"REVIEWED"

A STATUS REPORT ON LIQUID PROPANE DISPENSER TESTING IN UTAH WITH EMPHASIS ON A FULLY-AUTOMATED SEEDING SYSTEM

Arlin B. Super*, Erick Faatz**, Arlen J. Hilton*, V. Clark Ogden** and Roger D. Hansen*

* Bureau of Reclamation
** Utah Division of Water Resources

Abstract. Liquid propane dispensers were tested on the Wasatch Plateau of central Utah during the winters of 1992-93 and 1993-94. Remote operation of the radio-controlled dispensers proved to be highly reliable, in large part because of the mechanical simplicity of the devices. A prototype *fully-automated* liquid propane seeding system was tested during early 1994 on the west (windward) slopes of the Plateau. An icing rate device was used to detect supercooled liquid water at the center station of three exposed propane dispenser stations. Wind speed and direction and air temperature were also monitored at the center station. When certain predetermined weather criteria were met, the three propane dispensers were automatically turned on. Propane continued to be dispersed until one or more of the weather criteria were out-of-bounds for 2 h.

Post-season analysis of recorded data showed that the fully-automated seeding system operated as designed for the most part. Some minor problems were encountered, but can easily be corrected. Recommendations are made for simplifying the automated decision process.

A means of detecting supercooled liquid water in the absence of commercial electrical power was also tested during early 1994. It proved to be practical and reliable. Accordingly, the technology exists to operate fully-automated networks of liquid propane dispensers in remote mountain locations. Costs of such networks would not be excessive, and reliability can be expected to be high. However, further physical experimentation is recommended to document the effectiveness of liquid propane seeding for snowfall enhancement because such evidence is quite limited.

1. INTRODUCTION

Operational seeding of winter orographic (mountain-induced) clouds for snowfall enhancement has been conducted in the western United States and elsewhere since the 1950's. The basic concept is to convert excess SLW (supercooled liquid water) into additional snowfall. This is done by creating more ice crystals in SLW clouds expected to have low concentrations of natural ice crystals. Such clouds may be naturally inefficient in snowfall production.

By far the most common seeding agent for winter orographic clouds has been AgI (silver iodide). The AgI may be produced in relatively pure form, or complexed with other chemicals to alter ice nucleating characteristics. Silver iodide is released as very tiny particles from generators or pyrotechnic flares. Releases may be from ground locations or from aircraft. The Utah operational seeding program uses ground-based AgI generators primary at valley locations, with a few generators in canyon mouths (Griffith et al. 1991). The following discussion will not include aircraft seeding or use of flares, techniques not used in Utah because of associated expense and operational difficulties.

The effectiveness of AgI in nucleating ice crystals is determined by several factors including the particular chemical composition of the solution, generator characteristics, ambient winds, time available for nucleation and others. But the most important factor is the SLW cloud temperature. For commonly used AgI generators, solutions, and release rates, and typical AgI plume dispersion, ice crystal nucleation is believed negligible for temperatures above about -5°C. Ice crystal nucleation may be very limited even at -8 to -10°C for some operational seeding programs. The number of ice crystals produced per gram of AgI (yield) can increase by three orders of magnitude or more as the temperature decreases from -6 to -20°C (e.g., DeMott et al. 1995). There is usually no interest in seeding SLW clouds below -20°C because abundant natural ice crystal concentrations and limited SLW can be expected at such cold temperatures.

2. PROPANE SEEDING NEED AND FEASIBILITY

Research conducted in several western States during the past decade has revealed that most orographically-produced SLW cloud exists in the lowest 1 km above mountain barriers. This SLW zone is often too warm for effective seeding with typical AgI solutions and release rates. For example, the statistical analysis presented by Super and Heimbach (1983) strongly suggested that AgI seeding was effective over Montana's Bridger Range only when crest temperatures were below -9°C. About half the Montana winter storm periods had crest temperatures above -9°C, and these tended to be the wetter periods.

Several winters of observations over the Sierra Nevada of California led Reynolds (1989) to conclude that a seeding agent was needed to convert SLW into ice at temperatures between 0 and -5°C. Most of the SLW over the Sierra Nevada was observed in this warm temperature range where AgI is believed generally ineffective.

