

**PROPANE CLOUD SEEDING EXPERIMENT OVERVIEW:
WASATCH PLATEAU, UTAH, DURING WINTER OF 2003/04**

by

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March 2005

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Cover Photo

This is an image of the propane dispenser at the northwest end of a line of three high altitude dispensers used at the HAS high altitude seeding location on the west slope of the Wasatch Plateau. The view is across the Sanpete Valley toward the San Pitch Mountains. The propane dispensers, aligned across the prevailing southwest wind, were used during the Utah 2003-2004 randomized cloud seeding experiment. Horizontal separation between dispensers was about 100 feet to reduce aggregation of seeded ice crystals. The arms holding the two propane nozzles were also aligned across the prevailing southwest wind. Each nozzle had an upwind circular shield to protect it from rime ice buildup. Temperature sensors were immediately downwind of each nozzle to verify propane release by its cooling effect to about -100 deg F. The propane lines were insulated to prevent premature vaporization of the liquid propane. All three dispensers were controlled by a programmed data logger at the central release site, at an elevation of 8370 feet. Each dispenser had two nozzles and each nozzle released propane at a rate near 3.5 gallons per hour.

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Introduction

The Utah Division of Water Resources, with primary support from the Bureau of Reclamation, conducted an experimental cloud seeding program on the Wasatch Plateau of central Utah during the 2003/04 winter. While most cloud seeding has used silver iodide (AgI) for decades, the goal of the Utah experiment was to demonstrate that *liquid propane* could also be used to seed winter mountain-induced (orographic) clouds to increase seasonal snowfall. Spring and early summer melting of mountain snowpacks is the major source for runoff and stream flow in most areas of the West, utilized by agriculture, municipalities, industry, and aquatic environments.

The randomized propane seeding experiment was conducted from mid-December 2003 through March 2004. The experiment and substantial associated applied research is described in considerable detail in a final project report by Super and Heimbach (2005a)¹. A shorter version, still containing much more information than provided in this document, can be found in Vol. 37 of the *Journal of Weather Modification* (Super and Heimbach 2005b)². The current document is intended for water users and managers, and members of the general public who may desire a briefer and less technical overview of the 2003/04 winter project and its primary results. Accordingly, no equations are used and no references will be cited herein besides the two just noted. Readers interested in more detail, including references to considerable earlier work with propane seeding and related topics, are referred to Super and Heimbach (2005a, 2005b).

Silver iodide (AgI), propane and some other substances allow the artificial stimulation of the glaciogenic process by nucleating ice crystals in supercooled clouds made up of tiny droplets in liquid form in spite of having temperatures below the freezing point of bulk water. Ice crystals grow at the expense of surrounding supercooled droplets due to water vapor transfer from droplets to crystals because the latter have a lower vapor pressure. After sufficient growth time, on the order of ten minutes, some larger crystals fall relative to the smaller particles, sweeping out other crystals, termed "aggregation," and/or droplets, called "accretion" or "riming."

Previous work showed that propane seeding was effective in clearing supercooled liquid water (SLW) fog over airports. Similar seeding, by releasing liquid carbon dioxide from a moving vehicle, demonstrated widespread conversion of SLW fog to very light snowfall in the Salt Lake City area (Project Mountain Valley Sunshine). Prior laboratory and field experiments demonstrated that high concentrations of embryonic ice crystals result from propane release in SLW cloud or fog. Some brief case studies during the 1990's produced obvious evidence that propane seeding resulted in light snowfall on the Wasatch Plateau and the Sierra Nevada of California. However, it is unreasonable to extrapolate the results of a few case studies to estimation of the seasonal impact over many storms. A randomized seeding experiment is considered the "gold standard" for statistical testing of long-term seeding effects, if properly supported by physical observations and reasoning. The logical next step in advancing the emerging technology of propane seeding of winter orographic clouds was to conduct a randomized experiment. This was done during the 2003/04 winter on the same part of the Wasatch Plateau used for considerable previous applied research during the 1990s. It was the logical experimental site because routine targeting of seeding material and frequent existence of SLW cloud had already been demonstrated. Moreover, an all weather road access provided access to the plateau top making it practical to service instrumentation.

¹ Super, A. B. and J. A. Heimbach, Jr., 2005a: Final Report on Utah cloud seeding experimentation using propane during the 2003/04 winter. Final Report from the Utah Division of Water Resources to the Bureau of Reclamation, Financial Assistance Agreement Nos. 3-FC-81-0875 and 3-FC-81-0923, March 2005, 110 pp. plus appendices.

² Super, A. B. and J. A. Heimbach, Jr., 2005b: Randomized propane seeding experiment: Wasatch Plateau, Utah. *Journal of Weather Modification*, 37, 32 pp.

Establishing whether propane seeding could produce meaningful net snowfall increases from a population of several storms was a significant advance in the development of this potentially important seeding technology. Propane seeding has a very important advantage over AgI in being able to create ice crystals within "mildly" SLW cloud, at temperatures slightly below 0°C. Unless SLW cloud is colder than -8°C, AgI seeding is usually impractical, because its ability to nucleate sufficient ice crystals is highly temperature dependent. Silver iodide can be effective as warm as -6°C if released directly into SLW cloud, but this requires high altitude generators not used by most operational seeding projects. Because propane releases can provide abundant seeded ice crystals in the "warm temperature window" from -2°C to -6 or -8°C, its use can provide an important adjunct to AgI seeding. Winter observations from several ranges in the Intermountain West and the Sierra Nevada of California have documented that the SLW cloud zone near the mountainous terrain is frequently at relatively warm temperatures where AgI seeding is not effective.

