The Laboratory and Field Evaluation of Weathercord, a High Output Cloud Seeding Device

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ABSTRACT

Weathercord, a 40-grain detonating fuse containing about 20 per cent of silver iodide, has been evaluated as a cloud seeding nuclei generator in the laboratory, in the field, and in aircraft cloud seeding. Comparative data on the output efficiencies of several types of silver iodide generators are presented and show that, as a dispersal system, Weathercord provides in unit time and unit volume the highest concentration of nuclei available from any known source. The tests in supercooled fogs at Yellowstone National Park and two test cases of the seeding from aircraft of orographic cumuli are also described. Although of a preliminary nature these field tests suggest the effectiveness of the large concentrations of AgI nuclei, generated by Weathercord, in modifying relatively thin supercooled clouds.

1. Introduction

For almost 20 years, since the demonstrations by Schaefer (1946) and Vonnegut (1947) of the possibility of modifying clouds with freezing nuclei, atmospheric scientists have been searching for an efficient method of introducing suitable concentrations of effective nuclei into growing cumuli. Silver iodide nuclei have been generated by the conventional burner type ground generators (Fletcher, 1959; Fuquay, 1960) and evaluated for many years in extensive cloud seeding projects. The small output of these generators, and the perennial question of the trajectory of the nuclei they produce with respect to the clouds under study, results in severe limitations in the analysis of the observations. For several years burner generators have been flown through clouds in an effort to insure that the nuclei are introduced into the clouds. Although a step in the right direction, this operation does not ensure that a sufficiently high concentration of nuclei is injected into the cloud. Considering the speed of a seeding aircraft carrying burner generators, the concentration of nuclei per unit volume is very low.

In the past few years, pyrotechnic generators have appeared promising as a means of injecting very high concentrations of silver iodide nuclei into relatively small volumes of clouds. The results of Malkus and Simpson (1964) and Simpson and Malkus (1964) in the Caribbean appear to demonstrate the high efficiency of this method of cloud seeding in triggering the rapid growth of the seeded clouds. Russian cloud physics studies confirm this conclusion (Battan, 1965). Their claims of success in using artillery shells to introduce point sources of concentrated seeding nuclei are impressive.

Weathercord, an explosive type generator, also generates instantly very high concentrations of AgI in a very small volume. It may have important applications where an instantaneous and highly concentrated line source of freezing nuclei is desired in cloud seeding or in diffusion studies. Weathercord (U. S. Patent 3127107 and Canadian Patent 697557), a joint development of Canadian Safety Fuse, Brownsburg, Quebec and Weather Engineering, Dorval, Quebec, is a detonating fuse containing AgI. It contains approximately 3.2 gm of PETN (pentaerythritol tetranitrate) and 0.8 gm of AgI per foot of cord. It detonates at a velocity of about 18,000 ft sec^{-1}. The detonation is triggered by a standard No. 6 blasting cap actuated by a blasting machine, battery or black powder fuse.

2. Laboratory evaluation

The output of the cord, in terms of number of nuclei per gram of AgI, was compared at Colorado State University to that of several other AgI nuclei generators. Ten 3-ft lengths of cord (24 gm of AgI) were detonated in a series of successive shots in the hydraulics laboratory over a period of approximately 30 min.

TABLE 1. Test No. 2, 17 February 1964, with ten 3-ft sections of Weathercord having 0.8 gm AgI per ft or a total of 24 gm AgI.

Test firings at 1810, 1814, 1817, 1820, 1824, 1826, 1829, 1833, 1835, 1839	Nuclei per gm at −20C
1. 1833 MST floor (north center)	4.8×10^{13}
2. 1850 MST floor (north center)	4.9×10^{13}
3. 1905 MST floor (north center)	4.5×10^{13}
4. 1922 MST floor (north center)	4.1×10^{13}
5. 1934 MST floor (center)	4.1×10^{13}
6. 1947 MST floor (south center)	4.1×10^{13}
7. 2006 MST balcony (west end)	3.3×10^{13}
8. 2022 MST floor (north center)	2.4×10^{13}
9. 0300 MST (2/18/64) floor (north center)	1.4×10^{12}

The laboratory is a closed concrete structure of about 750,000 ft^3. The volume of air in which the nuclei were dispersed is thus relatively well known. Powerful fans near the top of the structure ensured a uniform distribution of the nuclei throughout the whole volume. Escape and deposition losses were neglected.

