THE FEASIBILITY OF OPERATIONAL CLOUD SEEDING IN THE NORTH PLATTE RIVER BASIN HEADWATERS TO INCREASE MOUNTAIN SNOWFALL

MAY 2000

Technical Report of the Platte River EIS Team
U.S. Department of the Interior
Bureau of Reclamation
Fish and Wildlife Service

U.S. Department of the Interior
Mission Statement

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Appendix A, dealing with technical cloud seeding material and a summary of results from previous cloud seeding projects and experiments was prepared by Dr. Arlin B. Super.

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EXECUTIVE SUMMARY

This document presents a proposed weather modification program of applying operational cloud seeding technology to enhance the winter snowpack in high-elevation mountainous areas of north-central Colorado and southern Wyoming (hereafter Headwaters Region) and consequently, provide additional streamflow to the North Platte River. Government officials and others are looking at several options for adding water to the river. The Secretary of the Interior is charged with the responsibility for development of the water resources of the Colorado River Basin (Colorado River Basin Project Act, 1968; Public Law 90-537), the protection of water quality (Colorado River Basin Salinity Control Act, 1974; Public Law 93-320), and the transfer of precipitation management technology (Reclamation States Emergency Drought Relief Act, 1991; Public Law 102-250). Several options are under consideration to provide additional water including reservoir management. Cloud seeding technology improvements in the past 20 years now provide a logistically feasible and cost-effective option to enhance fresh water resources in some mountain watersheds of the western United States.

The proposed program consists of two principal components, a cloud seeding design phase and the operational seeding phase. Lessons learned in previous cloud seeding studies indicate that each area presents hurdles to cloud seeding that are site specific. The proposed three-year design phase is aimed at conducting field and modeling studies to determine the proper approach, equipment, and installation sites appropriate for the Headwaters Region. Additionally, the design phase will enable dealing with environmental compliance and the conduct of associated studies. No cloud seeding can take place until compliance is achieved. Because average winter precipitation is expected to increase in the Headwaters Region from cloud seeding, environmental compliance efforts for a possible Environmental Assessment or Environmental Impact Statement are estimated to require three years for completion. Intended benefits of a three-year design effort include the development of an evaluation design proper for operational seeding in the Headwaters Region. The operational seeding period is structured for 10 years (equipment, permits, environmental compliance) and will involve automated cloud seeding systems that largely self-determine when seeding is appropriate and then proceed to treat clouds. Data collection is also expected to be largely automated. All data collection and cloud seeding system types should be installed and tested in the design phase.

Regarding the scientific support for cloud seeding, current policy statements of the American Meteorological Society and the World Meteorological Organization state that statistical analyses of some cloud seeding programs have suggested mountain snowfall increases of 10 to 15 percent per winter. Cloud seeding experiments conducted and/or supported by the Bureau of Reclamation in the 1980-90s have contributed sorely needed physical measurements and analyses that documented cloud and precipitation responses to cloud seeding and indicated that specific areas can be targeted for treatment effects. These studies along with the substantial improvement in computer modeling of weather and clouds provide methodology that can be applied to seeding winter clouds in the Headwaters Region and expect to obtain measurable additional precipitation.

Seeding trials conducted on winter clouds in the Grand Mesa of west-central Colorado and the Wasatch Plateau of Utah repeatedly indicated a precipitation increase response to seeding (see appendix A, sections 7 and 8, for details and references). Those studies did not include a component of statistical evaluation of precipitation, but were rather structured for physical measurements. To develop estimates of additional water from cloud seeding in the Headwaters Region, enhancement results of about 25 percent in the Bridger Range (Montana) and Climax I and II (central Colorado) Experiments were used. This increase combined with a storm seedability factor of 0.45, estimated from limited cloud modeling with the Colorado State University three-dimensional Regional Atmospheric Modeling System, yielded a precipitation seasonal increase of 11.25 percent, the value used to estimate headwaters additional precipitation.

Estimates of water volume increases were made with an approximate 28 percent areal coverage of the Headwaters Region resulting from use of a sample seeding design (shown in figure 4.1) and equipment placement for 55 seeding devices. This number of devices was obtained from brief study of terrain digital elevation data, wilderness area locations, estimated seeding plume widths and nonlocal winds, and is strictly a preliminary assessment. Applying the 11.25 percent increase to average winter precipitation in the Headwaters Region yielded an additional 60,000 acre-feet of water in the areas above 9000 feet in elevation covered by the seeding plumes of the 55 seeding devices. For the dry year (50 percent of normal precipitation), seeding yielded an additional 30,000 acre-feet, and the seeded wet year produced 90,000 additional acre-feet (150 percent of normal precipitation). The increases grow to the respective 85,000, 43,000, and 128,000 acre-feet of water when the areal coverage by seeding devices is increased to 40 percent through possible seeding design improvements. The design phase of the program will produce a proper seeding device siting and consequently, seeding areal coverage. These figures are not adjusted for possibly differing seeding opportunity from one year type to another. Additionally, they do not incorporate effects of cloud seeding suspension criteria (likely to mostly affect results in wet years) that will need to become a component of the program's environmental awareness.

The annual cost of the first year of operational seeding is estimated at $1,025,000 and the tenth year at $1,330,000 using a 3 percent inflation factor per succeeding year. The estimated 10-year cost of operations is $11,716,000. Assuming 55 cloud treatment devices are used in seeding, the average annual cost of operations per seeding device is $21,300. This figure includes annual costs for all operational tasks, assuming automated conduct of cloud seeding, largely automated collection of field data, no observations by aircraft or local scanning radar. Weather service routine radar information from the network's Grand Mesa Colorado system would be available. Cost estimates would be revisited at the end of the design phase.

The first year of the design phase will be devoted to planning, weather and cloud modeling, environmental compliance and permitting, study site selection for the design phase, preliminary surveying of the Headwaters Region, and contract procurement. The following two years will entail field data collection for two winters, data analysis, additional weather and cloud modeling, equipment specification and siting determination, environmental compliance, and public involvement. The cost of conducting the design phase effort, including environmental compliance estimated at $275,000, but short of equipment costs, is $1,498,000 for the three years. Total equipment costs are estimated at $1,800,000. The seeding equipment is estimated at $1,369,000.

Weather modification programs must comply with National Environmental Policy Act (NEPA) requirements if they include financial or regulatory participation by the Federal Government, or affect lands managed by Federal agencies. The proposed program faces compliance for the design phase possibly at a low complexity level, but because precipitation increases are expected in the operational seeding phase, compliance for it may be at a moderate to high complexity level requiring data collection and analysis. No cloud seeding or significant disturbance of ground or vegetation can occur until NEPA requirements are met. An interdisciplinary team of experts will be needed. Public involvement will be necessary. An involvement plan should be developed in consultation with appropriate Federal, State, and local agencies, plus interested and affected individuals and groups. A group of local citizens should be established to assist in scoping environmental issues and serve as a communications link to the public.

After recent knowledge gains in winter orographic cloud seeding, it is believed that a well designed and managed program can now be implemented in some watersheds of the West to produce cost effective additional water resources. In the proposed program, cloud seeding would target additional water for high elevations that supply water to the North Platte River. Additional snowfall from seeding accrues unprotected at high elevations. Estimated benefits to particular habitats will be determined in other studies. Clearly, additional water from successful cloud seeding can help satisfy increasing water supply demand and environmental water needs in areas of the West. Clean-source additional water can improve water quality and supplement domestic needs and uses of industry and recreation. Minimum streamflows can be improved for fish and wildlife.

1. INTRODUCTION

1.1. General Discussion

This document presents a proposed plan for the conduct of an operational cloud seeding project aimed at increasing winter precipitation (snowfall) in the high elevation headwaters area of the North Platte River Basin (hereafter Headwaters Region). The scientific basis lies largely in the increase in information on the treatment of winter orographic (mountain barrier induced) clouds in the western United States in the past 20 years. Studies were sponsored/conducted by the United States Bureau of Reclamation (Reclamation), National Oceanic and Atmospheric Administration (NOAA), National Center for Atmospheric Research (NCAR), Colorado State University, Desert Research Institute of the University of Nevada at Reno, University of Wyoming and others. Cloud studies and seeding projects of particular interest here were conducted at the Headwaters Region, the Grand Mesa of west-central Colorado, the Wasatch Mountains of Utah, the Sierras of California, the Bridger Range of Montana, and the Colorado central mountains (projects are described and discussed in appendix A, sections 7 and 8). These studies conducted many seeding trials to determine cloud responses to treatment. The projects also studied natural cloud processes. The diversity of study areas and weather conditions provided data for analysis covering a broad spectrum of conditions, thus broadening the knowledge base and understanding of cloud precipitation processes and treatment possibilities. Results from these recent projects provide the scientific basis and methodology for the proposed cloud seeding program presented here.

There is support for cloud seeding from professional organizations. The current policy statement of the American Meteorological Society (AMS) on the status of precipitation increase from supercooled orographic clouds states, "There is statistical evidence that precipitation from supercooled orographic clouds has been seasonally increased by about 10%" (adopted by the AMS Council 2 October 1998, Bulletin of the AMS, 72, 57). Stated elsewhere in the policy statement is, "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." Clearly, the AMS feels that physical measurements and their analysis are an important part of the evaluation of planned weather modification. The World Meteorological Organization (WMO) statement notes that, "In our present state of knowledge, it is considered that the glaciogenic seeding of clouds or cloud systems either formed, or stimulated in development, by air flowing over mountains offers the best prospects for increasing precipitation in an economically viable manner." The AMS and WMO policy statements were prepared by panels of experts.

The proposed cloud seeding program has some scientific hurdles to overcome. Most prominent is determining how to best apply the technology to the geographic, and winter weather and cloud conditions of the Headwaters Region. For success, the proposed program must apply state-of-the-art science and technology in conducting the cloud seeding, and executing a proper evaluation of results. Many operational cloud seeding projects seeking additional precipitation seem to eventually become embroiled in controversy as to their accomplishments. Their major problem centers on the inability to determine in a convincing fashion the seeding effects on precipitation. They suffer from inadequate evaluation design, data collection, and proper analysis. Most cloud seeding projects will eventually need to provide results that can withstand scrutiny from the scientific community. The large area and diversity of the Headwaters Region suggest the proposed project must include a thorough and credible evaluation component that includes statistical evaluation, and selected physical measurements that confirm the seeding of clouds. Prior projects have had great difficulty in ascertaining that clouds actually received treatment. Generally, operational seeding projects attempt to seed all potential cases to maximize results. This approach has complicated (usually negates) determining natural cloud responses in lieu of seeding.

The proposed project must confront the evaluation design issue in the program design phase.

The program design phase must also confront that previous studies suggest that the window of opportunity for obtaining precipitation increases from cloud seeding is narrower than previously conceived (Cotton and Pielke, 1995). Furthermore, it is apparent in previous studies that successful cloud seeding procedures for one area may be failures in another site. These results support that each area requires separate study and the development of an individualized cloud seeding design. A major concern for the design phase is the diverse terrain of the Headwaters Region and that cloud seeding effects must be targeted for the lee side for portions of the western barrier. The proposed project for the Headwaters Region must include a well-conceived design phase aimed at developing, among several components, an operational seeding plan for the specifics of the area.

Figure 1.1 presents a layout of the main high elevation areas of the Headwaters Region. The Park Range in northern Colorado extends into southern Wyoming where the barrier is called the Sierra Madre. The entire western barrier is sometimes referred to as the Park Range. The Medicine Bow Mountains on the east side of the Headwaters Region also extend from northern Colorado into southern Wyoming. Lengths of the higher elevation portions of the two primary barriers are about 65 mi for the Park Range north of Rabbit Ears Pass, and 70 mi for the Medicine Bow barrier from Cameron Pass on the south. Runoff from more southerly portions does not drain into the North Platte River. The figure shows large wilderness areas in the west and east barriers that will challenge the operational seeding design.

The proposed project must use the latest tools of measurement of field variables such as winds and cloud liquid water, and numerical simulation tools including three-dimensional cloud models that can assist and expedite the design of the cloud seeding component. Because of improvements in computers and cloud model development and testing the past couple of decades, computer models are available to assist in the project design, conduct and evaluation. For example, the Colorado State University cloud model known as the Regional Atmospheric Modeling System (RAMS) has had some application to differing winter storms over the Headwaters Region, at the high resolution of three-kilometer grid point spread. High resolution simulation is needed to provide more information on parameters of orographic clouds that are important to cloud seeding. Some results of recent cloud simulations with RAMS will be given later in this report.

1.2. Program General Plan

The proposed project is aimed at providing additional snowfall in the Headwaters Region. The project plan will consist of two principal components: (1) an operational phase with proper evaluation capable of determining cloud seeding effects on precipitation, (2) a cloud seeding design phase that consists of studies aimed at determining and testing how to best seed winter clouds in the headwaters region and what information must be collected in the operational phase for proper evaluation and environmental awareness. Because each geographical area presents different meteorological and terrain conditions than others studied, the project plan must include developing a cloud climatology and response to the highly varying terrain of the Headwaters Region. The design phase must establish what measurements and equipment are appropriate for the operational phase.

Supplementary studies may be conducted by partner agencies as part of the project design phase and/or the operational seeding phase. These studies can contribute additional information of value to the

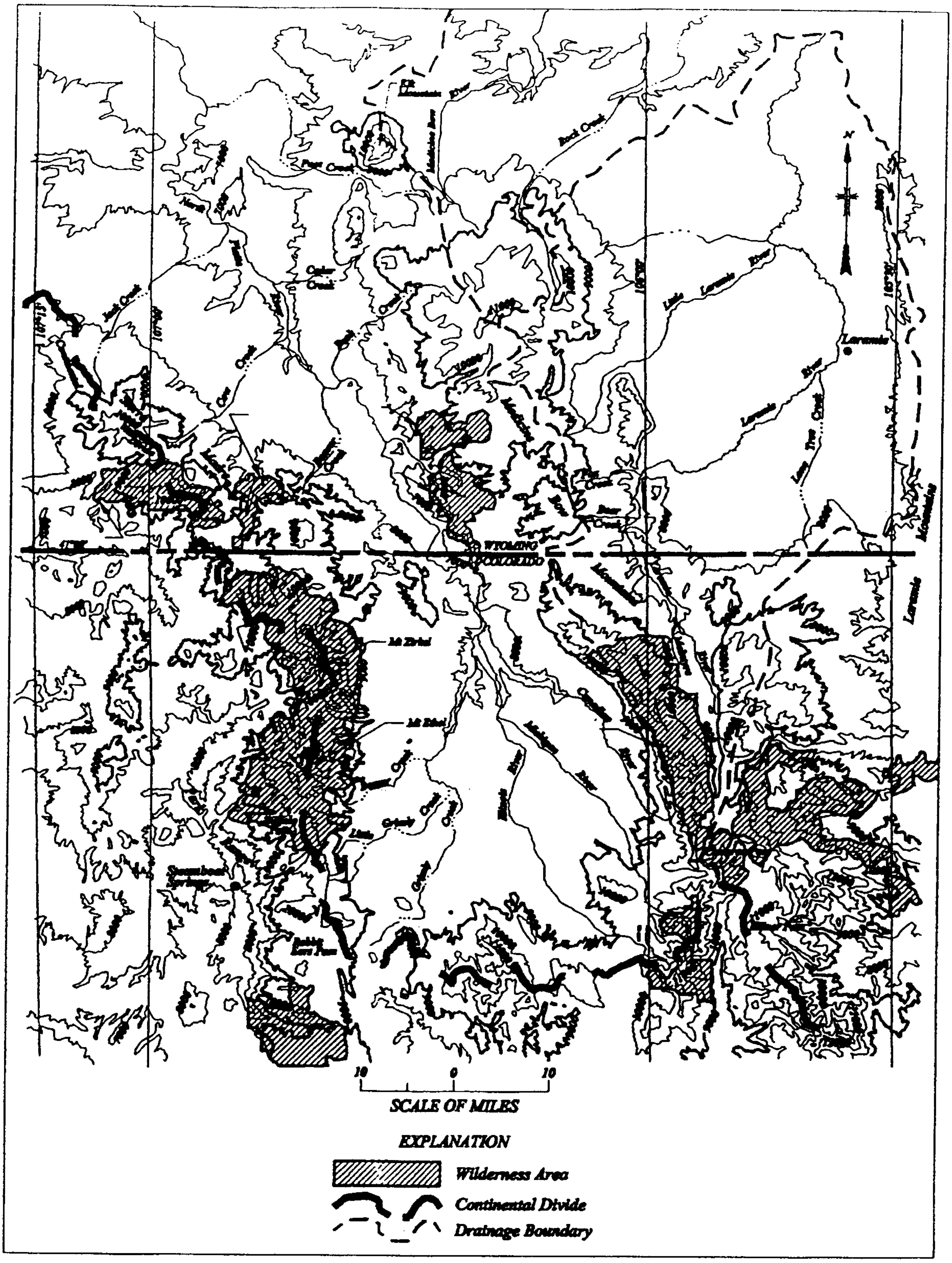

Figure 1.1 - Map of the Headwaters Region of the North Platte River Basin showing the proposed Park Range/Sierra Madre and Medicine Bow Mountains target areas and nearby terrain. Contour intervals are shown at 1000 foot intervals above mean sea level with the 9000-foot contour in bold. Drainage boundaries, including the Continental Divide, are shown by dashed lines. Wilderness areas are shaded. (Adapted from appendix A)

Proposed project and partnering agency research objectives. For example, collection of data by aircraft could add valuable information to the design phase, particularly, but also could be useful to the precipitation evaluation of the operational phase. This is also the case with doppler radar data. The collection of data by aircraft and land-based radar is very expensive and will be considered as important, but not essential to the design or operational phases. Weather service doppler radar information will be available to the program. Locally, a doppler radar is located on the Grand Mesa. Some aircraft data were collected in the Park Range during the Colorado Orographic Cloud Seeding Experiment (COSE) (for example: Rauber et al., 1986; Rauber and Grant, 1986; Rauber, 1987) conducted by Colorado State University in the early 1980s (supported by Reclamation, the National Science Foundation, Air Force Geophysics Laboratory, NCAR, NOAA and others) and those results were published.

A shortcoming of aircraft data collected from the Headwaters Region is that important cloud information cannot be retrieved within 2000 feet (vertical) of barriers when the aircraft must fly in clouds. Recent studies of aircraft and ground-based microwave radiometer (an instrument that estimates integrated cloud liquid water along the scan line) data indicate that most orographically-induced supercooled liquid water (SLW) is concentrated in the lowest 2000 feet or so above mountain barriers (Super, 1999). The SLW is a necessary, but not sufficient, cloud characteristic requirement for seeding. A radiometer can supply information on integrated SLW, but not data on the dispersal of seeding effects in cloud that an aircraft can sometimes provide. Nevertheless, the benefits from aircraft data in the proposed program are not felt large enough against the cost, to recommend their use in data collection.

The proposed program must deal with some essential components including environmental compliance, public awareness and information release, and program organization and management. Cloud seeding suspension criteria will need to be developed for the design phase, and separately for operational seeding because of much greater area-of-effect and the need to treat most potential cases. Weather and cloud modeling must be conducted using a three-dimensional model at high resolution.

The following report sections include chapter 2 that covers the scientific basis for conducting the operational cloud seeding. Chapter 3 discusses the program design phase, associated labor costs and equipment costs. Chapter 4 covers information on the operational cloud seeding phase including estimates of additional water and the costs to conduct the operational seeding. Compliance with environmental regulation is covered in chapter 5. The proposed program time schedule is presented in chapter 6. An appendix A authored by Arlin Super is included to present cloud seeding in more technical detail, discuss some important previous cloud seeding and observation studies more thoroughly, and provide an extensive list of references.

a. Some of the droplets may be "nucleated" and become embryonic ice crystals. This ice nucleation process requires the presence of very tiny particles known as ice nuclei, concentrations of which vary widely in time and space. Natural ice nuclei, in the form of clay particles and leaf litter, have concentrations much less than those of cloud droplets. There are some ice multiplication processes, including crystal fragmentation, that also provide "nuclei" for additional ice crystal growth.

b. After embryonic ice crystals form, they grow by the process of diffusion involving the vapor transfer of water molecules from droplets to crystals. This transfer occurs because the saturation vapor pressure is greater over water than ice.

c. Many droplets may be captured by, and freeze onto, faster falling individual ice crystals or snowflakes, a process known as accretional growth or "riming." In some clouds this can lead to the growth of graupel (snow pellets) and hail.

d. Aggregation is a process whereby smaller ice crystals collide and "chain together," becoming larger snowflakes with faster fall velocities. Sometimes riming will help this process by acting as a "glue." Stellar and dendritic crystal habits are especially prone to aggregation but other habits, such as needles, also aggregate. Heavy snowfalls usually involve aggregation into large, fluffy snowflakes.

Snow crystals have a variety of habits, or shapes, and growth rates, mostly based on the temperature of the cloud environment and to a lesser extent the moisture content of the air. Laboratory growth rates between -3 and -21 °C were reported by Ryan et al. (1976) for times up to about 3 min. Dendritic crystals grow the fastest at about -15 °C, which is at a peak in the vapor pressure difference between SLW and ice. A secondary growth peak may exist for needles and columns at about -7 °C. Thick plates, at about -10 °C and -20 °C have the slowest growth rates. Growth rates are slow between -3 to -4 °C.

Redder and Fukuta (1989) presented equations for ice crystal mass and dimensional growth. They used six experimental data sets from cloud chambers or supercooled cloud tunnels for growth periods up to 30 min. Molecular diffusion was the predominant growth mechanism in all reported experiments. The authors indicated that after 20 min growth time, the mass of individual ice crystals would be in the range of 5 to 10 μg for temperatures between -5 and -12 °C and for colder than -17 °C. Crystal masses greater than 10 μg were found between -13 and -17 °C in the dendritic growth zone, with the maximum of 30 μg at -15 °C. The minimum mass after 20 min growth was 2 μg at -4 °C, the warmest temperature considered. This same information is presented in table 1 in section 11b. While their results agreed with the -15 °C maximum found by the short duration studies of Ryan et al. (1976), a secondary maximum at -7 °C was not indicated after 20 min growth.

Super (1994) referred to earlier field observations which suggested that a typical natural ice crystal from an orographic cloud had a mass of approximately 20 μg. Of course, considerable variation existed among individual crystals and the "typical" value is roughly a median of the various field observations which were examined. The typical value is similar to the fastest diffusional growth results at 20 min but less than the masses expected for most of the supercooled temperature range of interest. Natural crystals often have growth times well in excess of 20 min because they form high in the cloud and have long growth and fallout trajectories.

Rauber (1987) found that the primary source region for ice particles observed near the Park Range was near cloud top. Most of the resulting snowflakes on the mountain surface likely originated tens of kilometers upstream from the Park Range, with travel times on the order of 30 to 60 min. He also discovered that many small ice particles were found well below cloud top in regions of strong orographic uplift. The latter naturally-formed crystals would have shorter travel and growth times and, therefore, be more similar to seeded crystals.

Redder and Fukuta (1991) presented a companion paper to Redder and Fukuta (1989) which included information on fall velocities. Fall velocities of individual crystals ranged between 30 and 60 cm s^{-1} with the maximum at -10 °C (columns and thick plates) and minimum near -5 (needles) and -15 °C (dendrites and stellars). Using a fall velocity of 45 cm s^{-1}, an average mass of 20 X 10^{-6} g and crystal concentration of 20 L^{-1} yields a snowfall rate of near 0.028 inch h^{-1}, a typical snowfall rate in the Intermountain West. It should be noted that snowfall accumulations and rates in this paper refer to melted snow water equivalent, not snow depth.

Super et al. (1986) discussed two winters of high resolution gage observations on the Grand Mesa of western Colorado. They showed that the median hourly snow water equivalent accumulation was 0.028 inch for all hours with at least 0.01 inch accumulation. This median is the same value as in the above calculated example. These simple calculations show that significant snowfall can be produced by about 20 L^{-1} individual crystals allowed to grow by diffusion for approximately 20 min at temperatures in the dendritic growth zone (-13 to -17 °C). Lighter but still meaningful snowfall rates would be achieved at warmer temperatures. Of course, greater crystal concentrations and longer growth times would produce greater seeded snowfall rates, as would riming or aggregation which can significantly increase fall velocities and mass growth rates.

Ice crystal size (not mass) growth rates were presented by Holroyd (1986) using aircraft observations from simple orographic clouds. He found a growth rate near 0.07 mm min^{-1} valid through 13 min at -13 °C and a rate near 0.1 mm min^{-1} valid through 15 min and probably through 30 min at -14 °C. These results from orographic rather than laboratory clouds are noted because they are in reasonable agreement with Ryan et al. (1976) and Redder and Fukuta (1989), adding credibility to the laboratory results.

3c. Artificial Ice Crystal Initiation

Ice crystals can be artificially formed (caused by seeding) within a population of SLW cloud droplets by either of two forms of nucleation, heterogeneous and homogeneous.

Heterogeneous nucleation involves interaction between a SLW droplet and a foreign particle known as an ice nucleus. Most natural atmospheric ice nuclei are tiny insoluble clay particles transported from the ground by the wind (Dennis 1980). It could be questioned whether such ice nuclei should always be considered "natural" because plowed fields are often the source of the clay particles. While some industrial emissions produce artificial ice nuclei they rarely have more than local importance.

The homogeneous nucleation process does not require interaction between foreign particles and water droplets, but only that cloud be chilled a little colder than -40 °C. Practical means of seeding by this process include dropping dry ice (solid CO_2) pellets into SLW cloud or the expansion of a (possibly liquified) gas to achieve very local within-cloud cooling colder than -40 °C. Such chilling of cloudy air produces very large supersaturations resulting in the condensation of vast numbers of tiny droplets which immediately freeze, forming embryonic ice crystals. Freezing of preexisting cloud droplets is of limited importance because of their much smaller concentrations. The most frequently used agents for homogeneous nucleation are dry ice and liquid propane, with occasional use of liquid nitrogen in foreign countries and compressed air in the laboratory. The use of compressed air released through a supersonic nozzle has been proposed for supercooled fog dispersal by Weinstein and Hicks (1976). However, this approach would require significant electrical power for pumps, making it impractical for mountain seeding sites.

Silver Iodide (AgI), either in rather pure form or with various additives, is by far the most commonly used heterogeneous seeding agent. It has a threshold temperature near -6 °C, where a small fraction of the total AgI particle population begins to nucleate ice particles. It has usually been impractical to achieve significant ice crystal concentrations several kilometers downwind from an AgI generator at temperatures warmer than -9 °C. The reason is the two to three or more orders of magnitude increase in ice nucleating activity between -6 and -9 °C. A typical generator has an output of about 10^{14} ice crystals per gram of AgI, effective at -9 °C.

Besides this strong temperature dependence, the effectiveness of AgI seeding depends on the specific type of chemical and particular generator design used and the atmospheric conditions at the release point. Many operational programs use relatively pure AgI released well below cloud. The resulting contact-freezing nucleation process depends on cloud droplet concentration. Because winter orographic clouds have relatively low droplet concentrations, the contact-freezing process is known to be quite slow. That is, only a fraction of the AgI particles with the potential to nucleate ice will do so over a typical in-cloud residence time of 20 to 30 min.

The effectiveness of various seeding solutions, loosely referred to simply as AgI but often much more complex, is known to vary widely. The strong temperature dependence and less pronounced wind speed dependence of the ice nucleation effectiveness of particular AgI solutions has been widely documented, such as by DeMott et al. (1995). This same reference shows that some types of AgI with additives are fairly fast acting because they operate by the condensation-freezing mechanism at water saturation which does not depend on droplet concentration. Changing from the commonly used AgI aerosol, which nucleates by contact-freezing, to the AgICl-0.125NaCl aerosol, which acts by a faster condensation-freezing process, would provide about an order of magnitude increase in seeding effectiveness during a 20 min in-cloud transit time. Other types of AgI have also been shown to be faster-acting, and more efficient in the important -6 to -9 °C range, than the relatively pure AgI aerosol which operates by contact-freezing. However, some of these agents cause operational problems in the field such as nozzle clogging.

A special case of condensation-freezing is the "forced" condensation-freezing mechanism discovered by Finnegan and Pitter (1988). It is achieved if AgI is released within cloud where the consumption of the AgI-acetone solution and propane add abundant local water vapor just above the generator stack. This approach causes large transient supersaturations, resulting in the formation of vast numbers of ice crystals immediately downwind from the generator stack if the cloud is colder than -6 °C. This mechanism has been shown to work with all silver iodide-containing aerosols in rapidly and efficiently forming ice crystals at the relatively warm temperature of -6 °C.

Li and Pitter (1997) reported on numerical simulations of ground-based AgI seeding for two ice crystal formation mechanisms, contact-freezing and "forced" (very rapid) condensation-freezing. A relatively simple orographic cloud model was used to investigate how the different mechanisms affect snowfall patterns and intensities. A temperature sensitivity analysis showed large effects on snowfall production by forced condensation-freezing because ice nucleation is a strong function of temperature. The authors cite Feng and Finnegan (1989) who showed ice nucleation efficiency is enhanced by four orders of magnitude from -6 to -10 °C. They considered the field results of Super and Heimbach (1983) at the Bridger Range of Montana to be strong evidence for forced condensation-freezing because suggested seeding effects were for ridge top temperatures of -9 °C and colder. That condition corresponds to high altitude generator site temperatures colder than -6 °C. The generators were usually operated in-cloud.

3. PROGRAM DESIGN PHASE

3.1. Background

Previous cloud seeding projects have provided information clearly pointing to the need for conducting a design phase for a program such as proposed for the Headwaters Region. However, design studies for the Headwaters Region are somewhat facilitated by the availability of results of prior studies conducted in the Park Range. Cloud physics and modeling studies were conducted as part of COSE (Rauber et al., 1986; Rauber and Grant, 1986; Rauber, 1987). Since the COSE studies, a high-altitude (10,520 feet) laboratory known as the Storm Peak Laboratory (Borys and Wetzel, 1997), currently managed by the Desert Research Institute of the University of Nevada at Reno, has been maintained for further study of winter clouds and aerosols. Other Park Range data collection occurred during the mid-1960s as part of a 5-year program of cloud seeding investigations (Rhea et al., 1969). Some experiments involved the release of AgI and airflow tracer material to study the transport and dispersion of ground-based and aircraft released cloud seeding agents. The results of studies by Rhea et al. should be used as additional background information on cloud seeding in the Park Range. The previous studies will provide useful information, but the proposed project is facing considerably more formidable tasks such as determining the placement of more than 50 seeding devices, most likely at high elevations and in rugged terrain. Placement must facilitate adequate residence time in-cloud for growth of seeding created ice particles for deposition in the intended target area.

The Grand Mesa winter cloud seeding studies (see appendix A, chapter 7) provide additional background information useful to pursuing field studies in the Headwaters Region. Aircraft and surface observations of seeding trials provide convincing results that cloud seeding can cause precipitation increases (Super and Boe, 1988). The early 1990s seeding experiments in the Wasatch Plateau of Utah (Super and Holroyd, 1994) provide more results in conducting orographic cloud seeding. Aircraft and surface observation collected before, during and after seeding trials also document precipitation increases and clear evidence that clouds were seeded.

Design studies are needed to develop an operational seeding plan that mitigates the following existing conditions in the Headwaters Region and allow for incorporation of new technologies that improve cloud seeding and reduce costs.

- The terrain differs widely within the Headwaters Region. Terrain differences and the presence of large wilderness areas will present additional problems and challenges to planning and program conduct. Design studies will enable determining the proper cloud treatment approaches, and equipment types, numbers and siting for the terrain and weather conditions of the Headwaters Region.

- Cloud treatment effects must be directed at the lee side of the Park Range and Sierra Madre Mountains for additional runoff into the North Platte River. Typically, targeted areas for cloud are located on the windward slope. Targeting the lee slope will require additional study and observations on ice particle growth and residence times in favorable cloud environments under typical storm wind conditions. Cloud modeling will help scope this issue.

- Design studies will allow the testing and incorporation of new technology for the Headwaters Region. In particular, automated seeding systems must be tested in the conditions of high elevations and winter weather. Power is not available for most likely equipment locations. The cost of power plants and their operation is considerable. It is hoped that solar energy systems and rechargeable batteries can be adequate to operate automated seeding and telecommunications systems. Additionally, some automated data collection systems are expected to be implemented in the operational seeding phase to assist in evaluating seeding results and maintain information for environmental awareness needs. These systems too must be tested in the design phase.

- The conduct of an operational program over the relatively large Headwaters Region will cause scrutiny from the scientific community, the general public, and water interests of the Platte River. Water users will be concerned about scientific proof of additional water. Design studies must produce a viable operational program plan with a credible evaluation component to deal with what is likely to be considerable program scrutiny.