Silver iodide causes "heterogeneous nucleation" involving the bringing together of tiny AgI particles with SLW cloud droplets resulting in formation of seeded ice crystals. However, propane seeding involves "homogeneous nucleation" as tiny SLW cloud droplets cannot continue to exist in liquid form at temperatures less than -40°C, but freeze into ice crystals. Propane expansion is a convenient means of locally chilling the air well below that temperature and, thereby, producing vast numbers of tiny cloud droplets which immediately freeze. As with AgI seeding, the resulting seeded ice crystals will grow within SLW cloud. When growth times are sufficient, as when the seeded crystals are transported by forced airflow up the windward slope of a mountain barrier, snowfall can result. The same forced airflow produces the orographic SLW cloud which is the "raw material" needed for winter mountain-induced cloud seeding to work.

As true for many gases, propane is technically a "greenhouse gas" but its lifetime in the atmosphere is under a month, too short to function in this manner. In contrast, CFCs have atmospheric lifetimes in the range of 60 - 500 yrs. For comparison, methane has stronger bonds which results in slower oxidizing allowing a buildup sufficient to contribute to the greenhouse process. There is no known influence of propane on the ozone layer.

The 2003/04 randomized experiment was limited in duration and target area size by available funding. It was not designed to answer all remaining questions, in particular the magnitude of seeding effects more than about 6.5 kilometer (hereafter km) downwind of the seeding site. (One km = 0.62 miles.) The gauge furthest downwind was only 2 km east of the plateau top's west (upwind) edge because of targeting uncertainties when using a single seeding location under varying wind directions. However, the experiment was intended to test whether routine seeding could produce meaningful additional snowfall over the upwind slopes and western portion of the plateau top. The experiment succeeded in demonstrating such increases to a reasonable level of statistical certainty, thereby providing justification for further use and development of this important emerging seeding technology.

Experimental Design and Conduct

Because the randomized experiment was "exploratory" in nature, without firm analysis rules stated beforehand, the convention will be to refer to all findings as "suggestions" rather than "proof" in the sense the latter word is used by scientists and statisticians. Establishment of firm hypotheses, rules and procedures usually requires knowledge not in existence prior to analysis of an exploratory experiment, and is used for follow-up "confirmatory" statistical experiments. On the other hand, testing methods for this experiment were specified in advance as was the automated randomized treatment scheme which was based on the glaciogenic hypothesis and previous research on propane seeding. When the entire experimental unit population is examined without partitioning into subpopulations, and when a partition is specified in advance as "the wind direction partition appropriate for targeting," referred to in the experiment's proposal, it could be argued that those portions of this experiment pass somewhat beyond the usual exploratory experiment limitations. That is, the statistical suggestions may have somewhat more weight than the usual exploratory experiment where many different tests are made searching for a possible seeding signal.

Seeding was done by expanding liquid propane through nozzles from a high elevation seeding location known as HAS for High Altitude Seeding location. Comprehensive plume tracking during earlier winter projects demonstrated routine targeting of the mountain top observatory, known as TAR for target, and nearby precipitation gauge, GTR, when HAS winds were from the southwest quadrant. All equipment locations are shown on Fig. 1, a map of

the experimental area. A limited number of physical case study experiments, which released either propane or AgI from HAS, showed obvious seeding effects at TAR.

An icing rate sensor just upwind of the propane dispensers was used to initiate a 2 hour experimental block whenever SLW cloud was observed to exceed a threshold. A programmed data logger then made a

random decision to seed either the first or second of the two 40 minute experimental units (EUs) within the 2 hour block, with the other unit receiving no seeding. The last twenty minutes of each hour were used as a buffer period, to minimize seeding contamination of any following nonseeded EU. The population of nonseeded units (placebos) provided the basis of comparison for statistical testing of propane seeding effectiveness in increasing snowfall.

