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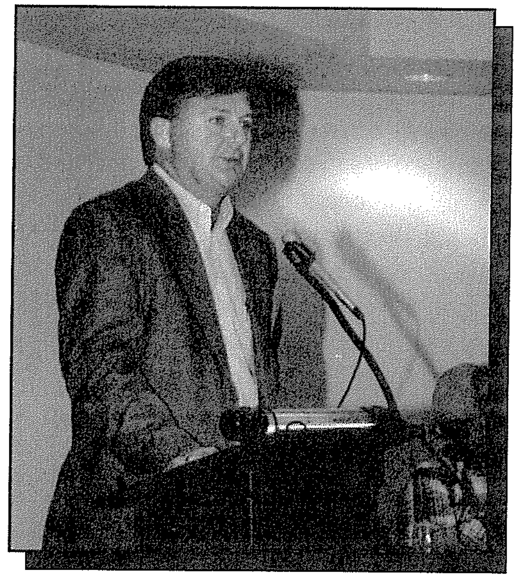

SOME FACTS ABOUT CLOUD SEEDING FROM RECENT RESEARCH ON RAIN ENHANCEMENT IN TEXAS

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With Texas likely to double its population within 35 years, the demand for adequate fresh water to meet the needs of some 35 million inhabitants will soar in the years ahead. The need for ample fresh water will be exacerbated, further, as periodic episodes of drought take their toll on the state. In knowing that sustained growth is a virtual certainty and drought is inevitable, those persons planning for Texas' future are looking for new, innovative ways to ensure that the supply of fresh water keeps up with the demand.

Among the many and varied technologies now receiving closer scrutiny as potential means of ensuring adequate water supplies for a multiplying populace is that of **weather modification**. It is this notion, that intervention in the natural processes of the atmosphere—specifically, the seeding of clouds—can stimulate added rain water. That is the focus of some who are actively mapping out water-management strategies for the 21st century.

After all, cloud seeding has been practiced in parts of Texas almost continuously now for over 25 years. A water district in West Texas, the Colorado River Municipal Water District, has used cloud seeding to augment runoff into its reservoirs on the upper Colorado River in virtually every summer since 1971! Other organizations have applied the technology for appreciable lengths of time, from the Pecos River in the West to the Trinity River in central Texas, and from the Texas Panhandle in the north to the coastal bend section of South Texas.

While Texas water agencies have been charged, by law, with regulating these rain-enhancement programs through a system of licenses and permits, officials have also sponsored, and overseen, intermittent research projects to afford some measure of assessment on some of these "operational" cloud-seeding efforts. Two federal agencies, the U.S. Bureau of Reclamation and the parent agency of the National Weather Service, the National Oceanic & Atmospheric Administration (NOAA), have invested funds in these research projects, most of which have centered on the West Central Texas area in the vicinities of Big Spring and San Angelo, where cloud seeding has been conducted extensively over the years.

The research in its early years gave mixed results, primarily because the investigations were dealing with a mostly unknown resource (cloud behavior) and funding levels oscillated between barely adequate amounts of research dollars in some years to virtually no money in other years. Scientific expertise critical to successful experimentation became available, then vanished, when funding momentum could not be sustained for any length of time. Thus, most of the research in the 1970s and early 1980s was devoted merely to getting some handle on how the Texas atmosphere functioned in its varied rainmaking modes. It was not until the onset of the current decade of the 1990s that some payoff from the investment in research could be realized. In the interim, more seeding material kept getting disseminated in broad expanses of West Texas as thirsty water districts searched earnestly for more water.