3.2. Design Phase Components

The design phase must produce answers to questions concerning influences on cloud seeding of the regional winter weather, cloud characteristics of clouds that form in different barriers of the Headwaters Region, and other terrain related and intra-area influences. Questions must be addressed such as the average extent storms are seedable. Some issues will be quite difficult to resolve such as determining the impact on cloud seedability of emissions from power plants located upwind of the western barrier (in many storm cases). The accuracy of cloud modeling for the Headwaters Region must be determined early in the program.

Design studies should be selected and structured to speed the advent of the operational program, yet provide the necessary answers and support that will withstand scientific scrutiny. The proposed design phase time length is recommended to be three years. This phase length fits well with obtaining permits for installing field equipment, conducting test seeding operations, and satisfying environmental compliance. Additionally, answers needed for operational seeding design will require two years of field studies. Some randomized seeding trials should be conducted to make comparisons in the highly varying conditions of the Headwaters Region.

Some components of the design phase field studies are outlined in the following.

- Conduct weather and cloud modeling during the first year of the program. Analyze modeling results and include previous information from the Headwaters Region as appropriate. Survey and analyze terrain characteristics of barriers involved in the seeding program.

- Plan a limited field program and install and test automated field equipment in the late summer and fall of the first year. Install a communications system that includes field equipment and an operations center.

- Conduct limited field studies for two winters that include seeding trials in which the transport and diffusion of seeding created ice particles are analyzed. Evaluate results and establish an operational program in the third year of the design phase. Randomized results should be properly analyzed to update estimates of additional water from seeding and develop an appropriate evaluation plan for the operational phase.

Field studies and cloud modeling will yield a design for the operational seeding phase. The analysis effort will conclude with a report that presents an operational cloud treatment plan for the Headwaters Region, including specification of equipment and personnel requirements, recommended data collection, and an improved estimate of precipitation increase expected from operational seeding.

Other work tasks of the design phase will entail contracting. Contracting work may include site surveying, modeling, equipment acquisition, equipment installation/removal and maintenance, some environmental compliance studies, and field study data and seeding result evaluation. Contracts will vary in work details but all must clearly spell out work items, supervision, work site requirements, and equipment provision. Reclamation must provide guidance to program components and participation in study analyses when appropriate.

3.3. Cloud Modeling Studies

Numerical modeling of winter orographic clouds has significantly improved in the past 20 years and faster computers have facilitated improvements. These conditions have led to increases in the understanding of cloud airflow and microphysical processes (Young, 1974; Cotton et al., 1986; Bruintjes et al., 1992). High resolution three-dimensional modeling can now assist the study of winter cloud precipitation processes for areas such as the Headwaters Region. A few results of the RAMS model's simulation of several storm days of the 1998 and 1999 winters in the Headwaters Region are given in section 4.6.1. Modeling with a sophisticated model such as RAMS is needed to assist the design process for the Headwaters Region. Model runs should include simulation of effects of cloud seeding for comparison with nonseeded model results and field measurements. Comparisons of modeling results with field measurements are needed to study model deficiencies and possibly improve the model. Routine application of a model during the operational seeding phase will assist with weather and cloud forecasting, operations planning, and the provision of covariate information for the evaluation process. Modeling can help assess when atmospheric conditions are suitable for cloud seeding in the Headwaters Region. This information will assist design phase studies and possibly provide valuable information for locations where equipment is not installed.

The availability of affordable, powerful computer workstations will allow use of sophisticated models for cloud seeding targeting decisions. Processes of particular interest that will be tested in a model include the three-dimensional airflow and associated transport and diffusion of ground-released seeding agents, and the growth and fallout of precipitation particles. The model should be tested for determining likely seeding release points for individual storms. Different cloud treatment strategies should be tested through modeling and as possible in seeding trials.

3.4. Cloud Seeding Hypotheses

A conceptual operational seeding model specific for the Headwaters Region will emerge from the design phase. Specific component hypotheses that are appropriate for the conceptual seeding model will be generated. The design phase will seek answers for each hypothesis. The following presents loosely stated examples of hypotheses that may apply to the Headwaters Region. Properly constructed hypotheses will be developed upon completion of design studies. The seeding hypotheses given here are based on knowledge gained in the COSE experiments (Rauber et al., 1986; Rauber and Grant, 1986; Rauber, 1987), the Bridger Range Experiment (Super, 1974; Super and Heimbach, 1983), the more recent Grand Mesa experiments (Super et al., 1986; Holroyd et al., 1988; Super and Boe, 1988), and recent Wasatch Plateau, Utah experiments (Super, 1999; Super and Holroyd, 1994; Super, 1995; Super, 1996; Super and Holroyd, 1997; Holroyd and Super, 1998; Holroyd et al., 1995).

The seeding hypotheses are based on dealing with orographically-enhanced supercooled winter clouds over the Park Range, using ground-based high-elevation propane dispensers and/or AgI generators.

G1. There exists SLW in excess of that naturally converted to snowfall when the prevailing wind produces a positive component normal to the mountain barrier.

G2. Cloud seeding devices (propane gas or AgI) reliably lead to the creation of ice particles in an environment favorable to the survival of ice, while in transport to cloud volume containing SLW.

G3. Seeding creates ice crystals in numbers, estimated by models and limited measurements, to be adequate in concentration, that turbulence and/or convection lead to transport and diffusion throughout a substantial portion of the targeted SLW zone.

G4. Favorable environments exist and growth time is adequate during transport such that ice particles can grow large enough to reach the intended target area before evaporation/sublimation occurs in the lee-side airflow.

G5. Additional precipitation caused by cloud seeding occurs in amounts that are detectable in the intended targeted areas when compared to control amounts.

The seeding hypotheses resulting from the design phase are expected to be largely based on the static seeding mode. However, the modeling results of Orville et al. (1987) suggested that seeding layer clouds may cause embedded convection under some atmospheric conditions, leading to enhanced liquid water production. Because dynamic effects may sometimes occur by presumed static seeding, observations in the Headwaters Region must be viewed in light of possible dynamic effects under favorable atmospheric conditions.

The field measurements necessary to deal with seeding hypotheses G1-G5 include some or all of the following.

M1. Assess SLW over the mountain barrier with radiometers and/or icing rate meters.

M2. Measure propane gas dispenser flow rate and nozzle temperature. Measure AgI generator solution flow rate and flame temperature. Automatically telemeter measurements via radio to a central monitoring site.

M3. Measure ambient temperature, humidity and winds at seeding device locations and at other selected locations of the mountain barriers. Telemeter measurements via radio to the central monitoring site.

M4. Estimate transport and diffusion of the seeding created ice particles with mobile detectors mounted on a four-wheel drive vehicle, at the Storm Peak Laboratory, and possibly one other fixed location in the Medicine Bow Mountains. Measuring devices may include 2D probes, ice nucleus counters, tracer gas detectors, and a cloud droplet measuring device (FSSP). Other equipment may include (optional) scanning Doppler radar for assessing winds to and from the radar and precipitation, and a radar profiler to monitor the vertical distribution of horizontal winds and virtual temperature.

M5. Measure precipitation with high resolution gauges with specifications to resolve to within five minutes and 0.1 millimeters of water equivalent. Gauge spacing will be determined during the project design phase.

M6. Periodically sample snow particles at selected precipitation gauge sites using a radio-controlled sampler and/or automated photography. Periodically collect samples and analyze later for silver and/or indium concentrations.

The Storm Peak Laboratory, located at the high altitude of 10,520 feet, is equipped for collecting typical weather information plus data on aerosols and some cloud physics variables (intermittently) such as cloud liquid water presence.

3.5. Field Instrumentation

The instrumentation systems necessary to conduct assessments M1-M6 are listed in table 3.1. Some of the instrumentation such as doppler radar will contribute observations only if provided by a partnering agency. The outcome of design phase studies will determine what equipment is appropriate for the operational seeding phase in the Headwaters Region.

Table 3.1. - Instrumentation options for the design phase (see appendix A for a description of sensors).

1. Three microwave radiometers for vertically integrated SLW observations.
2. Tower-mounted icing rate meters for surface SLW observations.
3. Rawinsonde system for vertical profiles of wind, temperature, and moisture.
4. Automatic weather stations for surface wind, temperature, and humidity fields.
5. High resolution precipitation gauges for measuring rates of snowfall water equivalent accumulation.
6. Instrumented vehicle for AgI, SF6, and ice particle sampling crosswind through the seeding plumes.
7. Two manned observing sites to monitor precipitation, ice particles, AgI, SF6, and snow samples for chemical analysis.
8. Remote-controlled snow samplers for chemical analysis.
9. Remote-controlled AgI generators.
10. Remote-controlled indium generators.
11. Remote-controlled propane dispensers.
12. Remote-controlled SF6 gas dispensers.
13. Radar wind profiler with RASS capability for vertical profiles of wind and virtual temperature.
14. (Optional) Research aircraft capable of monitoring 3-D position (altitude and GPS), ice particles (2D-C and 2D-P probes), cloud droplets (FSSP probe), liquid water content (King probe), air temperature (thermistor in reverse flow housing), dew point temperature (billed mirror hygrometer), AgI (acoustical, ice nucleus counter), SF6 (gas detector), and visual cloud structure (video camera). In addition, the aircraft will be capable of monitoring vertical and horizontal winds.
15. (Optional) Scanning Doppler C-band (5 cm) weather radar for general surveillance of storm clouds and horizontal wind estimates.

Warburton et al. (1989) studied the ratio of co-released silver from AgI and indium from indium iodide. Because indium does not nucleate ice, ratios can indicate which gauges were under seeding plumes. For propane only cases, indium presence will indicate the seeding plume. Chemical analysis of snow samples will provide a means of identifying which precipitation gauges were under the seeding plumes and which were not.

3.6. Field Studies

Design phase field studies recommended for two winters prior to large-scale deployment of seeding equipment must test new field equipment and operational procedures on a limited-scale basis. The use of propane release for seeding clouds has never been tested in the high altitude zones of the Headwaters Region. Scaling from an initial deployment of several test propane dispensers to a desired number is considered the proper approach. Prior to deployment of an entire seeding network, answers must be determined regarding seeding mode, targeting and seeding equipment siting for various components of the varying terrain of headwaters barriers. It is recommended that successful operations be achieved in a limited scale network consisting of two seeding zones before large-scale deployment is pursued.

The prototype seeding project studies should involve weather forecasting and cloud modeling. Field data collection should include the monitoring of SLW at propane dispensers and AgI generators (if used), and the measurements of ice crystal in the target areas with simultaneous monitoring of natural crystals, either crosswind of the seeded ice crystal plumes or in established control areas. Some local wind measurements should be made with heated sensors, and some accurate air temperature and dewpoint temperature observations should be obtained at dispenser and crest line elevations. A network of high resolution precipitation gages should be deployed with proper protection from wind effects in selected forest clearings (Brown and Peck 1962). These gauges will provide relatively accurate high-resolution snow water equivalent observations in seeded and control areas. These measurements should provide the basis for a useful physical evaluation of seeding effectiveness.

Because significant electrical power will be needed to operate some of the instrumentation, such as heated wind sensors, it is recommended that a primary prototype testing site be located (via permission and/or cooperative agreement) possibly at the Desert Research Institute's (University of Nevada at Reno) Storm Peak Laboratory, that is equipped with electrical power and is accessible via Steamboat ski lifts and by snowmobiles. The laboratory has shelters for instruments and data collection by technicians. A second prototype site should be selected and instrumented possibly at a somewhat lesser level, but must also be accessible by 4-wheel drive and/or oversnow vehicle. Currently, the Storm Peak Laboratory is manned periodically during winters to collect cloud and aerosol data. Observations by aircraft mounted instrumentation are not recommended as a necessary data collection component because aircraft can rarely operate low enough in orographic clouds to provide desired observations. However, any agency willing to supply an instrumented aircraft and personnel to collect data will be encouraged to do so.

Because natural snow showers will sometimes mask seeding effects, randomization should be used on some test seeding trials of the design phase. The randomization scheme should be determined after some modeling studies are conducted and the terrain has been surveyed and analyzed. Should the two-year field testing have normal or above seeding opportunities, there may be an opportunity to collect adequate treatment and control samples for a seeding effect statistical assessment on precipitation. Generally, contamination of the control will not be a significant problem with the propane seeding approach because topography will largely control the transport of seeded ice crystal plumes. Only a brief residual seeding effect will occur downwind from the propane dispensers as seeded crystals are transported out of the target area. Propane seeding will not have the long-distance ice nucleation "contamination" that may occur with AgI releases in which nucleation may occur well downwind. However, it may be found that certain zones of the Headwaters Region are best suited for AgI seeding. The seeding design should not eliminate this possibility.

An appropriate "buffer zone" of at least 3 miles wide should separate the two prototype study zones. The number of seeding devices per prototype site should be determined after some modeling studies and terrain inspection have taken place. The areas downwind from each seeding equipment zone should have similar instrumentation. Experimental units should be aimed at 1-3 hours in duration to help minimize natural temporal variations. Delays between experiments must be specified to allow for flushing of previous seeding effects. The test seeding trials should gradually work toward automation that requires little or no human intervention. In this mode of operation, many test trials can be accumulated over a winter, in simulation of the operational phase of the program.

A tracer gas should be used in the test trials to document the passage of propane-seeded air parcels. Ice particle concentrations (IPC) and associated snowfall rates should react to seeding and should be monitored. Some seeding trials will display an obvious effect in the targeted area while others will be impacted by high natural temporal and spatial variations in IPC and snowfall rate. Statistical evaluation is needed to assess highly varying natural cases that are seeded. Contamination is a threat in highly varying winds and must be considered in all trials. There should be monitoring of the SLW approaching the target and control areas by use of a microwave radiometer. The SLW data will be useful to assessing seedability and natural variability in the airmass approaching the target and control areas. Large differences in conditions from target to control may eliminate comparison in a test trial.

3.7. Automated Cloud Seeding Operations

Automated conduct of seeding needs to be developed and tested. This involves the development of computer software that includes the following components.

- Logic to initiate or terminate cloud seeding by individual seeding devices based on checking established criteria built into the software
- Logic to interrogate field equipment on the status of local weather measurements and the status of seeding equipment and weather measurement systems
- Logic to prepare periodic status reports and disseminate to selected sites
- Logic to archive received information
- Logic for override and easy updating of selected criteria such as for seeding
- Logic to test cloud seeding suspension criteria
- Logic to perform quality control and report results

The computer software should be installed in the field office main computer server that can communicate with the Reclamation and data analysis group intranets. The software system must have flexibility to incorporate additional seeding or data gathering equipment. This system will act as a controller of cloud seeding (with override), provider of systems and cloud seeding status, and enable data quality checking and archive. The software and communications system should be developed as early as possible for adequate testing and necessary revisions. Development of this software will be an important goal of the design phase.

Establishment of the cloud seeding criteria for incorporation into the controlling software will involve the results of field data gathering and analysis. Criteria may differ from one seeding device to another because of local terrain and other conditions. The criteria logic system must have the flexibility for easy revision. An experienced programmer will be needed to handle software development.

3.8. Design Phase Costs

When the decision is made to proceed further with possibly seeding the Headwaters Region, a detailed plan of the design phase should be developed, along with a detailed budget in current year dollars. Program planning should proceed for selected test studies and modeling, and the equipment and manpower resources needed. Once a program plan is acceptable, final budget planning for the design phase can be accomplished. Past test programs have cost several hundred thousand to several million dollars per year. An estimate of costs for conducting the design phase work is given here for initial planning purposes.

Given in table 3.2 are the project design costs estimated to be $1,498,000, including environmental and permitting cost of $293,000. The design costs do not include equipment purchase costs. The design phase costs are based on a three-year effort. Environmental compliance costs are estimated at $275,000 for an EIS of moderate complexity that requires two to three years to complete. The cloud seeding plan development costs are estimated at $1,094,000. Modeling costs are $165,000 for three years. Two winters of field studies that include data collection and analysis are estimated to cost $779,000. The costs for development of an evaluation plan for operational seeding and estimation of design-phase test seeding results are $61,400.

The design phase field studies will likely involve the letting of a contract to provide most of the analytical and support personnel, office facilities, and supplies necessary to conduct the physical studies and data analyses. Costs to Reclamation for dealing with and providing oversight on contracts for services are included in cost figures given in table 3.2. Should automated seeding and data collection not be successful or require unforeseen additional maintenance, cost figures would need to be revised higher to reflect additional manpower needs. Also, should pursuit of the proposed program be delayed a lengthy period, costs are likely to rise noticeably.

TABLE 3.2. - PROJECT DESIGN AND EQUIPMENT COSTS

PROJECT TASK	STAFF COSTS Time Required Calendar Days	Staff Days	SD Daily rate	Total Staff Costs	TRAVEL COSTS TDY Costs Days	Rate	Travel Misc.	Total Travel	EQUIPMENT AND CONTRACT COSTS Number of items	Cost per item	Other costs	Equip & Contract Total	Total Task
DESIGN OF PROGRAM													
Detailed Terrain Study	30	15	712	10680									10,680
Terrain Mapping/GIS Study		15	600	9000									9,000
Modeling Weather and Clouds and Seeding Targeting (Three Seasons)	120	20	712	14240	15	50		750				150,000	164,990
Equipment Siting and Logistical Studies	15	15	712	10680	5	50		250					10,930
support staff		10	600	6000									6,000
Survey of Possible Locations for Generators	30	20	712	14240	20	120	300	2700				15,000	31,940
support staff		20	600	12000	20	120		2400					14,400
Selection of Seeding Sites and Obtaining Approvals from USFS and Land Owners, Survey by Helicopter (7 days @$500/h)	120	50	712	35600	10	120	500	1700	56	250	15000	29000	66,300
Design Phase Field Studies; Seeding Design Development and Testing (two seasons); Final Seeding Design Development	160	100	712	71200	60	120	1000	8200				700000	779,400
Subtotal of Cloud Seeding Program Design	475	265		183640				16000				894000	1,093,640
Development of Evaluation Plan for Seeding Effects (Design Phase/Operational Phase); Evaluation of Design Phase Seeding	60	30	712	21360								40000	61,360
Subtotal of Design Development and Design Phase Seeding Evaluation	535	560	6784	205000				16000				934000	**1,155,000**
Environmental Assessment and Impact Studies and Final Permitting	365	200	712	142400	5	120		600				150000	293,000
Specifications Development for Seeding Generators	20	15	712	10680									10,680
Specifications Development for Seeding Generator Local Siting and Maintenance	20	15	712	10680									10,680
Specifications Development for Seeding Materials and Operational Maintenance of Seeding Solutions, Propane, Delivery Systems, and Related	10	15	712	10680									10,680

TABLE 3.2. - PROJECT DESIGN AND EQUIPMENT COSTS

PROJECT TASK	STAFF COSTS				TRAVEL COSTS				EQUIPMENT AND CONTRACT COSTS				
	Time Required Calendar Days	Staff Days	SD Daily rate	Total Staff Costs	TDY Costs Days	Rate	Travel Misc.	Total Travel	Number of items	Cost per item	Other costs	Equip & Contract Total	Total Task
USBR Contracting Office	180	30	600	18000									18,000
Subtotal of Environmental and Equipment Specification	230	75	2736	192440									343,040
Design and Environmental Costs													**1,498,040**
EQUIPMENT PURCHASE													
Purchase of Seeding Systems													
Seeding Generators with Auto Controls and Icing Meters, Wind: Park Range	180	10	712	7120					27	22000	0	594000	601,120
Seeding Generators with Auto Controls and Icing Meters, Wind: Medicine Bow Range	180	10	712	7120					29	22000	0	638000	645,120
Spare Parts Contingency and Backup Items												123200	123,200
Subtotal for Seeding Systems Procurement	180			14240								1355200	**1,369,440**
Seeding Effects and Weather Sensing Equipment													
Purchase of Precipitation Gauges and DCP Systems with Wind, Temp, RH, Precipitation, Solar Radiation, and Icing Rate Meters	180	20	712	14240					45	4000	70000	250000	264,240
Computers and Communications Equipment		15	712	10680					56	500	12000	40000	50,680
Radiometers for Detecting Cloud Water	90	10	712	7120					3	35000	5000	110000	117,120
Subtotal of Seeding Effects and Weather Sensing Equipment	180			32040								400000	**432,040**
Total Equipment Costs				46280								1755200	**1,801,480**
Design, Environmental and Equipment Costs													**$3,299,520**

3.9. Field Equipment Costs

The proposed program will need seeding devices and seeding site sensors that help determine if conditions are proper for initiation or termination of cloud seeding. Sensors including high-resolution precipitation gauges are required for determining seeding effects. Communications and computer equipment are needed to relay and archive information. Table 3.1 lists equipment that may be used in the design phase. For operational seeding, primary equipment needs will center on automated propane dispensers and possibly AgI generators. Some or all seeding sites should have an icing probe, monitors to assess seeding equipment status, and communications equipment to relay information.

Table 3.2 shows the estimated field equipment costs to be \$1,800,000 (rounded) for the proposed program. Seeding site equipment costs were estimated for 55 sites to be \$1,369,000. Equipment for assessing weather and cloud seeding results is estimated to cost \$432,000. Equipment costs include three microwave radiometers for assessing integrated cloud SLW , a necessary (but not sufficient) cloud component for cloud seeding. In recent years, small, portable, relatively inexpensive units have been built that may serve well for the Headwaters Region.

All major equipment items necessary for the program should be purchased by Reclamation during the design phase period. Purchase by Reclamation is the most cost-effective for a multiyear program. An alternative would be equipment leasing from the private sector. Lease rates typically average 5 to 10 percent of the purchase price per month of use. Outright purchase of the equipment will offer savings after about two to four years of program operations. In most cases, equipment should be provided to the service contractors to operate and maintain as Government-furnished equipment. Leasing may be an appropriate option for some equipment to be used only in the design phase.

3.10. Seeding Suspension Criteria

An environmental monitoring plan will be implemented that includes seeding suspension criteria. In general, seeding will be suspended during periods of well-above normal snowpack, avalanche hazards beyond a determined level, and perhaps other periods when specified criteria or conditions are exceeded. Criteria may vary depending upon month of winter. Suspension criteria will be developed appropriate for the design phase. It is expected that design phase criteria will be less restrictive because seeding impacts will be relatively minor in comparison to operational seeding impacts. Likely, separate criteria will be developed for the operational phase.

Possibilities for suspension criteria include seeding suspension any time the selected snowpack measurement sites exceed 200 percent of normal. Seeding resumes only after the snowpack decreases below the 125 percent of normal point. Possibly, seeding suspension occurs after the snowpack exceeds 150 percent of normal at specific later months of the winter.

An advisory committee of local citizens and agency members should monitor and advise the program, and serve as the focal point for public awareness on this issue. The Colorado licensing processes for conducting cloud seeding require dealing with seeding suspension criteria. Criteria must be discussed at local public meetings prior to finalization. Local concerns will be incorporated into the development of criteria and the program's environmental monitoring plan.

3.11. Extended Area Effects

The concept of cloud seeding "robbing Peter to pay Paul" seems to eventually arise in continuing seeding projects. The idea is that using cloud seeding to increase snowfall on a mountain barrier, for example, leaves less moisture for downstream areas. Some downstream water users become concerned that upwind seeding projects may be "robbing" some of their water. This issue will need to be considered in the design phase and some provision made for dealing with it in the operational seeding phase and possibly the design phase. The extended area effects item is discussed in more detail in appendix A, chapter 10.

The extended area effects issue has received attention in a number of studies. Dennis (1980) reviewed several projects and indicated extended area effects were tentative at best. Assessment of these effects poses a major challenge given that detecting precipitation changes in intended target areas has itself proven to be a formidable task. Generally, previous studies of extended area effects suggest tentative effects, if any (appendix A, chapter 10). From a statistical detection standpoint, very small changes are usually not detectable in the sample sizes of most experiments. In the proposed study, detection will face the same hurdles unless effects are well larger than previously thought, an unlikely possibility. If the primary cloud seeding mode is propane release, the issue of reactivation of AgI (and therefore possibly affecting precipitation) well downstream will not surface. Operational seeding requires that the target area be seeded in all potential cases, subject to suspension criteria. This operational mode eliminates extended area effects control cases. Solutions may include the monitoring of a large, currently-installed network of precipitation gauges and/or large radar-estimated, precipitation grid. Again, only large changes would be detectable in such a monitoring system. The extended area effects issue will need to be addressed in the operational phase evaluation plan. Extended effects in the design phase seeding are not anticipated because of limited seeding for small target areas.

4. OPERATIONAL CLOUD SEEDING PHASE

4.1. General Features

The operational seeding phase recommended in this plan is for 10 years of cloud seeding duration. Though there is no guarantee, it is believed that a 10-year period is not likely to be dominated by one prominent climate type such as drought. From a seeding result evaluation standpoint, it is preferable to encounter dry, wet and normal periods. Preferably, the sample sizes over a 10-year period would be adequate for seeding result evaluation on each climate type. Also, a permit period of 10 to 15 years for program field equipment siting seems prudent, given the substantial effort necessary to comply with permitting requirements and environmental regulation.

The operational seeding phase cannot be described in substantial detail until the design phase is conducted. It is anticipated that some field data collection will be necessary to at least periodically verify that clouds are receiving treatment and responses are obtained. The data collection must be adequate to satisfy needs of the operational phase evaluation, including extensive precipitation data collection. Some automated photography of snow crystals should be considered if the proper equipment is assembled and tested in the design phase. Prudent choices of data collection will reduce manpower and equipment needs and save money, yet provide physical information adequate to confirm that statistical evaluation results from precipitation were caused by cloud seeding. Periodic tracer work may be prudent particularly since the terrain varies highly in the Headwaters Region. Studies conducted by other agencies may contribute valuable verification of results.

It is clear that a strong and credible evaluation program must be an integral part of the operational seeding phase. An evaluation plan developed in the design phase must be implemented before operational seeding begins. It is likely that some limited randomization will be necessary in the operational phase. A possibility is the use of a randomly moving, limited-area control. Randomly selected zone(s) would intentionally not be targeted and therefore act as a control. Covariates will likely play a role in the evaluation to decrease natural variation.

Weather and cloud modeling is expected to continue during the operational phase to assist what is likely to be a limited forecasting mode in the operational phase. While an automated seeding system should largely conduct the cloud seeding, some weather forecasting and operations declaration is useful in scheduling equipment maintenance and specific data collection. The extent of data collection and day-to-day work functions will need to be determined in the design phase

Precipitation gauges will assess additional precipitation deposited from cloud seeding in the intended target area. Application of a watershed model is needed to estimate streamflow increases from snowpack enhancement.

4.2. Operational Seeding Protocol

On a broad basis, the operational seeding phase will consist of determining the seedable cases, conducting the seeding, and complying with the evaluation design (includes the conduct of scheduled data analysis). All potential cases will be treated within the evaluation design, environmental compliance rules and established seeding suspension criteria.

The day-to-day operational duties include some or all of the following.

- Field operations management and oversight
- Limited weather forecasting using modeling and weather service collected weather data
- Weather and cloud information monitoring in the Headwaters Region and surrounding area
- Simplified daily operational plan formulation and relay to project personnel and management
- Field equipment operation to conduct cloud seeding and collect scheduled data
- Field data collection, preliminary quality checking and archiving
- Limited automated data analysis
- Equipment maintenance
- Environmental compliance and public awareness maintenance

4.3. Seeding Operations and Data Collection

The design phase will produce the computer software that is used to conduct the operational cloud seeding. Based on established criteria, the software will determine if conditions are met for seeding and proceed to instruct field equipment to initiate cloud treatment. The software will verify that equipment has responded and continue to report the status of operations.

Data collection during the operational phase will be determined at the completion of the design phase. It is expected that in addition to data collected at the seeding sites, some data will continually be obtained from several instrumented towers installed at high elevations of the Headwaters Region main barriers. Data from these towers will be used to assist in determining seeding conditions. It may be necessary for environmental compliance and seeding criteria performance checks that some meteorological data be continually collected. Periodic data collection can provide confidence that clouds are being seeded and that results indicated in precipitation data are caused by cloud treatment. The data collection issue for the operational phase must be viewed in light of cloud modeling accuracy and, of course, design phase field tests.

4.4. Estimation of Operational Seeding Costs

Section 4.2 lists some of the prominent tasks of conducting operational cloud seeding. Each task will require costly resources for accomplishment. Other costs include those for annual seeding materials that for propane release are estimated at about $175,000 per season. Table 4.1 gives year-by-year operational project costs for a 10-year seeding period. Yearly cost estimates beyond the first year include a 3 percent inflation factor. Table 4.1 lists annual costs for seeding equipment installation and removal. All other costs are combined into a single table value for each operational field season. A more detailed account of operational costs for the first year of seeding is given in Table 4.2. Upon completion of the design phase, a revised set of operational costs will be developed for each program component.

The first-year operational cost is estimated at $1,025,000, and the cost for the tenth year is $1,330,000. Table 4.2 shows a 10-year cost of operations of $11,716,000. Assuming 55 cloud treatment devices are installed in the Headwaters Region, the average annual cost of operations per seeding device is $21,300. This figure includes costs for seeding materials, automatic data collection, annual data analysis, operational cloud seeding, equipment removal (when necessary) and maintenance, weather forecasting and monitoring, cloud modeling, periodic evaluation of seeding results, project management and oversight, environmental compliance, and public involvement. Data costs for environmental compliance are included in technician support costs. Estimates cannot be met if automation is not fully implemented. Costs do not include any observations by aircraft, or local scanning radar. Partnering with other agencies and groups will be pursued and may help maintain costs at manageable levels. The figures given do not assume annual assistance from partnering.

TABLE 4.1. - PROJECT TIME LINE AND 10-YR COSTS

PROJECT TASK	Days	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	Year 13	COST ($)
Design Period	375		xxxxxxxxxxxxxxxxx												
Contracting for Services and Equipment	230		xxxxxxxxxxxxxxx												
Delivery of Services and Equipment	180		xxxxxxxxxxxxxx												
Installation for Operations OPS YR 1	60			xxx											42,620
Operational Field Season Nov 16 - Apr 15	150				xxxxx										940,080
Removal of Generators for Servicing/Refueling	30				x										42,620
Installation for Operations OPS YR 2	30				x										43,899
Operational Field Season	150					xxxxx									968,282
Removal of Generators for Servicing/Refueling	30					x									43,899
Installation for Operations OPS YR 3	30					x									45,216
Operational Field Season	150						xxxxx								997,331
Removal of Generators for Servicing/Refueling	30						x								46,572
Installation for Operations OPS YR 4	30						x								45,216
Operational Field Season	150							xxxxx							1,027,251
Removal of Generators for Servicing/Refueling	30							x							45,216
Installation for Operations OPS YR 5	30							x							45,216
Operational Field Season	150								xxxxx						1,058,068
Removal of Generators for Servicing/Refueling	30								x						45,216
Installation for operations OPS YR 6	30								x						46,572
Operational Field Season	150									xxxxx					1,089,810

TABLE 4.1. - PROJECT TIME LINE AND 10-YR COSTS

PROJECT TASK	Days	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	Year 13	COST ($)
Removal of Generators for Servicing/Refueling	30									x					46,572
Installation for operations OPS YR 7	30									x					47,969
Operational Field Season	150										xxxxx				1,122,505
Removal of Generators for Servicing/Refueling	30										x				47,969
Installation for operations OPS YR 8	30										x				49,408
Operational Field Season	150											xxxxx			1,156,180
Removal of Generators for Servicing/Refueling	30											x			49,408
Installation for operations OPS YR 9	30											x			50,891
Operational Field Season	150												xxxxx		1,190,865
Removal of Generators for Servicing/Refueling	30												x		50,891
Installation for operations	30												x		50,891
Operational Field Season	150													xxxxx	1,226,591
Removal of Generators for Servicing/Refueling	30													x	52,417
SUMMARY					**Operational costs (10 years)**										**$11,715,638**
					Total cost per generator										**$213,012**
					Annual cost per generator										**$21,301.16**

TABLE 4.2. - PROJECT FIRST YEAR OPERATIONAL COSTS

	STAFF COSTS				TRAVEL COSTS				EQUIPMENT AND CONTRACT COSTS				
PROJECT TASK	Time Required Calendar Days	Staff Days	SD Daily rate	Total Staff Costs	TDY Costs Days	Rate	Total Travel Misc.	Total Travel	Number of items	Cost per item	Other costs	Contract	Total Task
Cloud Treatment Operational Costs per Season													
Reclamation Program Manager	250	60	712	42720	10	130	50	1800					44,520
Reclamation Operations Director	300	180	712	128160	60	130	50	10800					138,960
Contractor for operational seeding program ($50/h)	300	180	400	108000	60	130	50	10800					118,800
Technician support (4 people @ $30/h)	300	760	240	273600									273,600
Numerical model runs for operations, weather forecasting, data archive and evaluation	240	240	80	28800								98800	127,600
Generator deployment and removal for preventative maintenance	30	20	712	14240	20	120	50	3400	56	1000	15000	71000	88,640
Seeding materials and equipment maintenance									56	3000	20000	188000	188,000
Environmental Compliance and Public Involvement	30	20	712	14240	8	120		960				30000	45,200
Subtotal Operational Costs	300	1440	2856	609760				27760				387800	**1,025,320**

4.5. Estimate of Operational Seeding Benefits

Estimates of additional water and associated operational costs were developed assuming that cloud treatment would be conducted primarily over the western and eastern barriers surrounding the North Park of north-central Colorado. Clearly, additional water estimates depend on the areal coverage by the seeding device network selected. The sample seeding device placement selected for developing water estimates was developed by Holroyd (unpublished internal Reclamation memo, 2000) and is shown in figure 4.1. Holroyd used digital terrain information to position 55 seeding devices for efficient seeding coverage for a wind direction of 240 degrees (used in figure 4.1) and separately for winds of 360 degrees. The predominant wind direction during winter storms possesses a westerly wind component for a large proportion of most storm durations (wind roses developed and available from Randolph Borys, director of the Storm Peak Laboratory).