As in previous tests on other generators (Schleusener *et al.*, 1963), samples of 40 cc of air from several locations in the laboratory were taken at 15-min intervals for two hours following the detonations. The number of nuclei per gram was calculated from the average number of ice crystals observed on slides in a cold box maintained at −20C according to the equation

$$N=\frac{C}{\text{AgI}}\times 3.26\times10^{14}, \qquad (1)$$

where N is the number of nuclei per gram, C is the average number of ice crystals observed on the slide, and AgI the weight of silver iodide dispersed. The constant 3.26×10^{14} takes into account such items as the volume of the laboratory and of the sample, the cold box area and the microscope area.

Table 1 shows the decay of the nuclei concentration following the detonations.

The efficiency of silver iodide generators is probably most meaningful when looked at on a comparative basis. Table 2 allows comparison of the output of several different generators tested in the Colorado State University evaluation program.

TABLE 2. Output of silver iodide generators.

	Nuclei per gm at −20C
C.S.U. modified skyfire needle generator	3.2×10^{15}
MRI version of skyfire needle generator	1.3×10^{15}
C.S.U. modified Fuquay aircraft generator	1.7×10^{14}
NOTS Alecto (pyrotechnics)	2.0×10^{14}
Aluminum oxide fusee	4.2×10^{13}
Impregnated Primacord (Weathercord)	5.0×10^{13}
Fusee with 10 gm AgI/20 min	2.7×10^{13}
Fusee with 25 gm AgI/20 min	2.5×10^{13}
Fusee with 50 gm AgI/20 min	2.0×10^{13}
C.S.U. pilot model ammonia generator	4.8×10^{12}
Various NOTS sample formulations tested to date range from 1×10^{12} to 2×10^{14}	

Although Weathercord does not rate as the best in absolute output, its output in unit time is five times greater than the best pyrotechnics and orders of magnitude greater than any of the burners studied. The best of the pyrotechnics disperses 1.2×10^{17} nuclei per minute, or at an aircraft speed of 140 mph, 10^{13} nuclei per linear foot of travel. The detonation of one foot of Weathercord would instantly produce a line source of five times greater concentration. The detonation of 100 ft would better the output of any one of the tested generators, on the basis of time or volume.

The question now arises of determining the importance and relative effectiveness, in cloud seeding operations, of injecting point sources of extremely high concentrations of nuclei generated over periods of seconds, or of dispersing over periods of minutes or hours low concentrations of nuclei throughout cubic miles of clouds. Is it better to nucleate all supercooled droplets in a smaller volume of cloud or fewer per unit volume throughout a larger volume of cloud? The results of Malkus and Simpson's seedings in the Caribbean and of the Russian studies appear to favor the former alternative. Indeed, the most efficient use of the latent heat of crystallization, requires the freezing of all droplets in a given volume in the shortest possible time. Burner generators may finally inject into clouds as large a concentration of nuclei as pyrotechnics or Weathercord but over such a long time duration that the effect of the latent heat is so diluted by heat transfer mechanisms, that it becomes negligible. It is reasonable to believe that the apparent differences in results between the two seeding methods rest not only on the total number of nuclei introduced into clouds but on the release of latent heat of crystallization per unit volume and unit time. In this respect both pyrotechnics and Weathercord should be orders of magnitude more efficient than burner generators.

3. Field evaluation

During the 1964 Yellowstone Field Research Expedition (Schaefer, 1964) several tests of the effectiveness of Weathercord in nucleating the supercooled fog in the geyser basin were carried out. Because of the rich supply of moisture from the geysers, hot pools, and hot springs, the Old Faithful Geyser basin is usually blanketed in a thick layer of supercooled fog in the early morning hours (Schaefer, 1963). This condition and the availability of a precipitating cloud reliably generated at ground level by the regular eruptions of Old Faithful Geyser make this area a most versatile outdoor laboratory for research in cloud physics.