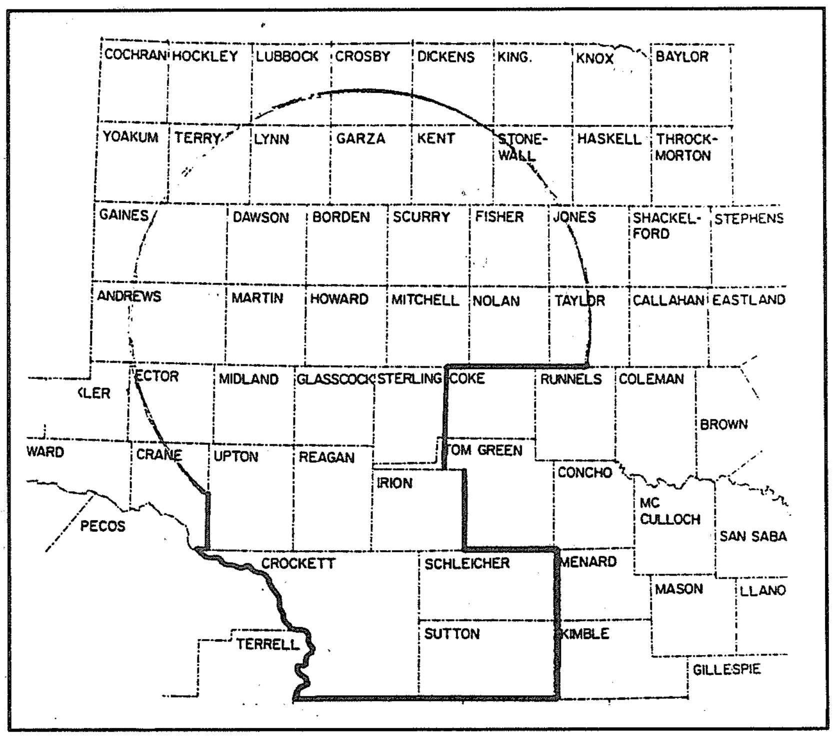

Figure 1. Site of rain-enhancement research in Texas, 1986-1996.

So what have we learned about cloud seeding and its potential to be a part of a solution to the pressing water demands of an entity that is now the second most populous state in the Union? This paper is meant to convey the essential elements in our understanding of what cloud seeding has accomplished—and what it may yet be able to deliver—as a potentially viable means of adding to our freshwater resources in the decades ahead.

The Southwest Cooperative Research Program, 1986-1990

With cloud-seeding technology having already been in use in the Big Spring area for some 15 years, and new rain-enhancement programs sprouting up elsewhere in West Texas, the impetus existed in 1985 to launch a series of cloud-seeding experiments to determine if the seeding was producing meaningful increases in rainwater and, if so, precisely by how much. With the U.S. Bureau of Reclamation as a co-sponsor, scientific personnel were committed to the task of conducting a series of seeding experiments in 1987, 1989, and 1990 in the Big Spring vicinity of West Texas (Figure 1).

In those three summer periods (each lasting 4-5 weeks in duration), a total of 34 experimental units was obtained. Since the experiments were randomized [in which some clouds (17) were seeded, others (17) were not seeded], comparisons of various cloud properties could be made, using a C-band weather