Seeding device numbers and placement may be impacted by the presence of large wilderness areas on both, the west and east barriers of the Headwaters Region. The Holroyd seeding device placement in figure 4.1 does not include some high-elevation areas because of terrain limitations where the 9000-foot contour was located. This problem may be solvable either by relocation of propane dispensers, and/or the use of AgI generators positioned at somewhat lower elevations. It may be that AgI generator placement well upwind may enable seeding of these difficult-to-target areas. These possibilities should be explored during the design phase. Generally, it is believed that high elevation seeding sites can be found along most of the length of each barrier without violating wilderness area boundaries.

To obtain estimates of aerial coverage by the seeding devices, Holroyd had to use several assumptions including that seeding effects began 10 minutes after seeding initiation and end at 40 minutes, and dispersal occurs within a 15-degree angle sector centered on the wind direction. The times and angle settings were estimated from seeding trials in the Grand Mesa and the Wasatch Plateau of central Utah (appendix A). Holroyd used digital terrain at 0.5-kilometer resolution to determine seeded area pixel numbers in 500-feet elevation bands down to 9000 feet elevation. With areal coverage known for each seeding device, an estimated treatment effect can be applied to natural precipitation estimates for selected elevation bands, then values summed over all seeded areas to obtain a total volume snow water equivalent (SWE).

Table 4.3 presents the seeded area coverages in pixel totals for elevation bands that are identified at mid-elevations (9250, 9750 feet, etc.). The table gives estimates of additional water from cloud treatment using the pixel areas within seeded plumes, for 240 and 360 degree winds, assuming for all elevation bands a 26-inch average SWE for 240 degree winds and 2 inch SWE for the 360 degree winds. The SWE values were obtained by area-weight averaging the 1961-1990, 1 April, SWE for five Park Range and seven Medicine Bow snowpack measurement sites. The overall outcome of the area-weight averaging is 28.1 inches of SWE. The use of two inches of SWE for the 360 degree wind cases is an estimate based on study of wind rose information from the Storm Peak Laboratory.

Additional water volumes from cloud seeding were estimated for average, dry and wet years based on 50 and 150 percent of average SWE, for the areal coverage estimated by Holroyd. Also, water estimates were developed for the higher areal coverages of 40 and 60 percent of total area (above 9000 feet elevation and contributing to the North Platte River). Holroyd's calculations led to 28 percent areal coverage (elevation band area weighted) by seeding plumes.

Estimates of additional water for the average year were (rounded) 60,000, 85,000, and 128,000 acre-feet, for the 28-, 40-, and 60-percent areal coverages, respectively. The comparable values for the dry year were 30,000, 43,000, and 64,000 acre-feet, and 90,000, 128,000, and 192,000 acre-feet for the wet year. The values for the wet year may be an overestimate in some winters if seeding suspension criteria suspends operations.

Table 4.3 does not take into account the varying opportunity across year type to conduct cloud seeding; namely, the possibly differing cloud numbers and level of favorable seeding circumstances in available

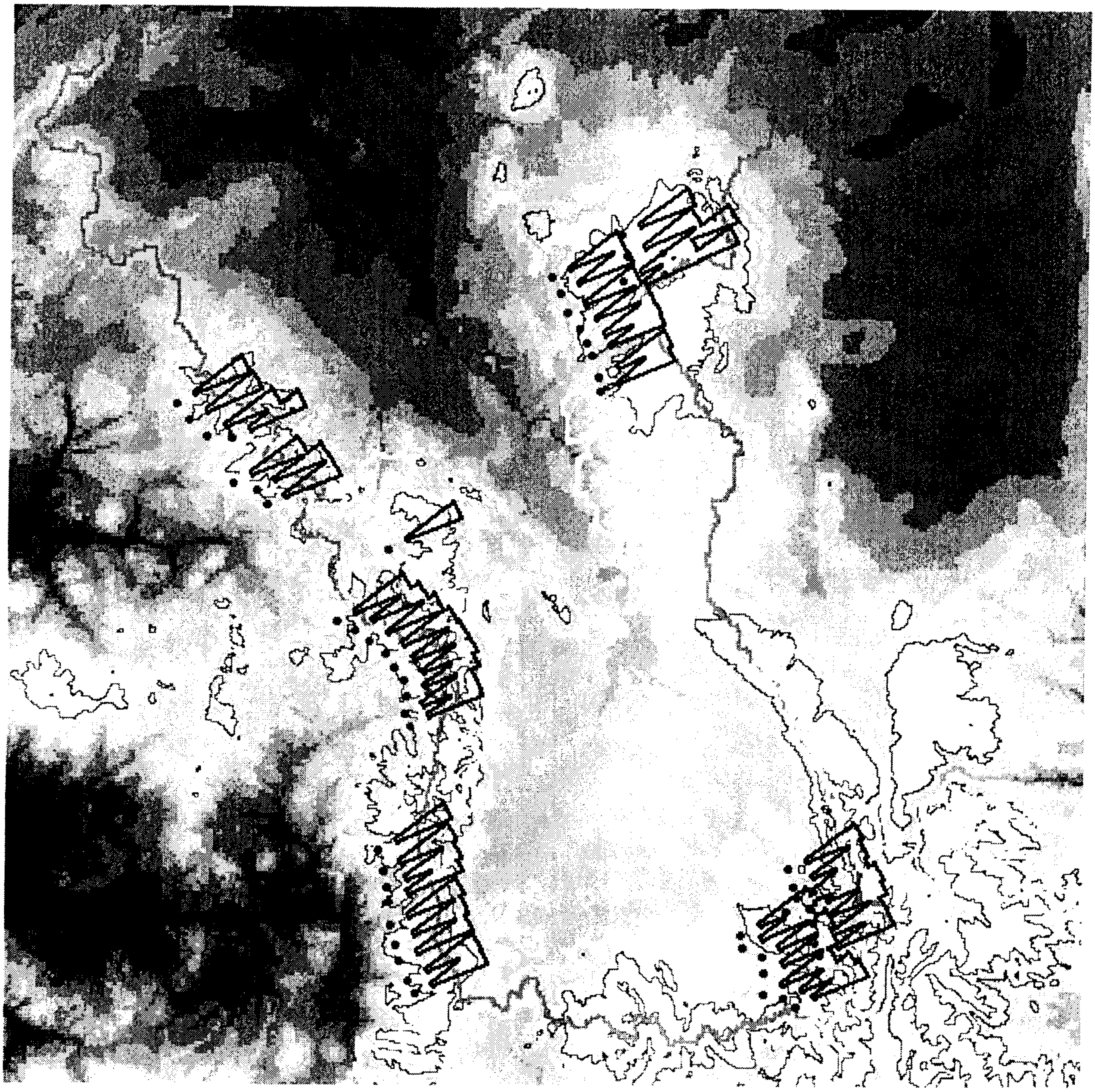

Figure 4.1. - Sample seeding device placement in the Headwaters Region for 240 degree winds (adapted from Holroyd's unpublished Reclamation memorandum, 2000).

clouds. The table values assume uniform opportunity across normal, dry and wet years. The design phase of the project will look into this issue. It may be that dry years offer more inefficient natural clouds than normal and wet years, thus presenting more treatment opportunities (or fewer opportunities).

TABLE 4.3. - ESTIMATES OF CLOUD TREATMENT ADDITIONAL WATER

Areal Coverage	Elevation Band (ft)	9250	9750	10250	10750	11250	11750	12250	12750	Total area (No.of 1/4 km²pixels)	Percent area seeded >9K ft	Area in acres (4pixels = 247.1054 acres)	Winter mean SWE (inches)	Total natural snow water (ac-ft)	Seeding effect on area > 9K ft
Western Ridge	**Sierra Madre**		No.	pixels											
	All points	1008	597	529	167	29	29			2359	100.0%	145730	26	315,749	
	240 deg	86	202	317	118	19				742	31.5%	45838	26	99,316	11,173
	360 deg	91	187	316	136	25				755	32.0%	46641	2	7,774	875
	Park Range														
	All points	1296	522	451	295	239	60	12		2875	100.0%	177607	26	384,815	
	240 deg	123	178	221	145	137	39	7		850	29.6%	52510	26	113,771	12,799
	360 deg	107	216	276	129	97	26	6		857	29.8%	52942	2	8,824	993
	Both areas														
	All points	2304	1119	980	462	268	60	12		5205	100.0%	321546	26	696,683	
	240 deg	209	380	538	263	156	39	7		1592	30.6%	98348	26	213,087	23,972
	360 deg	198	403	592	265	122	26	6		1612	31.0%	99583	2	16,597	1,867
	West Medicine Bow Mtns.														
	All points	595	418	395	286	231	135	95	15	2170	100.0%	134055	26	290,452	
	240 deg	58	200	186	134	133	70	37	6	824	38.0%	50904	26	110,291	12,408
	360 deg	2	114	130	113	121	74	30	8	592	27.3%	36572	2	6,095	686
Eastern Ridge	**West Medicine Bow Peak**														
	All points	1428	695	507	178	26	9			2843	100.0%	175630	26	380,532	
	240 deg	3	84	279	150	25	8			549	19.3%	33915	26	73,483	8,267
	360 deg	46	165	287	152	26	8			684	24.1%	42255	2	7,043	792
	North Medicine Bow Peak														
	All points	446	305	388	244	82	10	1		1476	100.0%	91182	26	197,561	
	240 deg	0	59	223	176	68	5	1		532	36.0%	32865	26	71,208	8,011
	360 deg	35	171	303	221	82	10	1		823	55.8%	50842	2	8,474	953
Southern Ridge	**North Rabbit Ears Range**														
	All points	1138	590	346	200	140	34	5		2453	100.0%	151537	26	328,331	
	240 deg	41	64	43	21	1	0	0		170	6.9%	10502	26	22,754	2,560
	360 deg	52	51	44	31	4	0	0		182	7.4%	11243	2	1,874	211

TABLE 4.3. (Cont.) - ESTIMATES OF CLOUD TREATMENT ADDITIONAL WATER

Estimates based on 1 April observed mean SWE > 9K ft	Area covered (acres)	Mean SWE (inches)	Natural Precipitation SWE (ac-ft)		Seeding Effect Estimate (ac-ft)			
AVERAGE YEAR					Areal coverage			
Area > 9000 ft msl within watershed (acres)	873,950	26	1,893,558		28%	40%	60%	100%
240 deg	226,534	26	490,823	240 deg	55,218	78,884	118,326	
360 deg	240,495	2	40,083	360 deg	4,509	6,442	9,663	
				Total	**59,727**	**85,326**	**127,989**	213,025
Seeding Factor 0.1125 .45*.25		Percent of possible seeded water volume			28.04%	40.1%	60.08%	100.00%
		Percent of total natural SWE			3.15%	4.51%	6.76%	11.25%
DRY YEAR 50% of Average								
Area > 9000 ft msl within watershed (acres)		13	946,779		30.30%	40%	60%	100%
240 deg		13	245,412	240 deg	27,609	39,442	59,163	
360 deg		1	20,041	360 deg	2,255	3,221	4,831	
				Total	**29,863**	**42,663**	**63,994**	106,513
WET YEAR 150% of Average								
Area > 9000 ft msl within watershed (acres)		39	2,840,338		30.30%	40%	60%	100%
240 deg		39	736,235	240 deg	82,826	118,326	177,489	
360 deg		3	60,124	360 deg	6,764	9,663	14,494	
				Total	**89,590**	**127,989**	**191,983**	319,538

4.5.1. Cloud seedability parameter estimated from model simulations

Values in table 4.3 use an enhancement factor of 0.1125 that estimates the percentage increase from cloud seeding. This value is based on the product of the two factors, 0.45 and 0.25. The first factor represents the concept that on average, 45 percent of the precipitation (above 9000 feet as used here) in the Headwaters Region is seedable. The 0.25 factor represents that the expected average increase in treated clouds is about 25 percent. The 25 percent increase value is obtained from consideration of the results of the Bridger Range Experiment (Super, 1974; Super and Heimbach, Jr., 1983) and the Climax I and II Experiments (Mielke et al., 1971; 1981).

The 0.45 factor was calculated as the average of 7 ratios of precipitation obtained from simulations by Colorado State University with the RAMS model, on 7 storms of the 1998-99 winter in the Park Range. The precipitation ratios were defined as model total precipitation (using hourly readings from the model) with liquid water present, to model total storm precipitation. The storm seedability ratios do not consider information when seeding leads to precipitation when none would occur naturally. Use of a different ratio was considered that consisted of storm time with liquid water present, to total storm time. However, values appeared unrealistically large and the more conservative ratio was selected. The model did indicate for some periods, lower or no liquid water amounts when the (model) precipitation rate was relatively high. Storms simulated were selected for varying storm types according to time of winter; small, moderate and high actual precipitation amounts, and predominant westerly and nonwesterly wind cases. Three storms were simulated at 3 kilometer grid point resolution and the remainder at 12 kilometer grid spacing. Model simulations appeared to overestimate precipitation (suitable comparisons could not be made because model point estimates at field gauge locations were not available). Simulations need to be compared with actual field observations. Generally, the 3 kilometer simulations yield substantial detail for comparisons. The simulations appear to produce useful information for purposes of the proposed program. These limited model results suggest that additional modeling be pursued should the program move forward.

5. COMPLIANCE WITH ENVIRONMENTAL REGULATION

Before cloud seeding is initiated, the requirements of the National Environmental Policy Act (NEPA) of 1969 (PL 91-190), as amended, must be satisfied. Environmental protection is a mandate of every Federal agency and department. Federal NEPA requirements are described in the Council on Environmental Quality (CEQ), Regulations for Implementing the Procedural Provisions of the National Environmental Policy Act (40 CFR Parts 1000-1508). Weather modification programs must comply if they include financial or regulatory participation by the Federal Government, or affects lands managed by Federal agencies. A brief summary of NEPA issues is discussed here. A more thorough treatment is presented in appendix D of a report by Super et al (1993).

The proposed program faces compliance for the design phase, at an expected low complexity level, and at a higher complexity level for the operational seeding phase. The design phase seeding will assume operations for limited periods of only two winters, changes in snowfall from seeding within the natural precipitation variation of the Headwaters Region, disturbances at ground-level to be minimal, adherence to any special use application procedures that may apply, environmental monitoring at a high level on any seeding trials, and public involvement to be an important component of the program. Furthermore, considerable environmental information exists for the Headwaters Region and similar surrounding areas that will reduce the data collection for describing the Region's environment for various resource categories.

In the operational phase, the proposed cloud seeding project is expected to increase the mean winter precipitation on the order of 10 to 15 percent primarily over higher terrain. The variance of high-elevation precipitation may be slightly reduced (naturally very wet years would be little impacted but very low and low years would be less extreme). Cloud seeding would be more intensive in time and space, and more seeding equipment would be installed. Impacts on the environment will likely warrant additional consideration. Furthermore, there has been some prior controversy regarding cloud seeding in the Park Range (more recently, as part of the COSE experiments). The CEQ regulations' (1508.27) criteria for significant impacts include those which are "highly controversial" or "uncertain." Environmental data acquisition must begin in the first stages of the program, and adequate data amounts must be collected for compliance with NEPA policy.

An important limitation that the proposed project must observe, indicates that a NEPA compliance document must be approved prior to any action that may affect or preclude possibly reasonable alternatives to the proposed action (appendix D of Super et al, 1993). In fact, actions are forbidden that may advance the program to an irretrievable point prior to compliance approval. Consequently, no cloud seeding or significant disturbance of ground or vegetation can occur until NEPA requirements are satisfied. However, temporary placement of precipitation and some other measuring devices can be accomplished under Forest Service and/or the Bureau of Land Management special use permits.

There are three levels of NEPA compliance that the program's proposed actions may need to address. These are in increasing levels of complexity, a categorical exclusion (CE), environmental assessment (EA), and environmental impact statement (EIS). The EA and EIS formats include (1) purpose and need for action, (2) alternatives including proposed action, (3) affected environment, (4) environmental consequences, and (5) coordination/consultation. Dealing with items (2) through (4) can involve substantial data collection and analysis. The CE has no standard format but usually includes a description of the proposed actions and an explanation of why the actions are environmentally nonmanipulative.

The proposed program may attempt to obtain a CE for the limited test seeding of the design phase.

Approval would allow data collection initiation that would assist an EA and/or EIS and satisfy data needs of design phase studies. An EA effort will take 9 to 12 months with an estimated cost of $275,000 (used in cost information). An EIS effort will take 6 to 12 additional months and approximately double the cost (appendix D, Super et al, 1993).

The NEPA process will require the efforts of an interdisciplinary team. At least a six-member technical team should be selected, consisting of a team leader, an environmental specialist, a public involvement specialist, one meteorologist, one biologist, and a water quality specialist/hydrologist. Public involvement will be necessary. An involvement plan will be developed in consultation with appropriate Federal, State, and local agencies, plus interested and affected individuals and groups. An advisory group consisting of local citizens should be established to assist in scoping environmental issues and to serve as a communications link to the public.

Because some cloud seeding studies conducted in the West have had to deal with environmental compliance, there exists some resource information that may be useful to the proposed program. Additionally, an interagency work group of the late 1980s consisting of resource specialists from Federal and State agencies began scoping compliance with environmental regulations of cloud seeding programs that may involve operational level seeding. The work group looked into applicable regulation, environmental study conduct, and likely required permitting. Possible impacts on wilderness areas were discussed. Unfortunately, interagency efforts terminated prior to completion of goals. However, some work study notes are available that may be useful to the Headwaters Region program.

The Colorado licensing process for cloud seeding will require that a license be obtained for conducting the seeding in the Headwaters Region. Regulation will require that a series of public meetings be conducted prior to any seeding to inform the public and incorporate any public concerns into the project design.

6. PROGRAM TIME SCHEDULE

The proposed program will be conducted over a 13-year period. The design phase would be conducted during the first three years and the operational seeding phase would begin at the end of the third year and continue through 10 winters. Table 4.1 (section 4.4) presents a time schedule for the overall program. Table 6.1 presents a more detailed time account for the design phase. Three years are required for the design phase because cloud seeding tests are needed for two winters, and environmental compliance and permitting will require two to three years. Moreover, equipment siting will likely proceed gradually. The three quarters of the first year will involve extensive weather and cloud modeling, historical weather data studies, and the initiation of environmental compliance and permitting. Once the design phase study sites are selected, permits can be obtained for installation of equipment, and compliance with environmental regulation pursued for anticipated limited effects of design-phase cloud seeding. It is hoped that cloud seeding tests can begin in the fourth quarter of the first year and continue through April of the second year. Seeding tests would be completed the following winter. Analysis of field data

Table 6.1. - Time Line for the Program Design Phase (calendar year quarters).

TASK	Q1 Y1	Q2 Y1	Q3 Y1	Q4 Y1	Q1 Y2	Q2 Y2	Q3 Y2	Q4 Y2	Q1 Y3	Q2 Y3	Q3 Y3	Q4 Y3
Conduct cloud modeling; analyze results & compare with SPL data	■	■	■	■	■	■	■	■	■	■	■	■
Conduct environmental compliance studies and permitting	■	■	■	■	■	■	■	■	■	■	■	
Develop design phase cloud treatment plan			■									
Obtain/install field equipment for design phase			■	■								
Conduct cloud treatment; collect data				■	■			■	■			
Analyze field data and model estimates						■	■			■	■	
Evaluate cloud treatment results; develop operational program seeding design										■	■	■

would be conducted after each winter with seeding. Evaluation of effects on precipitation for all test trials would occur in the fall of the third year. The finalizing of the operational cloud seeding design is expected to occur in the second and third quarters of the third year, along with completion of environmental compliance and permitting. Installation of additional equipment for the operational cloud seeding would occur in the late fall of the third year. Operational cloud seeding would commence about December of the third year.

There is the possibility that design phase seeding cannot be initiated the first winter after the program starts. This could occur because environmental compliance and/or permitting could not be achieved in proper time. Should a delay occur, operational cloud seeding should not be initiated until the fourth winter.

8. SUMMARY

A proposed plan is given for the conduct of operational cloud seeding on winter clouds in the headwaters of the North Platte River. The purpose of the seeding is to provide additional snowpack at high elevations of the barriers that feed the North Platte River. When properly conducted, cloud seeding offers technology that can now provide a logistically feasible and cost-effective option to enhance fresh water resources in some mountain watersheds of the West. The American Meteorological Society and the World Meteorological Organization state that statistical analyses of some cloud seeding programs have suggested mountain snowfall increases of 10 to 15 percent per winter. Reclamation cloud seeding studies in the 1980-90s have contributed physical measurements and analyses that document cloud and precipitation positive responses to cloud seeding.

It is recommended that the proposed program consists of a cloud seeding design phase of three years, followed by 10 years of operational seeding. Previous cloud seeding studies indicate that each area presents site specific problems that must be addressed in a design phase before operational seeding can be successful. The design phase work should develop seeding approaches that are proper for the Headwaters Region, and test automated seeding equipment and computer software. The design phase must deal with environmental compliance and the acquisition of necessary permits. No cloud seeding will be allowed until environmental compliance is achieved.

Estimates of additional water were made from a sample network of 55 seeding devices' placement (figure 4.1 shows device locations) that would cover an approximate 28 percent of high-elevation contributing area (downwind seeding plume areas above 9000 feet) to the North Platte River watershed. Applying an 11.25 percent increase to average winter precipitation yielded an additional 60,000 acre-feet of water in the network plume areas. Seeding in a dry year could possibly produce an additional 30,000 acre-feet, but 90,000 acre-feet in a wet year. With a seeded areal coverage of 40 percent, the increases grow to the respective 85,000, 43,000, and 128,000 acre-feet of water. These water volume estimates are from integrated additional precipitation occurring at high elevations in seeding plumes, and do not reflect water losses/gains after deposition on the terrain.

The estimated 10-year cost of operations is $11,716,000, so that for 55 cloud treatment devices, for example, the average annual cost of operations per seeding device is $21,300. The cost of conducting the design phase effort, including environmental compliance, but short of equipment costs, is $1,498,000 for three years. Equipment costs are estimated at $1,800,000.

With recent gains in knowledge, in part because of Reclamation support, it is believed that winter orographic cloud seeding has reached the point that a well designed and managed program can produce cost effective additional water in certain watersheds of the West. In the proposed program, cloud seeding would target the additional water to high elevation areas in downwind plumes from seeding devices such that additional runoff routes to the North Platte River. Additional water from seeding would be unprotected and simply an incremental amount over that occurring naturally. The exact device placements would be determined in the design phase and would depend on factors such as the location of wilderness areas and the influences of local terrain features on winter storm clouds. The additional water can help satisfy increasing demands of western watersheds. Properly conducted cloud seeding can improve water quality and domestic, and recreation uses. Other studies will estimate the benefits to habitats from the additional water.

APPENDIX A

SCIENTIFIC BASIS FOR CLOUD SEEDING TO INCREASE MOUNTAIN SNOWFALL IN THE WEST

by

Arlin B. Super
Bureau of Reclamation
Denver, Colorado
July 1999

CONTENTS

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Figures

1. INTRODUCTION

This study presents technical information on using weather modification technology, commonly called cloud seeding, to increase the winter mountain snowpack in the high elevation headwaters region of the North Platte River Basin (hereafter Headwaters Region). Unless otherwise noted, the term "cloud seeding" in this report will refer to approaches intended to increase snowfall from winter orographic (mountain-induced) clouds. The main high elevation areas in the Headwaters Region are shown in figure 1. The Park Range in northern Colorado extends into southern Wyoming where the barrier is called the Sierra Madre. For simplicity in this report, the entire barrier will usually be referred to as the Park Range. The Medicine Bow Mountains also extend from northern Colorado into southern Wyoming. Lengths of their higher elevation portions are about 65 mi for the Park Range north of Rabbit Ears Pass and 70 mi for the Medicine Bows north of Cameron Pass. Runoff from more southerly portions does not drain into the North Platte River. Subsequent melting and runoff of an enhanced snowpack over these large mountain areas could be expected to significantly increase downstream flows for environmental uses and other purposes.

This study has examined results from many past studies and has summarized those results which have special relevance to cloud seeding in the Intermountain West in general (as opposed to the Sierra Nevada or Cascades) and specifically in the Headwaters Region. Topics include supercooled liquid water availability, transport and dispersion of seeding agents, seeded ice particle concentrations, and statistical and microphysical evidence of seeding effectiveness. Some topics, such as valley-based silver iodide seeding, are provided to document why those approaches *are not recommended.* The earlier results present the basis for considering cloud seeding feasibility over the Headwaters Region.

The organization of this report is as follows. Section 2 provides some brief comments concerning inadvertent weather modification to help put intentional cloud seeding efforts into perspective. Section 3 describes the physics of the cloud seeding approaches applicable to snowpack enhancement in the Headwaters Region. Section 4 discusses delivery methods for seeding materials and why some would be unsuitable for the Headwaters Region. Section 5 discusses differences between statistical and physical evaluation approaches. Section 6 examines the availability of supercooled liquid water in orographic clouds. Section 7 provides various relevant information from past studies in other geographic areas, as well as within the Headwaters Region. Section 8 summarizes findings from a recent extensive physical evaluation program in central Utah. Section 9 briefly discusses some environmental impacts of cloud seeding and provides references for further study of this topic. Section 10 considers the possibility of extended area effects of cloud seeding often referred to as "downwind effects." Section 12 presents a brief summary of the findings and recommendations of this feasibility study.

2. INADVERTENT WEATHER MODIFICATION

Some people have the perception that any attempt to intentionally affect local precipitation by cloud seeding somehow interferes with nature in a deleterious manner. The saying that, "it is not nice to fool with Mother Nature" is sometimes quoted in discussions about cloud seeding. This perception seems to overlook the huge influences mankind has had, and continues to have at an increasing rate, on the "natural" (pre-man) environment. Mankind has vastly changed the earth's surface by converting forests and grasslands to agricultural lands. Wide-spread irrigation has converted semi-arid or arid lands to crop lands. Such practices have indeed had both negative and positive effects, but sustaining increasing population levels without them appears unlikely. The large area of agricultural lands in the United States were forest, grassland and even desert only 200 years ago. While some might argue that we should "turn back the clock," no one has explained how to then sustain the United States population of more than 270 million people or the total of six billion people worldwide.

Many people are unaware that mankind has inadvertently modified the atmosphere, and thereby altered weather and climate ("typical" weather over decades), for thousands of years. Possible effects of additional carbon dioxide on the climate since the beginning of the industrial revolution have received considerable media attention. But man began to affect the climate long before recent times. The large changes made to the earth's surface cover for agricultural purposes are a major contributor to changes in the composition and dynamics of the atmosphere. National and international conferences on weather modification have for many years contained sections dealing exclusively with "inadvertent weather modification." Inadvertent atmospheric modification by air pollution, the "heat island" effect of large metropolitan areas, deforestation of large areas, or conversion of large grasslands to agricultural uses are just a few of the better known examples.

Huff and Vogel (1978) reported on results from a large rain gage network operated for 5 years as part of the METROMEX project which investigated the urban effects of St. Louis, Missouri. They showed a maximum summer rainfall increase downwind from the city amounting to 30 to 35 percent. Such inadvertent weather modification increases are more than twice those generally claimed by commercial cloud seeders. The entire May 1978 issue of the *Journal of Applied Meteorology* was devoted to several studies of urban effects on weather and climate near St. Louis. Mankind has unwittingly been involved in weather and climate modification for thousands of years. For example, Bryson and Murray (1977) provide evidence that the Rajputana Desert in eastern Pakistan and northwestern India is partially, perhaps mostly, a manmade phenomenon. An early agricultural civilization with a large population arose there near 2,500 B.C. But that civilization rapidly declined about 1,700 B.C. Other groups with smaller populations have lived there during wetter periods but they too declined and dispersed during dryer periods. Moist monsoon air flows over this desert today, with four times the water vapor found over most deserts, but rain does not fall. The extremely dusty air subsides, hampering updrafts which could lead to convective clouds and rain, and the desert continues to expand. Scientists at the University of Wisconsin-Madison believe that deforestation and overgrazing lead to formation of the large desert and continue to sustain it today. An experimental fencing of a large area to prevent grazing resulted in abundant wild grasses in 2 years, without planting or irrigation. Bryson and Murray (1977) suggest that the desert might be reclaimed if a large enough area was fenced to allow resulting grass cover to greatly reduce the atmosphere's dust load. This should result in development of more clouds and, of at least equal importance, clouds with fewer and larger droplets much more likely to produce rainfall.

Many other examples could be cited of mankind's unwitting but deleterious effects on weather and climate such as today's widely used "slash and burn" agriculture. This practice has contributed to severe drought in the Southeast Asian region during the past few years, with dense smoke affecting vast areas.

3. INTENTIONAL WEATHER MODIFICATION

The question is often asked, "does cloud seeding work"? That is analogous to a physician being asked, "is the practice of medicine effective"? The answer is highly dependent upon the specific disease and the particular treatment an individual physician might favor. Some conditions are still incurable and modern medicine cannot be said to work in such cases. At the other extreme, considerable and convincing proof exists that many medical conditions can be cured. Between these extremes are a wide range of conditions for which physicians have honest disagreements about the best treatment, and evidence remains illusive of ability to totally cure. Hence, we refer to the "art of medicine" which is not always based on complete knowledge and understanding. So it is with the general field of cloud seeding.

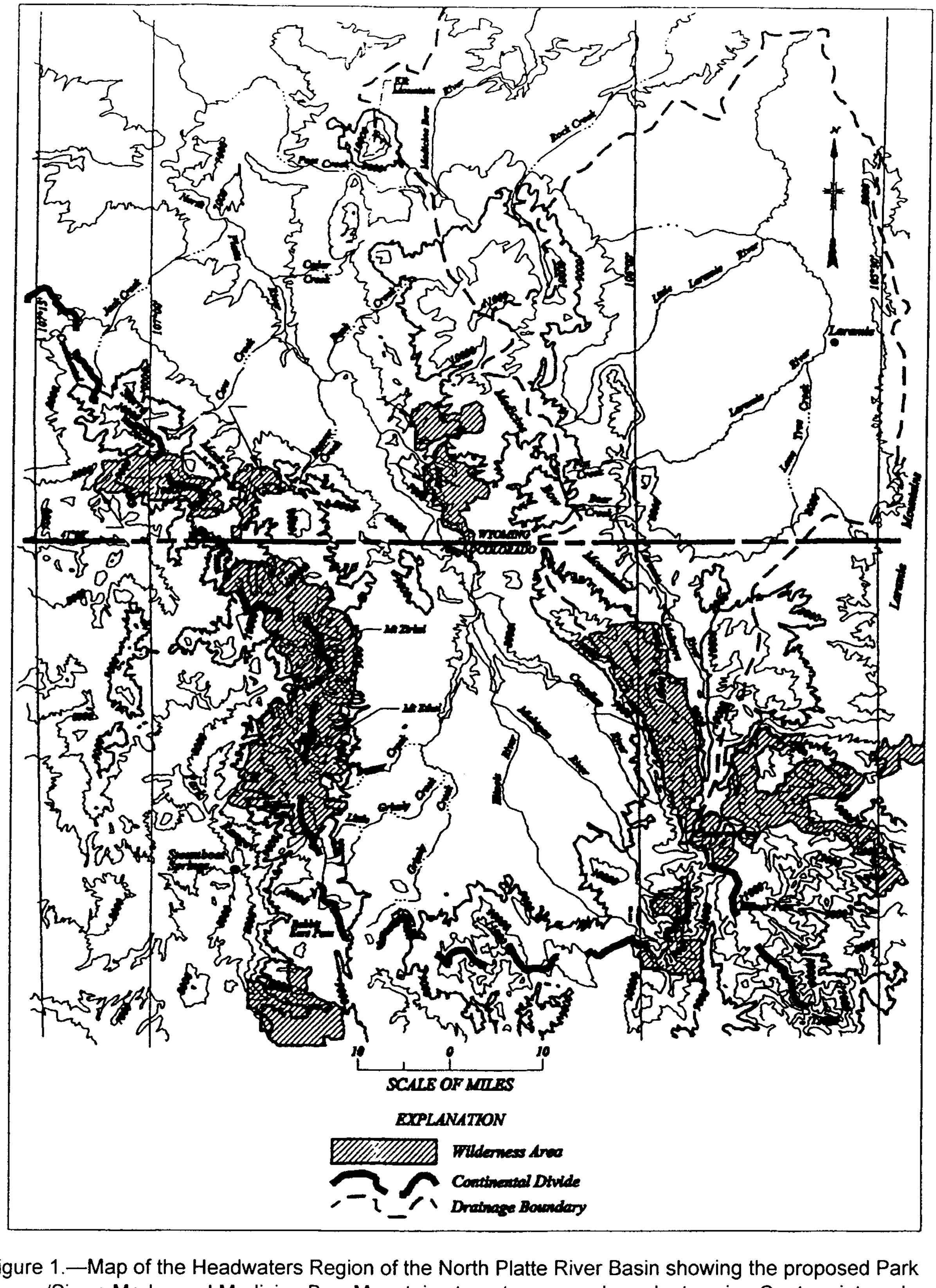


Figure 1.—Map of the Headwaters Region of the North Platte River Basin showing the proposed Park Range/Sierra Madre and Medicine Bow Mountains target areas and nearby terrain. Contour intervals are shown at 1000 foot intervals above mean sea level with the 9000 foot contour in bold. Drainage boundaries, including the Continental Divide, are shown by dashed lines. Wilderness areas are shaded.