On 10 January 1964, 79 ft of Weathercord, suspended from a captive balloon held at about 200 ft from the ground, and 200 ft from the cone of Old Faithful, were

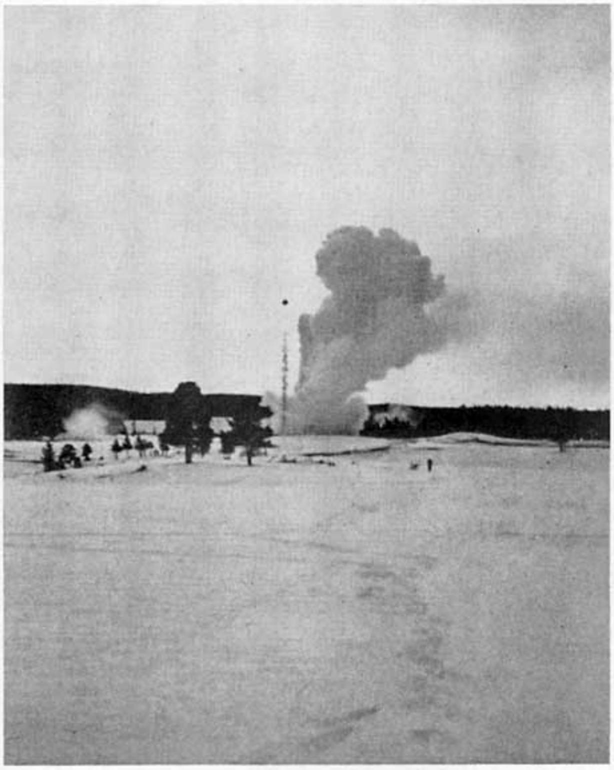

Fig. 1. Photograph of detonation at Yellowstone National Park. Courtesy of William G. Tank, Boeing Aircraft, Seattle, Washington.

detonated at a temperature of −6C during an eruption of Old Faithful (Fig. 1). Three phenomena observed at Castle Geyser approximately 2000 ft downwind from Old Faithful were used to detect the effects of the detonations. Dr. Schaefer, leader of the expedition, measured with his ice crystal replication technique (Schaefer, 1941) an increase in ice crystal concentration of about four orders of magnitude as soon as the smell of the detonation products was detected a few minutes after the detonation.

On 11 January 1964, a similar test was performed and was evaluated by a series of humidity measurements carried out by William G. Tank of Boeing Aircraft. The air temperature at the site was −18C and the hygrometer showed an absolute humidity of 1.3 gm m^{-3}, very nearly the saturation vapor density over water. Again a large increase of ice crystals was noticed at the site of the measurements with the arrival of the burnt powder smell. As soon as the number of ice crystals built up to a fairly high concentration, the humidity began to fluctuate and then fell more or less steadily. By the time the whole valley was covered by an ice fog the humidity read about 1.1 gm m^{-3} and remained constant until the ice fog dissipated. An accurate temperature reading was not recorded at the time, but the humidity attained was very nearly the the value corresponding to saturation over ice. About 10 min elapsed between the detonation and the re-

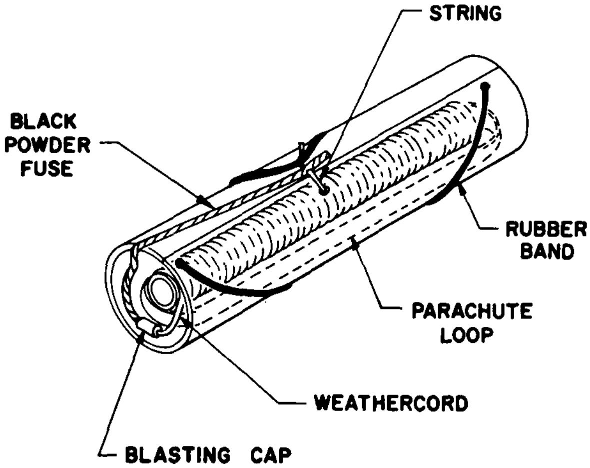

Fig. 2. Sketch of package.

cording of 1.1 gm m^{-3}. After that time diamond dust was seen floating in the air over the geyser basin. Later, magnificient optical effects were observed around the rising sun. The detonation of 80 ft of Weathercord containing about 64 gm of AgI produced, in 4.4 milliseconds, an 80-ft line source of about 3.2×10^{15} nuclei of AgI which sufficed to seed the whole valley in approximately 10 min.

