THE BUREAU OF RECLAMATION'S ATMOSPHERIC WATER RESOURCES RESEARCH PROGRAM

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1. Introduction

The following discussion describes the conceptual basis, the recognized requirements, and the current and planned contract activities for the Bureau of Reclamation's Atmospheric Water Resources Research Program, which came into being as a result of an insertion in the 1962 Public Works Appropriation Bill, Senate Report 1097, 87th Congress, 1st Session, p. 28: order to be printed September 20, 1961.

The broad objective of the Bureau's program is to ascertain whether it is economically feasible to increase the water supply available to Reclamation projects through the application of weather modification techniques for the purpose of increasing the precipitation in the headwaters of drainage basins providing the inflow to Reclamation reservoirs.

An early analysis by the Bureau of the state of weather modification knowledge and activity, performed with the advice of consultants, led to concepts and guidelines which still apply and can be stated as follows.

(a) The Bureau of Reclamation's program of weather modification research should be directed toward learning if it is possible to increase inflow into its reservoirs. The combination of the Bureau's reservoirs and hydrologic experience provides unique conditions for capitalizing on what is learned.

Although the physical process or process of precipitation is not completely understood, there is sufficient evidence that cloud seeding affects the production of precipitation to justify a program of engineering research designed to learn how to use cloud seeding to increase inflow to reservoirs. Careful, well designed field experimentation is essential to the necessary learning, but the experimentation required in the Bureau's program is operational in nature. Basic research in the atmosphere in pursuit of knowledge for the sake of knowledge is not the Bureau's mission.

(b) The hydrometeorological diversity of the regions in which the Bureau reservoirs are located precludes learning all that is required from any single experimental site, but care should be taken to focus on experimental sites which are representative of major portions of the area in which the Bureau operates.

(c) The Bureau should foster the strengthening of groups competent to perform the required experimentation. Judicious support of ongoing programs is an important means of fostering this development.

(d) As some areas provide greater opportunity for learning than others, the Bureau should foster the development of well instrumented outdoor laboratories in areas where the potential for learning is high.

(e) The Bureau of Reclamation's program should be a compatible part of the nation's efforts to understand and manage the atmosphere, seeking, whenever possible, to apply to the Bureau's program the results of work performed or sponsored by other agencies, with full credit given for the contribution.

These concepts guided the initial placement in 1961 of research contracts at the Universities of Nevada and Wyoming and the South Dakota School of Mines and Technology. The intensification of effort occasioned by the large increases in recent appropriations has been carried out in keeping with the above concepts, as will be whatever is continued or undertaken in the years to follow.

In general our work follows this sequence:

(a) study of meteorological and hydrological conditions of possible sites including storm and cloud census;

(b) design of experiments and evaluation procedures;

(c) installation of observing networks needed to supplement existing instrumentation; development of new instrumentation is undertaken when required;

(d) measurement of pertinent meteorological and hydrological parameters, both with and without coincident operation of seeding equipment.

(e) determination of the effects of cloud seeding on precipitation and evaluation of the amount of subsequent runoff that can be attributed to an induced increase in precipitation.

2. The problems

There are numerous gaps in knowledge which must be filled before the ultimate procedures for increasing precipitation and streamflow will be achieved. The task of filling these gaps is a complex one which will require the best efforts of cloud physicists, meteorologists, engineers, and social scientists. The Bureau of Reclamation program, while cognizant of the entire array of uncertainties involved, focuses on those which pertain to feasibility of operations, most of which have received too little emphasis to date. The attention of a number of investigators around the world has been directed to answering questions about how to affect the precipitation process. A considerably smaller amount of attention has been directed to the detection, measurement, and evaluation of the effect produced. It is entirely possible for economically important increases in precipitation and streamflow to go undetected or undemonstrated if the observing network is either too sparsely or too crudely instrumented. Much of the present uncertainty concerning the reality of seeding effectiveness may be the result of insensitive detection, measurement, and evaluation approaches. The smaller the

effect on precipitation that man is able to produce, the more critical is the requirement for precise methods of measurement of meteorological parameters and evaluation of precipitation and streamflow.