Successful intentional weather modification experiments began in the late 1940s with the 1946 discoveries by Vincent Schaefer and Bernard Vonnegut, respectively, that supercooled liquid water (SLW) could be converted to ice crystals by either homogeneous (colder than -40 °C) or heterogeneous (providing a freezing or sublimation nucleus) seeding agents. Additional studies developed technologies for introducing hygroscopic particles into clouds that were warmer than 0 °C for the purpose of increasing rainfall. The latter approach currently appears promising for some warm convective clouds as discussed by Mather et al. (1997). Seeding targets were both cumuliform and stratiform clouds of various sizes and temperatures. Treatment of supercooled (<0 °C) stratiform clouds in the form of cold fog and winter orographic clouds proved reliable, justifying policy endorsements (e.g., American Meteorological Society 1998a and 1998b). It is the wintertime seeding of orographic clouds that is appropriate for the Headwaters Region.

The other seeding styles are mentioned for their cloud physics insights. Cloud seeding definitely works for clearing supercooled fog from airports, as has been repeatedly demonstrated. On the other extreme, no sound physical hypotheses even exists for modification of hurricanes, although considerable past research explored this possibility. Hail suppression attempts (Smith et al. 1997) have provided some encouraging statistical assessments, but the physical basis for these apparent results has yet to be established (American Meteorological Society 1998a).

The units of measurement used in this report are worth noting. While metric units will usually be used, elevations and heights will be reported in feet (ft) and horizontal distances in statue miles (mi). This convention will help future planning, as many maps are still in English units. Moreover, some of the many references cited have used metric units for elevation, height and distance while many others reported in English units. The latter will be used to provide consistency and ease comparisons among studies. Also, the usual United States convention of reporting precipitation in inches will be followed in this report.

3a. Supercooled Liquid Water

Winter orographic clouds frequently consist, in part, of supercooled water droplets, typically in concentrations of 50 to 200 per cubic centimeter. The term "supercooled" means that the droplets are in liquid form even though their temperature is colder than 0 °C and sometimes even colder than -20 °C. (Much colder supercooled cloud can exist in the laboratory to about -40 °C, but natural snow-producing processes usually become efficient in orographic clouds colder than about -20 °C.) Cloud droplets are tiny (about 10 μm) and have negligible settling velocities because of the viscosity of the air. The droplets are essentially suspended as they are transported along the airflow through clouds. Supercooled liquid cloud droplets form as liquid condensate in the uplift zone over the windward slope of a mountain barrier, and rapidly evaporate in descending air over the lee slope. For SLW droplets to reach the mountain surface as snowfall, they must become ice crystals (ice nucleation) or freeze onto existing ice crystals.

A necessary but not sufficient condition for seeding to be effective in orographic clouds is the presence of SLW cloud in excess of that naturally converted to snowfall. Excess SLW is the "raw material" needed for seeding to enhance snowfall.

3b. Snow Crystal Growth

The cloud droplets exist in combination with much smaller concentrations of ice particles. Ice particle concentrations vary widely from less than one per liter to several hundred per liter. Conversion of SLW cloud droplets to snowfall requires the presence of one or more of the following processes:

a. Some of the droplets may be "nucleated" and become embryonic ice crystals. This ice nucleation process requires the presence of very tiny particles known as ice nuclei, concentrations of which vary widely in time and space. Natural ice nuclei, in the form of clay particles and leaf litter, have concentrations much less than those of cloud droplets. There are some ice multiplication processes, including crystal fragmentation, that also provide "nuclei" for additional ice crystal growth.

b. After embryonic ice crystals form, they grow by the process of diffusion involving the vapor transfer of water molecules from droplets to crystals. This transfer occurs because the saturation vapor pressure is greater over water than ice.

c. Many droplets may be captured by, and freeze onto, faster falling individual ice crystals or snowflakes, a process known as accretional growth or "riming." In some clouds this can lead to the growth of graupel (snow pellets) and hail.

d. Aggregation is a process whereby smaller ice crystals collide and "chain together," becoming larger snowflakes with faster fall velocities. Sometimes riming will help this process by acting as a "glue." Stellar and dendritic crystal habits are especially prone to aggregation but other habits, such as needles, also aggregate. Heavy snowfalls usually involve aggregation into large, fluffy snowflakes.

Snow crystals have a variety of habits, or shapes, and growth rates, mostly based on the temperature of the cloud environment and to a lesser extent the moisture content of the air. Laboratory growth rates between -3 and -21 °C were reported by Ryan et al. (1976) for times up to about 3 min. Dendritic crystals grow the fastest at about -15 °C, which is at a peak in the vapor pressure difference between SLW and ice. A secondary growth peak may exist for needles and columns at about -7 °C. Thick plates, at about -10 °C and -20 °C have the slowest growth rates. Growth rates are slow between -3 to -4 °C.

Redder and Fukuta (1989) presented equations for ice crystal mass and dimensional growth. They used six experimental data sets from cloud chambers or supercooled cloud tunnels for growth periods up to 30 min. Molecular diffusion was the predominant growth mechanism in all reported experiments. The authors indicated that after 20 min growth time, the mass of individual ice crystals would be in the range of 5 to 10 μg for temperatures between -5 and -12 °C and for colder than -17 °C. Crystal masses greater than 10 μg were found between -13 and -17 °C in the dendritic growth zone, with the maximum of 30 μg at -15 °C. The minimum mass after 20 min growth was 2 μg at -4 °C, the warmest temperature considered. This same information is presented in table 1 in section 11b. While their results agreed with the -15 °C maximum found by the short duration studies of Ryan et al. (1976), a secondary maximum at -7 °C was not indicated after 20 min growth.

Super (1994) referred to earlier field observations which suggested that a typical natural ice crystal from an orographic cloud had a mass of approximately 20 μg. Of course, considerable variation existed among individual crystals and the "typical" value is roughly a median of the various field observations which were examined. The typical value is similar to the fastest diffusional growth results at 20 min but less than the masses expected for most of the supercooled temperature range of interest. Natural crystals often have growth times well in excess of 20 min because they form high in the cloud and have long growth and fallout trajectories.

Rauber (1987) found that the primary source region for ice particles observed near the Park Range was near cloud top. Most of the resulting snowflakes on the mountain surface likely originated tens of kilometers upstream from the Park Range, with travel times on the order of 30 to 60 min. He also discovered that many small ice particles were found well below cloud top in regions of strong orographic uplift. The latter naturally-formed crystals would have shorter travel and growth times and, therefore, be more similar to seeded crystals.

Redder and Fukuta (1991) presented a companion paper to Redder and Fukuta (1989) which included information on fall velocities. Fall velocities of individual crystals ranged between 30 and 60 cm s^{-1} with the maximum at -10 °C (columns and thick plates) and minimum near -5 (needles) and -15 °C (dendrites and stellars). Using a fall velocity of 45 cm s^{-1}, an average mass of 20 X 10^{-6} g and crystal concentration of 20 L^{-1} yields a snowfall rate of near 0.028 inch h^{-1}, a typical snowfall rate in the Intermountain West. It should be noted that snowfall accumulations and rates in this paper refer to melted snow water equivalent, not snow depth.

Super et al. (1986) discussed two winters of high resolution gage observations on the Grand Mesa of western Colorado. They showed that the median hourly snow water equivalent accumulation was 0.028 inch for all hours with at least 0.01 inch accumulation. This median is the same value as in the above calculated example. These simple calculations show that significant snowfall can be produced by about 20 L^{-1} individual crystals allowed to grow by diffusion for approximately 20 min at temperatures in the dendritic growth zone (-13 to -17 °C). Lighter but still meaningful snowfall rates would be achieved at warmer temperatures. Of course, greater crystal concentrations and longer growth times would produce greater seeded snowfall rates, as would riming or aggregation which can significantly increase fall velocities and mass growth rates.

Ice crystal size (not mass) growth rates were presented by Holroyd (1986) using aircraft observations from simple orographic clouds. He found a growth rate near 0.07 mm min^{-1} valid through 13 min at -13 °C and a rate near 0.1 mm min^{-1} valid through 15 min and probably through 30 min at -14 °C. These results from orographic rather than laboratory clouds are noted because they are in reasonable agreement with Ryan et al. (1976) and Redder and Fukuta (1989), adding credibility to the laboratory results.

3c. Artificial Ice Crystal Initiation

Ice crystals can be artificially formed (caused by seeding) within a population of SLW cloud droplets by either of two forms of nucleation, heterogeneous and homogeneous.

Heterogeneous nucleation involves interaction between a SLW droplet and a foreign particle known as an ice nucleus. Most natural atmospheric ice nuclei are tiny insoluble clay particles transported from the ground by the wind (Dennis 1980). It could be questioned whether such ice nuclei should always be considered "natural" because plowed fields are often the source of the clay particles. While some industrial emissions produce artificial ice nuclei they rarely have more than local importance.

The homogeneous nucleation process does not require interaction between foreign particles and water droplets, but only that cloud be chilled a little colder than -40 °C. Practical means of seeding by this process include dropping dry ice (solid CO_2) pellets into SLW cloud or the expansion of a (possibly liquified) gas to achieve very local within-cloud cooling colder than -40 °C. Such chilling of cloudy air produces very large supersaturations resulting in the condensation of vast numbers of tiny droplets which immediately freeze, forming embryonic ice crystals. Freezing of preexisting cloud droplets is of limited importance because of their much smaller concentrations. The most frequently used agents for homogeneous nucleation are dry ice and liquid propane, with occasional use of liquid nitrogen in foreign countries and compressed air in the laboratory. The use of compressed air released through a supersonic nozzle has been proposed for supercooled fog dispersal by Weinstein and Hicks (1976). However, this approach would require significant electrical power for pumps, making it impractical for mountain seeding sites.

Silver Iodide (AgI), either in rather pure form or with various additives, is by far the most commonly used heterogeneous seeding agent. It has a threshold temperature near -6 °C, where a small fraction of the total AgI particle population begins to nucleate ice particles. It has usually been impractical to achieve significant ice crystal concentrations several kilometers downwind from an AgI generator at temperatures warmer than -9 °C. The reason is the two to three or more orders of magnitude increase in ice nucleating activity between -6 and -9 °C. A typical generator has an output of about 10^{14} ice crystals per gram of AgI, effective at -9 °C.

Besides this strong temperature dependence, the effectiveness of AgI seeding depends on the specific type of chemical and particular generator design used and the atmospheric conditions at the release point. Many operational programs use relatively pure AgI released well below cloud. The resulting contact-freezing nucleation process depends on cloud droplet concentration. Because winter orographic clouds have relatively low droplet concentrations, the contact-freezing process is known to be quite slow. That is, only a fraction of the AgI particles with the potential to nucleate ice will do so over a typical in-cloud residence time of 20 to 30 min.

The effectiveness of various seeding solutions, loosely referred to simply as AgI but often much more complex, is known to vary widely. The strong temperature dependence and less pronounced wind speed dependence of the ice nucleation effectiveness of particular AgI solutions has been widely documented, such as by DeMott et al. (1995). This same reference shows that some types of AgI with additives are fairly fast acting because they operate by the condensation-freezing mechanism at water saturation which does not depend on droplet concentration. Changing from the commonly used AgI aerosol, which nucleates by contact-freezing, to the AgICl-0.125NaCl aerosol, which acts by a faster condensation-freezing process, would provide about an order of magnitude increase in seeding effectiveness during a 20 min in-cloud transit time. Other types of AgI have also been shown to be faster-acting, and more efficient in the important -6 to -9 °C range, than the relatively pure AgI aerosol which operates by contact-freezing. However, some of these agents cause operational problems in the field such as nozzle clogging.

A special case of condensation-freezing is the "forced" condensation-freezing mechanism discovered by Finnegan and Pitter (1988). It is achieved if AgI is released within cloud where the consumption of the AgI-acetone solution and propane add abundant local water vapor just above the generator stack. This approach causes large transient supersaturations, resulting in the formation of vast numbers of ice crystals immediately downwind from the generator stack if the cloud is colder than -6 °C. This mechanism has been shown to work with all silver iodide-containing aerosols in rapidly and efficiently forming ice crystals at the relatively warm temperature of -6 °C.

Li and Pitter (1997) reported on numerical simulations of ground-based AgI seeding for two ice crystal formation mechanisms, contact-freezing and "forced" (very rapid) condensation-freezing. A relatively simple orographic cloud model was used to investigate how the different mechanisms affect snowfall patterns and intensities. A temperature sensitivity analysis showed large effects on snowfall production by forced condensation-freezing because ice nucleation is a strong function of temperature. The authors cite Feng and Finnegan (1989) who showed ice nucleation efficiency is enhanced by four orders of magnitude from -6 to -10 °C. They considered the field results of Super and Heimbach (1983) at the Bridger Range of Montana to be strong evidence for forced condensation-freezing because suggested seeding effects were for ridge top temperatures of -9 °C and colder. That condition corresponds to high altitude generator site temperatures colder than -6 °C. The generators were usually operated in-cloud.

Additional evidence was cited that aggregations of dense concentrations of ice particles from forced condensation-freezing is a major process for snowfall production.

Li and Pitter (1997) concluded that, "Forced condensation freezing produced a maximum precipitation intensity that was on average two orders of magnitude greater than that generated by contact-freezing, and the target region for forced condensation freezing was located close to the generator, in contrast to the precipitation pattern for contact freezing." These results argue strongly for AgI seeding programs to locate their generators in-cloud where forced condensation-freezing can occur. Moreover, the simulations indicate the generators must be at a sufficiently high elevation that the cloud temperature is -6 °C or colder for forced condensation-freezing to operate. According to Rauber and Grant (1986) Park Range cloud bases are usually between 650 and 1000 ft below crest line, with base temperatures between -5 and -10 °C. These results imply that AgI generators intended to seed the Headwaters Region should be no lower than about 800 ft below crest line to be in-cloud usually cold enough for forced condensation-freezing to occur.

Super (1990) considered the state of knowledge of the essential "links" in the chain of physical events required for successful AgI seeding of winter orographic clouds in the Intermountain West. The problems of reliable AgI production were noted. Automated AgI generators are known to have had serious reliability problems. One of the most sophisticated automated AgI generators is produced by the Desert Research Institute in Reno, Nevada. But even with maintenance by their own trained personnel, correct operation of these expensive units (over $40,000 each) was achieved only about 80 percent of the time (Huggins 1994). At least two commercial firms will provide automated AgI generators for about $20,000 per unit. The reliability of current units is unknown to the author, but some earlier commercial generators had numerous problems when operated at remote locations via radio link. Few automated AgI generators have had the ability to measure the low solution flow rates used. The author considers this measurement to be essential for monitoring generator reliability. While flame temperature is usually measured, there is a limited difference between flame temperature for propane only and propane combined with AgI-in-acetone. Consequently, a flame may exist in the generator burner stack while the AgI solution line or nozzle is completely plugged. Cases of inoperable automated AgI generators have been documented with no indication of any malfunction.

Even simple manual generators require routine maintenance to function properly. The author has observed a number of poorly maintained generators in operational seeding projects which could not possibly have been producing the anticipated AgI source strengths because of partial or complete clogging of solution lines, nozzles or burning chambers. Silver iodide solutions are very corrosive, requiring materials such as stainless steel, and are subject to clogging problems with the slow solution flow rates used. The more exotic AgI solutions, containing additives to enhance ice particle nucleation, often significantly increase generator clogging and corrosion problems in the field. While a particular solution may appear to be very desirable in laboratory cloud chamber testing, extensive field testing should also be done to determine its practicality for operational use.

A number of publications have demonstrated the difficulty of producing sufficiently dense ice crystal concentrations, especially at temperatures warmer than -10 °C, which are common near mountain barriers in the region of interest. Accordingly, one should use the most effective AgI type of aerosol practical for field use and also a fast-acting aerosol because transit times over mountain barriers are limited.

Homogeneous seeding has been done since dry ice was used in the earliest laboratory and field experiments in 1946 (Dennis 1980). Dry ice is not widely used for winter orographic seeding today primarily because large quantities need to be dropped from aircraft. However, homogeneous seeding can also be achieved by the expansion of some gases from surface dispensers. The expansion of liquid propane (C_3H_8) has been shown by Vardiman et al. (1971) to produce temperatures colder than -40 °C for a few tens of centimeters downstream of the nozzle. They demonstrated the practicality of this approach for clearing cold fog over airport runways.

Both laboratory and field measurements have shown that about 10^{11} to 10^{12} ice crystals can be produced per gram of released propane. Hicks and Vali (1973) presented cloud chamber results of 2 X 10^{11} to 6 X 10^{12} crystals per gram of propane for temperatures below -2 °C and 10^{10} crystals per gram within a few tenths of a degree of 0 °C. They also presented field measurements from Elk Mountain, Wyoming, shown near the top of figure 1. These data indicated that nucleating efficiency varied between 10^{11} and 5 X 10^{12} crystals per gram over a range of temperatures. They concluded that, "Thus, it can be stated that liquefied propane will produce 10^{12} crystals per gram of propane under average conditions and at temperatures colder than -2 °C."

Kumai (1982) found from laboratory studies that propane seeding had a threshold temperature of -0.5 °C. This was followed by an exponential rise in crystals created per gram of propane as the temperature decreased to -5 °C. While propane effectiveness was near 10^{10} crystals per gram at -2 °C, it increased to near 10^{11} crystals per gram at -5 °C and remained at that value for colder temperatures. This rapid decrease with warmer temperatures suggests propane seeding would have limited effectiveness at temperatures warmer than -2 °C. Kumai (1982) showed that hexagonal plates formed at temperatures warmer than -3 °C. Hexagonal columns always formed between -3 and -9 °C with columns and plates near -7.6 °C. Hexagonal plates of various types were observed between -9 and -22 °C, with stellar plates between -13 to -17 °C. This temperature range is the dendritic growth zone. Growth times were limited to a few minutes in the cold room cloud chamber. Some caution is appropriate interpreting any cloud chamber results warmer than about -2 °C because of difficulties in maintaining a saturated cloud environment.

Reynolds (1989, 1991, 1992, 1996) pioneered the use of automated, radio-controlled liquid propane dispensers for seeding winter orographic clouds. He based his developments on earlier dispensers designed for clearing supercooled fogs over runways by Vardiman et al. (1971). Super et al. (1995) used dispensers very similar to those developed by Reynolds and reported on a totally automated system that dispenses liquid propane only when SLW is detected on windward mountain slopes. The system used a data logger which opened and closed the value controlling propane flow according to the presence of SLW cloud observed by a commercial icing detector. Propane flow rate and temperature within the expanding propane plume were both measured, so there was no doubt whether the dispenser was operating properly. The system was automatically monitored by radio link and could be manually overridden at any time. The reliability of automated propane dispensers is high because of the simplicity of their design.

Liquid propane has a significant advantage over AgI in that vast quantities of ice particles can be formed at temperatures as warm as -0.5 °C. Winter orographic clouds in the Intermountain West frequently have SLW present at temperatures between -0.5 and -6 °C, too warm for AgI seeding, but seedable with propane.

3d. Basic Considerations About Winter Orographic Cloud Seeding

Winter orographic cloud seeding is a term used for many seeding approaches which have been applied to a wide range of meteorological and topographic conditions. It should not be surprising that the evidence of success has also varied widely. If, when asking, "does cloud seeding work?" the questioner means can it sometimes increase the winter mountain snowfall, the answer is an unequivocal yes. That answer is based on a limited number of well-documented but brief experiments applied to small areas or even a point target. However, if the questioner means, "can significant snowfall be produced on a mountain barrier over the course of a winter?" the answer is less certain. If by "significant" the questioner means about 10 percent on a seasonal basis, the author believes the appropriate answer is "very likely at mountain locations where seeding can be and is appropriately applied." The availability of plentiful excess SLW flux should be verified over any potential target barrier. Documentation of plentiful SLW over the Park Range already exists as discussed in section 6a. Moreover, it must be logistically practical to routinely seed the clouds, and adequate growth times must exist for seeded snowfall growth and fallout. These conditions appear to be frequently satisfied in the Headwaters Region based on various investigations cited in this report.

The author holds the opinion that many past attempts to operationally seed orographic clouds with AgI have failed to produce seasonal increases even approaching 10 percent. The primary problem has been failure to provide adequate concentrations of effective ice nuclei. In other words, past attempts to seed winter orographic clouds often failed to routinely deliver sufficient AgI particles capable of producing ice crystals at prevailing SLW temperatures. In short, cloud seeding often failed because the clouds were not seeded enough or were not seeded at all.

There is, of course, a wide range of opinions among scientists and commercial seeding operators about winter orographic cloud seeding effectiveness. While the author's opinion is certainly subject to challenge, it is based on decades of experience as an active participant in weather modification research. His stated opinions are based partially on review of the considerable body of work presented in this report. Moreover, the author has no financial "stake" in whether cloud seeding is applied to the Headwaters Region or anywhere else.

The basic conceptual model of how artificial nucleation (seeding) of winter orographic clouds can lead to increased snowfall has not changed markedly since the classic calculations of Ludlam (1955). Super and Heimbach (1983) stated similar ideas in discussing what general statements could be made about artificial seeding. They noted that, "In order for cloud seeding to increase snowfall from winter clouds over mountainous terrain, several links in a physical chain of events must exist. First, seeding material must be successfully and reliably produced. Second, this material must be transported into a region of cloud that has supercooled water or ice supersaturation in excess of that which can be converted to ice by naturally produced ice crystals. Third, the seeding material must have dispersed sufficiently upon reaching this region so that a significant volume is affected by the desired concentration range of ice nuclei or the resulting ice crystals. In the case of silver iodide (AgI) seeding this requires, fourth, that the temperature be cold enough for substantial nucleation to occur. Once ice crystals form, they must remain in an environment suitable for growth long enough to enable fallout to occur, generally prior to their being carried beyond the mountain barrier where downslope motion, cloud evaporation and ice crystal sublimation typically exist." These statements briefly summarize what cloud seeding must accomplish to be effective in snowfall enhancement.

Super (1990) examined the state of knowledge for each of these essential links in the chain of physical events leading from release of the AgI seeding agent to additional high elevation snowfall in the Intermountain West. A review of winter orographic cloud seeding throughout the western United States was given by Reynolds (1988), who noted that seeding delivery remained a critical problem, as did the ability to artificially nucleate ice at supercooled temperatures between 0 and -9 °C. Examination of the references in these two review articles shows that numerous publications have dealt with various aspects of cloud seeding for snowfall enhancement. This topic has been the subject of considerable research over the past four decades. Several additional articles have been published during the 1990s. For example, 29 recent papers are cited by Super (1999) just in summarizing a single research program in Utah. While recent Federal Government policy has severely limited research in this important area in the United States, weather modification research has increased in several other nations.

The following statements can be made specifically about winter orographic clouds over the Headwaters Region of northern Colorado and southern Wyoming. These statements are generally applicable to other mountainous regions of the Intermountain West, with the caveat that crest line temperatures tend to be colder at higher latitudes and higher elevations. Support for these statements is found in the discussion and many references contained in later sections.

1. Many winter orographic clouds are naturally efficient, with abundant ice particle concentrations which convert virtually all available SLW cloud to ice. It has also been well documented over several mountain ranges that many orographic clouds have limited natural ice particle concentrations, with the result that little of the available SLW is converted to snowfall. Approaches exist to introduce large concentrations of additional ice crystals into such inefficient clouds. A given storm passage of several hours duration may alternate a number of times between naturally efficient and inefficient phases. Some shallow orographic storms may have abundant SLW and almost no precipitation over many hours. Rauber and Grant (1987) described a southern Utah storm which appeared to have much seeding potential.

2. Observations over several mountain ranges have indicated that the inefficient storm phases have SLW flux that, if converted to snowfall, would be equivalent to a large fraction of the natural snowfall. If even a portion of these potentially seedable phases could be successfully seeded, seasonal snow water content increases in the range of 5 to 15 percent would appear reasonable. Such increases should significantly enhance the April through July runoff.

3. The bulk of SLW cloud is found upwind from and over the windward slope and crest of mountain barriers where upward motion and liquid condensate production are greatest. Downward motion (subsidence) over the lee slope rapidly causes the evaporation of tiny cloud droplets and sublimation of small ice crystals. Most SLW is within 1650 ft above the crest line with very little found more than 3300 ft above the crests. Cloud bases on the Park Range of northern Colorado were usually observed to be between 650 and 1000 ft below the crest line during snowfall, although bases ranged from 1650 ft below to 165 ft above the crest (Rauber and Grant 1986). Cloud base temperatures were normally between -5 and -10 °C. The temperature of the SLW zone is quite important, as will be discussed.

4. Assuming that the SLW layer "targeted" by seeding agents is between 800 ft below and 1650 above the crest line, the Park Range observations suggest a corresponding temperature range of about -5 to -15 °C. However, the actual seedable range may be somewhat warmer. Measurements on the Grand Mesa of west-central Colorado, 125 mi southwest of the Park Range, showed greatest SLW production was always coincident with 10,500 ft mesa top (not cloud base or top) temperatures between -4 and -10 °C (Super et al. 1986). (All altitudes and elevations noted in this report are above mean sea level.) Corresponding temperatures 800 ft lower in elevation would be about -2.5 to -8.5 °C, about 2 °C warmer than the Park Range. The Grand Mesa observations were based on SLW availability, not snowfall, which may explain their somewhat warmer temperature range.

5. Effective seeding of winter orographic clouds involves a "race" as seeded crystals are transported along quasi-horizontal trajectories through the SLW cloud zone. Seeding-caused embryonic ice crystals have a limited time (distance) in which to develop into larger snowflakes or snow pellets with sufficient fall velocities to reach the mountain surface. Otherwise, they are carried into the lee subsidence zone immediately downwind from the mountain barrier, where warming quickly evaporates the small SLW cloud droplets and more slowly sublimates the much larger ice particles. Over four decades ago Ludlam (1955) calculated that ice crystals introduced several hundred meters above ground would require about 25 min to settle to the mountain surface as snowfall. With less available time the crystals would sublimate in the mountain's lee. The results of more recent calculations are not dramatically different from Ludlam's. A valid concern is whether sufficient growth time exists before the seeded crystals are transported into the lee subsidence zone immediately downwind from the crest line. This concern is addressed in section 4c, along with the concern of limited horizontal dispersion with releases so close to the intended high altitude target region.

6. Cloud seeding is done with (1) aircraft releases of seeding material, (2) valley AgI generators, or (3) high altitude seeding material releases. Aircraft seeding is expensive and has logistic problems as discussed in section 4a. Valley AgI seeding is considered unreliable because of lack of routine targeting of adequate concentrations of effective ice nuclei as discussed in section 4b. The remaining alternative is high altitude seeding as discussed in section 4c. This is the only approach which has been shown to *routinely* target orographic SLW zones which are concentrated very near the mountain surface above the windward slope and crest line. It is best to locate high altitude AgI generators or propane dispensers within cloud, or not far below cloud base where ice saturation exists, because the result is that embryonic ice crystals are created immediately downwind from the seeding generator or dispenser. In effect, such seeding releases ice crystals into the SLW cloud which grow as they are transported upslope. Moreover, AgI is effective at temperatures as warm as -6 °C in this mode because of forced condensation-freezing nucleation.

4. DELIVERY OF SEEDING MATERIALS

Clouds often extend several tens of kilometers upwind from mountain barriers during storm passages. Natural snowfall typically begins with the formation of tiny ice crystals far upwind from, and well above, the mountain surface. Some of these crystals will have sufficient time for growth to snowflake sizes as they fall to the surface along quasi-horizontal trajectories.

This study will concentrate on seeding the orographic component of SLW cloud, produced by forced uplift over the barrier, and sometimes aided by weak embedded convection or gravity waves. There is no known practical way to consistently seed SLW cloud far upwind from the mountains, except by aircraft, or by high altitude seeding from an upwind barrier provided one exists nearby as in the Bridger Range Experiment (Super and Heimbach 1983). Silver iodide plumes released high on the windward slope of the Park Range would likely be quite diffuse upon reaching the Medicine Bows because of the distance between these barriers. Distances between crest lines range from less than 20 to about 40 miles (see figure 1).

Aircraft seeding is not recommended as the most reasonable option for the Headwaters Region at this time because of large costs, difficulties of filling a sufficient cloud volume with seeding agent, and safety issues involved with flying in icing conditions near mountains. These problems are discussed in section 4a.

As discussed in section 4b, vertical transport and dispersion of valley-released seeding agents are often limited by low-level inversions. The plume trajectories are not consistent over time, as the plumes may drift in various directions, even opposite the prevailing flow aloft (Heimbach and Hall 1994). This fact makes it impractical to *routinely* target cloud well upwind from a mountain barrier with valley generators. It also severely limits delivery of seeding materials to the SLW near the mountain barrier.

Ground-based seeding from high altitude sites will be recommended. This approach is discussed in section 4c. Should this approach prove impractical for any reason, such as failure to locate or receive permission for sufficient high altitude sites, the possibility of aircraft seeding should be reexamined.

4a. Seeding from Aircraft

Use of aircraft AgI-in-acetone generators has the significant advantage that the seeding material may be released well upwind from the target mountain barrier, sometimes even upwind from any cloud (Deshler et al. 1990). That may be the case for isolated barriers like the Sierra Nevada of California which is well separated from the next upwind barrier by a very broad valley. However, the Headwaters Region has more complex topography, and SLW cloud often exists near the barrier top at slightly supercooled temperatures. In such circumstances, it may be necessary to release the AgI with only limited vertical separation from the mountainous terrain.

High peaks or crest lines exist upwind and crosswind from the Headwaters Region target areas at most locations where it would be desirable to make aircraft releases. Therefore, while aircraft seeding several tens of kilometers upwind from a target barrier might first seem to be without safety problems, more detailed consideration will reveal that is often not the case. It is difficult to operate in close vertical proximity to even isolated peaks when clouds are present, and the Federal Aviation Administration (FAA) requires a minimum of 2,000 ft vertical separation between an aircraft and the highest peak within 5 mi of the flight path under instrument flight rules (IFR) conditions. Sometimes a special waiver can be obtained from the FAA, allowing a minimum of 1,000 ft vertical separation, but that requires a very experienced pilot **and** copilot, as well as a high performance, well-instrumented aircraft, all of which are expensive. But even with 1000 ft minimum separation from the highest nearby terrain, the practical result is the aircraft is typically 2,000 ft above the general mountain top terrain (Super 1995). Another 1,000 ft need to be added in the likely event that standard FAA flight rules must be followed, resulting in 3,000 ft vertical separation. That requirement will often place the AgI release above SLW cloud, rendering the seeding ineffective. A further complication with aircraft operations is potential conflicts with fixed air traffic routes.

Another serious shortcoming of aircraft seeding is the limited dispersion rate of the seeding material and any resulting ice crystals. Hill (1980) used aircraft observations to investigate this problem in Utah. He stated that, "It is concluded that both the vertical and horizontal diffusion of silver iodide released from airborne generators in the northern Wasatch Mountains during nonconvective winter orographic storms are much lower than that desired for effective seeding." Hill (1980) recommended that (1) AgI seeding be carried out several hours travel time upwind from the desired target, (2) dry ice be dropped from, preferably, a jet aircraft to permit rapid traverses to maximize the cloud volume filled with seeded crystals and (3) that, "an entirely new delivery system/seeding agent be designed for seeding winter orographic clouds."