Observations in Utah's Tushar Mountains (e.g., Sassen and Zhao 1993) and Wasatch Plateau (e.g., Super 1994, Huggins 1995) have indicated most SLW cloud is warmer than about -10°C. While Utah orographic clouds are generally colder than those found in California, a significant portion of Utah's orographically-produced SLW appears to be too warm for effective AgI seeding by current operational methods (Super 1995). This problem is common throughout the intermoutain West.

Vardiman et al. (1971) demonstrated that the release of liquid propane was successful in clearing fogs with temperatures only slightly below 0°C. The release of liquid propane as a fine mist results in rapid vaporization of the propane and subsequent chilling of the cloudy air immediately downwind of the spray nozzle. Some of the air is chilled cold enough for homogeneous nucleation of ice crystals. Hicks and Vali (1973) presented laboratory and field observations indicating that about 10^{11} to 10^{12} ice crystals resulted per gram of propane.

Assuming that liquid propane release produces 5×10^{11} ice crystals g^{-1}, the typical release rate of 3 gal h^{-1} discussed in this paper is equivalent to 6,000 g h^{-1} of propane, or 3×10^{15} ice crystals h^{-1}. For comparison, a recent calibration of the manual North American Weather Consultants (NAWC) AgI generator by DeMott et al. (1995) for natural draft conditions shows a liquid cloud temperature below -9.5°C is needed for the same ice crystal source strength with the generator's AgI release rate of 8 g h^{-1}.

The ice particle concentration to be expected downwind of a point source strength of 3×10^{15} ice crystals h^{-1} can be estimated by assuming reasonable average values for plume dimensions of 15 deg width and 600 m depth (e.g., Holroyd et al. 1988), and a typical wind speed of 5 m s^{-1} near the windward slope of a mountain barrier. It can be shown that the resulting average ice particle concentration 10 km downwind of the source is about 100 L^{-1}, an order of magnitude higher than the minimum concentration estimated by Super (1994) for production of observable snowfall. These calculations suggest that the liquid propane seeding rates used in the tests to be discussed are sufficient to potentially enhance snowfall under suitable conditions.

Reynolds (1989) expanded upon earlier fog suppression work by developing propane dispensing systems for mountain locations. The units were transported by helicopter to high altitude sites in the Sierra Nevada where electrical power was provided by solar panels. Radio telemetry was used to interrogate and control the propane dispensers from a valley base station. These dispensers have been tested and refined the past few years as documented by Reynolds (1991) and Reynolds (1994). The liquid propane dispensing system developed by Reynolds is considered fully operational. The system is relatively simple, with few moving parts (e.g., solenoid values), and has proven to have high reliability.

Propane release is confirmed in real-time by monitoring both the flow rate and the temperature near the propane nozzle.

Past work with propane seeding for snowfall enhancement has been limited and further research is needed to demonstrate how effective it might be with winter orographic clouds. However, prior observations have shown that liquid propane release can significantly enhance the ice particle concentration within SLW cloud that is only slightly below 0°C (e.g., Vardiman et al. 1971, Hicks and Vali 1973, Reynolds 1994).

3. PROPANE DISPENSER TESTS DURING THE WINTER OF 1992-93

The ability of liquid propane seeding to create abundant ice crystals at even slightly supercooled temperatures, and the successful operation of the State of California propane dispensing system, led the Utah Division of Water Resources (hereafter Division) to test a similar system in Utah. Such a system might eventually augment AgI seeding during warmer storm periods to increase overall seeding effectiveness. But the first step was to develop local experience and competence with a liquid propane dispenser.

A propane dispenser system was fabricated in Utah, based on the California design. The Utah prototype dispenser was somewhat simplified, having only one nozzle. A different type of data logger/controller (hereafter data logger) was used in Utah (a Campbell CR-10) because of local familiarity with that product. The data logger was programmed to control and monitor the propane dispenser and various other equipment, and a radio communication system was developed that could be accessed by telephone.