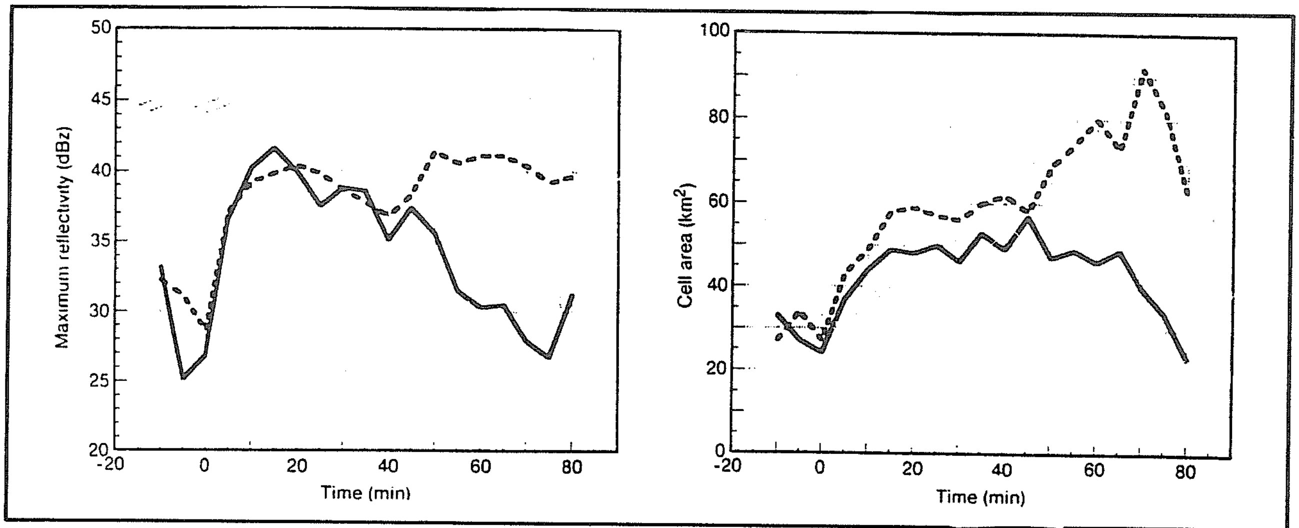

Figure 2. Mean maximum radar-echo reflectivities (left) and aerial coverage of the rain events (right), by time interval after seeding. Averages for both seeded (dashed) and non-seeded (solid) clouds are shown.

radar system, between the seeded and unseeded clouds. The results indicated that seeding with silver **iodide (AgI) more than doubled the amount of rain volume (230%) produced by the clouds; moreover, the seeded clouds lived 36% longer, expanded to produce rainwater over an area 43% larger, and tended to merge with adjacent convective cells nearly twice as often** (Figure 2). Interestingly, the seeded clouds grew only marginally taller (7%) than the unseeded ones. (It should be noted that the rainfall and merger statistics are significant at better than the 5% significance level.)

Other than quantitative measures of how much, for how long, and over what area seeded clouds produced rainwater, the most important finding from the 1987-1990 research effort was evidence that seeding with silver iodide increased the efficiency of the rain process. It could be determined, quantitatively, that seeded clouds, of a given radar-echo height, produced more rain volume than non-seeded clouds of the same height (Figure 3). These increases in rain output by seeded convective clusters have been partitioned with respect to time after initial seeding:

Time Interval (min) (after onset of seeding)	Ratio of Average Rain Output Seeded vs. Unseeded Clouds
0-30	1.37
0-60	1.27
0-90	1.37
0-120	1.26
0-150	1.27

Four additional experimental units were added to the collection during cloud-seeding research work in the summer of 1994. By extending the time period, after initial seeding, to 2.5 hours, it was determined that the mean cumulative rainfall was 45% higher in the seeded cases (with a rerandomization significance of 16%). If only the median rainfalls for the seeded and unseeded clouds are considered (to eliminate the influence of any large outlier values), the seed/no-seed ratio was found to be 2.44 (at a significance level of 11%).

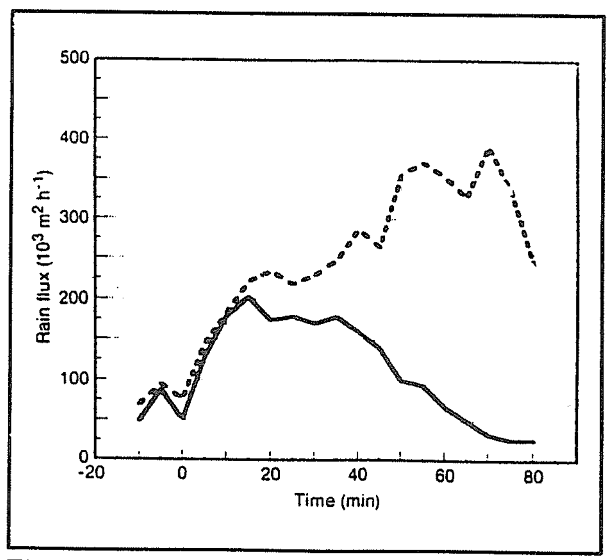

Figure 3. Mean maximum values of rain flux by time interval after seeding. Both seeded (dashed) and non-seeded (solid) cases are shown.