The author considers recommendation (1) of Hill (1980) to be impractical because of targeting uncertainties associated with complex air trajectories over mountainous terrain and the difficulty of predicting SLW availability hours in advance. Recommendation (2) is also considered impractical because of the very high costs of using jet aircraft and the limited dry ice payload which can be carried, plus the logistics and volume filling problems discussed by Deshler et al. (1990), based on the release of 172 dry ice seed lines. For a variety of reasons, seeded ice crystals were observed in only 33 of these seed lines. Fortunately, the technology to follow recommendation (3) has been developed over the past decade and has been demonstrated to be practical as will be discussed.

Based on aircraft and ground-based microphysical observations upwind from and over the Sierra Nevada of California, Deshler et al. (1990) concluded that, "Achieving fairly continuous coverage along the direction of seed line advection requires seed lines to be no longer than 37 km (23 mi), yet treatable cloud may extend for hundreds of kilometers along the barrier." A reasonably high performance twin engine aircraft (Aero Commander) was used for the Sierra Nevada seeding. Less expensive single engine aircraft are usually not used in icing conditions near mountains for safety reasons. Since the presence of SLW cloud is transient and cannot be well predicted, several twin engine aircraft and crews would need to be available on an almost continuous basis to effectively seed the entire Headwaters Region. The logistic problems and costs of such an operation would be considerable. Moreover, experience gained during an experimental program indicated that even a high performance research aircraft could not safely continue to operate during the heavier SLW periods because of moderate to severe icing, or during winder phases because of severe turbulence (Super 1999). Hours of exposure may cause serious ice buildup on those portions of a seeding plane airframe not equipped with deicing mechanisms, even if SLW amounts are limited. Aircraft seeding may be practical in situations where seeding may be done well upwind from the target barrier in a region where safe flight is possible down to within 1000 to 1650 ft of mountain crest altitudes.

If aircraft seeding were the only alternative, it would be advantageous to release a condensation-freezing type of AgI aerosol well upwind from the mountain barrier. The AgI could be released from acetone wing-tip generators along lines parallel to the barrier at altitudes where the temperature is colder than -6 °C (Deshler et al. 1990). Seeding would not have to be done in-cloud as long as the AgI aerosol entered SLW cloud downwind from the seed lines. Consequently, when cloud did not extend far upwind from the target barrier, aircraft seeding could be done under visual conditions at an appropriate altitude with minimal safety and air traffic concerns. This approach would simulate nature, allowing seeded ice crystals to reside in-cloud for sufficient time and distance to provide abundant growth and fallout. However, since aircraft seeding is not being considered for the reasons previously stated, a means of ground seeding needs to be chosen that will allow sufficient time for seeded ice crystal growth and fallout.

No detailed cost estimates were prepared for using aircraft seeding of the Headwaters Region. However, such estimates were made for some earlier planned Bureau of Reclamation projects. The most recent such estimate was given by Reynolds and McPartland (1993), who calculated an annual cost of $820,000 for an aircraft seeding experiment (not continuous seeding) of the Trinity watershed in northern California. The details behind this estimate are no longer available, but the proposed aircraft seeding program contained the following components. Two turbocharged twin engine aircraft with wing-tip AgI generators would simultaneously fly in opposite directions along a single seed line with at least 1000 ft vertical separation. While the seed line distance is not specified, a map of the area suggests it would be about 25 mi long.

The two aircraft would seed about 1 h airflow travel time upwind from the target. However, figure 3.5 of Reynolds and McPartland (1993) shows considerable separation between seed lines after 0.5 h, so suggested merging of the seed lines after 1 h seems doubtful. More likely, only a fraction of each seeded hour would produce snow on the ground with this arrangement. The authors note that a 23 mi long seed line from a single aircraft might affect surface precipitation for only 10 min even after 45 min travel time. Of course, use of two aircraft and wind shear should increase this fraction, but it is still doubtful that the aircraft seeding would be effective more than half of the time.

The proposed program was randomized so not each 4 h block was to be seeded. Moreover, 1 h buffer zones were permitted between seeded units to allow for refueling the aircraft and changing crews. It was estimated that by limiting (blocking) the experimental units into no more than two in a row with the same seed or no-seed decision, the number of pilot/copilot crews could be limited to four for 24 h daily operations.

It is difficult to extrapolate the above experimental aircraft seeding for a randomized program into an estimate for full-time, full-coverage operational seeding. However, as a first-cut estimate, total costs for seeding about 25 mi of barrier crest would appear to be about three times the above estimate in 1999 dollars, or about $2.5 million per winter. Since the crosswind lengths of the Park Range and Medicine Bows both exceed 65 mi, it appears that routine aerial seeding could cost several million dollars per season. Should it be necessary to consider aerial seeding as the only option for the Headwaters Region, detailed cost estimates could be developed.

Because of the considerable expense and noted operational limitations of aircraft seeding, only ground-based seeding will be considered further in this report.

4b. Seeding from Valley Floors

A considerable body of evidence from operational seeding programs indicates valley-released AgI plumes are often trapped by stable air, or are transported parallel to mountain barriers rather than over them. Even when the plumes are transported over the mountains, resulting concentrations of active ice nuclei are too weak for effective seeding unless cloud temperatures are relatively cold. Super (1994) summarized the results of monitoring valley-released AgI during 12 storm days on the Wasatch Plateau of Utah. He questioned the operational program's effectiveness because of the relatively warm SLW temperatures and weak effective AgI ice nuclei concentrations found in the SLW clouds.

Six case studies of valley-based AgI seeding over the Wasatch Plateau were described by Super (1995). These were the only 1991 field season sampling periods when AgI released from eight valley generators was detected at aircraft sampling altitudes over the plateau. Silver iodide concentrations, effective at -20 °C in ice nucleus counter cloud chambers, were about an order of magnitude less 2000 ft above the plateau top than observed on the plateau top. The AgI was seldom transported up to 3300 ft above the plateau top. Cloud physics aircraft measurements failed to indicate any ice particle concentration (IPC) increases during three of the six experiments, when sampling level temperatures were warmer than -9 °C. Evidence existed that seeding-caused IPC increases during at least two of the three colder cloud experiments. However, any associated increases in snowfall were minor, even during an experiment with heavy aircraft icing in cloud cold enough for plentiful nucleation by AgI. The observational evidence from the 1991 field season indicates the valley-based operational seeding was ineffective.

Reynolds et al. (1989) reported upon ground-based seeding experiments with AgI generator sites ranging from the foothills to far up the west slope of the Sierra Nevada of California . A network of 24 generators consisted of 3 long-term operational networks of remote-controlled generators and 1 specially-installed network of manually-operated generators. All generators were operated in a coordinated fashion during a 2-mo period. Of 18 randomized events, 12 were seeded and 6 were left unseeded. A numerical targeting model was used to compute nucleation and fallout locations for each generator on a given day. The model appeared to provide reasonable estimates of AgI plume transport and dispersion. Aircraft plume tracing studies indicated a 10 to 15 deg angle of AgI spread downwind from the generators.

Silver iodide plumes released from foothill generators frequently had trajectories parallel to the mountain barrier rather than over it. Targeting was more successful downwind from higher elevation generators, above 6600 ft. The numerical model predicted best results for the intended target area during low freezing levels and light westerly winds. Snow fallout during such favorable conditions was predicted to occur 6 to 19 mi downwind from the generators.

Extensive snow chemistry analysis was used to examine targeting effectiveness at 14 sampling sites within the intended target area. Finding increased silver-in-snow does not prove that AgI seeding produced snowfall because natural snowfall will scavenge AgI and bring it to the surface. However, failure to find silver greater than natural background levels in a given snow sample indicates the AgI plume missed passing over that particular sampling location during the sampled snowfall period, and, therefore, that seeding was ineffective. A total of 1,681 individual snow samples were collected for chemical analysis of silver concentration soon after seeding events. Less than 15 percent of the samples indicated any silver greater than background. In summarizing the silver sampling program, Reynolds et al. (1989) concluded that, "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."

These results are indeed disturbing, especially since some of the generators were located at relatively high elevations. They raise serious concerns about generator siting, inadequate crosswind coverage by adjoining generator plumes and the reliability of remote-controlled AgI generators.

The cited evidence leads the author to conclude that use of valley or even foothill generators generally does not provide a reliable seeding method. It is recognized that this view is at variance with many in-house statistical analyses of operational projects and even some peer-reviewed analyses of experimental research projects. Reasons for regarding statistical results with caution, especially if they are not supported by confirmatory physical evidence, are given in section 5a.

Considerable evidence exists to support the view that the transport and dispersion of *adequate concentrations of effective AgI* has been the weakest link in many, probably most, attempts to seed winter orographic clouds from the ground. Analysis of the snow silver content in a number of operational seeding target areas have shown targeting to be marginal at best. Conversely, Super (1990) cites evidence of large silver enhancements in two projects that used high altitude AgI generators. More recently, Super and Huggins (1992) presented silver-in-snow and other evidence from central and northern Utah that cast doubt about the transport and dispersion of Utah's operational seeding with valley generators.

Besides the problem of achieving transport and dispersion of AgI from valley or foothill generators to the SLW zone above mountain barriers, the relatively warm temperature of that zone often makes AgI seeding impractical. Super and Heimbach (1983) showed that even in southwest Montana, about half the seeded periods were too warm for effective seeding by ground-released AgI. The problem is worse at more southerly, warmer locations. Sassen and Zhao (1993) discussed the dominance of mildly supercooled orographic clouds in the 0 to -10 °C range in southern Utah. They concluded that mainly the upper portions of relatively warm clouds with base temperatures warmer than -7 °C and abundant SLW present had significant seeding potential. Moreover, they showed that southern Utah clouds with top temperatures colder than about -12 °C were often naturally efficient users of orographically produced SLW. Sassen and Zhao (1993) concluded that a rather limited temperature window exists for effective seeding in southern Utah.

Super (1999) reviewed the multi-winter central Utah experimental program and showed that the lowest kilometer above the Wasatch Plateau was often too warm for seeding with AgI with any practical source strength. Yet ground-released AgI and tracer gas were seldom transported as high as 3300 ft above the mountains. This finding, that ground-released AgI and tracer gas are usually transported no more than about 2300 ft above mountain barriers, is in accordance with several earlier investigations. For example, see Holroyd et al. (1988), who also pointed out that the warmer one-third to one-half of the winter storms over the Grand Mesa (top altitude 10,500 ft) were too warm for adequate nucleation rates at plume tops with pure AgI (AgI-NH_4I-acetone solution) released from high altitude generators.

4c. Seeding from High Altitude Locations

High altitude releases are recommended for seeding the Headwaters Region. Plumes from high altitude windward sites have been observed over only a limited number of Intermountain West mountain ranges. However, those observations have been consistent and are strongly relevant.

High altitude seeding may be done with some type of AgI ice nucleant or with some homogeneous agent like liquid propane. The latter can be released from economical dispensers which are far less complex than remote-controlled AgI generators. Liquid propane has the advantage of widespread availability in large pressured tanks that are usually used to supply fuel to furnaces. Tanks can be transported by helicopter to remote locations in the fall in sufficient quantity to provide seeding for the entire winter. Reynolds (1989, 1991) used two 575 gal propane tanks per winter in the Sierra Nevada where SLW cloud is frequent. Solar panel power is sufficient to operate a propane dispenser system consisting of plumbing between the tanks, one or more elevated spray nozzles, solenoid valves to turn flow off and on, flowmeters to monitor flow rate, and a microprocessor (data logger) and radio for control. The addition of an icing detector permits automatic operation only when SLW is present (Super et al. 1995) at some or preferably each of the dispensers. An alternative, more economical approach is to monitor SLW at a few locations along a mountain barrier for use in helping decide when to release propane from an entire network (Reynolds 1992). It is sufficient that propane be released only when SLW is detected at or near the high altitude dispensers.

While additional observations may be interesting, it is not necessary to monitor temperature, wind velocity or parameters other than SLW presence near propane dispensers. The reason is that significant SLW will exist there only when the temperature is colder than freezing and the wind is blowing upslope toward the target area. The ability to decide to seed based solely on the local presence of SLW (or icing) greatly simplifies the seeding decision process. It eliminates the need for supporting instrumentation such as radar and rawinsondes (unless needed by seeding suspension criteria) and reduces technical personnel to a minimum, thereby significantly reducing operating costs. There is also no need to use a targeting or cloud physics model since ice crystals will be formed just above the mountain surface and the vertical fall distance will be trivial for some of them. Other crystals will be dispersed higher in the SLW cloud, so their fall distance becomes a serious consideration. However, the question of whether sufficient time (distance) exists for significant snow to fall cannot be answered with sufficient accuracy by a numerical model because of uncertainties in small-scale transport and dispersion near rugged terrain, and in nucleation and growth processes. A model might indicate insufficient time for significant growth and fallout of individual seeded crystals. However, riming, aggregation and scavenging (sweep out) by natural snowflakes can all assist small seeded crystals in reaching the mountain surface before sublimating downwind from the barrier.

. . . Headwaters Region, Colorado and Wyoming

Some of the earliest airborne AgI plume tracking results over the Headwaters Region were reported by Langer et al. (1967) during testing of a new ice nucleus counter. A limited data set resulted, "under conditions approximating those conducive to cloud seeding." It was found that much of the AgI released from the 8,200 ft top of Emerald Mountain was trapped in the Yampa valley between the release point and the Park Range. None of the tests showed reasonable AgI concentrations more than a few thousand feet above the ground.

Smith and Heffernan (1967) commented that the Langer et al. (1967) results were in agreement with their more comprehensive series of measurements of AgI plumes released from an Australian mountain top. They stated that under their conditions AgI should be released from aircraft and, "---suggested that in other conditions persons who release silver iodide from the ground *would be wise to find out where it goes"* (emphasis added). Unfortunately, their seemingly obvious advise has seldom been followed, in part because tracking seeding plumes over mountainous terrain is difficult and expensive. Most past winter orographic projects have not documented where their AgI went, much less in what concentrations as effective ice nuclei. In other words, most past and current ground-release seeding projects cannot physically demonstrate that their target clouds were routinely seeded. Reynolds (1988) and Super (1990) echoed earlier concerns that the transport and dispersion of ground-released AgI remained the most serious problem for winter orographic cloud seeding. The difficulties of targeting SLW regions in winter orographic clouds were most recently noted in the review article of Bruintjes (1999). The approach recommended in this report (section 11) essentially eliminates the targeting problem by releasing seeding material directly within orographic SLW cloud upwind from the target area.

Auer et al. (1970) reported on plume tracking over the Elk Mountain of Wyoming in the northern portion of the Headwaters Region (see figure 1). Generators were operated from 6 to 11 mi upwind from, and approximately 4000 ft below, the 11,000 ft Elk Mountain Observatory. All plume tracking experiments were conducted on cloudless days, with occasional superadiabatic (very unstable) temperature lapse rates and no evidence of inversions between the base and top of Elk Mountain. Consequently, results are likely to be atypical of more stable orographic storm days. Nevertheless, vertical dispersions of the AgI plumes were limited to only 1000 to 1500 ft above the mountain.

Rhea et al. (1969) reported on the results of a 5 year program of statistical and physical cloud seeding investigations on the Park Range. A large number of tests were conducted to track the transport and dispersion of ground-based and aircraft releases of both AgI and tracer material. The authors made the important point that valley-based inversions were present during at least half of the hours with snowfall. The inversions totally trapped any seeding material released below them which greatly limited the effectiveness of the valley-based seeding generators. The trapping inversions were found to typically occur up to a height of at least half of the mean terrain height of the main barrier, but with many variations. Trapping inversions often existed between 8,000 and 9,000 ft. For reference the Yampa Valley to the west has elevations below 7,000 ft and the Park Range crest line exceeds 10,000 ft. Consequently, ground-based generators should be located more than half-way from the valley floor elevation to the crest line elevation.

*. . . **Bridger Range, Montana***

Super et al. (1970) reached the same conclusion from temperature and wind observations from the upwind valley floor, along the west (windward) slope, and on the crest of the Bridger Range in southwest Montana. Consequently, the Bridger Range Experiment reported by Super and Heimbach (1983) used seeding generators about two-thirds of the way vertically up the windward slope, a "rule-of-thumb" which still appears appropriate. Super (1974) discussed the results of several AgI plume tracking flights over the Bridger Range. While not in the Headwaters Region, these and later Bridger Range AgI plume observations are considered quite relevant because seeding material was released well up the windward slope.

All winter plume tracking flights reported by Super (1974) were made during visual flight rules (VFR) conditions but with broken or overcast higher level clouds to approximate storm conditions. Two high altitude AgI generators were operated on the windward slope, about two-thirds of the vertical distance from the upwind valley floor to the 8600 ft crest line. The crosswind spacing between the generators was 4.3 mi. Good plume width estimates were available from five tracking missions through the southern plume. Observations were made directly over the crest line 3 mi east and 1400 ft above the generator, which was on a ridge extending west from the crest. The median plume width was 27 degrees or 1.4 mi over the crest line. Silver iodide was confined to the lowest 1500 ft above the crest line. This rather rapid vertical and horizontal dispersion was believed to have been caused by the strong mechanical turbulence experienced during these sampling flights. The northern plume was also released 1400 ft below the crest, but only 1 mi upwind from it, in a bowl-like setting. This resulted in a shallower plume over the main crest than was detected on several passes made in the lowest 500 ft over the crest, sometimes at crest altitude immediately west of the ridgeline. Only a few alternating passes, flown in opposite directions, both detected the northern plume. Therefore, widths could seldom be estimated since instrumentation documented only the aircraft's entry position into the plume. The two plume widths reported by Super (1974) were 80 and 88 degrees, respectively, corresponding to 1.8 miles over the main crest. It is speculated that the northern plume tended to fill the bowl containing the generator with the result that a relatively wide but shallow plume "spilled out" over the main crest line.

Super and Heimbach (1983) summarized the above and additional observations over the Bridger Range. The overall body of evidence confirmed that the southern AgI plume was confined to the lowest 1500 ft above the main crest and that little additional vertical ascent was evident over the intended target area.

The target was a broad secondary ridge centered about 8 miles east of the main crest. Based on the total of 42 passes through the plume on 13 different days it was concluded that plume widths were usually in the 10 to 30 deg range (1.0 to 1.7 mi) over the main crest. Limited observations over the target indicated further crosswind broadening with widths between 2.5 and 3.1 mi. However, it would be desirable to create a nearly continuous crosswind zone of seeded crystals over the main crest where SLW is abundant because of forced uplift. These observations suggest that if seeding material is released about 3 mi upwind from a mountain barrier, it would be optimum to locate seeding sites at less than 2 mi intervals across the wind (parallel to the crest line). However, more limited observations of the northern AgI plume, released only 1 mi windward of the crest, suggested a similar width but more shallow plume was usually transported out of the bowl containing the generator and over the main crest. Thus, northern and southern plumes appeared similar in width over the target ridge although data are limited for the former.

An operational seeding program intended to target the Bridger Bowl Ski Area, immediately downwind from the northern generator, produced apparent seeding results (Heimbach and Super 1988). The seeding plume and microphysical evidence of seeding effects were detected on the crest line above the ski area on a number of occasions. Silver-in-snow sampling was done after the seeding program immediately to the lee of the main crest. These measurements showed much greater than natural background values of silver for about 2 mi crosswind distance. Of course, this width represents several winter storms so the instantaneous plume was likely narrower. The only sample on the downwind secondary ridge, at its center, also showed silver concentrations much greater than natural background. That ridge was the target for the previous Bridger Range Experiment (Super and Heimbach 1983). The overall evidence indicates that both the northern and southern seeding plumes were effective immediately to the lee of the main crest and over the downwind secondary ridge.

Super and Heimbach (1988) reported on six cloud physics aircraft sampling flights over the same Bridger Range Experiment target during several January 1985 winter storms. These storms were stable as is typical of winter orographic storms in that area. The southern generator site was again used. The AgI plume was clearly detected over the broad secondary target ridge 11 mi east of the generator on all six missions. Silver iodide and seeded ice crystals were confined to the lowest 1500 ft or less above the elevation of the upwind main crest. This finding is in agreement with earlier non-storm observations. Estimated AgI plume widths over the target were usually in the range of 3 to 5 mi, somewhat wider than indicated by more limited non-storm plume tracking reported earlier. These observations provided proof that the southern seeding plume used in the Bridger Range Experiment routinely passed over the intended target area.

. . . *Grand Mesa, Colorado*

Holroyd et al. (1988) discussed the results of several airborne plume tracking experiments with high altitude ground-based AgI seeding generators on the Grand Mesa of western Colorado. Sampling was done under a variety of cloud, wind and stability conditions. Ground releases were made from different sites, ranging from 650 to 2300 ft below the 10,500 ft mesa top. Instantaneous plume widths were almost always within a factor of two of the 15 deg median angle. The instantaneous plumes meandered through a wider angle with a median of 38 deg. With a single exception plumes were confined to within 2600 ft of the mesa top, and the median vertical extent was about 1800 ft. These results were in close agreement with earlier observations from the Bridger Range of Montana. Both mountain barriers rise about 5000 ft above upwind valleys.

Super and Boe (1988) presented various airborne observations for two of the cases discussed by Holroyd et al. (1988). They showed that the ice crystal concentrations and estimated snowfall rates were markedly increased about 2000 ft above the mesa top approximately 3.7 mi downwind from the high altitude AgI generator. One of the seeding experiments with a shallow stratocumulus deck produced weak snowfall coincident with the AgI plume. No other snowfall existed anywhere else over the mesa during that experiment.

. . . Sierra Nevada, California

Reynolds (1996) presented the results of many plume tracing experiments over the Sierra Nevada of California. Tracer gas was released from two locations near 6700 ft, one on a ridge line and the other about 2 mi upwind from the ridge line. Plumes were tracked over the downwind valley and the intended target which was the next ridge about 15 mi downwind from the release sites. Average plumes widths over the target ridge were 10 to 15 degrees (2.5 to 4.3 mi). In-cloud sampling revealed the aircraft was just skimming the plume tops about 2000 ft above the release sites. It was concluded that mountain-induced gravity waves often carried the plumes downward over the valley between the release ridge and target ridge, which was detrimental for ice particle growth and trajectories. It appeared that release sites farther back from the crest would have allowed more time for plume dispersion and better lift into cloud. Reynolds (1996) final remark was that, "Again, it would seem imperative that detailed transport and dispersion studies be performed prior to the onset of any long-term snowfall enhancement program in order to confirm that successful targeting is possible for a majority of storm periods when liquid water is observed."

. . . Wasatch Plateau, Utah

Many high altitude, ground-based seeding experiments were conducted during the multi-winter research program on the Wasatch Plateau of central Utah summarized by Super (1999) and described in section 8. Either AgI or liquid propane was released well up the windward slope at 1050 ft vertical distance below the plateau top. Sometimes a tracer gas was simultaneously released to permit detailed plume definition using a fast-response detector. Results from these experiments have been reported by Super and Holroyd (1994), Super (1995), Super (1996), Super and Holroyd (1997) and Holroyd and Super (1998). Holroyd et al. (1995) discussed an additional experiment where both AgI and tracer gas were released from another high altitude site 1850 ft below the plateau top.

Many of the Wasatch Plateau experiments used a single well-instrumented target site on the plateau top's west edge so plume width and depth observations were not available. However, several other experiments sampled AgI and tracer gas plumes with an instrumented aircraft at a number of altitudes along the plateau top's west and east edges. An instrumented van was driven along the plateau top's west edge which also sampled AgI and tracer gas plumes. Super (1999) summarized the many experiments which used high altitude releases. In addition, many hours of aircraft and van sampling over the Wasatch Plateau have never been reported as detailed case studies. Nevertheless, this large body of plume tracing observations made strong impressions on the scientists involved. For example, plumes from both seeding sites were routinely transported over the plateau.

The main findings from the Wasatch Plateau work relevant to transport and dispersion over the Headwaters Region mountains are now briefly summarized:

1. Valley releases of AgI are very unlikely to produce significant high elevation snowfall enhancement in the Headwaters Regions. Use of valley or even foothill AgI generators is not recommended for seeding winter orographic clouds over this mountainous area.

2. Plumes released on windward slopes, within 1000 to 1800 ft downslope from the mountain crest line, will be routinely transported over the crests. The author does not recall any instance of a failure to detect AgI or tracer gas from the higher, more northerly site, along the road paralleling the plateau top's west edge when the plateau top wind had a westerly (upslope) component. Plateau top winds seldom have a non-westerly component when significant SLW exists (Super 1994). Plumes from the lower, more southerly seeding site were also often found on and above the plateau top. However, unless winds were from the southwest, these plumes were too far south to be sampled along the plateau top roads.

3. Seeding plumes will be concentrated in the lowest 2000 ft above the crests. This was the lowest in-cloud aircraft sampling altitude over the Wasatch Plateau. Aircraft sampling often detected AgI and tracer gas plumes 2000 ft above the average plateau top elevation and sometimes higher. However, there were frequent cases of failure to detect even at lowest aircraft sampling levels while dense concentrations were observed on the plateau top. Often the aircraft instruments would detect plumes only during a fraction of the lowest passes. This result indicates that the typical plume top was near 2000 ft above the average plateau top elevation.

4. Determination of plume widths was not a major priority in the Wasatch Plateau work and such data have been published for only two detailed case studies, one with each of the seeding sites. These plume widths are based on nearly instantaneous observations of tracer gas over the plateau top's west edge, analogous to mountain barrier crest lines. Plume widths varied from 6 to almost 90 degrees, the latter due to a wind shift. However, typical (median) plume widths were 20 deg about 3.7 mi downwind from the higher seeding site and 15 deg about 2.5 mi downwind from the lower site. These widths correspond to about 1.2 mi crosswind distances. Since most of the observations were made at aircraft levels, near plume top, somewhat wider plumes might be expected at the surface. It is estimated that the ideal spacing of high altitude seeding sites should be about 2 mi crosswind to provide nearly continuous filling of the SLW zone by the crestline. However, cost considerations and the ability to locate suitable seeding sites may require some relaxation of this ideal spacing.

5. Concentrations of ice crystals over the plateau top's windward edge were typically in the 10 to 100 L^{-1} range when conditions permitted detection of seeded crystals. These concentrations are believed to be in the appropriate range for seeding to be effective. In fact, light snowfall rates in the range of 0.01 to 0.04 inch h^{-1} were observed to result from some of the seeding experiments. These values are typical of most hours of natural snowfall on Intermountain West mountains. Silver iodide release rates with the AgI-NH_4I-acetone seeding material ranged from 8 to 30 g AgI h^{-1}, depending upon the generator type used. Liquid propane release rates were about 6500 g h^{-1} using one nozzle which typically produced 10 ice crystals L^{-1} at the surface target 2.6 mi upslope (downwind) from the dispenser. Two nozzles were used the final winter which released about 13,000 g h^{-1} of propane. This approach produced about 20 ice crystals L^{-1}, a statistically significant difference from concentrations produced with one nozzle (Holroyd and Super 1998).

5. STYLES OF CLOUD SEEDING EVALUATION

A recent Policy Statement by the American Meteorology Society (1998a) states that, "There is statistical evidence that precipitation from supercooled orographic clouds (clouds that develop over mountains) has been seasonally increased by about 10%. The physical cause-and-effect relationships, however, have not been fully documented. Nevertheless, the potential for such increases is supported by field measurements and numerical model simulations." The accompanying statement on the scientific background for the Policy Statement (American Meteorology Society 1998b) notes that, "Both (measurements and model simulations) show that SLW exists in amounts sufficient to produce the observed precipitation increases and could be tapped if proper seeding technologies were applied. The processes culminating in increased precipitation have also been directly observed during seeding experiments conducted over limited spatial and temporal domains." Such experiments are referred to as "physical experiments" in this report (and discussed in section 5b) as opposed to experiments with a heavy reliance on statistics but limited documentation of key physical processes. The latter are sometimes called "black box" experiments. When they fail, there is no way to determine what went wrong within the "black box" design between release of seeding material and intended increased target area precipitation.

5a. Statistical Evaluation

There are a number of reasons for the current state of limited knowledge concerning seasonal increases from cloud seeding, not the least of which is the lack of statistical replication (repeating an experiment) for weather modification experiments. Statisticians greatly recommend this approach and some consider it essential. Nevertheless, it has rarely been possible to replicate cloud seeding experiments. Support for such long-term winter orographic experiments has not been available with the exception of the Climax I and II experiments discussed later. Those Colorado experiments were conducted many years ago, on very limited budgets, and without the significantly improved knowledge and observational capabilities now available. It is the author's admittedly biased view (he was involved) that the Bridger Range Experiment, conducted in the early 1970s but with later (1985) supporting cloud physics aircraft observations, provides perhaps the best overall statistical and physical evidence that at least 10 percent snowfall increases can be achieved. That experiment, which seeded a limited target area with high altitude AgI generators, is discussed in section 4c.

A sizable body of literature exists which discusses the many difficulties with *post hoc* (after-the-fact) statistical analyses of non-randomized operational seeding projects and why such attempts should be viewed with considerable skepticism. Dennis (1980) and Gabriel (1981) discuss many of these potential problems, such as lack of randomization needed to provide a suitable "control" against which to compare seeding results. Many statisticians regard randomization as essential for meaningful analysis. Target-control area analysis of non-randomized seeding assumes the long-term (often decades) stability of precipitation or streamflow observations in areas sometimes located far apart. Solak et al. (1987a, 1987b) reported 13-15 percent increases in average annual streamflow from two well-correlated southern Sierra Nevada drainages seeded with aircraft flares and/or ground-based generators. These are impressive results if indeed they are caused by seeding. However, Dennis (1980) discusses some of the reasons why the assumption of long-term stable relationships between two areas can provide a major difficulty. Examples of activities that may change long-term relationships include housing and other manmade developments, forest and brush fires and timber harvesting if they affect one drainage more than the other. Climatic change could also be a factor if the target and control areas are far apart.

Super (1999) comments on changes in target and control gage selections over time for three different analyses of a long-term operational project in Utah done by the same company. Even if the same gages had been used for evaluation over many years, the exposure of particular gages can change with time (e.g., trees grow up nearby or are cut down, buildings are constructed close to the gage, etc.). Changes in exposure result in changes in gage catch, especially with snow which is quite difficult to measure accurately in the presence of even limited wind (Goodison 1978, Groisman and Legates 1994).

An additional serious concern is that analysis of most operational projects has been done by the same firm which conducted the seeding. They presumably have interest in future business and, therefore, potential conscious or unconscious bias for reporting positive results. The author has read numerous reports of operational seeding aimed at rain or snow enhancement over the past three decades. Most claim increases in the range 5 to 20 percent on a seasonal basis while "in-house" reports of nil or negative effects are rare. This result could lead one to conclude that cloud seeding is a proven technology which is almost always effective and some would agree with that point of view. But the American Meteorology Society Policy Statement (1998a) has a markedly different point of view. The author of this report strongly recommends that the results of statistical analysis of operational seeding projects be given little weight unless the analysis was done by, or favorably reviewed by, knowledgeable persons disinterested in the results. Moreover, the statistical suggestions must be in accord with known physics.

Even statistical analysis published in the peer-reviewed open scientific literature can result in misleading conclusions if not supported by strong physical evidence of seeding effectiveness. Probably the best known statistical analyses of winter orographic seeding experiments, as opposed to operational seeding, were done with the Climax I and Climax II experiments near Leadville, Colorado (Mielke et al. 1971, Mielke et al. 1981). Climax II was a randomized experiment that replicated (repeated) Climax I. The combined Climax results were widely regarded for some years as proof that valley AgI releases could produce meaningful mountain snowfall increases under some conditions. But even the replicated Climax statistical results have been seriously challenged over the years on physical and other grounds. For examples, see Hobbs and Rangno (1979), Rhea (1983), and Rangno and Hobbs (1993), plus several of their references dealing with this long running controversy. Many scientists now view the Climax results with serious skepticism as a consequence of these challenges and lack of collaborating physical evidence in what was admittedly an early seeding experiment conducted with quite limited funding.

Analysis of a number of experimental projects have shown no results when judged by the original criteria. For example, Elliott et al. (1978) reported on a major 5 year winter orographic experiment, the San Juan Pilot Project sponsored by the Bureau of Reclamation. This experiment failed to show more precipitation on seeded days. There may be a variety of reasons for failure to demonstrate seeding effects including improper experimental design and failure to routinely seed the target clouds, both of which occurred in San Juan Pilot Project. Another important consideration may be the Type II statistical error in which a real effect is not detected because of inadequate power-of-the-test related to too few experimental units. Heimbach and Super (1996) used Monte Carlo techniques to show that experimental durations may often have to be longer than expected in the likely event that seeding responses range widely among a population of experimental units. Some earlier estimates of experimental duration assumed the same percentage response for each seeded unit, now recognized as a naive notion. But experimental durations have often been determined rather arbitrarily with 3 to 5 years being a typical range, largely dependent upon the patience of the funding agency. Such durations may often be inadequate to "prove" whether the experimental design concept is correct. Unfortunately, there exists a tendency, even among scientists who should know better, to conclude that seeding did not work when experiments have failed to demonstrate a statistically significant seeding effect in the time period available. The reality is that the durations of several statistical experiments were probably too limited to prove or disprove anything, and that is the only valid conclusion to be drawn from them.