A testing program for various equipment was conducted from December 1992 through March 1993 on the west slope of the Wasatch Plateau. The test site was at the HAS (High Altitude Site) east of Fairview, Utah, shown on Fig. 1 of Super (1995). The site's elevation was 2500 m (all elevations above mean sea level). Technicians frequently traveled to the test site by over-snow vehicle throughout this period, especially during and after storms. The only equipment to be discussed in this paper is the propane dispenser and associated weather sensors. An internal report, which documented the results of the 1992-93 tests, was prepared by Hansen et al. (1993). The report concluded, with respect to the propane system:

a. The modified propane dispenser was very reliable and should prove to be a useful addition to Utah's operational cloud seeding program.

b. One possible improvement to the modified (propane) dispenser would be to provide enhancements so the units could be automated (turned on and off without human intervention).

c. The real-time radio/telephone communication system was very reliable.

4. PROPANE DISPENSER TESTS DURING THE WINTER OF 1993-94

Based on the success of the 1992-93 testing of a single propane dispenser, it was decided to continue and expand propane dispenser testing during the winter of 1993-94. The single propane dispenser used in 1992-93, and all five tested in 1993-94, had the same type of nozzle. Propane release rates, as monitored by a flowmeter with each dispenser, were usually in the range 2.5 to 3.5 gal h^{-1}. Different rates could be achieved with different nozzle designs, if desired. It would be desirable to compare calculated propane consumption based on flowmeter measurements with actual consumption based on before and after weighing of the propane tanks. Such a comparison has not yet been accomplished.

4.1 Testing of Two Radio-controlled Propane Dispensers

The 1993-94 tests were conducted in two areas on the Wasatch Plateau. Two high altitude propane dispensers were operated as part of the Utah/NOAA AMP (Atmospheric Modification Program) field program between mid-January and mid-March 1994. One site was the "new" HAS at 2540 m elevation, located 1 km south of the previous winter's HAS in order to be more exposed to south and southwest winds. The second site was AHS (Aspen Hills Site), located 4 km south of the new HAS at 2340 m elevation. These sites are shown on Fig. 1 of Holroyd et al. (1995). Both sites were southeast of Fairview, and were controlled by radio as during the prior winter. That is, someone decided when to turn the dispensers on and off and manually did so via computer, modems and radio telemetry. One or both of these dispensers were operated during a limited number of short-term experiments when instrumented aircraft sampling was conducted and ground observations were made during orographic storms.

The purpose of the HAS/AHS propane seeding experiments was to physically evaluate the effectiveness of such seeding in enhancing the ice particle concentration in SLW clouds. The effectiveness of propane seeding in enhancing snowfall will also be examined, but this is a far more difficult problem to physically evaluate. Analyses of the propane seeding experiments have yet to be accomplished, so little can be stated about the results. The propane dispensers proved to be reliable, similar to the prior winter's tests. Tracer gas co-released with the propane was routinely detected on and above the Wasatch Plateau. Consequently, it can be assumed that ice crystals created by releasing propane in SLW cloud were also transported over the Plateau. Ice particle characteristics were monitored with three 2D-C imaging probes as discussed by Holroyd et al. (1995). Results of analyzing data from these ice particle imaging probes will be presented in future papers.

4.2 Testing of an Automated Propane Seeding System

The main topic of this paper is the preliminary testing of a prototype automated propane seeding system. Such a system, if successful, would have a number of advantages. As far as the authors are aware, the propane seeding system tested during early 1994 was the first fully-automated system ever used for winter orographic cloud seeding. Once the system was installed, it required no human intervention or decision-making.

The system was intended to respond to observed weather conditions. This would eliminate the need for weather forecasting which is costly and of limited accuracy in mountainous terrain where observations are scarce. Seeding material (propane) would be released only when conditions were suitable for the formation of ice crystals. This would enable potentially seedable conditions to be seeded which does not happen when weather forecasts are "blown."