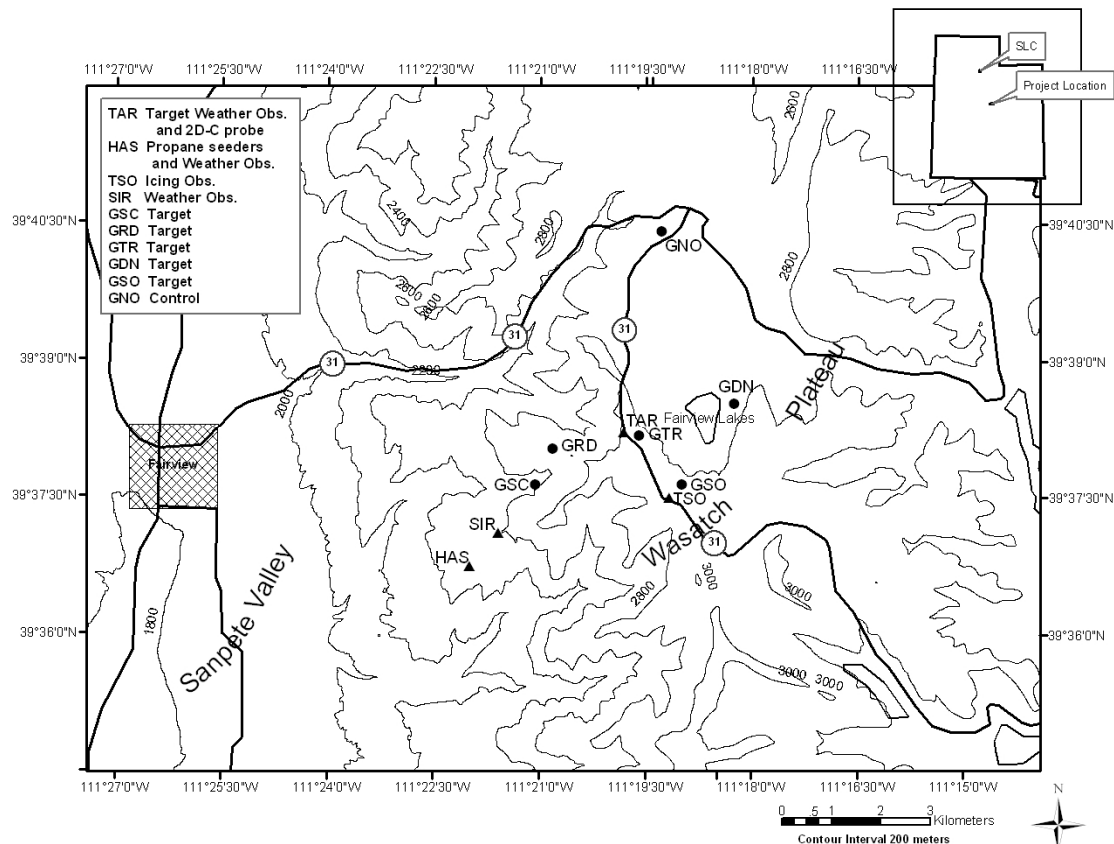


Figure 1. Map of the experimental area and site locations for the Utah 2003-2004 randomized propane cloud seeding experiment. The contour interval is 200 meters.

Experimental unit snow water equivalent (SWE) observations provided the test variable for each EU. These data were obtained by high resolution digitized precipitation gauges. Times of estimated seeding plume (or placebo) passage over the TAR and each gauge were based on HAS and TAR wind speeds and a relationship developed from prior plume tracing experiments. Five gauges were located on the windward slope and plateau top along the expected plume trajectory. This network permitted investigation of seeding effectiveness by distance from about 2 to 6.5 km downwind of the HAS. One of the gauge locations, GRD, proved to be too windy for suitable observations as discussed in the two

references, and will not be considered further. Control gauge GNO was also maintained on the plateau top, crosswind of the seeding plume. It was well-correlated with the remaining four target gauges. Measurements at GNO were essential to reducing the high natural variance (variability) in snowfall during statistical testing. Wind, temperature, icing which indicates SLW presence, and other observations were made at the HAS and TAR for the purpose of partitioning the precipitation data set into subpopulations for most of the testing. Some limited observations were made at stations SIR and TAO shown on Fig. 1, but they had minimal impact on the statistical testing. For all practical purposes the map

positions of interest are the HAS seeding location, the TAR instrumented weather station, the four target gauges GSC, GTR, GSO and GDN listed in order of increasing downwind distance, and the GNO

crosswind control gauge. Figure 2 shows the instrumented TAR station instruments atop a platform at about 25 ft above ground level.



Figure 2. The TAR instrumented target facilities in early winter looking toward the west-southwest. The power generator and satellite dish for Internet connection are on the far right. The instrumentation platform was immediately west of the heated trailer which housed computers, electronics and other equipment.

Primary measurements for statistical evaluation were from high resolution precipitation gauges protected from the wind in small natural clearings in evergreen forest. They were equipped with Alter-type wind shields to further reduce wind-caused undercatch, a serious problem for snowfall observations. Gauge time resolution was about 1 minute and data logger times were quite stable, frequently checked against a standard time signal. Each of the highly sensitive load cell gauges was carefully calibrated and the individual coefficients were used in that gauge's data logger program which converted the weight of the antifreeze and melted snow water solution into recorded 1 minute averages. The gauges proved to be very reliable, resulting in no missing data for any experimental period. Figure 3 show the control gauge with data from the data logger being downloaded into a Palm Pilot device as was done during approximately weekly service visits. These data were transmitted to project scientists via the Internet. Running means of five were fitted to all 1 minute gauge samples, centered on the middle

minute, before making calculations of SWE accumulations over time. Examination of resulting smooth time history plots suggested that gauge resolution was between 0.002 and 0.003 inch SWE.

Three propane dispensers were used at the HAS seeding site, located about 100 feet apart on an axis across the prevailing southwest wind to reduce aggregation losses of the high initial concentrations of seeded ice crystals. Two nozzles were used with each dispenser at the ends of a 10 foot horizontal tube, again to reduce aggregation. All dispenser valve controllers, propane flowmeters and temperature sensors near each propane nozzle were hard-wired into a data logger at the central dispenser. Figure 4 shows the central propane dispenser and instrumented tower at HAS with the view toward the south-southeast. The propane controller and data logger were in the box at the base of the tower. A propane dispenser is a relatively simple and inexpensive device, consisting of a propane supply, readily available from commercial sources, an

insulated exhaust tube to release liquid propane, a particular type of nozzle at the end, and a remotely-controlled on/off valve in the tubing. Inclusion of a temperature sensor immediately beyond the nozzle and a flowmeter in the exhaust tube provide monitoring that propane is indeed being dispensed and at the desired rate. Propane dispensers have proven to be very reliable because of their simplicity.

In contrast, radio-controlled AgI generators are much more complex, susceptible to clogging from highly corrosive seeding solutions. They are seldom equipped to monitor actual AgI-in-solution flow rate but only flame temperature. Therefore, one cannot be certain from afar that AgI was actually released which has sometimes been demonstrated to be a serious problem.