These experiments left no doubt in the minds of the observers concerning the high efficiency of Weathercord.

Fig. 3. Close-up of aircraft showing packages and chute.

4. Seeding from aircraft

Weathercord was finally evaluated in cloud seeding test cases by Atmospherics, Inc., Fresno, Calif. Approval for the tests was obtained from several federal and state government agencies concerned with the safety of aircraft operations and the use of air space over private and government property.

A suitable package for safely dropping the explosive cord into clouds was developed. It consists of a split cardboard cylinder containing a standard meteorological parachute and a 2-inch diameter cardboard mandrel on which the cord is coiled. The halves of the 5-inch diameter split cylinder (Figs. 2 and 3) are held together by a rubber band fastened to one side with a short piece of string. The string is inserted through the black powder fuse used to detonate the charge through a standard No. 6 blasting cap. The length of the fuse ahead of the string determines the delay for opening the package after ejection, and the total length, the delay for detonating the charge. The cap is crimped to the charge just prior to the ignition of the fuse. The parachute opens, the Weathercord unwinds and slowly descends under the pull of the inner mandrel which now serves as a weight. After a given period, determined by the length of the fuse, the charge detonates. Lengths of up to 60 feet of Weathercord have been successfully tested with this experimental package. Fig. 3 shows the 7-inch chute for ejecting the package from the baggage compartment door of the aircraft.

Preliminary cloud seeding tests were carried out on growing cumuli over the Kings River Valley in California during March of 1965.

5. Test cases

One of the Weathercord field tests was made 7 March 1965 on a small supercooled cloud located over the Sierra Range east of Fresno, Calif. The surface weather map on this day positioned a closed low pressure center over southeastern Arizona with strong high centers over Texas and off the coast of British Columbia. The 500-mb chart indicated a closed low over central California with a reasonably good westerly flow over most of southern California. The buildup of cumulus types were orographic in nature and not influenced by any frontal activity.

Fig. 4 shows the test cloud just prior to the aerial drop of Weathercord. The base of this cloud was 8000 ft MSL (−5C) with the top at 12,300 ft MSL (−13C). The large anvil shown in the photo is some 30 miles beyond the test cloud and about 9000 ft higher. Ambient air temperatures around the test cloud were as follows:

4000 ft	+2.5C	9000 ft	−6.5C
5000 ft	+0.5C	10,000 ft	−8.0C
6000 ft	−1.0C	11,000 ft	−10.0C
7000 ft	−3.0C	12,000 ft	−12.5C
8000 ft	−5.0C	13,000 ft	−14.0C

Two 25-ft lengths of Weathercord were dropped into this supercooled cloud and detonated about 1300 ft

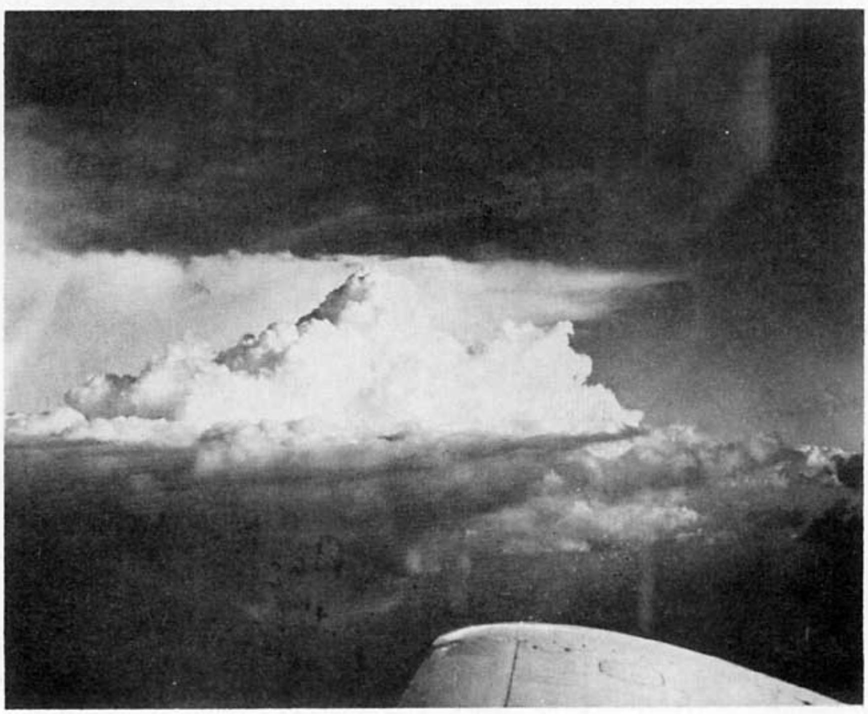

FIG. 4. Cloud before seeding.