The test area for the automated propane seeding system was on the west slopes of the Wasatch Plateau east of Ephraim, Utah, approximately 30 km south of the two propane dispensers east of Fairview (see Fig. 1 of Holroyd et al. 1995). This area was judged to be sufficiently crosswind to prevent possible seeding effects from influencing the Utah/NOAA (Fairview) experimental area. Yet all five dispensers were in close enough proximity to be interrogated by radio from a single base station located at the Utah/NOAA headquarters near Fairview. The data logger at each dispenser stored observations for about one week before the earliest observations were overwritten by new observations. The data logger's memories were periodically downloaded via radio telemetry and modems to a personal computer at the base station.

Three high altitude propane dispensers were configured into a network in the Ephraim test area. The center dispenser was located on an exposed windy ridge known as Freds Flat at an elevation of 2755 m. This site was near an existing electrical power line which permitted operation of various weather instruments. The most important instrument for deciding when to seed was a tower-type Rosemount icing rate device which detected the presence of SLW. Supercooled liquid water is crucial to effective cloud seeding since it is the "raw material" that is intended to be converted to snowfall. Unfortunately, SLW is difficult to automatically monitor at remote locations without electrical power. Power availability at Freds Flat also permitted use of a heated Hydrotech wind vane and anemometer for wind direction and speed measurements. (Rosemounts and Hydrotechs consume too much power for practical operation with solar panels). Air temperature and relative humidity were also measured at Freds Flat, but these sensors required little power.

It would, of course, be preferable to monitor the weather at each propane dispenser and to operate individual dispensers only when they were in SLW cloud with appropriate wind speed and direction. The approach used in the 1994 testing assumed that the Freds Flat observations represented all three dispenser sites. This assumption is simplistic but is probably valid for many storm periods since the sites were not far apart and had similar altitudes and local exposures. Moreover, it is more realistic to base a seeding decision for a particular site on measurements made even several kilometers distant than on a weather forecast for mountainous terrain based on synoptic-scale observations.

The Freds Flat data logger was programmed to monitor SLW presence, wind speed and direction and air temperature. When certain criteria were met, noted in Table 1, the Freds Flat propane dispenser was automatically turned on. Similar dispensers were also turned on via radio link between Freds Flat and the data loggers at two satellite locations near the same altitude. These sites were on the south end of Hell Hole Ridge, located 3 km north of Freds Flat at 2785 m, and near the top of Bald Mountain, located 6 km southwest of Freds Flat at 2575 m. All three sites were expected to frequently be in SLW cloud during storms.

Propane continued to be released by all three dispensers until the specified weather criteria were not met for a pre-selected time. The data logger's "decisions" could be manually overridden at any time; for example, if it were desired to suspend seeding because of a well-above-normal snowpack. Manual override of individual data loggers was possible either from the base station or from any computer connected to the base station by modem and commercial telephone. Moreover, each satellite dispenser had its data logger programmed to stop releasing propane if either:

(a) no communication was received from the weather observing site for an extended period, or

(b) the sensor in the propane stream did not detect a substantial temperature decrease which was expected with proper propane release.

Table 1 shows that 1 h averaging periods were used for all measurements with the exception of the Rosemount icing meter. It was decided to require 2 cycles of the Rosemount icing meter before initiating seeding to insure that a "significant" SLW episode was occurring. For example, it was thought that the slow accumulation of "feather rime" might sometimes cause a single icing meter cycle when seeding potential was negligible. A 2 h period was used with the icing rate device because of concerns that 2 cycles might not occur within 1 h with light winds and/or low SLW contents. Low frequencies of icing meter cycles have been experienced at some mountain locations with the low cloud water contents characteristic of orographic clouds.

Seeding was continued for 2 h after the last Rosemount cycle, if other weather criteria were

---

TABLE 1. Criteria for automated propane seeding based on Freds Flat meteorological observations.*

I. Initiate liquid propane release from all dispensers when:

A minimum of two Rosemount cycles occurred during the past 2 h, and the average values for the past 1 h for air temperature was at or below 0.0°C; wind direction was greater than 180 but less than 330 degrees true; and wind speed** was greater than 1.0 m s^{-1}.

II. Terminate liquid propane release from all dispensers when:

No Rosemount cycles have occurred during the past 2 h and/or one or more of the average values of air temperature, wind direction and wind speed was outside the criteria stated above for the past 1 h.