Earlier over-reliance on "black box" statistical design has given way to increased emphasis on fundamental physical understanding of key processes during the past two decades (e.g., Braham 1981, American Meteorological Society 1998b). As the latter reference awkwardly states, "The physical plausibility that the effects of seeding suggested by the results of the statistical experiment could have been caused by the seeding intervention, that is, the physical evidence is consistent with the statistical evidence, must then be established through measurements of key links in the chain of physical events associated with the seeding conceptual model."

The recently adopted American Meteorological Society (1998a) Policy Statement on weather modification recommends that, "Planned weather modification programs are unlikely to achieve greater scientific credibility until more complete understanding of the physical processes responsible for any modification effect is established and linked by direct observation to the specific seeding methodology employed." The Policy Statement further notes, "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." The latter recommendation has rarely been followed with some partial exceptions like the Bridger Range Experiment cited by Reynolds (1988). This Policy Statement has recently been agreed to by several scientists quite knowledgeable about weather modification.

5b. Physical Evaluation

Knowledgeable and unbiased scientists would generally agree that several experiments in different locations have documented obvious large increases in IPC in seeded orographic clouds. These experiments have admittedly been conducted over small areas, sometimes just a "point" target, and over brief intervals no longer than an hour. Such increases are, in fact, obvious when (1) SLW cloud exists that, (2) is appropriately seeded, and (3) is widespread enough for seeded crystals to grow for several minutes, while (4) natural ice particle concentrations (IPCs) are very limited. The effects of seeding on the IPC are masked when natural IPCs are moderate to high.

Weickmann (1973) pioneered in this "physical approach" by conducting many such experiments in Great Lakes winter lake effect storms. He concluded those studies by stating, "This research constitutes one of the few available studies that have shown unambiguously without post-experimental data manipulation that artificial precipitation can be generated, and that the cases in which 'nature misses her chance' do occur often enough to warrant continued exploration. One of the most obvious examples of success in seeding lake effect storms was reported by Holroyd and Jiusto (1971).

Among the best documented physical seeding experiments with winter orographic clouds is the work of Hobbs and Radke (1975) and their two companion articles, dealing with the Cascade Mountains in Washington State. More recent examples include Super and Boe (1988), Super and Heimbach (1988), Deshler et al. (1990), Deshler and Reynolds (1990), Holroyd et al. (1995) and Super and Holroyd (1997). Holroyd and Super (1998) presented a statistical analysis of many physical experiments conducted over a two-winter period in Utah under a wide range of conditions.

Physical seeding experiments that track released seeding material, resulting ice crystals and subsequent snowfall on the surface are relatively easy to conceptualize and design with the availability of modern instrumentation. However, they are often difficult to successfully carry out in clouds over mountains. It is especially difficult to clearly demonstrate the final and most important link in the chain of events; that is, seeding-produced additional snowfall on the ground. Besides the numerous logistic difficulties involved with sampling in and over mountainous terrain, the main complication is that natural mountain snowfall is greatly variable. It is common to begin a seeding experiment in the absence of natural snowfall only to have seeding effects masked by brief pulses of natural snow within the next 15 to 60 min as shown by Holroyd and Super (1998). As they discussed, seeding still may have increased snowfall in some of the masked cases. For example, it is likely that multitudes of small seeding-produced ice particles are swept out (aggregated) by larger, faster falling, natural snowflakes. However, natural snowfall variability makes it impractical to determine the magnitude of such probable but undocumented seeding effects.

Results of physical evaluation applied to several well-documented seeding experiments are discussed in section 7.

6. SUPERCOOLED LIQUID WATER AVAILABILITY

Availability of excess SLW cloud, in addition to that naturally converted to snowfall, is essential for cloud seeding to succeed. The upper limit for cloud seeding effectiveness is determined by the excess SLW flux across a mountain barrier. It is highly unlikely that seeding can convert more than a fraction of the SLW flux to snowfall, but it is certain that seeding can produce no more snowfall than the water equivalent of excess SLW flux. Moreover, the excess flux must be seedable. For AgI seeding this requires, in part, that the SLW be cold enough for effective ice crystal nucleation. Therefore, it is important to examine the evidence for SLW availability and its temperature range.

6a. SLW at the Park Range, Colorado

It is fortunate that considerable work has been done on SLW availability and related topics over the Park Range of northern Colorado, an important part of the Headwaters Region. Most of this work was done by scientists from Colorado State University.

Temporal variations of the SLW field were examined during 10 wintertime storms over the Park Range by Rauber et al. (1986). Primary observations were from a microwave radiometer sited just south of Steamboat Springs, and measurements were made at 15 deg elevation angle just above the Park Range's west slope. Observations from vertical-pointing radar, rawinsondes, and various surface equipment, were also available. Measurements included the degree of ice crystal riming and liquid water content at Storm Peak Laboratory (SPL) on the Park Range crest.

Primary findings were that greatest liquid water contents were most likely when snowfall rates were light and cloud top temperatures were warm. The results suggested that cloud seeding should concentrate primarily on the shallow orographic cloud systems which often are of limited horizontal extent. Each of the three orographic storms examined in detail exhibited an inverse association between snowfall rate and the amount of liquid water. Similar orographic cloud systems were observed on several occasions during the 2-month field program, and periods of shallow orographic clouds also occurred during some of the major storm passages.

The companion paper by Rauber and Grant (1986) relied primarily on aircraft observations during eight separate missions. All flights occurred in stable to neutrally stratified cloud systems with no more than weak low-level convective instability (weak embedded convection). Three regions of SLW were identified over the Park Range - one near cloud top, one near cloud base and the largest one in regions of strong orographic forcing found above the windward (west-facing) mountain slopes.

A major limitation of the aircraft sampling was that Federal Aviation Administration restrictions limited sampling to altitudes of 14,000 ft and above. Since the mountain-top observatory was at 10,370 ft, and cloud base was often 800 ft lower, the aircraft was unable to sample the important lowest 4400 ft or so of the clouds. Other investigations have shown that ground-based seeding plumes are usually confined to a portion of the lowest kilometer above mountain crests. Moreover, most available SLW cloud was within the lowest several hundred meters.

Observed cloud top SLW amounts were usually limited and are unlikely to be seedable with ground releases. Accordingly, they will not be discussed further. The cloud base occasionally lowered to as much as 1650 ft below ridge top or raised to about 165 ft above ridge top, but was typically about 800 ft below ridge top. Cloud base temperatures normally were between -5 ° to -10 °C. Measurements over other mountains where aircraft sampling was practical nearer the terrain have shown most SLW is within about 2000 ft of the crests. Corresponding temperatures at that altitude would be about -10 to -15 °C.

The large majority of clouds with tops warmer than -22 °C had few ice crystals nucleated and grown at temperatures warmer than -10 °C, and available SLW, as evidenced by rimed crystals and other observations. Consequently, these warmer, shallower cloud systems should have seeding potential if seeded crystals can be produced and grown in the -5 to -15 °C zone. Deeper cloud systems with colder tops usually had abundant natural crystals which fell through the low-level SLW and converted it to snowfall, greatly reducing seeding potential. Cloud base SLW regions often extended tens of kilometers upwind from the Park Range.

Both aircraft and microwave radiometer measurements showed greatest liquid water contents directly upwind from the mountain crest in the region of greatest forced orographic uplift. Moreover, weak convective motions may enhance the SLW in this region. In all cases the SLW was rapidly depleted in the subsidence zone of descending air immediately to the lee of the crest. Shallow stratiform cloud systems with tops warmer than -22 °C had SLW extending 35 mi or more upwind from the Park Range. Similar far upwind SLW cloud was reported upwind from the Sierra Nevada by Heggli et al. (1983).

Cloud droplet concentrations were very diffuse at aircraft sampling levels, seldom exceeding 300 cm^{-3}, and usually between 50-200 cm^{-3}. One of the possible reasons cited for these diffuse concentrations is the frequent winter inversions present over broad portions of the northern Colorado Rockies. These inversions largely prevent mixing between the boundary layer and cloud layers which likely limits the rate at which cloud condensation nuclei, needed for droplet formation, are supplied to the clouds. The frequent presence of inversions would also inhibit the transport and dispersion of valley-released AgI to the orographic clouds.

A conceptual model was presented of SLW distributions. Briefly, shallow cloud systems with warm (-15 to -20 °C) tops occurred between 30 to 40 percent of the time that radar observations were conducted. They had the greatest seeding potential with SLW often available at cloud top, cloud base and especially in the forced orographic zone. However, SLW varied significantly during individual events and from one cloud system to another as has been found over other mountain regions. Therefore, not all portions of all shallow systems are seedable because natural processes sometimes make them efficient snowfall producers. Deep, cold-topped cloud systems, which also occurred between 30 and 40 percent of the time, had SLW confined to the orographic uplift zone immediately upwind from the Park Range. But natural ice crystal concentrations were usually large enough to efficiently convert this SLW to snowfall without need of cloud seeding. A third type of system, sampled only during two events, had a deep convective region embedded in a shallow stratiform system. Supercooled liquid water was available in all three zones during the shallow leading edge of such systems but rapidly decreased as the deeper clouds approached.

Rauber and Grant (1986) concluded that SLW was present most consistently in shallow cloud systems with warm top temperatures. The SLW presence satisfies one criteria for cloud seeding potential. But the authors pointed out that many additional factors help determine the true potential including natural ice crystal production, crystal growth rates and trajectories and seeding methods.

Hindman (1986a) presented surface observations of SLW cloud from six ski area locations across Colorado where manual measurements were made at or near mountain tops. Professional ski patrol members used wood-dowel rime ice collectors to obtain 30 to 60 min samples each morning and afternoon of the ski season. Observations were made whenever either liquid water (fog) or snowfall were present, or both were present, over one to four winters depending upon the ski area. Frequencies of SLW cloud existing when these observations were made (i.e., cloud and/or snowfall existed) at the six locations from south to north across Colorado were 95 percent at Wolf Creek Pass, 82 percent at Monarch Pass, 20 percent at Beaver Creek, 45 percent at Vail, 57 percent at Berthoud Pass and 90 percent near Steamboat Springs at the SPL atop the Park Range.

Frequencies of mostly rimed crystals during snowfall periods, indicating SLW cloud aloft, were 62, 74, 30, 44, 34 and 62 percent for the respective ski areas in the same south to north order. It was concluded the SLW cloud was more frequent at the southern and northern Colorado Rocky Mountain sites than at the central sites. This finding is consistent with expectations because Wolf Creek Pass, Monarch Pass and Steamboat Springs are located on primary mountain barriers, all well exposed to prevailing winds. The other three ski areas are located on secondary barriers, usually downwind from primary barriers, and consequently blocked by them. This suggestion of higher seeding potential on unblocked primary barriers is supported by examination of April 1 snowpack observations for this feasibility study. Figure A-3 of appendix A reveals higher snow water equivalent amounts at any given elevation over the primary Park Range than over the downwind, secondary Medicine Bow Mountain. However, the northern, higher portion of the Medicine Bows is wide open to winds from west through north and may be more seedable during west to northwest flow.

Liquid water contents were calculated for the six mountain sites. They averaged between 0.14 and 0.23 g m^{-3} with a maximum of 0.60 g m^{-3}. To put these values into perspective with vertically-integrated SLW amounts observed by microwave radiometers, let it be assumed that the radiometer SLW amount is a typical value of 0.10 mm. Let it further be assumed the SLW is concentrated in the lowest 1650 ft above the radiometer as suggested by many observations. Then it can be shown that the average liquid water content in the 1650 ft thick column averages 0.2 g m^{-3}, similar to the above surface measurements.

The findings of Hindman (1986a) indicate a high frequency of SLW cloud (90 percent) at the 10,370 ft SPL atop the Park Range whenever the SPL was in cloud or experiencing snow. (The SPL has since been moved 0.5 mi north to a 10,520 ft site.) These are very encouraging results which suggest considerable cloud seeding potential. Hindman (1986a) stated that the duration of 80 percent of the liquid cloud episodes was between 3 and 20 h. Similar rather brief SLW cloud episodes were common over the Grand Mesa where the median duration was about 3 h using the definition of Boe and Super (1986). These findings imply that a rapid seeding response would be needed for the frequent shorter events of 1 to 4 h duration. For example, it would often be impractical to bring seeding aircraft into position based on the observed onset of SLW. The SLW episode would often be near its end by the time aircraft seeding began. It would then be prohibitively expensive to maintain aircraft in their seeding position in anticipation of another SLW episode beginning during the limited aircraft on-station time of perhaps 4 h. It can be seen that the brief durations of many SLW episodes pose serious operational difficulties for effective aircraft seeding. One of the major advantages of using automated propane dispensers or AgI generators is that they can begin seeding as soon as SLW is detected, and can be shut down after some predetermined period without SLW.

The results reported by Hindman (1986a) do not indicate the frequency of cloud over the mountain barriers with one important exception. He notes that the Park Range SPL was enveloped in liquid cloud 24 percent of the time during December 1981 and January 1982. While it is unknown how representative this period is of long-term wintertime conditions, having SLW cloud present a quarter of all hours is certainly encouraging. Significant SLW was estimated to be present over the Grand Mesa 17 percent of the time using the Boe and Super (1986) results discussed in section 6b. Thus, it can be assumed for planning purposes that SLW cloud exists near crest line altitudes in the Headwaters Region about 20 percent of all wintertime hours.

Cloud base altitude is an important consideration when siting propane dispensers which must be in-cloud or just below cloud base (ice saturation) to be effective. Rauber and Grant (1986) stated that cloud base over the Park Range's windward slope was typically about 650 to 1000 ft below the 10,370 ft crest line (Borys and Wetzel 1997) which would place typical bases near 9400 to 9700 ft. Rauber and Grant (1986) also noted that occasionally cloud base would lower to as much as 1600 ft below crest line or rise 150 ft above it. This range would place cloud bases from as low as 8800 to as high as 10,500 ft.

Hindman et al. (1994) cites a typical cloud base value for the windward slope of the Park Range as 9200 ft. Since detailed statistics on Park Range cloud base altitudes have apparently not been published, the author spoke with the two scientists believed to be most experienced with Park Range surface observations. One estimated that cloud bases were usually in the range 9100 to 9700 ft (Ed "Ward" Hindman, personal communication). The other, who currently directs the SPL, believes that cloud base descends as low as 8300 to 8500 ft infrequently, but often enough to be considered (Randy Borys, personal communication). However, he estimated that "typical" cloud bases were between 9000 to 9500 ft. He also noted that cloud base is above crest line only 10 percent of the time when snow is falling at the SPL. Borys also stated that cloud bases were rarely warmer than 0 °C from December 1 through April 1. In that case, propane seeding would almost always produce ice crystals as long as the dispenser was in-cloud or not far below cloud base.

Based on the information presented, it appears reasonable to assume most seedable winter orographic clouds over the Park Range, and presumably the Medicine Bows, will be in the range 8500 to 10,500 ft. In order to usually locate propane dispensers in-cloud, or not far below cloud base (ice saturation), they should be sited no lower than about 9000 ft.

As a matter of interest concerning ice saturation, the levels of ice and water saturation are identical at 0 °C. For the altitudes and pressures relevant to this study, it has been calculated that the ice saturation level would be about 240 ft below the water saturation level (liquid cloud base) at -5 °C, and about 460 ft below it at -10 °C. Consequently, propane dispensers will often be ineffective if sited more than a few hundred feet below liquid cloud base. Since visual cloud base may be related to both liquid droplets and falling ice crystals and snowflakes, it will sometimes be significantly lower than liquid cloud base.

6b. Orographic SLW at Other Locations

Boe and Super (1986) examined SLW and other observations made over the Grand Mesa of west-central Colorado. The mesa is 125 mi southwest of the Park Range with a 300 ft higher crest line elevation. The authors concluded that, "SLW was most often concentrated in the lower levels above the mesa top, and usually diminished sharply as the air subsided on the lee side. Because the (mesa top) surface temperature during SLW episodes was normally between -4 to -10 °C, the liquid water zone might be too warm for effective silver iodide seeding in many cases." They also concluded that, "The seeding potential over the Grand Mesa appears quite promising, based on radiometer and aircraft data from two winters."

The Grand Mesa range of -4 to -10 °C would be about -2 to -8 °C if extrapolated to the typical Park Range cloud base elevation about 1150 ft lower than the mesa top. The Grand Mesa observations were based on SLW availability, not snowfall, which may explain their somewhat warmer temperature range. Silver iodide seeding would often be ineffective unless the plumes were transported well above the mesa top to colder temperatures.

Boe and Super (1986) showed that the SLW spatial distribution over the Grand Mesa would provide SLW cloud for ice particle growth for about 0.5 h given typical 10 m s^{-1} wind speeds. SLW was relatively frequent during storm periods. They calculated an upper limit for cloud seeding potential over a 3-month period with vertically-integrated SLW amounts from a microwave radiometer, wind speed observed 230 ft above the mesa top and mesa top precipitation gage observations. It was estimated that if all the SLW flux was converted to uniform snowfall across the 6.2 mi wide mesa top, an almost 50 percent snowfall increase would result, equivalent to an additional 5.0 in snow water equivalent over the 3-month period. About 22 percent of the excess SLW flux would need to be converted to snowfall to achieve a 10 percent increase over the natural snowfall.

Thompson and Super (1987) presented SLW flux estimates across the Grand Mesa based on instrumented aircraft observations from nine missions. These estimates were in reasonable agreement with the earlier estimates of Boe and Super (1986) based on microwave radiometer and tower wind measurements, increasing confidence in both approaches. Flux estimates for individual missions ranged from very limited when natural snowfall rates were heavy, to the largest flux observed when natural snowfall was negligible. The flux estimates were converted to snowfall rates assuming all flux was converted to uniform snow over the 6.2 mi wide mesa top. Calculated precipitation rates ranged from 0.002 to 0.038 inch h^{-1} with a mean (median) of 0.013 (0.009) inch h^{-1}. These values suggest that even very effective seeding would produce light snowfall rates, in the range of about 0.004 to 0.04 inch h^{-1}, for the conditions sampled during the nine missions. A few missions were aborted because of heavy aircraft icing likely resulting in under-representation of greater SLW fluxes. For comparison with the flux conversion to snowfall estimates, Super et al. (1986) reported that the mean (median) hourly accumulations observed on the Grand Mesa over two winters were 0.040 (0.028) inch h^{-1}. Therefore, it appears unlikely that even effective seeding would produce heavier snowfall rates than the light rates most often observed in nature. Perhaps somewhat greater snowfall rates could be achieved during the occasional period of large flux when aircraft sampling is impractical because of heavy icing.

In summary, effective seeding can be expected to produce snowfall rates similar to natural rates but somewhat lighter on average. This finding should not be surprising because SLW availability limits snowfall rates for both natural and seeded snowfall. Natural rates will tend to be greater because most natural snowflakes and snow pellets likely have longer growth times with embryonic crystals forming many kilometers upwind from the mountain barrier.

Super and Huggins (1993) estimated storm total SLW flux over three Rocky Mountain orographic barriers and for the Mogollon Rim of Arizona. Most of each field season's SLW flux was produced by one to a few storms in each mountain area, and these storms also tended to produce abundant snowfall. The implication is that large SLW flux-producing storms are efficient in snowfall production during some phases and inefficient during others. A detailed case study of a moderate-sized Utah storm supported this conceptual picture with the prefrontal phase producing most of the storm total SLW flux but little snowfall, implying this phase had significant seeding potential. The frequency of storms which produced little SLW flux was similar in all four areas, between 50 to 67 percent. These findings imply that half or more of winter storms have little or no seeding potential. Therefore, blindly seeding each winter storm without regard to available SLW would be wasteful. This study confirmed several recent investigations which have indicated winter orographic storms are not the "steady-state" systems once envisioned.

Super (1994) used the per storm SLW flux estimates provided by Huggins et al. (1992) for 20 storm days of the 1991 Wasatch Plateau field season. He calculated that if the total flux for the 20 days could have been converted to uniform snowfall across the 6.2 mi wide plateau, the average precipitation would have been 8.3 inches, almost double the observed amount. These calculations indicated the existence of abundant excess SLW flux. The fraction of this flux which can be converted to snowfall by seeding is another question. But excess SLW flux does not appear to impose a limit on seeding-caused seasonal snowfall increases of about 10 percent.

The most important finding from this section is that calculations of SLW flux are sufficient that seasonal snowfall increases on the order of ten percent should be readily achievable. This statement presumes, however, that SLW cloud regions are routinely targeted with effective concentrations of ice nuclei or crystals.

An important factor in estimating possible seasonal seeded snowfall accumulations is the frequency of hours per winter with seedable SLW cloud. Seasonal observations of this type are limited. However, Boe and Super (1986) presented vertically-integrated microwave radiometer observations of SLW over the Grand Mesa of western Colorado from two different winters. Valid data were recorded for 3351 h or 92 percent of all possible hours during the 5 months of observations near the southern edge of the east-west oriented mesa top. Twenty-nine percent (958 h) of these hours had SLW of 0.01 mm or more. However, only 12 percent of these hours (412 h) exceeded 0.10 mm and the median value was 0.08 mm. It can be shown that if all a vertically-integrated SLW amount of 0.10 mm were precipitated into uniform snowfall over a 10 km (6.2 mi) downwind distance with a typical wind speed of 10 m s^{-1}, the resulting snow water equivalent accumulation would be 0.014 inch h^{-1}. Consequently, hourly trace precipitation accumulations, defined as less than 0.005 inches, are equivalent to vertically-integrated SLW amounts less than about 0.05 mm. Such low SLW amounts can be safely ignored. The observations presented by Boe and Super (1986) were in 0.10 mm intervals and amounts in the lowest interval, between 0.01 and 0.10 mm, contributed only 16 percent of the total flux. It is estimated that about 575 h (17 percent) of all hours of observation had SLW amounts of 0.05 mm or greater, that is, significant SLW amounts.

7. INSIGHTS FROM OTHER MOUNTAIN EXPERIMENTS

Another approach to considering seeded snowfall is provided by examination of the results of physical seeding experiments. While only a limited number of such experiments were able to demonstrate increased snowfall, such evidence is quite important. Several experiments that produced estimates of seeded snowfall rates are reviewed in the following sections.

Results from several research investigations reviewed in this feasibility study demonstrate that high altitude seeding *can routinely target the SLW cloud zone*. Both the SLW and the seeding plumes are concentrated in a shallow layer immediately above the windward slope and crest line of mountain barriers. The importance of routine targeting cannot be overemphasized. Evidence presented in section 4b shows that targeting is anything but routine with valley seeding. It is obvious that seeding will fail unless appropriate cloud zones are treated. In effect, operational cloud seeding with valley generators frequently is not really cloud seeding when the AgI fails to reach target clouds in adequate concentrations. Valley seeding can be a very economical approach, especially when there are large crosswind distances between generators and their AgI outputs are limited. However, it is physically difficult to justify the approximately 10 percent precipitation increases often claimed by operational valley seeding projects (e.g., Super 1999).

A number of estimated or observed snowfall rates from seeded orographic clouds will be cited. The estimates are based on airborne and ground-based 2D-C laser probe observations of ice particles, often used with the software of Holroyd (1987). Super et al. (1988) discuss why 2D-C estimates are frequently underestimates, especially when particles larger than 1 mm are involved. It was shown that the 2D-C probe, with a 0.8 mm wide sampling region, significantly underestimates larger particle concentrations which can make significant contributions to the snowfall rate. However, for growth times of the order of 20 to 30 min, individual seeded crystals will be small enough that ground-based 2D-C precipitation accumulation estimates should be reasonably accurate. Underestimates may result if the seeded crystals aggregate into snowflakes larger than a millimeter. When aircraft level precipitation estimates are given, it should be recognized that the observed particles may undergo significant additional growth in the 2000 ft or so between the aircraft and the mountain surface. This zone usually has the greatest SLW amounts.

7a. Bridger Range, Montana

Super and Heimbach (1983) discussed the Bridger Range Experiment (BRE) conducted in southwestern Montana. As pointed out by the review of Reynolds (1988), the Bridger Range was the only orographic research program with both a randomized statistical cloud seeding experiment and detailed physical observations. Some of the physical evidence over the Bridger Range was collected during the BRE. For example, Super (1974) discussed a considerable amount of AgI plume tracing conducted over the main ridge line, just a few kilometers downwind from the high altitude generators, and over the intended target which was a parallel secondary ridge several kilometers farther east (downwind) as discussed in section 4c. Besides this verification of proper targeting (rare in cloud seeding experiments), silver-in-snow analysis showed marked increases in the target snowpack at several locations at the end of both seeded winters. Detailed microphysical measurements were made over the Bridger Range several years later when airborne cloud physics instrumentation was much improved (Super and Heimbach 1988). These observations strongly supported the earlier statistical findings.

The BRE was a randomized exploratory single-area cloud seeding experiment. Since the analysis was *post hoc*, and no subsequent confirmatory experiment was conducted, the statistical results should be considered to be no more than strongly suggestive. The main statistical finding was that seeding increased snowfall in the intended target, and sometimes downwind as well, when the temperature on the main ridge line was colder than about -9 °C. Plume tracing revealed that the AgI was largely contained within the lowest 1500 ft above the main crest line so plume top temperatures were colder than about -12 °C when seeding appeared to be successful. Seasonal snowfall increases were about 15 percent on the target ridge and perhaps even greater on the lee slope of the main ridge, centered about 2.5 mi downwind from one of the generators. About half the storm periods had temperatures colder than -9 °C suggesting the warmer, wetter storm periods were not significantly affected by the AgI seeding. It is noteworthy that the suggested 15 percent seasonal snowfall increases were achieved with a crosswind distance of 4.3 mi between AgI generators, not the optimum of 2 mi or less suggested by plume tracing results discussed in section 4c. A limited program of aircraft sampling over the Bridger Range was recommended by Super and Heimbach (1983) which was later carried out as discussed by Super and Heimbach (1988).

Super (1986) presented some additional *post hoc* statistical analysis of the BRE. This was limited to 6 h periods with a main ridge line temperature of -9 °C or colder and strong westerly airflow component. It was suggested that seeding was highly effective during a small portion of all seeded episodes but had little or no effect for the other periods. Seeding appeared to be especially effective when cloud top temperatures were warmer than -25 °C; that is, with relatively shallow clouds. A strong cross-barrier wind flow, expected to produce abundant cloud liquid water, was also associated with the larger apparent seeding effects. No suggestions of decreased snowfall associated with seeding were found. It is speculated that the periods with apparently large seeding effects were those when nature was inefficient and SLW was abundant. However, physical observations were not routinely available to test this hypothesis.

Heimbach and Super (1988) reported on a one-winter project aimed at increasing the snowfall on the Bridger Bowl Ski Area. One of the BRE seeding sites was used with the same type of AgI generator and solution. Analysis of data from the single useable snow course then on the Ski Area suggested a 40 percent seasonal increase during that unusually dry winter. However, the snowpack amounts were at or near record minimums throughout the area, requiring extrapolation beyond historical data, which is a suspect practice with statistics. Supporting evidence included large silver-in-snow concentrations on the Ski Area that rapidly decreased north and south of it. Crest line observations above the Ski Area showed SLW present during 7 percent of all hours that dry winter, and AgI was frequently detected from the generator located 2 mi upwind. Evidence was found of small presumably seeding-caused particles (AgI was present) aggregating into larger particles because of their dense concentrations. Moreover, small rimed particles were sometimes found which may have been seeded crystals exposed to dense SLW concentrations during their upslope journey.

During a separate project, aircraft microphysical sampling was conducted over the secondary ridge target of the BRE, using one of the high altitude seeding sites with same type of generator and seeding solution. As reported by Super and Heimbach (1988), these observations showed that, "The successful seeding was done with Main Ridge temperatures of -9 °C or colder, moderate to strong westerly flow, warm cloud tops, and SLW present. This is in agreement with earlier statistical suggestions and current physical understanding." The response of clouds to AgI seeding under such conditions was very noticeable. Several-fold IPC increases were measured, typically from less than 1 L^{-1} natural background levels to mean values near 10 L^{-1}. Mean widths of the enhanced ice particle zone were 3.2 to 5.2 mi about 11 mi downwind from the seeding site. This finding suggests that crosswind generator spacing should be about 3 mi and certainly less than 6 mi for plumes to overlap the target in a similar mountain setting. However, many mountain barriers do not permit seeding over an upwind barrier with the intent of affecting the SLW zone over a nearby downwind target barrier as was done in the Bridger Range. In the more typical case where a single barrier is seeded, crosswind spacing of seeding material dispensers should be less than 3 mi.

These successful seeding experiments had estimated 2D-C snowfall rates between 0.001 and 0.004 inch h^{-1} about 1650 ft above the target. Since these estimates were made 11 mi downwind from the high altitude AgI generator, many of the larger crystals may have already descended below aircraft levels. While increases in IPC and estimated snowfall rate were obvious within the AgI plumes, the latter were only at the trace level. It is likely that considerable additional growth occurred below lowest aircraft sampling levels, but no surface snowfall measurements were available to test this speculation.

7b. Grand Mesa, Colorado

Super and Boe (1988) presented both aircraft and surface observations over the Grand Mesa of western Colorado during seeding experiments with shallow orographic cloud. During one of two high altitude AgI generator seeding experiments the estimated aircraft level snowfall rate within the AgI plume was 0.006 inch h^{-1}, three times the natural rate, on a crosswind flight track 3.9 mi downwind from the generator. Most seeded crystals were embryonic dendrites at the -14 °C sampling level and most had sizes less than 0.6 mm with few crystals exceeding 1.0 mm. No precipitation gages were under the seeded plume and the nearest crosswind gage recorded no snowfall. The second seeding plume had a rate of 0.004 inch h^{-1} with nil crosswind snowfall about 6 mi downwind from the generator. Cloud bases were above the mesa during this experiment which permitted AgI plume sampling under the cloud deck. During these low passes the only visually-detected snowfall was at very light rates but only within the AgI plume. Visibility was excellent so any nonseeded snowfall should have been apparent to at least 35 mi distance. Seeded crystals were predominantly hexagonal and smaller than 0.6 mm in size although the fraction of larger particles contributed two-thirds of the calculated precipitation. The shallow cloud deck was between -8.5 and -11.5 °C. No gage observations were available under the AgI plume.

A series of six airborne seeding experiments was summarized by Super and Boe (1988) which had crosswind lines of AgI released at various distances upwind from the mesa top Snow Lab. The mean estimated aircraft level snowfall rate was 0.008 inch h^{-1} in the seeded zones compared with 0.002 inch h^{-1} in the nonseeded zones, a four-fold increase. Large numbers of ice crystals smaller then 0.6 mm, either hexagonal plates or tiny dendrites, were sampled in the seeding lines for all six experiments. A fraction of the seeded crystals grew to larger sizes with habits consistent with sampling level temperatures. These larger particles contributed significantly to calculated precipitation rates. The three experiments that succeeded in targeting the Snow Lab had individual seed lines released from 12 to 23 mi upwind at temperatures near -14 °C. Continuous cloud deck extended from 6 to 12 mi upwind from the Snow Lab during these experiments. The three seed lines produced average ground level (Snow Lab) rates between 0.013 and 0.017 inch h^{-1} as the AgI seed lines passed overhead. Peak rates exceeded 0.04 inch h^{-1} in each experiment while negligible natural snow fell before or after. Most of the Snow Lab snowfall mass from the first experiment, discussed in most detail, consisted of 0.6 to 1.0 mm dendrites, aggregates of these dendrites and some graupel-like particles. Aircraft estimated rates for these three experiments were between 0.006 to 0.016 inch h^{-1}. The limited increased growth between the aircraft and surface, no more than a factor of two, may be related to the lack of low-level SLW in the relatively cold and dry northerly flow. An icing sensor 230 ft above the mesa top detected some SLW water only during the first of the three successful experiments. Aircraft level cloud liquid water contents were small, near 0.05 g m^{-3}, and the amount of SLW between the aircraft and mesa top is unknown.

7c. Wasatch Plateau, Utah

Super and Holroyd (1994) discussed observed changes in IPC during ten passes through an AgI plume released from a high altitude site on the Wasatch Plateau of Utah. Aircraft sampling was done near the -14 °C level and at downwind distances of 3.7 and 9.3 mi from the generator. Previously unpublished 2D-C estimated snowfall rates for the same passes averaged 0.013 inch h^{-1} in the AgI plume and 0.005 inch h^{-1} crosswind from it. The difference of 0.008 inch h^{-1} at aircraft levels about 2000 ft above the plateau can be attributed to seeding. The seeding plume did not pass over any precipitation gages and no other surface precipitation observations are available.