Designing a Conceptual Cloud Model for Texas

The results from experiments in the late 1980s led to the development of a new conceptual model for growing cumulus clouds in West Texas, a model which has been verified repeatedly by subsequent experimentation. At the core of this cloud model for Texas is the assertion that **seeding for dynamic effect can also produce a substantial increase in rainfall without causing a sizeable increase in the maximum height of the seeded cloud** (Figure 4).

Seeding works best, according to the conceptual model, when the clouds have updrafts (1) strong enough to carry the rainwater to temperatures where the water can be nucleated artificially (using the AgI "seeds"), but (2) not strong enough to transport the rainwater to heights where the temperature is cold enough for complete natural freezing. As a rule, updraft velocities should be at least comparable to the terminal-fall velocity of the raindrops at that level (about 10 m/sec). It should be stressed that **artificial seeding merely imitates a natural process, and it is most effective when the cumulus convection cannot be transformed into cumulonimbus convection on its own.**

On the other hand, according to the conceptual model, seeding can be counterproductive, if it is done too late in the life cycle of a cloud. If a mass of supercooled rainwater is glaciated artificially without an attendant updraft, the resultant load of frozen precipitation eventually melts and cools the cloud, destroying the updraft and, ultimately, the cloud itself.

The Texas Experiment in Augmenting Rainfall through Cloud-Seeding (TEXARC) Project, 1994-1996

Cloud-seeding research in West Texas prior to 1993 had, as its primary focus, quantifying how much rainfall was being produced by clouds and cloud systems that were seeded with silver iodide. When Texas gained admission to NOAA's Atmospheric Modification Program (AMP) in 1993, the emphasis in weather-modification shifted toward an understanding of how these rain increases were taking place. Previous analysis of seeded and unseeded clouds using weather-radar data had supplied enough corroboration of the revised, dynamic-seeding conceptual model; the next step in the research involved internal measurements of cloud properties using an airborne platform, to allow more investigation of the microphysical rain-producing mechanisms within the convective clouds being seeded. Until 1993, the response of seeded clouds had been measured at some distance, first from ground-based rain gages, then with ground-based weather radar. It became time to send instrumented aircraft in-