III. Terminate liquid propane release from either or both of the two satellite dispensers when:

They have lost radio communication with the Freds Flat station for over 12 h, or the temperature sensor just downstream of the propane nozzle did not detect a significant temperature drop after the dispenser was turned on.

* All averages for the past 1 h, and the total Rosemount cycles for the past 2 h, were recalculated every 12 min.

** Because of the high starting threshold of the Hydrotech anemometer, a zero voltage output was considered to represent 0.7 m s^{-1} in all calculations.

---

still being met. It is known that ice crystals can be created by expansion of liquid propane in the absence of SLW as long as the atmosphere is saturated with respect to ice. Such crystals will even grow if the atmosphere is subsaturated with respect to water but supersaturated with respect to ice. Ice saturation is very difficult to measure in the field. Therefore, seeding was continued for 2 h after the end of SLW detection in anticipation that the atmosphere might still permit ice crystal formation and growth by release of propane.

The propane tanks, dispenser systems and weather instruments were installed during the fall of 1993 when truck travel to the sites was still practical. The propane dispensers were not visited during the January to March 1994 test period, partially because of higher priority work (the Utah/NOAA physical seeding experiments east of Fairview; e.g. Holroyd et al. (1995). Measurements from the network were periodically reviewed and a problem was recognized with one site as will be discussed. The problem's cause was suspected and verified by on-site inspection after the winter season.

The California experience, described in the previously cited articles by Reynolds, was that dispensers rarely required visitation after installation each fall.

5. SUMMARY OF AUTOMATED PROPANE DISPENSER SYSTEM OPERATION

5.1 Freds Flat Dispenser Operation

The Freds Flat propane dispenser system automatically turned itself on and off 17 times between January 5 and mid-March 1994. This was a period with a low storm frequency. For example, the Utah/NOAA program did not have any weather suitable for experimentation from mid-January until 26 January, or after February 27 till the program end on March 15. No SLW was monitored at Freds Flat during the latter period.

Every time 2 or more Rosemount cycles occurred within a 2 h block, the Freds Flat system began to dispense propane, as the wind speed and direction were always within the limits specified in Table 1. The air temperature criteria was, of course, redundant. The Rosemount will not cycle (i.e., rime ice will not form on the probe) unless the temperature is below 0°C. In most instances the 2 Rosemount cycles occurred within 0.5 h or less, often in adjoining 12 min sampling periods and sometimes in the same sampling period.

Propane was released from the Freds Flat dispenser for a total of 83 h so the average release duration was 4.9 h. Individual release periods ranged from a single 1.0 h period to maximum 10.4 h. The median period was 4.0 h. It is apparent that SLW episodes were relatively brief at Freds Flat.

Examination of the data revealed that had a single Rosemount cycle been used to initiate seeding, only 8 cases existed without a second cycle within 2 h. Four of these 8 cases would have been rejected because either the wind speed or wind direction was out of limits.

Termination of seeding at Freds Flat was always based on the absence of SLW for about 2 h, although in 2 cases the last hour's wind direction became greater than 330 degrees which would also terminate seeding. The period between the last Rosemount cycle and termination of propane release was not always 2 h as had been intended. With the 12 min sampling interval, 2 h corresponds to 10 intervals. In fact, the intervals between the last Rosemount cycle and propane shutoff ranged between 8 and 13 intervals (1.6 to 2.6 h) in 15 of the 17 seeding episodes. Shutoff occurred after only 3 and 5 cycles in the remaining 2 episodes. In none of the early shutoff cases were the wind or temperature criteria out of bounds. It is believed that a programming "bug" was responsible for the variation in shutoff time, although this was not verified. At any rate, the dispenser system always turned itself off after icing ceased, and usually about 2 h after the last Rosemount cycle as intended.

The lack of SLW was always the determining factor in propane shutoff. Few "false alarms" would have occurred if seeding had been initiated by a single Rosemount cycle. Consequently, future automated propane seeding could be simplified, at least if based on Freds Flat observations. It is recommended that seeding be initiated whenever the first Rosemount cycle occurs, and seeding should thereafter continue until 2 h pass without any Rosemount cycles. This would insure that all potentially seedable episodes are seeded in their entirety. Some limited seeding would occur during periods with unsuitable meteorological conditions with this simplified scheme. However, the only negative consequence should be the loss of relatively small amounts of propane.