Figure 3. The high resolution precipitation gauge at the north control site with the view toward the north. In this picture, gauge data logger data are being downloaded to a portable Palm Pilot device. The 12-inch diameter gauge orifice is surrounded by an Alter-type wind shield made of clear Lexan plastic.

A Goodrich icing rate sensor, similar to the freezing rain sensors used in the national network of Automated Surface Observing System (ASOS) weather stations, was used to declare beginnings of 2 hour experimental periods containing a pair of 40 minute EUs plus their 20 minute buffers. This device has a 1 inch high by 1/4 inch diameter sensing rod extending vertically from a cone-shaped structure. Both were automatically heated once rime ice buildup on the rod reduced its frequency by a preset amount. The HAS data logger monitored 1 minute frequency observations from the Goodrich sensor. The frequency had to decrease over a 10 minute period by at least a specified amount, equivalent to about 0.005 inch thickness of rime ice buildup from SLW droplets freezing on the sampling rod, in order for an experimental period to be declared by the data logger program. The 10 minute period provided a reasonable time sample and minimized the impact of any frequency noise spikes. After the first EU of a pair was randomly declared as either seeded or

nonseeded, the opposite decision was used for the second EU of the pair. The icing sensor continued to be monitored throughout the 2 hour period. However, the sensor frequency output was not used to test conditions for start of another EU pair until two full hours had passed. A following pair would be declared as soon the required rime ice buildup again occurred, sometimes immediately after the first 2 hour period if SLW was still present. At the other extreme, if a storm had ended, the next EU pair would not be declared until the next storm period with sufficient SLW, perhaps days or sometimes weeks later.

The randomized seeding experiment was totally automated, requiring no human decisions or intervention except for routine equipment maintenance. Consequently, experimentation was conducted on a 24/7 basis which maximized the resulting population size of seeded and nonseeded experimental units. The propane experiment was

conducted during a generally dry period which received only 69% of the long-term average SWE for December 2003 through March 2004 as monitored by a nearby SNOTEL snow pillow. A total of 98 EUs

were obtained, of which 94 were paired in 2 hour blocks. The remaining 4 had their paired EU rejected because of very light winds, resulting in unreliable estimation of plume transit times.



Figure 4. The central propane dispenser and tower at the High Altitude Seeding (HAS) location with the view toward the south-southeast where the Wasatch Plateau top is in cloud. The propane controller and data logger are at the base of the tower.

Statistical Testing

Three statistical methods, all specified prior to data collection, were applied to the precipitation gauge SWE observations for the population of EUs. All three used the crosswind control gauge to reduce natural variance, an approach specified before the experiment was conducted. The methods were selected to explore different means of objectively measuring potential seeding effects. They are referred to as pairs testing, linear ranking of residual precipitation amounts (Wilcoxon test), and mean double ratio (MDR) testing. All three tests provided impressive and often similar results as discussed by Super and Heimbach (2005a, 2005b) with the Wilcoxon being somewhat less sensitive as expected.

High sensitivity and inclusion of confidence intervals gives the MDR approach advantages. In the interests of brevity and simplicity of explanation most results presented herein will be from MDR testing. However, reference will be made to "mean residuals" calculated by the pairs method because they provide estimates of the mean difference in

SWE between given groupings of seeded and nonseeded EUs.

The traditional but somewhat arbitrary α -value used to define "significance" in weather modification evaluation is 0.05. Because it is assumed that seeding cannot decrease precipitation, the tests were 1-tailed. Statistical tests giving probability values (P -values) $\leq \alpha$ are termed significant. A P -value equal to $\alpha = 0.05$ means there are 5 changes out of 100 for the apparent seeding increase to be due to chance rather than a real effect. The lower the P -value the more significant the result, indicating greater likelihood of having detected an actual seeding effect.

When applied to all 98 EUs, MDR testing provided the results shown in Table 1 where target gauges are ordered by increasing distance from the HAS seeding site. Each target gauge is well correlated with the GNO control gauge observations so much of the natural variance was eliminated by using GNO as a covariate. Significant P -values between 0.03 to 0.06 are seen for the three target gauges GSC, located

midway from the HAS to the TAR on the west edge of the plateau top, GTR near the TAR, and GSO 1 km due south (crosswind) of GTR. These three are referred to as the "core" gauges, located within 2 km or less of one another. The downwind gauge GDN had a P-value of 0.09, somewhat suggestive of seeding effectiveness, but not meeting the 0.05 criterion. These test results, from the entire EU

population, provide a strong statistical suggestion that propane seeding increased the "seasonal" 3.5 month experimental period snowfall on the windward slope and upwind portion of the plateau top. The "seeding signal" is less obvious at the gauge furthest downwind which had a lower likelihood of routinely being under the seeding plume because of variations in wind direction.

Table 1. Summary for all available 98 EUs with no partitioning: 47 pairs, 50 seeded and 48 nonseeded EUs.