Although the Bureau of Reclamation program, as presently constituted, places emphasis on solving the problems of detection, measurement, and evaluation of effects produced by cloud seeding, attention is also paid to those problems of influencing the precipitation process which relate to the design of operational procedures. Questions in this category for which answers are being sought include:

(a) Where and when is the Bergeron-Findeisen process a significant factor in the production of precipitation? Can the apparent results of seeding cold clouds be explained by another mechanism such as stimulation of buoyancy due to release of heat of fusion? Can the coalescence process be effectively stimulated by artificial means? How should the design of seeding operations be varied to allow for treating whichever process can be productively affected?

(b) What are the characteristics of a storm which can be beneficially seeded? Are there critical values to temperature, humidity, wind, and nuclei concentration that characterize a "seedable" situation? Can we observe or predict these characteristics with sufficient leadtime to tailor make an operation to a specific situation? What are the instrumentation, date acquisition, and data processing requirements for the operational decisions that would be involved?

(c) What are material, equipment, and staffing requirements for producing desired effects on the precipitation processes in the various regions where the Bureau operates reservoirs?

The questions which pertain to detection, measurement, and evaluation for which answers are being sought include:

(a) What are the most practical methods for detecting and delimiting seeding effects? Are there reliable and inexpensive methods for detecting seeding and tracing materials in precipitation? How can we determine if the seeding material present in precipitation played a role in the production of the precipitation?

(b) What observing and measuring network characteristics are required to ensure that the space and time distribution of precipitation and resulting streamflow are adequately defined?

(c) What evaluation techniques are suitable for determining the results of an experiment?

(d) How do we determine if the benefit from an operation justifies its cost?

There are questions about operational hazards, liability, and social acceptance that will have to be answered eventually, but the program does not presently include work in these areas.

3. The approach to finding answers

Experimentation in the atmosphere should be carried on within a framework of understanding of the budgets of energy, mass, water (vapor and liquid), and nuclei. Observation of the three dimensional wind field, frequent temperature

and moisture soundings at the inflow and outflow boundaries, counts of freezing nuclei in the air, knowledge of the location, timing and amount of precipitation and streamflow are essential to this understanding.

It is our procedure to instrument, equip, and staff for as complete a description of the atmosphere as practicable in each area where experimentation is undertaken. Radar, rawin, balloon or kiteborne sounding equipment, and instrumented aircraft supplement surface observing networks when it is practicable to install and/or operate them.

Some of the gaps in knowledge involve questions for which answers must be found at each location where experimentation and possible subsequent operation is to be carried out. Other questions can be answered at one place in a manner that is applicable elsewhere. For example, the characteristics and frequency of occurrence of potential seeding situations must be learned. Those for north central Colorado may have significant differences from those for central Washington or western Nevada. A technique for detecting silver iodide in snow, on the other hand, could be applied to samples taken from all areas. In assigning responsibilities to the various groups which are involved in our program it has seemed good sense to fit, to the extent possible, the work assignment to the skills and interests of the group. Some of the leading atmospheric scientists and engineers in the United States are now actively working on this basis (see appendix)—work which, hopefully, will produce one or more answers of general applicability was combined, in several cases, with investigation of locally pertinent problems.

4. The details

4.1. *The Colorado River Basin Program.* An October 1964 report [1] as the result of a one year research program sponsored by the National Science Foundation, pointed up the advantages of this area as the site for a major physical experiment. This report, which introduces a new concept of cloud seeding evaluation, has become the basis for the Bureau of Reclamation's experimentation in Colorado.

The area east of Steamboat Springs, Colorado, rises steeply from a valley floor elevation of 6,800 feet to a ridge of the Park Range with elevations ranging from 10,000 to 12,500 feet. To the west of Steamboat Springs isolated mountains provide vantage points for radar surveillance and high altitude seeding. Studies of possible field experimentation sites performed by Bureau consultants were in agreement that the Steamboat Springs site offered a good combination of potential for acquiring information and acceptable access for instrumentation and observation.

The principal hypotheses being tested sequentially in this experiment are:

(a) the autocorrelation and power density spectra of precipitation rate are stable under natural precipitation conditions;

(b) seeding with silver iodide can produce increases in precipitation rates

which will detectably alter the stable natural precipitation signature provided by the power spectra of precipitation rate;

(c) Increases in precipitation will produce greater percentage increases in streamflow.