5.2 Hell Hole Ridge Dispenser Operation

Hell Hole Ridge data were inadvertently not downloaded for a week period in early February which had 4 Freds Flat seeding episodes. However, data are complete for the remaining 13 seeding episodes. With a single exception, Hell Hole Ridge propane releases were an exact match in time with the Freds Flat releases. That is, both initiation and termination of propane release were always within the same 12 min sampling periods as had been intended.

On February 19 the Hell Hole Ridge dispenser was turned on at the same time as Freds Flat. However, the Hell Hole Ridge dispenser continued to release propane for 5.6 h after Freds Flat shut down. The reason for the shutdown delay is not known, but may have been caused by radio communication problems. With this single exception, the available data indicate that Hell Hole Ridge propane dispensing system worked just as intended.

5.3 Bald Mountain Dispenser Operation

The Bald Mountain dispenser did not operate as well as the other 2 dispensers in the automated network. The main problem was verified after the field season when the site was visited for the first time since early winter. The temperature sensor for the propane spray did not have a secure mechanical holder. As a consequence, the sensor did not hold the same position, but could be moved by the propane spray and the local airflow.

All 3 data loggers were programmed to shut down their dispenser if the temperature sensor did not indicate at least -40°C when the propane valve was turned on. The Bald Mountain sensor was seldom this cold. With a single exception, the Bald Mountain dispenser was turned on at the same time (within 12 min) as the Freds Flat master unit. However, in the large majority of the 17 seeding episodes, the Bald Mountain dispenser would turn itself off after 24 min. It would later respond to the continued signal from Freds Flat that seeding should be conducted and would turn on again about 0.4 or 0.6 h after shut down. The Bald Mountain dispenser would continue to cycle on and off in this manner throughout the seeding episode.

During a few storms the propane spray temperature sensor was cold enough that the Bald Mountain dispenser operated properly throughout the seeded period.

The solution to the Bald Mountain dispenser problem is simple. A more rigid holder for the temperature sensor needs to be fabricated.

6. FURTHER PRACTICAL CONSIDERATIONS AND TESTING

Electrical power lines are uncommon in mountains. Consequently, it would be desirable to use meteorological sensors that did not require much electrical power in future applications of automated propane seeding. Unfortunately, the authors are not aware of any icing rate sensor that requires significantly less power than a Rosemount icing rate device. Testing of relative humidity sensors from three manufacturers (Handar, Rotronics, Vaisala) at the HAS in 1992-93 did not encourage their use for estimation of SLW cloud presence. The sensors would sometimes indicate relative humidities below 90 percent when in cloud, and sometimes higher relative humidities when no cloud was present. It appeared that use of conventional relative humidity sensors would result in a high frequency of false alarms. That is, seeding often would be initiated when conditions were not suitable, and often would not be initiated when conditions were suitable.

Propane-heated wind sensors have been developed, and thermal wind sensors exist which consume much less power than a Hydrotech system. Consequently, it is believed practical to measure wind (and air temperature) at remote sites that do not have power lines or electrical generators. The chief problem is the measurement of SLW presence. To further address this problem, a test was conducted in early 1994 at the HAS. A propane-powered Telan thermoelectric generator (60 watt output) was used to continually charge batteries which powered a Rosemount icing meter through a dc-to-ac inverter (tower-type Rosemounts require 115 vac power). This approach proved to be practical and very reliable, and icing rate observations were obtained at the HAS throughout the field season.

It is desirable to further simplify and economize remote observations of SLW and wind within orographic cloud on windward mountain slopes. However, the existing technology is adequate to obtain such observations and to use them to control the release of cloud seeding agents. Remote-controlled AgI generators are available, but existing units are expensive and complex. The simplicity of propane dispensers results in their much lower per-unit price and significantly higher reliability compared with remote-controlled AgI generators.