A strong seeding signature was found both on top of the Wasatch Plateau and at aircraft levels above it during the February 21, 1994 experiment (Holroyd et al. 1995). A 3300 ft thick orographic cloud marked the ending phase of a storm passage. Quite limited vertically-integrated SLW amounts were observed with a microwave radiometer. Silver iodide and tracer gas were released from a high altitude seeding site. Snowfall rate estimates were made with observations from 2D-C probes on an aircraft and an instrumented van driven through the plume along the west edge of the plateau top. Van 2D-C measurements averaged 0.018 inch h^{-1} for the four passes within the seeded zone, much greater than the average crosswind value of 0.002 inch h^{-1}. The average of three low-level aircraft passes made in the plume essentially above the van during the same time period was 0.005 inch h^{-1} with negligible cross-plume snowfall. The snowfall rate estimates suggest over a three-fold increase from aircraft levels to the plateau top.

Three gages were operated at 5.9, 7.5 and 10.3 mi downwind from the seeding site. All should have been under the AgI plume for 3.5 h according to the Clark mesoscale model as discussed by Holroyd et al. (1995). The gage total accumulations for that period decreased with increasing downwind distance with values of 0.055, 0.050 and 0.045 in. Two nearby crosswind gages both recorded 0.030 in during the same 3.5 h period suggesting that seeding produced average hourly rates near 0.004 to 0.007 inch h^{-1} across the plateau. The west edge received the greatest seeded rate of 0.016 inch h^{-1} where the plume was likely narrower than over the gages. Much smaller accumulations were observed by two gages immediately east of the plateau top's east edge, in the lee subsidence zone. The Clark model indicated that SLW amounts rapidly decreased downwind from the plateau top's west edge which could also reduce crystal growth rates.

Holroyd et al. (1995) concluded that, "Seeding appeared to significantly increase the aggregation of snowflakes along the upwind highway. Best estimates of snowfall rates caused by the seeding are 0.4 mm h^{-1} (0.016 inch h^{-1}) based on 2D-C estimates along the upwind highway and less than half that rate from gages on the central and eastern portions of the plateau. Of course, SLW amounts were quite limited during this weak and diminishing final portion of the storm, so seeding potential would be expected to be quite limited as well."

Super and Holroyd (1997) discussed a number of pulsed seeding experiments with the target on the west edge of the Wasatch Plateau 2.6 mi downwind from the high altitude seeding site, and 1035 ft above it. A major canyon routinely funneled the seeding agent toward the target which was at the canyon head. There is no reasonable doubt about seeding effectiveness in the two experiments discussed next as natural snowfall was very light or less and seeding effects were obvious.

The December 15, 1994 experiment released AgI when the seeding site was in-cloud at an unusually cold temperature of -7.8 °C. Supercooled liquid water was detected by an icing sensor at the target where the temperature was -10.4 °C. The high resolution Universal weighing gage at the target received 0.01 in during the hour prior to seeding, 0.05 in during the seeded hour, and 0.007 in the following hour. The results, shown in figures 3-7 of Super and Holroyd (1997), clearly indicate that seeding produced over 0.04 h^{-1} additional snowfall at the target where the AgI passage was monitored by an acoustical ice nucleus counter. The increase in IPC was 140 L^{-1}. It is encouraging that hourly snow accumulation estimates based on the target 2D-C probe were very similar to the nearby gage values, adding credibility to the 2D-C precipitation rate estimation scheme, at least for smaller crystals. Assuming nucleation at the seeding site, crystals had an average transport (growth) time of 15 min before reaching the target. Seeded crystals were about 0.3 mm size, mostly hexagonal plates, implying a growth rate of 0.33 $\mu m\ s^{-1}$ in accordance with known slow growth rates near -9 °C. Seeding apparently also increased the snowfall during the seeded hour by 0.014 inch at a gage 3.7 mi downwind from the target. The positioning of that gage relative to the plume's centerline is unknown so its increased accumulation does not necessarily represent the maximum seeded snowfall at that gage 6 mi downwind from the AgI generator.

A propane seeding experiment on March 5, 1995, also showed an obvious seeding signature with relatively warm seeding site and target temperatures of -2.1 and -4.1 °C, respectively. Sensors detected icing at both sites, each estimated to have about 0.04 $g\ m^{-3}$ cloud liquid water during propane release. The obvious results of this experiment are shown in figure 2, taken from Super and Holroyd (1997), which also shows a later AgI seeding experiment.

Figure 2 has three panels showing the temporal variations at the target of IPC (top), AgI ice nuclei L^{-1} observed at -20 °C within an acoustical ice nucleus cloud chamber (middle) and precipitation rate calculated from the ice crystal observations (bottom). Ice crystals produced by 1 h of propane seeding were transported past the target from about 0818 to 0918 MST as shown by vertical lines. The seeded period was verified by observations of AgI ice nuclei, co-released for 3-min periods at the beginning and end of the propane seeding. These brief AgI "tags" appear to be much longer in the middle panel because of significant hold up in the acoustical counter cloud chamber. Calculations showed that seeding enhanced the hourly average target IPC by about 30 L^{-1} and the snowfall by 0.01 inch h^{-1} (0.25 mm h^{-1}). The latter estimate was based on both 2D-C probe estimates and the nearby target high resolution precipitation gage which closely agreed. Natural snowfall was almost nil before and after the propane seeding.

An AgI release soon after the propane experiment failed to increase either the IPC or snowfall rate. The hour of AgI transport past the target was from 0941 to 1041 MST as shown by the second set of vertical lines on figure 2. The IPC and snowfall increases after 1030 MST were caused by a natural shower. The failure of AgI to increase the IPC would be expected with such slightly supercooled temperatures. The limited snowfall increase associated with the propane seeding is encouraging because of the warm temperatures and associated slow growth rates.

Transport time from the seeding site to the target was about 17 min during the March 5, 1995, propane seeding experiment. Most seeded crystal images observed by the 2D-C laser probe appeared to be small plates, short columns or thick needles, and most were between 0.3 and 0.6 mm in size. A size of 0.45 mm after 17 min is about 4.5 times the C-axis length calculated by Redder and Fukuta (1989) for the faster growth temperature of -5 °C. These field observations correspond to a reasonably fast growth rate of 0.44 $\mu m\ s^{-1}$. This difference raises concerns about the laboratory results because the conditions during the seeding experiment were well documented. The average 30 L^{-1} increase in IPC uniformly throughout the propane-seeded hour and the uniformity in crystal types and sizes shown by Super and Holroyd (1997) make it almost certain that the observed crystals were chiefly produced by seeding. Moreover, the before and after AgI "tags" observed at the target, and the seeding site and target wind measurements, all verify targeting success.

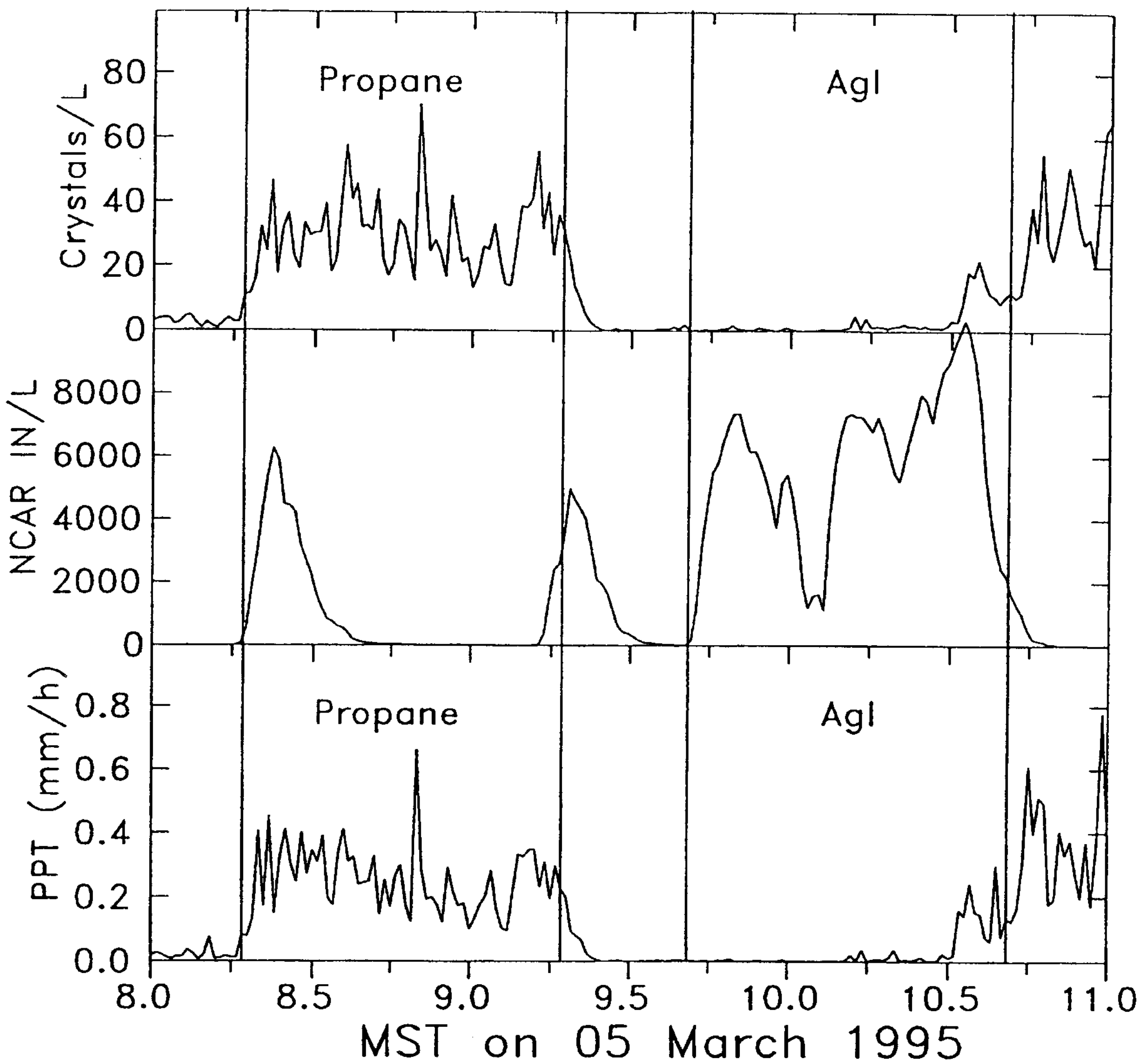
Holroyd and Super (1998) summarized the results of many attempted seeding experiments using the same high altitude seeding site and target just discussed. Usual transport times between the two ranged from 10 to 30 min with a median of 17 min (1020 s), based on the times required for AgI to reach the target in large concentrations. Seventeen minutes corresponds to an average transport speed of 4 m s^{-1} up the windward slope if the seeding material went directly from the seeding site to the target 2.6 mi away. More likely, the plumes meandered up the canyon rather than following a straight line. Propane experiments had 3 min AgI "tags" released at their beginning and end times that were detected by an acoustical ice nucleus counter with -20 °C cloud chamber temperature operated at the target. Propane seeding was only done when the orographic cloud temperature was definitely too warm for the AgI to create ice crystals. This practice resulted in a lack of propane seeding experiments during colder temperatures with faster crystal growth rates.

Comparisons during natural snowfalls revealed that all but a small fraction of the many samples had an IPC in excess of 10 L^{-1} with snow water equivalents of 0.01 inch h^{-1} or more. Most of the natural population had IPC values between 10 to 200 L^{-1}. These natural observations provided further confirmation for the estimates of Super (1994 - section 8.2) that cloud seeding must produce IPCs in excess of 10 L^{-1} to be effective in producing meaningful snowfall. The same conclusion was reached from earlier work with Great Lakes winter storms (Weickmann 1973). Chappell and Johnson (1974) presented simple numerical model results which showed that IPC less than 5 L^{-1} were likely inadequate for timely glaciation of winter orographic clouds whereas IPC of 30 L^{-1} or greater were probably sufficient. They found that concentrations up to 200 L^{-1} were unlikely to seriously overseed. Claims by some commercial operators that seeded crystal concentrations of about 1 L^{-1} are adequate should be considered with grave skepticism.

Grouping of several propane seeding cases using two nozzles, which released about 3.7 g s^{-1}, yielded a 2D-C average precipitation rate increase of 0.007 inch h^{-1} for seeding site temperatures between -0.4 and -3.4 °C. Target temperatures were about 2 °C colder. Slow growth rates would be expected at such slightly supercooled temperatures. Gage measurements were too insensitive to reveal these light precipitation rates. A similar average value of 0.006 inch h^{-1} was calculated for AgI seeding experiments for which target temperatures were colder than -7 °C. Less than 20 percent of the cases had target temperatures that cold. Greater precipitation rates would be expected for both propane and AgI seeding in colder temperature clouds with faster crystal growth rates.

When considering seeded snowfall rates, it is useful to put them into the perspective of natural snowfall rates. For example, the median natural hourly snowfall accumulations on the Wasatch Plateau were just under 0.015 inch for a 20 storm-day period (Super 1994) with frequent snowfall. Ninety percent of all hours with detectable snowfall (0.01 inch) had accumulations of 0.06 inch or less. The median hourly accumulation was similar over a four winter period at Climax, Colorado, a high altitude site. Snowfall occurred at hourly accumulations of 0.02 inch or less 71 percent of the time (Grant et al. 1969). A somewhat greater hourly median of 0.028 inch was reported over the Grand Mesa of western Colorado (Super et al. 1986). But hourly accumulations near 0.02 in are common in the central Rocky Mountains. Accordingly, the values cited for seeding-caused snowfall are not unlike the typical natural values for light snowfall, the most frequent type observed in the Rocky Mountains.

Figure 2.—Temporal distributions of observed ice particle concentration (top) and calculated precipitation intensity (bottom) at the target site 2.6 mi downwind from the high altitude seeding site for two seeding



experiments. The propane seeding experiment and later AgI seeding experiment were conducted on the Wasatch Plateau of central Utah on March 5, 1995. The central panel shows AgI concentrations at the target, effective at a cloud chamber temperature of -20°C (see text). The estimated hour of maximum seeding plume presence is shown by vertical lines for the two experiments conducted within mildly supercooled cloud.

7d. Park Range, Colorado

Rauber (1987) discussed a large body of natural ice crystal and precipitation data from 17 storm systems which passed the Park Range of northern Colorado. Both aircraft and surface observations were considered. While much of the provided information would be of interest to atmospheric scientists, only the main points relevant to Headwaters Region cloud seeding potential will be briefly summarized.

Approximately 80 percent of measured IPCs were in the range 1 to 100 L^{-1}, with 50 percent less than 20 L^{-1}. It was found that IPCs generally increased near the mountain crest because of the natural small particle enhancement, and that IPCs in deep clouds gradually increased at lower altitudes.

Surface snowfall was dominated by irregular crystal habits (70 percent) and dendritic crystals (20 percent). The former consisted of various combinations of habits, rimed particles "hidden" by the accretion of numerous supercooled cloud droplets and fragments too small to identify. Many of the fragments may have been broken branches of dendritic crystals known to require a water-saturated environment in the narrow temperature range of -13 to -17 °C. A large fraction of the irregular particles appeared to originate at temperatures colder than -20 °C, which must have had trajectories that began high in the clouds many kilometers upwind from the Park Range. When dendrites were common, they typically "chained" together into larger aggregates of many such crystals.

The Hallett-Mossop ice multiplication mechanism, known to be quite significant in warm temperature (-3 to -8 °C) ice particle production in maritime environments like the Cascades of Washington State, did not appear to be important over the Park Range. Continental clouds generally lack the large cloud droplets required for this mechanism to operate. This finding is in agreement with earlier work over the San Juan Mountains of southwestern Colorado and Elk Mountain of southern Wyoming. It suggests that cloud seeding at such warm temperatures should have potential over the Rocky Mountains since nature is inefficient. The only significant ice multiplication mechanism documented was the fragmentation during crystal-crystal collisions when dendrites are common. In general, few ice particles were found that nucleated or formed at temperatures warmer than -10 °C. Therefore, seeding should have potential if it can provide adequate ice crystal concentrations at such warm temperatures and can provide them in locations where crystal growth and fallout to the surface occur upwind from the lee subsidence zone.

Blumenstein et al. (1987) used laboratory results of ice particle nucleation with the silver iodide-sodium iodide seeding agent as input to a two-dimensional orographic cloud particle trajectory model. This interesting approach used two different nucleation mechanisms. One was a slow process characteristic of water saturation cloud and the other was a fast process which has been observed in supersaturated clouds in the laboratory. The slow process required about 30 min for ice particles to settle out in the cloud chamber while almost all particles settled within 2 min when the fast process was operable.

Modeled snowfall trajectories were shown for two case studies over the Park Range of northern Colorado for each mechanism. One case study had a mountain crest temperature of -10 °C and strong 14 m s^{-1} winds near that level. The other had a cold crest temperature of -14 °C, light 6 m s^{-1} winds, and a very shallow cloud about 3000 ft thick. Based on Rauber and Grant (1986), cloud base temperatures only about 800 ft below the crest are typically between -5 and -10 °C. Corresponding crest temperatures would be between -6.5 and -11.5 °C. Therefore, even the warmer case study may be optimistic of most orographic clouds because ice crystal nucleation by AgI is highly temperature dependent between -6 and -12 °C. The authors point out that previous work with this seeding agent has shown the warmest temperature at which ice production can be detected varies from -6 to -9 °C.

The results should be considered only qualitative because of model limitations and other factors. Moreover, it is important to recognize that seeding was assumed to occur at the upwind edge of the orographic clouds, which may be impractical to achieve. This provides a second reason why the results may be overly optimistic.

With these limitations in mind, model simulation of the warmer, windier case showed almost all snow fell on the lee (downwind) side of the Park Range with westerly flow and seeding near cloud base. The fast nucleation mechanism was more effective. However, it is uncertain where and when sufficient supersaturation exists in orographic cloud for this mechanism to operate. Such a mechanism would seem unlikely at the upwind cloud edge, modeled to exist almost 37 mi upwind from the crest line, because upward motion and associated cloud water (condensate) production would be limited there. Large supersaturations would be most likely near the Park Range's upper windward slopes. Modeled seeding much higher in the cloud, at the -15 °C level, resulted in no snowfall because ice particles were carried far downwind from the mountain barrier.

Model simulation of the colder, light wind case showed snow particle trajectories on both the windward (west) and lee slopes of the Park Range because of the much longer (180 min) transit time of air parcels within the cloud. Even seeding at the higher elevation -15 °C level resulted in snowfall on the windward slopes because of the much greater ice crystal yields with the unusually cold temperatures.

This study indicated that the spatial distribution of snowfall is strongly affected by ice nucleation characteristics. For reported typical Park Range crest temperatures, it often may be difficult to nucleate ice particles with AgI which grow large enough to settle as snowfall even on the lee slopes. Other studies have shown that the assumption of model "seeding" at the upwind cloud edge, tens of kilometers west of the crest, is impractical to accomplish with ground releases of AgI.

Peterson et al. (1991) discuss the effect of decoupling of near-surface airflow upwind from the Park Range from the synoptic (large-scale) airflow aloft. Their hypotheses was that low-level decoupled flow acts as a westward extension of the mountain barrier for orographic lift, resulting in production of liquid water condensate tens of kilometers farther upwind (for winds aloft) than the case of no decoupling. This presumed barrier "extension" then tends to shift the precipitation distribution upstream.

Three approaches were used to test their hypotheses. First, low-level winds and precipitation from several automated surface weather stations in the Yampa River Valley west of the Park Range were examined. Second, two detailed case study analyses were presented. Finally, a sophisticated numerical model was used to simulate orographic clouds and precipitation with and without decoupled flow.

While the authors conclude that their working hypothesis was "strongly supported" by their study, this report's author is not totally convinced. A detailed analysis of winter storms over the San Juan Mountains of southwest Colorado by Marwitz (1980) suggested that blocked flow reduced lift contrary to the hypothesis of the Peterson et al. (1991) study. In this reviewer's opinion, the most important result of the latter investigation concerning seeding of the Park Range is the numerical model simulations. While the model shows some upwind extension of cloud liquid water with decoupled flow, the large majority of liquid condensate was directly over the windward slope and crest of the Park Range with both coupled and decoupled low-level flow. Some additional condensate was simulated immediately downwind from the crest in apparent narrow gravity waves which were separated by narrow zones of subsiding air and associated rapid depletion of the liquid water field. This portrayal indicates that successful seeding must rapidly convert the SLW concentrated just above the windward slope to snowfall prior to the strong lee subsidence zone just downwind from the crest line. Formation of seeded ice crystals many kilometers upstream in the upwind portion of the SLW field would be highly desirable. However, that would require aircraft seeding, likely too expensive and impractical in stormy weather. Moreover, problems of attaining an adequate seeded volume with aircraft seeding because of limited dispersion rates are discussed elsewhere in this report. Relying on transport of ground-released AgI into the clouds tens of kilometers upstream of mountain barriers is a questionable proposition. Most experimental evidence suggests that the latter cannot be routinely accomplished as discussed in section 4b.

7e. Sierra Nevada, California

Reynolds (1996) discussed results from a 3-year randomized seeding experiment with liquid propane in the northern Sierra Nevada in California. The experiment was terminated early and the sample size proved too small for statistical evaluation. However, various physical studies provided useful results.

The experimental design envisioned that the target area would be a second ridge line running parallel to and slightly lower than the main Sierra crest and approximately 12 mi farther downwind. Liquid propane dispensers were used because of the mild temperatures associated with mountaintop SLW (warmer than -4 °C about 80 percent of the time). The dispensers were located along the main crest where SLW was known to be abundant because of forced ascent up the windward slope. It was assumed that the resulting embryonic crystals would survive their transport in the dissipating liquid water cloud above the valley and then grow to snow particle sizes over the liquid water production zone over the second ridge's upwind slope. The snow particles were expected to settle onto the second (target) ridge.

Winter storm rawinsonde balloon ascent rates and aircraft and ground-based tracer studies showed gravity waves to be common just downwind from the main Sierra crest. Simulations with a basic numerical model also supported the view that the associated strong downward motions had a significant detrimental impact on the growing ice crystals produced by propane seeding. Aircraft sampling showed that tracer plumes released near two propane dispensers rarely rose more than 1650 ft above the release altitude. This investigation supported the view of previous work that detailed transport and dispersion studies should be performed prior to the onset of any long-term snowfall enhancement program to ensure proper targeting during most seedable storms. The complexities associated with trajectories of seeded crystals was once again demonstrated.

8. SUMMARY OF RECENT CENTRAL UTAH STUDIES

Super (1999) summarized the findings of 29 publications and papers resulting from the National Oceanic and Atmospheric Administration (NOAA) Atmospheric Modification Program (AMP) conducted in Utah during the years 1990 through 1998. The NOAA/Utah AMP conducted several field programs on the Wasatch Plateau of central Utah during this period. This is the most recent body of physical evidence concerning cloud seeding in the general vicinity of the Headwaters Region. In general, the NOAA/Utah AMP findings confirm and expand on those found in the Intermountain West the past few decades.

The NOAA/Utah AMP main goals were to investigate the effectiveness of the long-running Utah operational (applied) cloud seeding program and to recommend ways to improve that program's effectiveness. The two major areas of study involved (1) when, where and in what quantities does SLW exist within orographic clouds and (2) when, where and in what quantities does the AgI seeding agent affect the SLW cloud by converting portions of it to ice crystals. The feasibility of liquid propane seeding also received significant attention during the latter years of the program.

Section 7.3 of Super (1999) is repeated below in its entirety because it summarizes the key physical findings of several years of recent work quite relevant to the Headwaters Region.

Section 7.3: Key Physical Findings

Brief answers to the above questions, based largely on the work reported herein, are now stated.

a. A considerable body of evidence from the plateau investigations and some other work shows that significant SLW cloud exists over western mountains in excess of that naturally converted to snowfall. This "excess" SLW flux represents a large fraction of seasonal snowfall amounts. While the existence of excess SLW water cloud has been assumed for decades, and is necessary for operational seeding to have any potential, adequate documentation has been provided only during the past several years. Field deployment of microwave radiometers has been especially important in this documentation.

b. Orographic cloud SLW varies rapidly in time and space. Some of the greatest SLW amounts have been found during storms with strong synoptic support which are naturally very efficient snow producers during some phases but inefficient during others. Conversely, weaker localized storms typically produce lesser SLW amounts but these persist over many hours per winter. Both storm types are important in total seasonal SLW flux production.

c. Orographic cloud SLW is usually found over the windward slopes and crests and rapidly diminishes further downwind, even as cloudy air moves across the relatively flat plateau top, about 6 mi wide. The SLW is depleted by a combination of snowfall production and subsidence.

d. The SLW cloud is confined to a shallow layer above the plateau. Most SLW condensate exists in the lower 1650 ft above the terrain and SLW amounts are usually negligible by 3300 ft above the terrain. Forced orographic uplift, weak embedded convection, and gravity waves all combine to produce the liquid condensate.

e. The SLW cloud found near the mountainous terrain is typically mildly supercooled over Utah's mountains. Frequently, the SLW cloud is too warm for significant ice nucleation with

AgI, except perhaps in its upper portions. Often natural ice nucleation processes become efficient as cloud temperatures become cold enough for effective AgI nucleation. Consequently, the window of opportunity for effective AgI seeding is limited to a fraction of the periods with excess SLW. To restate this important point, *most SLW periods cannot be effectively seeded with the present type of operationally applied AgI, especially when it is released from the ground with resulting limited vertical dispersion.*

f. The frequency of successful transport of AgI plumes over the plateau is directly related to generator elevation relative to the mountain barrier. Plumes released from high altitude sites within 1000 to 1650 ft of the plateau top were routinely transported over the barrier when winds had a cross-barrier component, necessary for significant SLW production. Similar results have been demonstrated at several other mountainous locations, including Montana, Colorado, and Arizona. High altitude release sites on the plateau were usually just below or just above cloud base.

g. While experimental cases are limited, a definite impression developed over the course of the experiments that canyon mouth releases have a significantly greater probability of over-plateau transport than valley releases.

h. Plumes released from the valley floor are less likely to be transported over mountain barriers than plumes released from higher elevation sites. A number of experimental periods showed that AgI was trapped near the valley floor for several hours. However, storm periods with relatively abundant SLW over the plateau and embedded convection present usually also had valley AgI transport to the plateau top. Nevertheless, effective ice nucleus concentrations from valley-released AgI were usually quite small at prevailing cloud temperatures.

I. On some occasions, the gravity wave mechanism transported valley-released AgI over the plateau in spite of valley-based inversions. The timing and frequency of gravity waves, and the specific surface locations affected by them, are all uncertain, but this mechanism is sometimes important in vertical transport of the AgI aerosol.

j. High altitude AgI generators have at least three advantages over valley-released generators. First and very important is their ability to routinely target the intended cloud zones.

k. Second, concentrations of AgI released by high altitude generators are usually much higher as are resulting ice particle concentrations. This was repeatedly shown by observations along the plateau top and above the plateau. The results of model simulations were in agreement with these surface and aircraft observations. The main reasons for the higher concentrations are less horizontal dispersion (vertical dispersions were similar) and greater probability of transport over the plateau. Of course, this result likely means significantly less crosswind spacing between high altitude generators compared with the typical 10 mi or so spacing between Utah valley generators. But closer spacing of valley generators, perhaps about 2.5 to 3.0 mi apart, has been recognized as desirable for plume overlap by the operational seeding firm (Griffith 1996).

l. The third advantage of high altitude generators is that they are usually located within cloud or just below cloud base. The AgI generators produce a large water by-product from combustion of propane and acetone. The resulting great supersaturation very near the generators allows for instantaneous activation by the condensation-freezing mechanism (Finnegan and Pitter 1988, DeMott et al. 1995). Thus, under favorable conditions, embryonic ice crystals may be formed immediately downwind of the generators, providing important additional time for growth to snowflake sizes. The condensation-freezing mechanism is unlikely to occur with valley-releases of AgI. If ice crystals are occasionally formed because valley fog is present, they cannot be expected to survive transport to orographic cloud altitudes.

m. A fourth possible advantage of high altitude AgI releases is reduced potential for photo-deactivation of ice nucleating ability. This may not be a significant factor since limited sunlight penetrates the usual cloud deck over valley generators during storms. Moreover, earlier concerns about photo-deactivation (Dennis 1980) may be unwarranted, at least for the type of AgI aerosol operationally used in Utah (Super et al. 1975).

n. Disadvantages of high altitude AgI generators include the practical difficulties of installing and maintaining them at remote locations, and limited horizontal plume dispersion. While aerosol from high altitude generators will routinely be transported over the mountain barrier, cross-wind spacing of such generators should not exceed perhaps 3 mi if most of the SLW condensate zone is to be affected. However, it may be more important to routinely seed a portion of the SLW cloud with adequate ice nuclei concentrations than to sometimes seed more of it with weak AgI concentrations. Vertical dispersion from the high altitude generators appeared similar to that from the valley-based generators, but this impression may be partially based on the much greater ice nuclei concentrations found during aircraft sampling within high altitude released plumes. Valley-released plumes generally had weak ice nuclei concentrations at aircraft altitudes.

o. A seeding solution was tested in the Colorado State University Cloud Simulation Laboratory which produces an AgICl-0.125NaCl aerosol rather than the AgI aerosol used in the Utah operational program. The laboratory results showed that the former solution can nucleate ice crystals by the condensation-freezing mechanism rather than the contact-freezing nucleation mechanism resulting from the operational seeding (in the absence of supersaturation at the generators). *This fast-acting aerosol was shown to increase the number of effective ice nuclei by over an order of magnitude in the limited time available for transport through orographic SLW cloud.* It is strongly recommended that the operational seeding program use this improved solution. This is one of a number of actions which could increase effective ice nucleus concentrations over Utah's mountain barriers.

p. Numerous physical seeding experiments demonstrated that sufficiently great AgI concentrations exposed to sufficiently cold SLW cloud will produce abundant ice particles. Ice particle concentrations were similar to those expected, based on earlier laboratory results, tending to verify laboratory findings in actual orographic cloud. When obvious seeding-caused snowfall occurred, rates were light as is typical of natural snowfalls. The heaviest hourly accumulation observed during the seeding experiments was 0.04 inch liquid equivalent.

q. Propane releases at rates of 3-7 gal h^{-1} were clearly demonstrated as capable of producing 10 to 20 ice crystals per liter at the plateau top target site even during slightly supercooled conditions. This approach offers a practical adjunct or alternative to AgI seeding during the mildly supercooled episodes typical of Utah winter orographic storms. Moreover, propane seeding was totally automated, using an icing rate meter to detect SLW cloud and a data logger to "decide" to release the liquid propane only during seedable conditions.

The above findings can be briefly summarized as follows:

1. Over the course of a winter, abundant SLW exists over the windward slopes and crest line that is not naturally converted to snowfall. Significant seeding potential should exist if even a fraction of this "excess" SLW can be converted to snowfall. The SLW is highly variable in time and space, and is rapidly depleted in subsiding air downwind of the crest line. Most SLW cloud is within 1650 ft of the barrier top with SLW amounts negligible by 3300 ft above the top. Most of the time this SLW layer is too warm for effective AgI seeding. When cloud temperatures are cold enough for effective AgI nucleation, natural snow-producing processes often become efficient. Consequently, the window of opportunity for AgI seeding is limited to a fraction of the periods with excess SLW. This finding confirms the earlier results of Sassen and Zhao (1993) over the Tushar Mountains of southern Utah.

2. The frequency of successful AgI plume transport over the barrier is highly dependent upon generator location. Valley-released plumes are frequently trapped in stable air near the valley floor and may undergo low level transport parallel to the barrier rather than over it. Even when transported over the barrier by embedded convection or gravity waves, effective AgI ice nucleus concentrations are quite small for the valley generator network used in Utah's operational seeding program. Conversely, high altitude generators located within about 1650 ft of the barrier top are routinely transported over the top, as has been demonstrated over several mountain barriers. Plumes from high altitude and valley generators appear to have similar vertical dispersions over the crest. That is, AgI plumes from either type of site are concentrated in the lower 2000 ft above the barrier crest and are rarely transported as high as 3300 ft above it. Valley-released plumes have greater horizontal dispersion with resulting lesser concentration. Another advantage of high altitude, within-cloud AgI release is that propane and acetone combustion results in large transient supersaturations very near the generator. This environment allows instantaneous activation by the forced condensation-freezing mechanism (Finnegan and Pitter 1988, Li and Pitter 1997) resulting in great concentrations of embryonic ice crystals just downwind of the generator if the cloud temperature is colder than -6 °C.