The experimental design involves:

(a) installation of a dense network of precipitation rate sensors;

(b) collection, data processing, and analysis of one year's natural storm data;

(c) collection, data processing, and analysis of a series of storm data in which silver iodide seeding has been carried out;

(d) comparison of natural and seeded signatures.

To help assure adequate seeding procedures, a series of tracer experiments have been conducted using zinc sulfide and fluorescent detection equipment. The three dimensional picture of the plume obtained from a point source located on Quarry Mountain, known locally as Emerald Mountain, indicates that adequate coverage of the target area in the Park Range can be expected. During the winter and early spring of 1965–66, seeding with silver iodide was carried on simultaneously with zinc sulfide dispersal. Detection by neutron activation analysis of the zinc sulfide and silver iodide in snow samples taken from the target area and environs is expected to define the lateral dimension of the seeded area. Monitoring of the vertical extent of the plume of zinc sulfide will be carried out by airborne detection equipment to the extent that flying weather permits.

Although the principal evaluation technique to be applied in the Park Range activity will involve comparisons of power spectra of precipitation rate data under seeded and unseeded conditions, there will be other approaches made to evaluate seeding effectiveness. Comparison of mountain to valley precipitation ratios under seeded and unseeded conditions and comparisons of streamflow from the seeded target and unseeded areas located both north and south of the target area are contemplated. Supporting work by the Soil Conservation Service for snow course readings, the Geological Survey for streamflow measurement, the USDA Forest Service for studies of the effect on runoff production of forest management practices in the area, and with Colorado State University for streamflow evaluation techniques will be continued as part of the overall evaluation approach. By mid-1966 we plan to have a basis for comparing a year of unseeded storm experience with a year of seeded experience and a preliminary indication of the sensitivity of power spectra as evaluation tools.

In another portion of the Colorado River Basin, a summer activity complements the Park Range program. A program of research into the behavior of orographically induced convective clouds is being conducted near Flagstaff, Arizona, by Dr. Paul MacCready's group, Meteorology Research, Inc., and several interested cooperators.

With a background of seven years' field experience in the Flagstaff area, the Meteorology Research, Inc. group is seeking the following goals:

(a) identification of the dominant features of seeded and unseeded convective clouds. Many of the observations are to be made in the surface convergent area

downwind of the San Francisco Peaks, called the "Convective Mountain Wake," where highly repetitive major storms have been observed in previous years. Some of the features to be observed are ice crystal concentration, buoyancy effects, hydrometeors, electrification, and cloud system growth.

(b) determination of quantitative requirements for seeding convective clouds. The techniques used will be ground and/or airborne seeding with silver iodide and/or dry ice. Massive volume seeding (spreading of seeding materials in appropriate quantities over a major percentage of the cloud volume) techniques will be employed. The emphasis is on producing obvious physical effects. No statistical evaluation is contemplated at this stage.

(c) continued exploration of the effects of the peaks on cloud, precipitation, and windflow patterns. Emphasis here is to be placed upon balloon trajectories, smoke trails, and surface anemometer observations and their relationship to cloud formation and precipitation initiation.

(d) determination of the frequency of occurrence, by seasons, of clouds suitable for effective seeding. This is planned as a preliminary step toward developing the concepts for both summer and winter seeding.

In the summer of 1965 this work was carried out in cooperation with investigators from the Pennsylvania State University under National Science Foundation sponsorship, University of Nevada, State University of New York, Boeing Aircraft Company, and the National Center for Atmospheric Research. Each organization also pursued related individual goals.

The equipment complement for these experiments includes four radars, instrumented aircraft, and ground based weather observing and communication facilities and silver iodide generators. It is expected that this program will be conducted for at least two more years. Eventually, we expect to receive a comprehensive report which should provide a procedure for operation on orographically induced convective clouds.