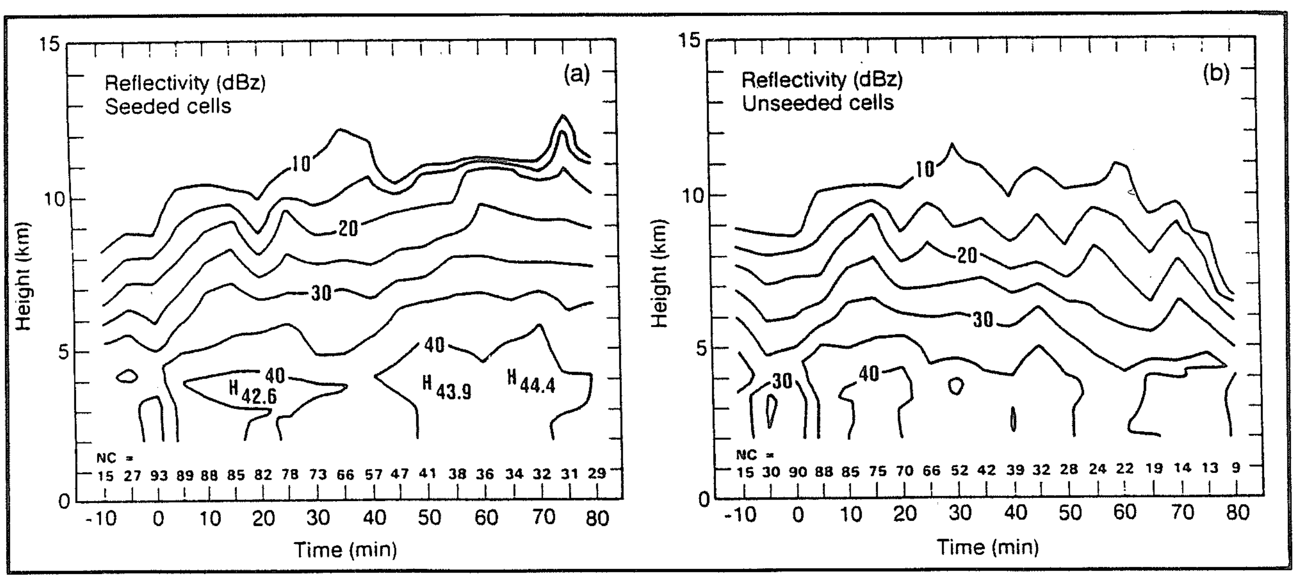

Figure 4. Composite time-height radar-echo reflectivity values for seeded (left) and non-seeded (right) clouds.

to the core regions of these growing cumulus clouds to sample them before, during, and after the seeding event.

A number of "cloud-physics" missions were conducted in August 1994 and, again, in August 1995 to document the physical processes operative within vigorous supercooled convective towers at the time of treatment with silver iodide. Here is what was learned from these in-cloud penetrations by instrumented aircraft which also had the capability to conduct seeding missions:

- The internal cloud structure is strongly dependent on the cloud-base temperature (CBT). Clouds with low bases and warm cloud-base temperatures usually glaciate well naturally, growing large graupel particles that accrete much of the abundant cloud water. On the other hand, clouds with high bases and cold cloud-base temperatures and having only a little supercooled water tend to glaciate very slowly. In this instance, seeding with silver iodide appeared to produce more ice crystals, but they grew too slowly within the available time frame to convert much cloud water into precipitation-size particles (i.e., > 500 microns in diameter). In other words, some clouds do well enough on their own as rain producers; other clouds, with inadequate cloud water, cannot be helped along fast enough, given their limited life spans.
- Seeding can, and does, work well in those clouds having an abundance of supercooled rain. Seeding with silver iodide leads to rapid freezing of that supercooled rain and its continued growth as graupel. A greater concentration of ice particles was found in the updraft regions of seeded clouds than in unseeded ones. It is critical that glaciation be produced artificially in this vigorous, supercooled updraft region, for it is there that large, artificially nucleated precipitation-size particles can be grown most efficiently. (They have a greater cross-sectional area for accretion of cloud water than water drops of the same mass.) Moreover, those particles have a lesser density than water drops, so they fall slower, giving them a longer residence time in the cloud for the sweeping out of cloud water.
- Another bit of evidence that seeding facilitates the growth of precipitation-size particles in the updraft regions of growing cumuli is the time needed to reduce the maximum amount of cloud water to half of its initial value. In seeded clouds, that maximum cloud-water content is halved an average of 2 to 3 minutes earlier than in the unseeded cases.

Though Texas in recent years has asserted leadership in the U.S. in developing and refining a fiscally responsible, environmentally sensitive, and socially acceptable technology for managing our atmospheric water resources, intensive research and extensive operational use of cloud-seeding methodologies have occurred in other parts of the world in just the past decade. Two rain-enhancement projects, using a method of cloud seeding very similar to that applied in Texas, have now generated multi-year collections of data. These data, when analyzed, have delivered findings that tend to corroborate what has been learned from experimentation in West Texas. A summary of the gist of the research results from these two projects is given below.

Results from Seeding Experiments in Thailand

Virtually identical seeding concepts (for dynamic "cold" clouds), like those examined in Texas, have been tested in Thailand (Rosenfeld et al. 1994). Forty-six (46) experimental units have been obtained over several spring seasons in this project, known as the Applied Atmospheric Resources Research Program (AARRP). Seeding convective cells with silver iodide appears to have increased the rain volumes by 27%, on average, while the maximum cell areas increased by 16%, and the durations by 14%. Little effect was observed on cloud cell heights. We are unsure as to why the apparent effect of seeding on convective clouds in Thailand is less than that observed in Texas. When only the median rainfall of seeded clouds is compared with that of unseeded clouds, the ratio is 1.78 (at a significance level of 16%).