Of course, AgI seeding has advantages over propane seeding that may favor the former in particular circumstances. For example, unlike propane, AgI can be released well upwind of supercooled cloud and well below cloud base and still be effective in causing ice particles. Such AgI releases would be expected to disperse through a much larger volume of atmosphere than would ice particles caused by propane release within the cloud. These factors favor AgI seeding provided that AgI released upwind of orographic cloud is transported into sufficiently cold cloud regions in adequate concentrations to be effective in snowfall enhancement.

7. SUMMARY AND RECOMMENDATIONS

A propane dispenser was tested during the 1992-93 winter, well up the west slope of the Wasatch Plateau east of Fairview, Utah. The dispenser was based on the design of Reynolds (1989, 1991), with some modifications. The dispenser was turned on and off by a data logger/controller upon receipt of appropriate radio signals from a valley base station. Human intervention and a computer were used to initiate the radio signals. Various data were logged at the site and periodically downloaded to the base station.

A technician was often at the dispenser site, monitoring its operation, while a second technician turned the system on and off. These visual observations helped to confirm the very reliable operation of the propane dispenser.

Further testing was done during early 1994, in two different modes. In the first mode, two dispensers were used during physical seeding experiments with system start-up and shutdown done as in the prior winter (human intervention, radio telemetry and computers). The physical seeding experiments have yet to be analyzed and reported, but dispenser operation was again very reliable.

The second testing mode involved a prototype seeding system which was automatically turned on and off according to weather observations. The weather (SLW, wind and temperature) was monitored at a central dispenser. That dispenser, and two satellite dispensers, were controlled by the presence/absence of SLW, wind measurements, and (redundant) air temperature observations.

The automated seeding system had some problems, but they are considered minor and easily correctable. The system generally functioned very well, especially considering that no visits were made to the dispensers once testing started. Some improvements should be made in the data logger program. A more rigid holder for the propane stream temperature sensor would eliminate the cycling problem experienced by the Bald Mountain dispenser.

It is recommended that future use of an automated propane dispenser system use simplified criteria. The presence of SLW would continue to be measured by a Rosemount icing rate device well up the windward slope. Seeding would commence as soon as the first Rosemount cycle occurred. Seeding would continue for some time (about 2 h) after the last Rosemount cycle in an episode. Wind speed and direction could be monitored but are not believed essential because SLW rarely occurred unless wind speed and direction were appropriate for targeting the Wasatch Plateau. (It is anticipated that most north-south oriented mountain ranges would experience similar conditions.) Some propane would be released during essentially unseedable conditions if only SLW presence/absence was used to control seeding. However, the amount of wasted propane is expected to be minor.

A thermoelectric generator-battery-inverter combination, as used at the HAS in early 1994, is a practical means of powering a Rosemount icing rate device, a data logger/controller, a propane dispenser and radio gear at an exposed remote location in all weather conditions. This system could be the master station controlling a number of satellite dispensers located at similar high altitude sites crosswind of the master station. All sites should be chosen where local SLW production is expected. If one wanted to be sure that SLW existed at each dispenser, each site could monitor SLW with a Rosemount device. This would be a superior but more costly approach.

Propane dispenser testing in California and Utah in recent years has demonstrated the feasibility of a completely automated system that is both reliable and economical. Analysis of the early 1994 physical seeding experiments should improve understanding of the snowfall-enhancing capability of propane seeding. Prior research leaves no doubt that propane seeding can markedly enhance ice crystal concentrations with liquid cloud at or below 0°C. However, it is recommended that the ice crystal yield of the currently-used (in Utah) propane nozzle and release rate be documented. The previously-cited yield values of 10^{11} to 10^{12} ice crystals per gram of propane are based on investigations done over two decades ago. These studies used different release rates and nozzles than recently used in California and Utah. It is of obvious interest to test the current design to determine whether yield values are as high as expected.

Additional key questions to be answered concern ice crystal growth and fallout times downwind of propane dispenser sites. To be effective, propane dispensers need to be within SLW cloud, or at least not far below SLW cloud base where saturation with respect to ice exists. This requires that dispensers be located well up the windward slopes of mountain barriers. Such siting limits the time (distance) available for ice crystal growth to snowflake sizes and fallout to the mountain surface. There is concern that this time (distance) may frequently be too limited for significant snowfall to occur before the seeded ice crystals are carried into the lee subsidence zone where sublimation and evaporation occur.