4.2. *Cap Cloud Program of the University of Wyoming.* Among the orographic clouds of Wyoming, the cap cloud offers some unique advantages for experimental purposes. As a persistent stationary cloud that rarely produces precipitation naturally, it can be seeded with little doubt that subsequent precipitation is the result of seeding. For this reason no effort to conduct a statistically designed experiment has been made. Experiments conducted by the Natural Resources Research Institute of the University of Wyoming have demonstrated that cap clouds can be manipulated to an extent not evident in other clouds. Cyclic seeding produces similarly cyclic precipitation. Translation of the generator normal to the windflow produces corresponding translation in the precipitating plume. The amounts produced appear to offer promise of economic significance.

At Elk Mountain, northwest of Laramie, Wyoming, a natural laboratory well suited to study of cap clouds had been partially instrumented. Plans include further installation of instrumentation and construction of an observatory and

shelter near the mountain crest. When completed, the laboratory will provide unique opportunities for experimentation with various seeding techniques.

The planned instrumentation complement includes hygrothermographs, radiometers, recording anemometers, snow pillows, radar, and an instrumented aircraft equipped to permit communication with ground observers. Equipment for taking soundings and measuring the liquid water content of clouds will be installed when funds permit.

It is planned that the work of the University of Wyoming group will be expanded as funds become available to permit the study of the occurrence and characteristics of cap clouds in other areas of Wyoming. Preliminary study has indicated that the Wind River, Snowy, and Big Horn Ranges have cap clouds which could be seeded from ground based generators. It would be in these areas that programs of precipitation augmentation would most likely be economically feasible.

4.3. *The Interior Basin Program.* The research interests of two university groups located at opposite sides of the Great Basin are being sponsored to provide necessary answers to questions about the production, detection, and measurement of the effects of cloud seeding.

At the University of Nevada a diversified group under the leadership of Dr. Wendell A. Mordy has been building toward a program ranging widely from theoretical studies of cloud physics to actual weather modification operations and to the development of instrumentation and data acquisition systems. Efforts in these areas, including field experimentation, have been carried out under other sponsorship. The Bureau of Reclamation is sponsoring the continuation of those efforts in this broad program which pertain to the practical problems of weather modification. Primary emphasis is being given the development of a data acquisition system which will coordinate calibrated radars, instrumented aircraft, balloon probes, and telemetered ground networks to provide a real time display of the meteorological and hydrological data necessary to the understanding of what happens during an experiment or operation on clouds. While the final design of the system is not complete, some portions, such as the telemetering system, have been specified. It is planned to construct an operational system that will permit the taking of cloud data by airborne sensors, the combining or multiplexing for transmission to the ground, storing on magnetic tape, demultiplexing, and real time displaying. The magnetic tape will subsequently be processed for digital storage. Operation of this system in the Mount Rose area will provide a well instrumented outdoor laboratory in which to carry out future studies of seeding effectiveness.

At Utah State University a prior interest in telemetry as applied to automatic precipitation measuring and reporting networks is being supported. Once equipment is adequately developed, a dense network will be employed in a statistically designed seeding experiment along the Wasatch Front between Salt Lake City and Ogden. In this experiment, which is in its initial planning stages, a network

of silver iodide generators located at valley and mountaintop sites will be operated selectively under radar surveillance to affect individual convective cells in orographic systems as they pass across the reporting precipitation network. Operation of the generators will be such as to permit division of the precipitation network into treated and untreated areas. This experiment is an outgrowth of a project conducted for a period of the past ten years by North American Weather Consultants. This firm will cooperate in the present experiment.

Principal emphasis during the coming year will be on adapting existing Utah State University 30 mc telemetry designs to permit operation on 170 mc at higher power and antenna gains and on solution of the problems of network operations. Concurrently, assembly of past hydrologic data for the experimental area will be accomplished.

4.4. *Southern Sierra Program.* The southern portion of the Central Valley of California has been a focal point of intense interest in cloud seeding. Several commercial operators have been active in the area and each has his own group of enthusiastic backers. In addition, a group at the Naval Ordnance Test Station (NOTS), under the leadership of Dr. Pierre St. Amand, has been active in the development of silver iodide pyrotechnics and studies of condensation nuclei. The Bureau of Reclamation is attempting to contribute to the coordination of efforts of the interested groups in order to increase the probability of solid learning about the effectiveness of cloud seeding in the area. A contract with NOTS which provides for performance of engineering research including cloud seeding experiments has, as its primary purpose, the furthering of efforts to develop improved airborne nucleating devices.