Target Gauge	Pooled Target – GNO Correlation	Sample MDR	Re-randomized 1-tailed P-value	1-tailed 95% Confidence Interval
GSC	0.85	1.22	0.06	1.02 - ∞
GTR	0.88	1.22	0.04	1.04 - ∞
GSO	0.89	1.23	0.03	1.06 - ∞
GDN	0.84	1.21	0.09	0.98 - ∞

Whereas a significance test can imply there is a seeding effect, confidence intervals can quantify the possible range of effect which seeding may cause. Rerandomization, the repetitive simulation of the experiment using the same data but with different random seeding decisions, was required for the derivation of P-values and confidence limits shown in Table 1. The same set of 1000 rerandomized MDRs used to derive the P-values was applied to estimation of confidence limits. For example, a test of significance using $\alpha = 0.05$ might estimate from the MDR that treatment provided an additional 10% SWE. The upper limit of the confidence interval for the 1-tailed application, which assumes seeding can increase but not decrease snowfall, cannot be specified. Hence, upper limits in the tables are given by the " ∞ " symbol meaning infinity. The lower limits for the core gauges in Table 1 range from 1.02 to 1.06 corresponding to minimum precipitation increases of 2, 4 and 6%, respectively. The lower limit for gauge GDN is 0.98 meaning that it is possible that decreased precipitation could have resulted there, but by no more than 2%. That gauge also has the highest P-value (lowest significance). All the confidence interval values are valid at the 95% level. It is reiterated that these are *minimum* possible values and actual increases may be substantially higher. The sample MDRs range between 1.21 and 1.23 implying about 22% more precipitation for the seeded EUs than for the nonseeded control EUs for the entire available sample population of 98 EUs with no partitioning.

Partitioning

Applying statistical tests to EU groups which meet one or more meteorological criteria can give insight to the credence of physical hypotheses. This is termed "partitioning" or "stratification." The most obvious and physically reasonable partitioning of the available EUs was by HAS wind direction. No real seeding effect can exist if the wind did not transport the seeding plume over the target gauges. Considerable prior plume tracing with tracer gas and AgI was conducted with the same HAS seeding site, primary intended target, TAR, and its associated gauge, GTR. These earlier data sets were analyzed in detail for this experiment. They showed that plumes released at the HAS when winds there were from about 170 to 270 deg routinely reached the GTR/TAR area with typical 2 km across-the-wind plume widths by that downwind distance. Plumes released when HAS winds had any northerly component did not target that area but were transported further south. The obvious wind partition was for HAS median wind directions of 270 deg true or less, as the lowest EU value was 169 deg.

This wind direction partition provided a total of 32 pairs, and a total of 35 seeded plus 34 nonseeded or 69 EUs. The target-control correlations of Table 2 are almost as high as those of Table 1. Strongly suggestive P-values of 0.03 and 0.05 are shown in Table 2 for gauges GSO and GTR, respectively. Downwind gauge GDN had a respectable 0.06 and

GSC, nearest the HAS, had a somewhat suggestive P-value of 0.09.

While not shown in the tables, the three core gauges had mean residuals from the pairs testing equivalent to 0.012 to 0.015 inch per hour. This means that, on average, the seeded EUs in this partition had precipitation rates that much higher than the nonseeded EUs with minor variation from gauge to gauge. The stated values averaged 1.5 times as much mean SWE per EU as suggested by testing the entire population in Table 1. The 47 pairs of Table 1 represent 1.5 times as many EUs as the 32 pairs of Table 2. Consequently, these results indicate that the entire seeding effect at the core gauges was contained

within the wind direction partition. This is a physically reasonable result which would be expected if targeting was limited to southwest quadrant winds at the HAS, as demonstrated by prior plume tracing studies. If the seeding effect was not concentrated in this wind direction partition, doubts should be raised about the reality of the statistical suggestions. Conversely, finding the seeding effect concentrated within this partition lends considerable physical support to the statistical results. Also, if the seeding effect was not concentrated in this partition, the lower number of EUs would have produced larger P-values than the tests using the unpartitioned data set. The fact that they were approximately the same gives further confidence in these results.

Table 2. HAS wind direction partition ≤ 270 deg.
32 pairs, 35 seeded and 34 nonseeded

Target	Pooled Target – GNO Correlation	Sample MDR	Re-randomized 1-tailed P-value	1-tailed 95% Confidence Interval
GSC	0.82	1.22	0.09	1.00 ~ ∞
GTR	0.85	1.24	0.05	1.05 ~ ∞
GSO	0.86	1.26	0.03	1.07 ~ ∞
GDN	0.80	1.27	0.06	1.05 ~ ∞

Mean double ratios increased somewhat from Table 1 to the 22 to 27% increase range and the confidence intervals show minimum increases of 5 or 7% for the three gauges with P-values between 0.03 and 0.06. The minimum increase for gauge GSC nearest the HAS may have been as low as none by the confidence interval but the MDR was a respectable 1.22.

Two other single partitions were attempted, for SLW presence and by HAS air temperature. A number of dual partitions were tested with one always rejecting HAS wind directions with a northerly component (> 270 deg). That latter requirement alone reduced the population size to 69 EUs as in Table 2. Therefore, any second partition would reduce the sample size further so dual partitioning attempts were recognized as challenging. Detecting a real seeding effect at an acceptable level of statistical significance becomes problematic with small sample populations.

The most successful dual partition removed the larger natural snowfall periods with the expectation that a seeding signal would be more detectable during lower natural snowfall rates. Experimental units in the specified wind direction range were excluded

when control gauge GNO accumulation exceeded 0.05 inch for the 40 minute EU period. That criterion removed 20% of the EU population which met the wind direction criterion of 270 deg or less, and had the highest observed natural SWE amounts. In other words, the 0.05 inch SWE value was the 80th percentile for GNO of the ordered 69 EUs with wind direction no greater than 270 deg. The remaining sample population was still of reasonable size with 55 EUs of which 48 were paired. Some of the excluded EUs might be considered outliers.

