. and D.A. Griffith, 1981: Seven years of weather modification in central and southern Utah. J. Weather Mod., **13**, 141-149.

Warburton, J.A., 1969: Trace silver detection in precipitation by Atomic Absorption Spectrophotometry. J. Appl. Meteor., **8**, 464-466.

Warburton, J.A. and L.G. Young, 1968a: Neutron activation procedures for silver analysis in precipitation. J. Appl. Meteor., **7**, 433-443.

Warburton, J.A. and L.G. Young, 1968b: Neutron activation measurements of silver in precipitation from locations in Western North America. J. Appl. Meteor., **7**, 444-448.

Warburton, J.A., M.S. Owens, A.V. Anderson and R. Stone, 1979: Temporal & spatial distributions of seeding material in a ground-based seeded target area. Extended Abstracts, Seventh AMS Conf. on Inadvertent and Planned Weather Modification, Banff, Alta., Canada, Oct. 8-12, pp. 43-44.