By separate contract with Precipitation Control Company of California, a seeding aircraft and flying personnel are made available to NOTS for purposes of testing nucleating devices. The airplane is operating under the radar control of the Navy scientists.

A mathematical statistician at Taft College is working to develop an experimental design for the evaluation of seeding efforts associated with the aforementioned seeding tests.

Fresno State College has been retained to perform a study of the feasibility of activating a coordinated effort in the Southern Sierra area. The desired result of this effort would be a joint experiment in which cooperating private seeding groups would conduct discrete portions. This would minimize the conflict resulting from one group's control area becoming another group's target area. This entire program is in the very first stages of planning. It is expected that more specific details will be available by mid-1966.

4.5. *The Pacific Northwest Program.* Under a contract with the Weather Modification Board of the State of Washington, planning has begun for a program of experimentation which hopefully will lead to the development of techniques for shifting precipitation from areas of surplus to areas of deficit.

In Washington and Oregon the windward slopes of coastal mountains receive large amounts of precipitation, on the order of 100 inches a year, the runoff from

which flows back to the ocean unused. Further inland, there are areas where precipitation is on the order of 10 inches per year. If it were possible to achieve transmountain diversion of the coastal excess by cloud seeding techniques, considerable economic benefit would result.

At the present time an effort is being made under the leadership of the Weather Modification Board to put together a group of interested meteorologists who would design the necessary experiments to test whether the desired transmountain diversion of precipitation is possible. We expect the experimental design to be accomplished by mid-1966.

4.6. *The Northern Great Plains Program.* At the South Dakota School of Mines and Technology, a group under the leadership of Dr. R. A. Schleusener, Director, Institute of Atmospheric Sciences, has come together for the purpose of developing the mutual goals of beneficial weather modification techniques and procedures for the Northern Great Plains. The interests of the group are broad. Those interests that pertain to putting more water in reservoirs are being sponsored by the Bureau of Reclamation. Working under a concept that the Institute will eventually operate as a regional center for the Northern Great Plains, a program has started which includes climatological studies concerned mainly with precipitation anomalies, numerical model studies which attempt to simulate a natural growth of cumulus clouds, cumulus cloud penetrations from instrumented aircraft, and a randomized seeding experiment.

In preparation for the cloud physics studies, a light twin-engine airplane was instrumented under the supervision of D. R. Booker, President of Weather Science, Inc. Displayed and recorded on an 18 channel light beam oscillograph are measurements of pressure altitude, rate of climb, true airspeed, turbulence, cloud liquid water content, temperature, wet bulb depression, infrared temperature of the underlying surface, longitudinal velocity, vertical velocity, magnetic heading, manifold pressure, and distance from a VORTAC (very high frequency omnidirectional range tactical air navigation) station. An event condition marker is also included. Time lapse cameras looking forward and downward, a balloon launcher, and a tape recorder intercommunication system, the operations of which are all keyed to the recording oscillograph, complete the instrumentation package.

Using the instrumented aircraft in coordination with a Nike-Ajax radar system, a cloud physics program including cloud penetrations has begun with several specific objectives:

(a) to determine the presence or absence of ice particles at $-5°$ C in cumulus clouds in the Great Plains;

(b) to determine by a cloud census, the characteristics of the cloud systems which yield precipitation naturally;

(c) to determine the causes of "hot spots" which favor the formation of cumulus clouds.

Preliminary results indicate that the occurrence of ice crystals at the $-5°$ C level in the Northern Great Plains is about 20 to 25 per cent. Approximately

four out of five cumulus clouds sampled have shown no ice crystals present during the first pass of the observing aircraft.

The randomized seeding experiment consists of operations over two experimental areas. One is designated as the Rapid City Project and the other as the Shadehill Project. Operations on the Rapid City Project are conducted by personnel of the Institute of Atmospheric Sciences of the South Dakota School of Mines and Technology, while the Shadehill Project is operated by Atmospheric, Inc., under the personal supervision of Thomas J. Henderson, President. Operational procedures for the two projects have been arrived at jointly so as to increase comparability of the results from the two areas. The concept involved is the trading of space for time in order to shorten the required period of learning.