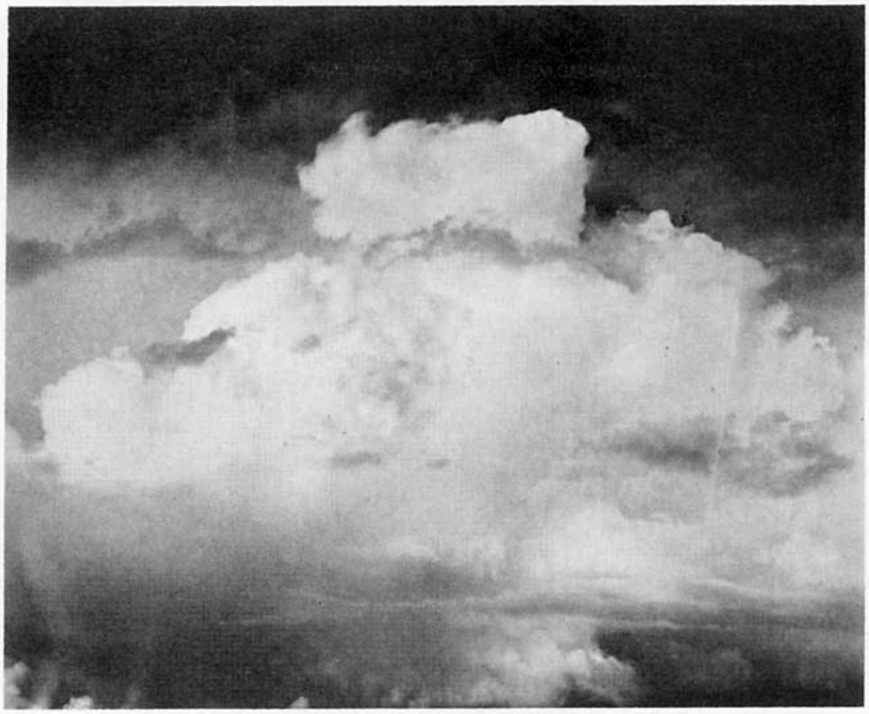

FIG. 5. Cloud after seeding.

below the top. The detonation generated about 2.5 $\times 10^{13}$ nuclei. An interesting and important feature of this cumulus is its relative shallow depth of 4300 ft. While seeding this type of cumuli often produces an observable effect, it is not common for them to produce measurable quantities of precipitation on the ground, either in their natural state or artificially stimulated.

Fig. 5 shows the same cloud 11 min after the Weathercord detonation. The cloud top was now at 13,400 ft MSL, an increase of 1100 ft. Considerable glaciation over the total volume of the cloud is apparent. Twenty-three minutes after seeding, precipitation cores developed under the test cloud. Some of the precipitation was in the form of rain but most of the particles were snow pellets or small hail. In the following four minutes the precipitation intensity increased and remained in the form of snow pellets and hail. Thirty minutes after detonation, snow pellets and small hail were still falling from the test cloud in easily measurable amounts. By flying through the precipitation cores the precipitation types were easily identified.

Another test was made 1 April 1965, further south along the Sierra Range east of Visalia, Calif. The surface map on this date positioned one low pressure center along the coast of southern California and another center over northeastern Nevada. A frontal system was plotted running southerly from this latter low pressure center and down across lower California. The 500-mb chart indicated a low center over the northern portion of California with a moderate westerly flow across the central portion of the state.

Cumulus buildups along the Sierra Range were orographic in nature and associated with post frontal activity. Four 25-ft lengths of Weathercord were dropped into one of the supercooled cumulus and detonated at about 1300 ft below the top. Cloud base in this instance was at 7800 ft MSL (−4C) with the top at 13,600 ft MSL (−16C). Observed effects following detonation were similar to the first case although the total depth of this cloud was greater than the other test cloud by about 1500 ft.