3. A seeding solution that produces the AgICl-0.125NaCl aerosol rather than the conventional AgI aerosol is able to nucleate ice by the condensation-freezing (not forced) mechanism rather than the contact nucleation mechanism. The condensation-freezing approach has been shown in the laboratory to increase the number of effective ice nuclei by over an order of magnitude in the limited time available for ice crystal nucleation, growth and fallout within orographic SLW cloud. Seeding operations which rely on valley generators should benefit from the use of the AgICl-0.125NaCl aerosol.

4. Liquid propane releases within even slightly supercooled cloud (-0.4 to -3.4 °C) were effective in producing 10 to 20 ice crystals L^{-1} observed 2.6 mi downwind of the propane dispenser. These concentrations are considered great enough to be effective in snowfall enhancement. A totally automated network of three propane dispensers, controlled by an ice (SLW cloud) detector, has been operationally used in Utah the past several winters.

9. ENVIRONMENTAL IMPACTS OF CLOUD SEEDING

It is beyond the scope of this feasibility study to summarize in detail the many investigations which have addressed the effects of cloud seeding on the environment and human health. However, several studies will be cited to aid the interested reader in pursuing this topic. A number of investigations of this type were funded by Reclamation's Project Skywater, particularly during the 1970's and early 1980's, in connection with several on-going and planned cloud seeding programs. Federal interest in funding weather modification research has greatly waned during the 1990's and the author is not aware of any significant recent work on this subject.

Considerable work concerning possible environmental effects of cloud seeding has focused on whether AgI seeding has toxic effects, since silver is a heavy metal. Any such effects will be irrelevant if the proposed liquid propane seeding program is adopted. However, several silver effect studies can be found in the reports cited below in case a decision is made to use AgI seeding in the Headwaters Region. Some of them show that natural amounts of silver in western soils are orders of magnitude higher than concentrations measured in seeded snowfall. By way of demonstrating the very low silver contents in seeded snowfall, the author, who has some silver fillings, once spit into a snow sample. Analysis laboratory personnel were not amused because this deliberately contaminated sample drove their instruments far off scale since it contained much more silver than seeded snow.

Standler and Vonnegut (1972) provided estimates based on medical and meteorological literature showing that the extremely low silver concentrations in seeded precipitation did not pose any danger to human health. Sokol and Klein (1975) investigated soil surrounding an AgI seeding generator in the Park Range of Colorado and indicated that the much lower silver concentrations in seeded target areas should have no serious effects on the soil microbial environment. However, they recommended monitoring of target areas subjected to AgI seeding over very long periods.

Frank (1973) concluded that a 10 percent increase in snowpack due to cloud seeding would have little, if any, immediate effect on mountain grassland productivity in western Colorado. Similarly, Weaver and Super (1973) and Weaver (1974) investigated mountain meadows within the target area of the Bridger Range Experiment in southwestern Montana. Weaver and Super (1973) concluded that harmful effects were not expected from silver deposits that might accumulate in 100 years or less, and that 20 percent snowfall increases were unlikely to significantly affect vegetation of fescue meadows typical of the target area. Weaver (1974) used aerial photography to identify durations of snowcover and later measured meadow diversity, cover and productivity. He concluded that 10 to 15 percent snowfall increases in seeded target areas would have small effects. Weaver and Collins (1977) used snowfences to artificially induce drifts on a large mountain meadow in the Bridger Range. They stated that, "It appears that the impact of seeding winter orographic clouds for 10 to 30% increases in snowfall on the vegetation of *Festuca idahoensis* meadows would be slight."

A large body of environmental information may be found in the final reports of the following major investigations and in their numerous references. One of the first major studies, which has frequently been cited, is by Cooper and Jolly (1969). They performed a valuable problem analysis of the ecological effects of cloud seeding. A large study conducted by the University of Wyoming has special relevance to the Headwaters Region because it was concerned with winter cloud seeding in the Medicine Bow Mountains. The reader is referred to Knight et al. (1975) for the details of this multifaceted research program. Another major investigation into environmental effects of winter cloud seeding was conducted in the San Juan Mountains of southwestern Colorado as reported by Steinhoff and Ives (1976). The Uinta Ecology Project, reported by Harper (1981), is yet another major study in the general area of the

Headwaters Region. It dealt with potential ecological impacts of increased snowfall on the Uinta Mountains of northeast Utah which extend into southwest Wyoming. While primarily concerned with the Sierra Nevada far from the Headwaters Region, the multi-volume Sierra Ecology Project reports have considerable useful information. In particular, Volume Four by Smith and Berg (1979) provides an extensive bibliography on the environmental effects of weather modification.

Howell (1977) considered several research projects into weather modification impacts on the environment and provided numerous references. He noted that, "Studies of physical and biological processes relating precipitation and ecosystem changes show relatively few discernible effects, all of them minor in nature and magnitude. Direct effects of nucleating agents no longer appear consequential." Howell (1977) acknowledged that possible long-term effects on ecosystems deserved further attention.

10. EXTENDED AREA EFFECTS OF CLOUD SEEDING

The possibility of "robbing Peter to pay Paul" has been raised many times during the modern era of cloud seeding. People often assume the atmosphere behaves like a river. If that were the case, it would seem obvious that using cloud seeding to increase snowfall on a mountain barrier would leave less moisture for downstream areas. Some downstream water users are, therefore, concerned that upwind seeding projects may be "robbing" their water.

In reality, the atmosphere is not confined by banks and a streambed and, consequently, does not behave at all like a river. Liquid water condensate, needed for cloud production, is governed by humidity and vertical motions in the atmosphere. Upward motion produces liquid cloud droplets once 100 percent relative humidity is achieved and downward motion rapidly evaporates the tiny droplets once the relative humidity falls below 100 percent. Airflow over mountains is but one process resulting in cloud production and decay. Large scale atmospheric motions, related to convergence and divergence associated with passages of cold fronts or low pressure centers, are primarily responsible for liquid cloud formation and dissipation within widespread winter storms. Thunderstorms have medium scale vertical motions that are quite intense. Fair weather cumulus clouds are caused by small scale gentle vertical motions. In fact, vertical motions over a wide range of scales are associated with major storms. Usually, the orographic uplift and lee descent caused by a mountain barrier are superimposed on a much larger scale but less intense vertical motion field that causes widespread cloudiness; that is, a storm. The result is that unless upward motion is imposed upon an already moist atmosphere, cloud will not form and snow will not fall. The removal by cloud seeding of a tiny percentage of the vertically-integrated water (vapor plus liquid plus ice) in the atmosphere is very much a secondary effect compared to the overriding influence of large scale motion fields. The vertically-integrated liquid water cloud over a downwind mountain range may be more or less than that over a seeded range depending primarily on the ever-changing large scale atmospheric motion field. For the North Platte Headwaters region, under prevailing westerly flow, there are no more mountain ranges to the east upon which to release precipitation by orographic processes. Downwind precipitation on the plains is generated by synoptic and convective motions and is fueled by a new source of water generally coming from the Gulf of Mexico. If the moisture is not dropped as precipitation in the Headwaters region, no one downwind will be receiving that moisture. The false analogy of the atmosphere behaving like a river has led to much confusion and needless concern.

Serious consideration has been given to possible "downwind effects" or "extended area effects" of cloud seeding for some time. A more likely reason to expect such effects than the removal of water from the atmosphere by seeding is the possible persistence of silver iodide well beyond the intended target area. The author attended a 3-day seminar on extended area effects in 1971 (Elliott et al. 1971) during which evidence was considered from several projects. The majority of studies suggested extended area precipitation increases rather than decreases. However, these suggestions were largely based on statistical analyses which had all the uncertainties discussed in section 5a and often more. At the time, the Climax, Colorado, experiments were considered to have demonstrated increased snowfall in the target area and downwind as well. Now that the Climax experiments have been subjected to more scrutiny as discussed in section 5a, previously claimed Climax target area increases are much in doubt. As a consequence, past suggestions of extended area effects associated with Climax should also be regarded with caution.

Dennis (1980) reviewed several projects and stated that the evidence of seeding effects at large distances was tentative at best (see p. 95). The author of this report holds the view that few winter orographic cloud seeding programs have produced solid evidence of significant seasonal increases *within the* *intended target.* It should not be surprising, therefore, that evidence beyond the target is even more tenuous. Moreover, few projects have been designed to seriously examine hypothesized extended area effects. Since analyses have largely been after the fact, using whatever measurements happened to be available, any statistical suggestions should be viewed with appropriate caution.

This is not to say that extended area effects cannot exist. Long distance persistence of silver iodide and dynamic effects of seeding are two reasonable hypotheses for considering such effects. Since the proposed seeding program would use liquid propane, resulting in very localized ice crystal production, it can be assumed that associated dynamic effects would be negligible. Moreover, the only persistence could be of seeded crystals that manage to survive until reaching the next mountain barrier downwind. This possibility seems unlikely for the Medicine Bow Mountains because of its large distance downwind from the Park Range. Even if some seeded crystals survived the journey to the Medicine Bows, the result should be increased snowfall within the Headwaters Region. Some seeded crystals formed over the Medicine Bow Mountains might survive transport to the Laramie Mountains of Colorado just to the east. However, they would likely increase snowfall on the west portion of the southern Laramie Mountains. Because this area drains into the Laramie River and eventually into the North Platte River, there should be little cause for concern about possible downwind persistence of propane-seeded ice crystals.

Probably the most relevant work on this topic for the Headwaters Region is by Hindman (1986b) who presented calculations of the wintertime water balance over the Park Range. He showed an average of 9 percent of the inflow moisture was precipitated on the barrier. Assuming 10 to 15 percent seasonal increases from cloud seeding, Hindman (1986b) concluded that, "It was found that, on average, a small amount of atmospheric moisture precipitates on the mountain barrier (6 to 14%). Cloud seeding activities are estimated to increase these values 1.3%. Thus, cloud seeding activities on the upwind Park Range barrier should not rob moisture from the downwind Front Range barrier."

A fairly recent controversy dealt with the possibility of decreased snowfall caused by operational seeding of clouds over the Uinta Mountains of northeastern Utah and southwestern Wyoming. As a consequence, two university groups were funded by the State of Utah to pursue investigations relevant to possible extended area effects. One group pursued statistical analyses of precipitation gage and snowcourse observations, using a target-control approach with the non-randomized dataset. The other group evaluated the climatology of winter storms in the Uinta Basin.

Grant and Mielke (1990) directly considered the likelihood that cloud seeding upwind from the Uinta Mountains, and specifically in the Wasatch Range, were affecting precipitation in the Uinta Mountains and Basin. Possibilities of both negative and positive precipitation changes were considered in their analyses which relied solely on statistical approaches because no direct physical evidence was available. The authors properly pointed out several complications in attempting these statistical analyses and noted that highly definitive results could not be expected. Both precipitation gage and snow course observations were considered and some conflicting indications resulted from these two types of measurements.

In spite of the several cited difficulties, Grant and Mielke (1990) were rather positive in their findings. They concluded that, "The results for both the seeded target and downwind areas are consistent with the results of analyses of other research and operational cloud seeding programs of wintertime cloud seeding in mountainous areas. These analyses in other areas have generally shown precipitation increases in such seeded areas to be in the range of 10-15 percent, considerably higher under some weather situations but lower or negligible with others. These results are also compatible with consistent indications of an increase in precipitation in the 25 to 100 mile area downwind from wintertime, orographic cloud seeding programs in other areas. These authors know of no analysis reported in the literature where this has not been the case. As with this analysis, many of the other analyses of downwind effects have shown greater indicated increases in the downwind areas than in the seeded targets."

The conclusions of the above paragraph could be interpreted as rather convincing evidence of cloud seeding effects from 25 to 100 miles downwind from mountain targets with the intended targets having lesser increases than the downwind areas. Certainly it is encouraging that no studies were known to have shown downwind precipitation decreases. However, closer examination of the Grant and Mielke (1990) report reveals a number of acknowledgments that *neither their target area nor downwind area results were statistically significant*. This is a very important fact. With the lack of statistical significance for whatever reasons, the results can at best be considered as somewhat suggestive but certainly far from convincing proof of either target area or downwind effects. The authors previous reference to, "--- many of the other analyses of downwind effects ---" might suggest that such studies have been abundant. Yet only four references are cited in their report, one of which addresses statistical assessment, not downwind effects. Another is the Jensen et al. (1990) report reviewed next. One reference is admittedly to a workshop where it is likely that several projects were considered. However, such presentations are not published results in the open refereed literature. In fact, only limited publications exist in the open scientific literature addressing extended area or downwind effects of intentional cloud seeding. In contrast, numerous articles address the downwind effects on inadvertent weather modification caused by large urban areas and other manmade changes such as large irrigated regions. The reality of significant downwind effects from cloud seeding is very much an open question in this author's judgement and one that is quite difficult to test. However, there seems to be little reason for concern that any downwind effects would approach the magnitude of precipitation increases in mountain target areas.

Jensen et al. (1990) pursued a less direct approach to the Uinta Basin downwind effects controversy. They developed a winter storm climatology in the Uinta Basin and along the Wasatch Front to evaluate Utah terrain and its effect on orographic precipitation patterns. They concluded that much of the Uinta Basin precipitation results from storms from southerly directions. The Uintas are oriented east-west unlike most western mountain ranges which are oriented north-south. Jensen et al. (1990) made the important point that wet and dry periods in Utah and the Uinta Basin are largely influenced with large scale atmospheric conditions. They noted that most of the period 1979 through 1988 was normal to very wet in the Uinta Basin. However, the Uinta Basin fell into moderate drought by late 1988 and began to experience severe drought by the spring of 1989. That drought continued through the fall of 1990 when their report was published. While not explicitly stated, one might infer from the authors' remarks that the then current concerns about possible precipitation decreases downwind from the Uintas were primarily the result of large scale atmospheric conditions. That is, large scale flow and moisture patterns were causing dry conditions in the Uinta Basin which were perceived by some to be caused by cloud seeding.

11. HEADWATERS REGION SEEDING PROGRAM

This section briefly describes recommended key elements for a winter orographic cloud seeding program for the high elevation headwaters region of the North Platte River Basin. It also presents some "ballpark" estimates of how much water might be produced by the seeding program during an average winter. The Headwaters Region largely consists of the Park Range/Sierra Madre and Medicine Bow Mountains (see figure 1) which extend from northern Colorado into southern Wyoming. Discussion will concentrate on seeding those two mountain ranges. The mountainous region that drains into the North Platte River Basin is bordered on the west by the Continental Divide, forming the crest line of the north-south oriented Park Range. The Continental Divide is also the southern boundary of the Headwaters Region as it runs approximately east-west from the southern end of the Park Range at Rabbit Ears Pass to the southern end of the Medicine Bow Mountains south of Cameron Pass. This east-west oriented mountain region lies parallel to the prevailing westerly winds and has considerable blockage from upwind barriers. Consequently, it receives less snowfall than similar elevations in the Park Range and Medicine Bows and is not recommended as a primary target.

The Medicine Bow Mountains are completely contained within the Headwaters Region, which has its eastern boundary formed by the crest line of the Laramie Mountains of Colorado. Figure 1 shows the highest elevations in the basin are along the crest lines of the Park Range and Medicine Bow Mountains. The higher elevations of the east (lee) side of the Park Range and of both sides of the Medicine Bow Mountains provide the optimum target areas for the Headwaters Region. The west side of the Medicine Bows drains into the North Platte while the east side drains into the Laramie River which joins the North Platte near Fort Laramie. Both barriers are oriented across the prevailing westerly winds and have high frequencies of cloud and snowfall during winter and early spring.

Other mountain barriers could be considered for seeding in addition to the two recommended. For example, part of the southern end of the Wind River Range of Wyoming drains into the Sweetwater River which joins the North Platte at Pathfinder Reservoir. But the high elevation drainage is small and lies on the windward side of the range. Another possible target is the Laramie Mountains of Wyoming extending from near Casper to east of Laramie. While these mountains have little upwind blockage and lie across southwesterly windflow, they have limited high terrain.

While not discussed in this report, another type of winter cloud seeding should at least be mentioned as it appears worthy of further consideration. Winter upslope storms affect large regions of the Upper North Platte drainage. The author is not aware of any widespread seeding of such storms, but their potential has been seriously considered in the past. For example, NOAA proposed a High Plains Precipitation Enhancement Research Project in 1972 which would have included seeding of winter upslope storms just east of the Rocky Mountains (NOAA 1972). Such widespread shallow storms were believed to be similar to the shallow lake effect storms discussed by Weickmann (1973), known to have significant seeding potential. Considerable recent investigation of natural winter upslope storms has been reported, some of which suggests significant seeding potential (e.g., Politovich and Bernstein 1995). The feasibility of seeding shallow winter and early spring upslope clouds in the Upper North Platte drainage is a topic worthy of serious consideration. However, such work is beyond the scope of this report and the author knows of no recent work that has seriously considered the seeding potential of upslope storms.

11a. Some Recommended Program Components

Although it is also beyond the scope of this report to provide a detailed project design, key elements of the recommended cloud seeding program are discussed below. The described approach has the major advantages of simplicity, near certainty of routine targeting and release of seeding material only when SLW cloud is present. Moreover, the approach offers significant economy. Once seeding equipment is installed and tested, limited personnel would be required to monitor and maintain the seeding program. The seeding program would be totally automated although seeding could be manually suspended at any time.

1. Seeding should be done using automated propane dispensers along the windward sides of both the Park Range and Medicine Bows. Dispensers should preferably be on very exposed ridges or peaks likely to produce local SLW condensate. The ideal crosswind spacing between dispensers would be about 2 mi and certainly no more than 3 mi. Several investigations suggest that a plume width near 15 degrees may be assumed.

   It will be necessary to use helicopters to install and maintain most dispensers. However, a complete automated dispenser with radio and data logger plus a season's propane supply can be packaged to be carried in a single lift with a large helicopter. Well-designed dispensers should not generally require more than annual servicing. The program discussed by Reynolds (1991) helicopter-lifted ten dispensers into position each fall and removed them each spring. Of course, problems sometimes arise even with simple and reliable equipment, and winter maintenance would require helicopter transport or oversnow travel. Clearly, dispensers should not be located in known avalanche chutes. All dispenser systems would radio their operational status and other information to a central location where problems could be identified. Both propane flow rate and the temperature immediately downstream of the propane nozzle would be frequently measured, leaving no doubt whether the propane dispenser was operating properly.

2. In theory, propane seeding could be successfully conducted when SLW cloud base was somewhat above the dispensers. That situation would provide an ice supersaturation zone so seeded crystals could survive their transport into cloud. However, it is very difficult to routinely monitor ice supersaturation. Therefore, it is recommended that SLW sensors and propane dispensers be co-located which also had practical advantages. Propane would be released only when individual dispensers were in SLW cloud, determined by rime ice build-up on a nearby icing sensor. An alternative approach would be to equip only some of the dispensers with icing detectors and use that information to activate a number of neighboring dispensers. The presence of SLW cloud could be monitored by other means as well such as remotely with microwave radiometers.

   It appears that propane dispensers should be sited near the 9500 ft elevation contour to usually be in-cloud, based on the various cloud base estimates cited in section 6a. Dispensers could be located lower, near the 9000 ft contour, and seeded crystals would still be routinely transported over the crest according to several studies (e.g., section 4c). Such lower locations would provide longer crystal growth times when ice saturation existed that low, but at the expense of missed seeding opportunities when both ice and water saturation existed above the dispenser. It would probably be unwise to locate any propane dispensers lower than the 9000 ft contour based on available visual cloud based information.

3. It is strongly recommended that a prototype seeding project be conducted for two to three winters prior to deployment of any large network of dispensers. The need to test equipment, procedures and especially targeting on a small-scale before full-scale deployment has been a

lesson relearned on every major project the author is aware of that seriously monitored its effectiveness (e.g., Elliott et al. 1978, Reynolds 1996). Not all of what seems reasonable while planning at the office will prove to be so under field conditions, even if the planners are well experienced in field operations.

While all the elements of the proposed propane seeding program have been field tested in California and Utah, the largest dispenser deployment to date has been ten units. Moreover, the proposed seeding approach has never been applied to the Headwaters Region high altitude target areas. Gradually scaling up from an initial deployment of several dispensers is considered essential. It is strongly recommended that the urge to deploy large seeding networks be resisted until convincing physical evidence of successful operation exists from a small scale network.

4. Testing in a prototype seeding project will require, at a minimum, monitoring of SLW at some dispensers and measurements of ice crystals in the target area with simultaneous monitoring of natural crystals crosswind of the seeded ice crystal plumes. Some local wind measurements should be made with heated sensors and some accurate air temperature and dewpoint temperature observations should be obtained at dispenser and crest line elevations. A network of high resolution precipitation gages, protected from wind effects in forest clearings (Brown and Peck 1962), should provide accurate high-resolution snow water equivalent observations in and crosswind of the seeded area(s). These measurements would provide the basis for a reasonable physical evaluation of seeding effectiveness. However, significant electrical power will be needed to operate some of the instrumentation, such as heated wind sensors and 2D-C ice particle probes. It may be possible to locate some power-intensive equipment near existing power lines but it is likely that some instrumented shelters equipped with electrical generators will be required by the testing program. Reasonable access by oversnow vehicle will also be a requirement. Possible use of the SPL on the Park Range crest, described by Borys and Wetzel (1997), should be investigated for use in a prototype seeding program. Aircraft observations are not strongly recommended for the prototype seeding program because aircraft can rarely operate low enough in orographic cloud to provide desired observations.

   The testing program could be done on just one of the two target barriers, likely the Park Range because of easier access. However, at least SLW water should be monitored over portions of the Medicine Bow Mountains to determine whether amounts are similar over both ranges as expected.

   While increased IPCs will be obvious when SLW is present and natural snowfall is nil, natural showers will often mask seeding effects. It is recommended that a highly efficient randomized design, such as the crossover design (Schickedanz and Huff 1971, Dennis 1980), be considered in testing prototype seeding. The main problem with most designs has been contamination of the control area. Contamination would not be a significant problem with the recommended seeding approach because topography will largely control transport of seeded ice crystal plumes. Furthermore, there will be only a brief residual seeding effect downwind from the propane dispensers as seeded crystals are transported out of the target area. Propane seeding will not have the long-distance ice nucleation "contamination" sometimes found with AgI releases.

   With this design limited north and south lines of perhaps five dispensers each should be separated by a "buffer zone" of perhaps 3 to 6 mi width. Mountainous terrain downwind from both dispenser lines and the buffer zone should have similar topography. Each propane dispenser site should be equipped for simultaneous releases of tracer gas. Either the north or south propane dispenser line, and co-located tracer gas dispensers, could be activated at random whenever sufficient SLW was detected along *both lines*. The areas downwind from each dispenser line would have similar instrumentation. One would be the target and the other the control depending upon which seeding line was activated, and the buffer zone could serve as another control area. Experimental units should be on the order of 1 h in duration to minimize natural temporal variations. Limited delays between experiments would allow for flushing of seeded crystals from the area. The entire randomized test program could be automated requiring no human intervention. Many experimental pairs should thereby be accumulated over a winter.

Detection of tracer gas would document the passage of propane-seeded air parcels. Ice particle concentrations and associated snowfall rates would be expected to be, on average, higher downwind from the activated propane dispenser line than downwind from the other line. Some propane releases will have obvious downwind seeding effects when natural IPC and snowfall are very limited. Other seeding events will be contaminated by natural temporal and spatial variations in IPC and snowfall rate, which necessitates statistical testing. Contamination could affect the seeded area, the non-seeded area, or both. Statistical testing may be markedly "sharpened" by using partitioning (stratification) according to natural IPC and snowfall. This could be accomplished by suitable instrumentation within the buffer zone. Microwave radiometer scanning of SLW distributions approaching the target and control areas would also be helpful in detecting natural changes that will contaminate experimental events.

5. Once prototype testing indicates proper operation and desired seeding results, a full-scale propane dispenser network can be deployed on an operational basis. While desirable, it is not essential that a major testing program be employed during the operational seeding.

6. Should a decision be made to proceed further with consideration of seeding the Headwaters Region, detailed planning of a limited area prototype seeding program should be developed along with a detailed budget. Program planning should include site selection for propane dispensers and all instrumentation needed for evaluation. Once a program plan is well developed, serious budget planning can proceed. Past experimental programs have cost from several hundred thousand to several million dollars per year, depending upon many diverse factors.

12. SUMMARY

A major portion of this investigation involved an extensive literature review of past work that is relevant to winter orographic (mountain-induced) cloud seeding in general with emphasis on those many articles with specific relevance to the Headwaters Region or nearby regions in the Intermountain West. The following reference section lists the numerous articles cited in this report.

Convincing evidence exists that winter orographic cloud seeding (hereafter cloud seeding) sometimes increases snowfall over limited temporal and spatial domains. Many "physical experiments" (as opposed to statistical "black box" experiments) have been conducted over various mountain ranges, especially during the last 15 years as improved instrumentation became available. These physical experiments have attempted to document the key links in the chain of physical events from release of seeding material to increased snowfall accumulation on the mountain surface. Several experiments have monitored the transport and dispersion of seeding agents, resulting seeded ice crystals and, in some cases, co-released tracer gas which "tagged" the seeding plume. Large increases in ice particle concentration (IPC) were evident in numerous experiments within the seeded plumes. The IPC increases were usually observed by instrumented aircraft flying crosswind in order to intersect seeding plumes and compare them with neighboring non-seeded cloud. Aircraft sampling has been limited to no closer than about 2000 ft above mountain surfaces. Lower aircraft sampling is impractical in-cloud and under icing conditions. Unfortunately, most orographically-produced SLW and most ground-released seeding plumes are concentrated in the lowest 2000 ft or so above mountain barriers.

Some studies have been able to document seeding-caused IPC increases on mountain surfaces, usually at a fixed installation. Cross-plume sampling was possible on the Wasatch Plateau because of the plateau top road network, but this is an unusual situation. Several mountain top experiments have shown seeding-caused IPC increases.

It is possible to calculate snowfall rates from IPC measurements. When this has been done, associated snowfall rate increases have usually been associated with the IPC increases. Snowfall accumulation calculations have often been in good agreement with nearby precipitation gage measurements in the limited number of reported experiments able to document that final important link in the chain of physical events. The most obvious seeding results have been from experiments conducted during periods with abundant supercooled liquid water (SLW) cloud and negligible natural snowfall. However, short-term natural spatial and temporal variations in snowfall rates are common and they frequently mask seeding effects in attempted physical experiments.

There is no reasonable doubt that appropriately applied seeding can increase snowfall when cloud conditions are suitable, that is, the mountain is shrouded in SLW cloud and natural snowfall is nil. However, it has been much more difficult to provide quantification of the *seasonal impact of routine cloud seeding*. Many past statistical evaluations have suggested seasonal increases in the 5 to 20 percent range and 10 percent increases have been cited as typical for decades. Several of these evaluations should be regarded with skepticism for reasons discussed in section 5a. The recent Policy Statement on Weather Modification by the American Meteorological Society (AMS) emphasizes the need for physical documentation of statistical suggestions before accepting them. Nevertheless, a 10 percent seasonal increase in snow water equivalent remains the best estimate available, and it may well be achievable over the Headwaters Region *if seeding is properly applied*. The Bridger Range Experiment conducted in southwestern Montana is cited for providing both statistical and physical support for the view that about 15 percent seasonal snowfall increases were achieved with high altitude silver iodide (AgI) known to have routinely targeted desired cloud regions.

Supercooled liquid water in excess of that naturally converted to snowfall is essential for cloud seeding to succeed. Knowledge of SLW availability and its spatial and temporal distributions has increased dramatically since the early 1980's because of improved instrumentation, especially microwave radiometers. The availability of abundant excess SLW has been documented over several Intermountain West mountain ranges. This essential "raw material" appears to present no limitation to seeding-caused seasonal snowfall increases of 10 percent or more. Moreover, sophisticated numerical modeling simulations support the possibility of such increases. However, actual field documentation that seeding can produce such increases is limited. To quote the 1998 AMS Policy Statement on Weather Modification, "There is statistical evidence that precipitation from supercooled orographic clouds (clouds that develop over mountains) has been seasonally increased by about 10%. The physical cause-and-effect relationships, however, have not been fully documented. Nevertheless, the potential for such increases is supported by field measurements and numerical model simulations."

The main problem in attempting to reliably convert excess SLW over mountains into snowfall has been failure to routinely target the SLW cloud zones with appropriate concentrations of seeding material. It is difficult to reliably seed mountain clouds with the commonly used approach of operating low-level, often valley, AgI generators. Reasons include frequent trapping inversions and complex low-level airflows that often transport the seeding material parallel to the mountain barriers rather than over them. Moreover, much of the excess SLW is too warm for effective seeding with AgI, by far the most commonly used seeding agent. There is little evidence that AgI seeding can produce sufficiently high concentrations of *effective ice nuclei* at temperatures warmer then -9 °C with one important exception. It appears that any type of AgI released within SLW cloud can be effective at temperatures colder than -6 °C because of the forced condensation-freezing mechanism. A large fraction of the excess SLW flux over the major barriers of the Headwaters Region is warmer than -9 °C and even -6 °C in the 2000 ft or so above crest line elevations where most SLW is concentrated. Ground-released seeding materials are seldom transported to higher altitudes in adequate concentrations.

It is recommended that liquid propane seeding be used on the Park Range and Medicine Bow Mountains of the Headwaters Region. Liquid propane is a readily available material which can be expanded to locally chill the air below -40 °C whereupon vast numbers of tiny liquid droplets are condensed which immediately freeze (homogeneous nucleation). In effect, propane seeding is seeding with embronic ice crystals. The very tiny crystals must be produced within SLW cloud, or no lower than about 350 ft below SLW cloud base in order to survive transport into the SLW cloud before sublimating back into vapor. This means that propane dispensers must be located high up the windward slope, only about 1000 to 1500 ft below crest line elevations. However, such siting practically guarantees routine targeting of the SLW zone over the windward slope and crest line, overcoming the major problem of most ground-based seeding programs. Moreover, propane seeding is effective at temperatures as warm as -0.5 °C, adding considerable seedable cloud water compared with that which can be affected by AgI seeding. Conversion to ice crystals is immediate with propane seeding while the most commonly used type of AgI (almost pure AgI) works by contact nucleation, known to be a slow process for forming ice crystals. When contact nucleation is the primary process, most AgI particles capable of nucleation at prevailing temperatures may actually be transported beyond the orographic SLW cloud before creating ice crystals.

Propane dispensers are simple, reliable and economical devices which can be completely automated to seed only when SLW is locally present. The main drawback of such high altitude seeding is the limited time and distance available for the seeded crystals to become sufficiently large snowflakes or snow pellets which fall to the surface before sublimating in the subsidence zone immediately downwind from mountain crests. However, even valley-released AgI may not provide more growth time, on those infrequent occasions when it is transported into cloud in adequate concentrations. The reason is that AgI is likely transported within the lowest 1000 to 1650 ft above the windward slopes although it is impractical to make direct observations within this near-surface layer. The AgI does not become effective until passing through cloud base and, moreover, until it reaches altitudes where the cloud temperature is colder than -6 °C where a small fraction of the AgI particle concentration can nucleate ice. By -9 °C a much larger fraction nucleates ice but that temperature level is sometimes above the mountain barrier. In contrast, propane dispensers would be near cloud base, often producing ice crystals at lower elevations (warm temperatures) than possible with AgI.

It is not proposed to embark on a full-scale seeding program for the Headwaters Region without prior testing using a small-scale prototype seeding program. The history of weather modification contains a number of examples of programs that were scaled up too rapidly because of overly-optimistic views of the "state-of-the-science" (e.g., Changnon and Lambright 1990). These programs failed and the ramifications have been severe for the entire field of weather modification. Cloud seeding has too much potential benefit for mankind and the environment to repeat past mistakes by again "over-selling" what can be accomplished to the serious detriment of future progress.

It is proposed to embark on a small-scale prototype program, likely in the Park Range, to thoroughly test out the proposed design, equipment and procedures before pursuing a large-scale operational program that attempts to maximize streamflow. The experimental program would obtain considerable physical documentation expected to support the results of statistical testing. Physical observations would be sufficient to document what went wrong if statistical testing suggested the physical hypothesis was not totally correct. Unless any breakdown in the hypothesized chain of key links in the physical chain of events is identified, it cannot be repaired. The author believes that enough is known from considerable previous work to make it possible to design a prototype program which will demonstrate and quantify increased seasonal snow accumulations from seeding. However, the author is also aware of the history of modern weather modification and the oft-cited quote by George Santayana, "Those who cannot remember the past are condemned to repeat it." It would be foolhardy to commit to a large-scale operational seeding program before adequate testing with appropriate observations on a smaller scale. A properly planned prototype seeding experiment would permit any needed modifications to be made to the large-scale design.

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(NOTE: The *Journal of Applied Meteorology* and the *Journal of Climate and Applied Meteorology* refer to the same journal published by the American Meteorological Society. The latter name was used only during the years 1983 through 1987. The *Journal of Weather Modification* is published by the Weather Modification Association)

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