The MDR results for this dual partition are given in Table 3. It is noted that correlations are much reduced from Tables 1 and 2 as might be expected with elimination of the higher values. The reduced correlations make it more difficult to detect a seeding signal with the available sample population, all else being equal. Therefore, the results are especially encouraging with P-values of 0.10, 0.04, 0.01 and 0.02 ordered by distance from the HAS. The associated confidence intervals indicate a 95% certainty of a *minimum* increase of 9% for GTR and between 16 to 21% minimum increases for the other gauges. The MDRs ranged between 1.30 and 1.51 suggesting large percentage increases of 30 to 51% from seeding within this dual partition. While it

might be expected that a real seeding signal would be more evident during light to moderate natural snowfalls than during heavy snowfalls, these results

are remarkable in view of considerably weaker associations (correlations) with the control gauge.

Table 3. HAS direction partition ≤ 270 deg combined with GNO SWE ≤ 0.05 inch:
24 pairs, 30 seeded and 25 nonseeded

Gauge	Pooled Target – GNO Correlation	Sample MDR	Re-randomized 1-tailed P-value	1-tailed 95% Confidence Interval
GSC	0.52	1.30	0.10	1.16 ~ ∞
GTR	0.67	1.32	0.04	1.09 ~ ∞
GSO	0.58	1.45	0.01	1.21 ~ ∞
GDN	0.60	1.51	0.02	1.20 ~ ∞

Somewhat encouraging suggestions resulted from other single and dual partitions mentioned above but not presented in detail here. There were suggestions that effective seeding might have been associated with the presence of SLW as detected by icing sensors, with warmer than median HAS temperatures and with less than median HAS wind speeds. But none of these tested partitions provided results as convincing as those already noted. It is suspected that lack of a significant seeding signal for SLW (icing) partitions was partial due to limitations in the icing rate sensors discussed in the references. Most of the resulting statistical suggestions should be regarded more as tantalizing than as conclusive. The main underlying problem is very likely the limited population sizes tested when any two partitions were applied. If any actual seeding effects existed, the available sample size was too limited to detect them to an acceptable level of statistical significance. Such results should be considered inconclusive, neither demonstrating an actual seeding effect *nor the lack of one*. Only testing a larger population than available would offer the possibility of providing more definitive results.

The most solid and important results of the statistical testing can be summarized as follows. It is highly likely that a real seeding effect resulted from propane seeding when transport winds carried the seeding plume over the target gauges. Overall, seeded units provided at least 20% more snowfall than nonseeded units. Based on those results, it was hypothetically estimated that if all hours containing the 69 EUs had been operationally seeded, the overall precipitation increase would have been 8% in the "seasonal" precipitation averaged for gauges GSC and GTR for the 3.5 month experimental period. This result was provided both by considering the

mean residuals from the pairs testing and from the mean double ratio testing emphasized above.

Case Study Analysis

A case study analysis was performed for three adjoining EUs on 21 December 2003, with two of the EUs nonseeded and the middle EU seeded. By chance, this particular seeded EU coincided with a time period having minimal natural snowfall, seldom observed during other EUs. The adjoining nonseeded EUs had considerably more natural snowfall than the seeded EU, both with highest accumulations at the control gauge. But that gauge received only 0.009 inch during the seeded period while target gauges had 2 to 4 times as much SWE, increasing with distance downwind of the seeding site. The most convincing evidence that seeding produced much of the increase was provided by examination of 2D-C probe ice particle images from TAR. These were very similar to those published from pulsed seeding experiments conducted during earlier winters. As seen in Figure 5, based on the 2D-C probe observations of individual ice crystals, the seeded images were relatively small and generally uniform in size and shape. They were in much higher concentrations than observed during the adjoining nonseeded periods which had much greater natural snowfall rates. The first nonseeded period would be classified as having heavy snowfall rates and the last as having moderate rates. Even with conservative assumptions detailed in the references, it was estimated that seeded snowfall rates exceeded 0.010 inch per hour at the core target gauges and likely approached twice that rate at the downwind gauge. Such seeding-produced precipitation rates are in good agreement with earlier cases study experiments in Utah and elsewhere in the Intermountain West.