Results from Seeding Experiments in Cuba

Other seeding experiments involving growing convective complexes were conducted in the Camaguey area of Cuba during the period 1985-1990. The methodology, dropping silver iodide flares from, at or near cloud top, was similar to that used in Texas during roughly the same time frame. The experiments led to a collection of 82 clustered convective cells, 42 of which were seeded. The largest apparent effect was noted for clouds having initial radar-echo tops in the height-range of 6.5-8.0 km, where cloud-top temperatures ranged between -10° and -20°C. Seeding appeared to increase the rain volumes by 65%, while the duration of seeded cells was 21% longer than for unseeded cells. The area covered by precipitating cells that were seeded was 28% more than for unseeded cells, whereas the maximum cell height increased by 17% in the seeded cases compared to the non-seeded ones.

Conclusions from All Research to Date

From an assortment of carefully constructed scientific experiments on growing convective clouds, using silver iodide as the seeding agent, in Texas, Florida, Cuba, and in southeast Asia, the following conclusions may be drawn, given a growing amount of strong, compelling evidence (Woodley and Rosenfeld 1993):

- It is becoming increasingly clear that the timely seeding of convective clouds with silver iodide increases the rain production of those clouds by enabling those clouds to live longer, spread laterally so as to cover more ground surface, and grow slightly taller.
- The seeding enables the clouds to produce rain more efficiently, as evidenced by measurements of greater rain amounts in seeded clouds that grow to the same height as their non-seeded counterparts.
- Timing and targeting are critical determinants in seeding clouds for rain enhancement. Seeding at the wrong time and in the wrong place(s) may actually decrease the rainfall. It now seems possible, given continental clouds with weak updrafts, to seed in such ways as to hasten the dissipation of clouds, leading to "craters" in the cloud field.

What Remains To Be Done

Solid answers to many of the questions now being posed about cloud seeding and its efficacy continue to be elusive. So where must we go from here, in the operational use of seeding materials and in the scientific assessment of how and when clouds respond to human intervention?

Continued field work, in which both glaciogenic (AgI) and hygroscopic (CaCl) seeding material is used, is a must if the technology of rain-augmentation is to be refined further, for widespread use in Texas and elsewhere, and effectively demonstrated.

- Additional experimental units, particularly with clouds seeded hygroscopically, are needed to corroborate further the findings from previous field research in Texas. Sampling of growing cumuli in other parts of Texas should be done, to allow researchers to adapt seeding methodologies to fit the climatic regimes predominant in Texas, especially in times of drought. Additional field research will allow "decision trees" to be developed to help project operators fine-tune their seeding techniques, so as to minimize the likelihood that untimely and/or inappropriate seeding would decrease, rather than, increase the amount of rainwater produced. The additional field research should:
    - develop covariate rainfall relationships; and,
    - identify in-cloud microphysical differences produced by nuclei acting in a contact mode and those acting in a condensation-freezing mode.
- A more concerted effort to use advanced modeling techniques to simulate real, natural cloud processes must be made. Closer interaction between modelers and field researchers will allow improvements in assessments made of operational rain-enhancement programs. Better use of existing mesoscale cloud models will yield better estimates of the rain volumes of natural (unseeded) clouds, thereby aiding researchers in identifying what portion of the rain episode was due to seeding.
- More attention should be directed toward an understanding of the long-term, "downwind" effects of concentrated cloud-seeding. Study areas should be expanded to allow more rain-gage and weather-radar data for regions up to 150 km removed from the cloud-seeding "target" area to be examined. Moreover, an effort to detect concentrations of silver in rainwater should be made to ensure that the level of seeding activity is not producing an adverse impact on the environment.
- Some attention must be paid to the role of cloud seeding in suppressing the undesirable prodigy of large thunderstorms, most particularly, hail. With more people resorting to the use of hardware like the "hail cannon" to control, even abet, the perni-

cious behavior of certain severe thunderstorms, the need for credible research data showing how seeding of maturing convective clouds can inhibit their capacity to foster hail has never been greater.

For additional information about weather modification, contact George Bomar in Austin at (512) 239-0770 (fax: 239-2214).

Suggested Reading Material

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