Ambient temperatures around this test cloud were:

4000 ft	+3.0C	9000 ft	−6.5C
5000 ft	+1.0C	10,000 ft	−8.5C
6000 ft	−1.5C	11,000 ft	−10.0C
7000 ft	−3.0C	12,000 ft	−12.0C
8000 ft	−5.0C	13,000 ft	−14.5C

It must be noted that precipitation was observed from untreated cumuli in the general area. However, it seems significant that no precipitation was observed from untreated cumuli which had tops less than 16,500 ft MSL or three to four thousand feet higher than the treated clouds. It is also of some significance that, in all cases, relatively small charges of Weathercord appeared to convert large volumes of supercooled water clouds to ice crystals and that shower activity followed.

Further tests are being planned to gather additional data on the effect of Weathercord on other cloud types.

6. Conclusions

The results of the tests described above establish Weathercord as a AgI generator of unique characteristics. The laboratory measurement of its output shows that, as a dispersal system, Weathercord provides in unit time and unit volume the highest concentration available from any known source. It is a high output stationary line source, that still can be improved by using a larger concentration of AgI in a more powerful detonating cord.

Because of its unique properties, Weathercord can be used at advantage for specific purposes. It can be of value in diffusion studies since it permits the precise determination of the location of the plume of freezing nuclei at a precisely determined time zero, and consequently a more accurate study of its diffusion under varied topographical and meteorological conditions. It can thus be used as a very efficient source of tracer material.

Although of a preliminary nature, the cloud seeding tests, supported by additional evidence from the field tests, strongly suggest the effectiveness of the large concentrations of freezing nuclei, generated by Weathercord, in modifying relatively thin supercooled clouds. The dramatic effects observed in all four test cases warrant further investigation before a firm conclusion can be reached in this respect.

Moreover, because of the very much larger output of Weathercord per unit time when compared to conventional ground burner generators, a study of its effectiveness in seeding from the ground is warranted. Weathercord now makes possible the almost instantaneous injection from the ground of very large concentrations of AgI nuclei into the updraft of a storm. Consequently, Weathercord may make the more economical ground seeding operations also more efficient than aircraft cloud seeding operations. Further work is being planned to verify these concepts.

Finally, since Weathercord is an explosive it should be treated accordingly. Although it is a very stable explosive under normal conditions, its use requires familiarity and compliance with the standard safety regulations for the storage and the use of any explosive material. In some states, its use may require a blaster's license for the operator. Any seeding operations from aircraft imply formal approval from the several federal and state government agencies concerned with aircraft operation and public safety.

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REFERENCES

Battan, L. J., 1965: A view of cloud physics and weather modification in the Soviet Union. *Bull. Amer. Meteor. Soc.*, **46**, 309–316.

Fletcher, N. H., 1959: The optimum performance of silver iodide smoke generators. *J. Meteor.*, **16**, 385–387.

Fuquay, D. M., 1960: Generator technology for cloud seeding. American Society of Civil Engineers, Irrigation and Drainage Division, *Journal IR*, **86**, 79–91.

Malkus, J. S., and R. H. Simpson, 1964: Modification experiments on tropical cumulus clouds. *Science*, **145**, 541–548.

Schaefer, V. J., 1946: The production of ice crystals in a cloud of supercooled water droplets. *Science*, **104**, 457–459.

——, 1949: The formation of ice crystals in the laboratory and the atmosphere. *Chem. Rev.*, 44, 291–320.

——, 1963: Studies of atmospheric nuclei in Yellowstone Park. *J. Recherches. Atm.*, **1**, 79–82.

——, 1964: Fourth Yellowstone Field Research Expedition. Final Report available from the Atmospheric Sciences Research Center, State University of New York, Albany.

Schleusener, R. A., L. O. Grant and R. Steele, 1963: Preliminary tests on a non-combustion type silver iodide generator. *Proc. 31 Ann. Meeting Western Snow Conference*, 122–130.

Simpson, R. H., and J. S. Malkus, 1964: Experiments in hurricane modification. *Sci. Amer.*, **211**, 27–37.

Vonnegut, B., 1947: Nucleation of ice formation by silver iodide. *J. Appl. Phys.*, **18**, 593–595.