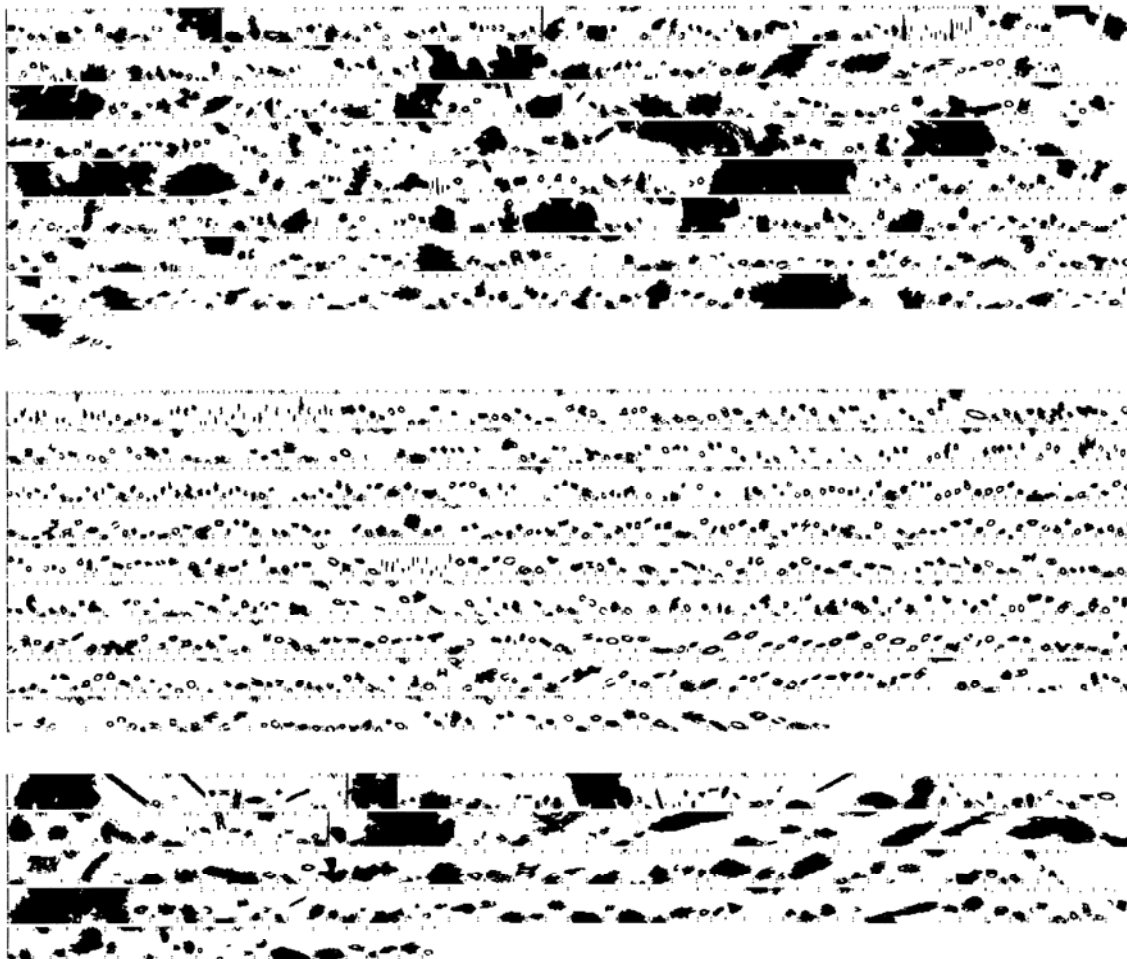


Figure 5. Thirty second "snapshots" of 2D-C ice crystal images during times of peak ice particle concentration for 3 adjoining EUs used in the case study of 21 December 2003. The strip widths are 800 microns, the field of the 2D-C probe. Measurements along the wind are unlimited. The upper and lower panels show typical 2D images of natural snowfall while the central panel shows seeded ice crystals. Mean ice particle concentrations for the 3 periods from top to bottom are 67, 148 and 28 per liter.

While such rates are light snowfall, about half of all hours with detectable natural snowfall fall at the rate of 0.010 inch per hour or less in the experimental area. Frequent hours with light snowfall are common at higher elevations in the Intermountain West. The seasonal contribution of light snowfall is important because of its high frequency of occurrence. Increasing the snowfall rate by 0.010 inch per hour for 200 hours would result in a seasonal increase of 10% for a normal November through March winter, based on long-term snow pillow observations in the experimental area. Examination of past icing rate sensor and other SLW data from the Wasatch Plateau revealed that approximately 200 hours with available SLW could be expected during a typical November through March winter. Consequently, there is both statistical and physical support for the expectation

that propane seeding might produce an all winter SWE increase in the vicinity of 10% for the limited target area examined.

Consideration of Ice Particle Concentrations

Ice particle concentrations (IPCs) of smaller ice crystals were monitored at the TAR with a 2D-C particle imaging probe. Only 21 seeded and 22 nonseeded EUs had available 2D-C measurements and HAS wind directions suitable for targeting because of electrical generator and other problems. The IPCs were compared for these seeded and nonseeded sample populations which may not be totally representative of all 69 EUs meeting the HAS wind direction criterion. The comparison of the seeded and nonseeded samples revealed about a 1/3

increase in IPC for the seeded distribution, with most of the seeded minus nonseeded differences in the range of 10 to 20 crystals per liter. These differences are very similar to TAR 2D-C probe results from previously published propane seeding case study experiments which had lower propane rates released from the HAS. The probability that the seeded and nonseeded differences were caused by seeding, as suspected, cannot be stated because of the limited sample size and lack of crosswind control observations.

All natural IPCs, averaged over the 40 minute EU periods, were between 10 to 90 per liter whatever the SWE observed by nearby gauge GTR. This is in good agreement with a previously published much larger data set which showed that all but a small portion of natural TAR IPCs were between 10 to 200 per liter when precipitation was 0.01 inch per hour or more. These findings demonstrate that natural IPCs are seldom low enough to prevent masking of seeding effects in case studies. Another important implication is that natural snowfall of detectable (and meaningful) rates requires a minimum IPC of at least 10 per liter on the plateau top. A minimum of 20 per liter is probably a more realistic threshold. Seeding attempts which cannot achieve higher IPCs are unlikely to produce useful snowfall, especially since seeded crystals tend to have more limited growth times and, therefore, smaller masses than natural crystals.

Summary of Randomized Experiment

To summarize, the essential features of the Utah randomized experiment were:

- Used propane releases to treat SLW clouds which were often too warm to be seeded with AgI.
- Conducted using a seeding site already demonstrated to provide routine targeting.
- Used a fully automated operation with seeding or placebo treatment triggered by SLW detection.
- Experimental Units (EUs) blocked into pairs with one EU randomly seeded.
- Target precipitation gauges operated along the expected seeding plume trajectory.
- Control gauge operated crosswind to monitor natural precipitation variations.

- Supporting wind and other observations collected for partitioning EUs into similar subpopulations.