In both areas individual convective storms will be seeded with silver iodide dispensed from seeding aircraft. Selection of the storm will be made from the ground by a radar meteorologist with the decision to seed or not seed being made on a random basis when the seeding aircraft is airborne and in a position to begin an actual seeding run. The raingage networks which have been installed over each of the target areas are read at noon and at 2000. It is intended that the seeding procedures for the coming season be revised as lessons are learned from the cloud physics studies.

5. Conclusion

The projects described above are viewed as the beginning of a concerted drive to find practical answers to the many questions which confront the Bureau of Reclamation in discharging its Congressionally assigned obligation to find out if the water supply to Reclamation projects can be increased by weather modification techniques.

Our program is an evolving one with flexibility deliberately built in so as to permit changes when indicated by subsequent learning wherever it occurs. We are building our engineering research effort on the foundations laid by university and private meteorologists with the support of the National Science Foundation and the other agencies whose programs have contributed to the present state of knowledge. We are adding to the supply of trained minds by encouraging participation of graduate students. We are attempting to make the best use of both expensive facilities and outstanding intellects involved in our program by arranging for joint utilization and periodic meetings of project scientists and engineers.

It is our aim to proceed aggressively toward the goal of practical application of weather modification knowledge as rapidly as is consistent with good engineering practices.

APPENDIX

Partial list of persons actively engaged in the Bureau of Reclamation's Atmospheric Water Resources Research Program.

Colorado River Basin Program

E. Bollay Associates, Inc.: E. Bollay, D. O. Zopf, R. A. Begun, P. T. Willis; V. J. Schaefer, Research Consultant;
J. A. Fuquay, Battelle Memorial Institute.
Colorado State University: V. M. Yevdjevich.
Meteorology Research, Inc.: P. B. MacCready, Jr., T. B. Smith, A. I. Weinstein, T. R. Mee.
U. S. Department of Agriculture:
Soil Conservation Service: J. A. Washichek.
Forest Service: H. Fletcher, M. Hoover, R. W. Gardner.
U. S. Department of the Interior:
Geological Survey: J. D. Odell.

Cap Cloud Program

University of Wyoming, Natural Resources Research Institute: J. C. Bellamy, M. C. Williams, D. A. Veal.

Interior Basin Program

University of Nevada, Desert Research Institute: W. A. Mordy, J. P. Chisholm, T. E. Hoffer, F. Clark, H. Klieforth, C. K. Stidd.
Utah State University, Utah Water Research Laboratory: V. E. Hansen, J. E. Fletcher, D. G. Chadwick;
R. D. Elliott, North American Weather Consultants.

Southern Sierra Program

U. S. Naval Ordnance Test Station: P. St. Amand, P. T. Jorgensen, S. D. Elliott, F. K. Odencrantz, L. Burkardt, F. Davis.
Precipitation Control Company of California: D. D. Merrill.
Taft College: L. E. Peahl.
Fresno State College: T. H. Evans.

Pacific Northwest Program

State of Washington Weather Modification Board: S. E. Shumway.

Northern Great Plains Program

South Dakota School of Mines and Technology, Institute of Atmospheric Sciences: R. A. Schleusener, A. S. Dennis, H. Hart, H. Orville;
T. J. Henderson, Atmospherics, Inc.; D. R. Booker, Weather Science, Inc.

Cooperative Program

U. S. Department of Commerce, ESSA, Weather Bureau: W. H. Kline, H. J. Mason, J. Smagorinsky, J. F. Miller, G. A. Lott, N. F. Helfert, A. T. Angelo, R. F. Strickler, W. E. Sangster, S. Manabe, J. L. Holloway, G. D. Hembree.

General Support

U. S. Department of the Interior, Bureau of Reclamation: B. P. Bellport, W. U. Garstka, A. M. Kahan, R. C. James, R. E. Trainor.

REFERENCE

[1] E. Bollay Associates, "Design for an experimental weather modification program," Report to NSF, 1964.