Another concern with high altitude releases of propane (or AgI) is that crosswind dispersion may be limited, requiring that the crosswind spacing of generators also be limited to avoid unseeded "gaps" between seeding plumes. It may be possible to have greater spacing between AgI generators located further downslope or in upwind valleys thereby requiring fewer seeding sites. Of course, use of lower altitude sites assumes adequate routine transport from them into SLW cloud zones as well as adequate source strengths.

It is recommended that analysis of the early 1994 microphysical observations, and additional future observations, be combined with numerical modeling to address the above concerns. A sophisticated microphysical model, combined with a two or three dimensional airflow model, should be adequate to address ice particle growth and fallout trajectories.

It may be that only relatively wide mountain barriers offer sufficient time and distance for propane seeding to routinely affect snowfall on that barrier. In that case, the best use of high altitude propane seeding may be in seeding a secondary downwind barrier similar to the Bridger Range Experiment target (Super and Heimbach 1983). In any event, the frequency of orographic SLW cloud at temperatures too warm for AgI nucleation is significant over mountains of the western U.S. That fact alone argues for continued experimentation with alternative seeding methods such as release of liquid propane which might augment AgI seeding when slightly supercooled clouds are present.

Acknowledgements. The authors gratefully acknowledge the considerable efforts of Joe Hanks who served as a field technician for the Fairview area tests, and the overall guidance from Barry Saunders of the Utah Division of Water Resources. This work was supported by the NOAA Atmospheric Modification Program and the Bureau of Reclamation, both in cooperation with the Utah Division of Water Resources.

8. REFERENCES

DeMott, P.J., A.B. Super, G. Langer, D.C. Rogers and J.T. McPartland, 1995: Comparative characterizations of the ice nucleus ability of AgI aerosols by three methods. *J. Wea. Mod.*, **27**, in press.

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

Hansen, R., A. Super, C. Ogden and A. Hilton, 1993: Evaluation of remote-controlled cloud seeding technologies, Bureau of Reclamation Technical Assistance to States Report for the Utah Division of Water Resources: Fiscal Years 1992 and 1993.

Hicks, J.R., and G. Vali, 1973: Ice nucleation in clouds by liquified propane spray. *J. Appl. Meteor.*, **12,** 1025-1034.

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.

_____, J.A. Heimbach and A.B. Super, 1995: Observations and model simulation of AgI seeding within a winter storm over Utah's Wasatch Plateau. *J. Wea. Mod.*, **27,** in press.

Huggins, A.W., 1995: Mobile microwave radiometer observations: Spatial characteristics of supercooled cloud water and cloud seeding implications. *J. Appl. Meteor.*, **34,** 432-446.

Reynolds, D.W., 1989: Design of a ground based snowpack enhancement program using liquid propane. *J. Wea. Mod.*, **21,** 29-34.

_____, 1991: Design and field testing of a remote ground-based liquid propane dispenser. *J. Wea. Mod.*, **23,** 49-53.

_____, 1994: Further analysis of a snowpack augmentation program using liquid propane. *J. Wea. Mod.*, **26,** 12-18.

Sassen, K., and H. Zhao, 1993: Supercooled liquid water clouds in Utah winter mountain storms: Cloud-seeding implications of a remote-sensing dataset. *J. Appl. Meteor.*, **32,** 1548-1558.

Super, A.B., 1994: Implications of early 1991 observations of supercooled liquid water, precipitation and silver iodide on Utah's Wasatch Plateau. *J. Wea. Mod.*, **26,** 19-32.

_____, 1995: Case studies of microphysical responses to valley-released operational AgI seeding of the Wasatch Plateau, Utah. *J. Wea. Mod.*, **27,** in press.

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

Vardiman, L, E.D. Figgins and H.S.Appleman, 1971: Operational dissipation of supercooled fog using liquid propane. *J. Appl. Meteor.*, **10,** 515-525.