- Applied three sophisticated statistical testing procedures, all using the control gauge as a covariate to substantially reduce the variance caused by natural snowfall fluctuations.

Summary of Statistical Conclusions

Results of statistical testing of the available EU sample population were considered significant and "strongly suggestive" if the probability of indicated seeding-caused differences between seeded and nonseeded EUs not being by chance was at least 95 out of 100 (α -level = 0.05). Results were considered "somewhat suggestive" if the same probability was from 90 to 95 out of 100 (α -level = 0.06 to 0.10).

Results to follow discuss the four gauges consisting of (1) GSC midway between the seeding location and (2) GTR, the primary intended target gauge on the west edge of the plateau top, (3) GSO located 1 km due south of GTR also on the plateau top, and (4) GDN, the only gauge downwind of GTR, about 6.5 km plume travel distance from the seeding site. Because results vary among the statistical tests, each having different strengths and weaknesses, the predominant findings of two or more tests will be noted below. The results of statistical testing of the Utah randomized experiment can be briefly summarized as follows:

- Tests of the entire sample of 98 EUs without any partitioning were strongly suggestive of a real seeding effect of increased snowfall at gauges GSC, GTR and GSO.
- Results for the 98 EUs were inconclusive at the downwind gauge GDN meaning no valid conclusion can be made whether seeding was effective there or not.
- Results for the 69 EUs partitioned by southwest quadrant seeding site winds, known to transport seeding plumes by the primary target, were also strongly suggestive of snowfall increases at the GTR and GSO gauges on the plateau top. Results were somewhat suggestive at the GSC gauge closest to the propane dispensers, and also at the downwind gauge GDN furthest from the seeding location.
- Comparisons of the wind direction-partitioned 69 EUs with all available 98 EUs revealed

that basically all the seeding signal was contained within the 69 EUs where targeting was highly likely. The same partition excluded northwest flow EUs expected to transport seeding plumes south of the target gauges.

- A dual partition used the same wind direction partition combined with exclusion of the larger 20% of natural SWE amounts observed at control gauge GNO. Overall results were encouraging, suggesting that real seeding effects were particularly detectable and pronounced when natural snowfalls were no more than moderate in spite of reduced correlations with the control gauge.
- Results were analyzed for several other single and dual partitions, the latter always including the southwest quadrant winds at the seeding site. These results were mixed, ranging from strongly suggestive to somewhat suggestive to inconclusive depending upon the particular partition, gauge and statistical test. A number of partitions provided interesting suggestions but none of the results were as convincing as the wind direction partition or entire population testing.
- There were suggestions that seeding may have been more effective when SLW cloud (icing) was detected, when seeding plume temperatures were warmer and when wind speeds were lighter. But rigorous testing of these interesting but mostly inconclusive suggestions would require a larger sample size than available from the limited 3.5 month experimental period.

Recommendations for Further Development of Propane Seeding

The statistical results from the 2003/04 Utah randomized experiment, together with supporting physical observations during that period and from considerable past investigation at the same location, present a strong case for propane seeding effectiveness in increasing mountain snowfall. To date, applied research into propane seeding has been limited by available resources as federal funding for weather modification research has significantly declined over the past several years. Those who would be critical of limited progress should bear that reality in mind. The randomized propane seeding experiment was not designed to answer all remaining questions, and a number remain. In particular, the downwind extent of seeding effects received little attention. But there is certainly sufficient evidence to justify further development of this promising emerging technology, especially given propane's

ability to seed significantly warmer SLW cloud than possible with AgI. That fact alone is a powerful argument for continued development of propane seeding for winter orographic clouds in the western United States and elsewhere.

It is strongly recommended that a follow-on confirmatory randomized experiment be conducted on the Wasatch Plateau or similar mountain barrier over at least three winters. The experiment would require a minimum of three high elevation propane seeding sites separated by 2-3 km crosswind distance. A significantly larger precipitation gauge network would be required extending further downwind. The central downwind gauges should be targeted by at least one of the seeding sites as wind directions shifted within a reasonable range. Crosswind control gauges would be maintained both south and north (crosswind) of the target gauges. Because of the difficulties of finding naturally protected clearings in evergreen forest at higher elevations some gauges might require elaborate double-fence wind shields. A numerical model should be verified and used which has the capability of handling local transport and dispersion over the rugged terrain, and with sophisticated microphysics. The experiment should be provided with comprehensive physical observations to include a microwave radiometer to monitor the SLW cloud zone, and to provide much improved microphysical measurements, both in target and crosswind control locations.

These specific recommendations for a propane seeding experiment follow the general recommendations of the most recent (1998) American Meteorological Society Policy Statement on Weather Modification which stated, "Whereas a statistical evaluation is required to establish that a significant change resulted from a given seeding activity, it must be accompanied by a physical evaluation to confirm that the statistically observed change was due to the seeding." Until that approach is followed, with results published in the peer reviewed scientific literature, there will continue to be controversy and uncertainty concerning winter orographic cloud seeding effectiveness with either AgI or propane. With ever developing demands on limited water resources in the western states, and recent evidence of declining mountain snowpacks since about 1950, policy makers should be able to make decisions based on physical reality as revealed through sound scientific inquiry. Such information remains limited in the field of winter orographic cloud seeding. In the meantime, water users interested in using cloud seeding to increase the winter mountain snowpack will continue to make

choices with the best available information. The 2003/04 Utah randomized experiment has provided important new evidence that propane seeding is an option which should not be ignored, especially where mildly SLW cloud predominates.

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