"NON-REVIEWED"

AN APPLICATION OF HYGROSCOPIC FLARES
PHOTOGRAPHIC PAGE 1.

Photo 1, 1645: Looking toward Sierra crest at about 50° m.n. from camera site (3.109 m. msl) prior to seeding event.

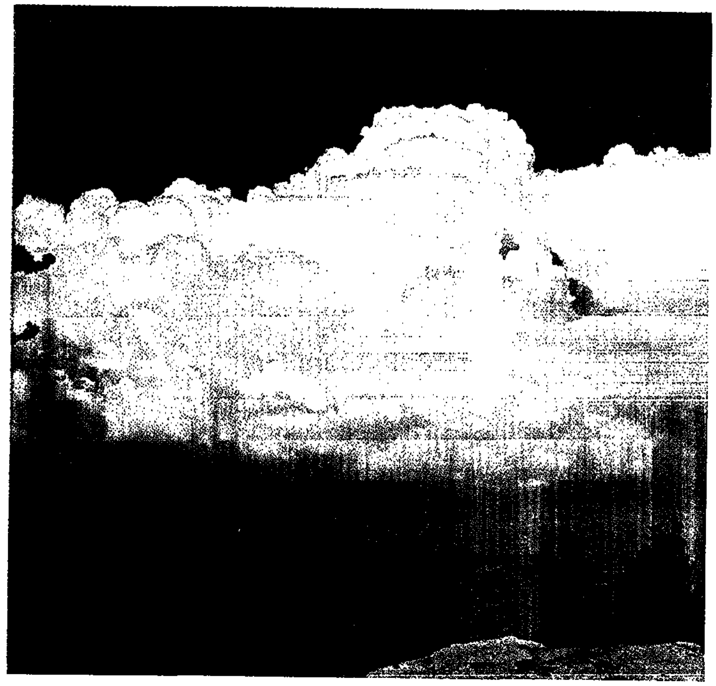

Photo 2, 1655: Small cumulus continue to grow. Seeding begins in updraft area at cloud base (center).

Photo 3, 1708: Eleven minutes after initial seeding with hygroscopic flares. Ice crystals in mid-cloud elevation.

Photo 4, 1722: Precipitation core is reaching ground level twenty-seven minutes after start of hygroscopic seeding.

AN APPLICATION OF HYGROSCOPIC FLARES - A SINGLE CASE STUDY

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ABSTRACT

A case study is presented here of seeding a single cumulus cell with hygroscopic flares. The test took place on 31 July 1996 over a section of the South Fork of the San Joaquin River in the Sierra Range of California. A 5 cm radar system focused on the area noted that the seeded cell grew to higher altitudes, produced a more intense precipitation echo, and lasted longer than any of the non-seeded cumulus cells growing simultaneously in adjacent areas. As previously observed in several hygroscopic flare applications, it was confirmed again that, in addition to rain, abundant amounts of small graupel and clear hailstones were produced within the seeded cloud.

1.0 BACKGROUND

The science and technology of hygroscopic materials to modify droplet spectra has been an important part of weather modification concepts for more than fifty years. In 1940 the development and field application of these materials were focused on the production of smokes and relevant generators. In more recent years the interest has moved toward the use of hygroscopic compositions for dissipating warm fogs and augmenting precipitation from both cold and warm cloud systems.

It would be nearly impossible to trace the complete lineage of hygroscopic particle production and types of generators because much of the initial work was a part of classified government investigations within the design of improved gas masks for the military, as well as production of screening smokes. It is enough to mention that during the period October 1940 through February 1944, scientists at the General Electric Research Laboratory in Schenectedy, New York, formed one of several groups which conducted a series of investigations with smoke, gas masks and filters under contract with the Office of Scientific Research and Development (GE Research, 1944). Fortuitously, scientists working at GE Research included Dr. Irving Langmuir and Vincent Schaefer who ultimately were two of the primary players in the discovery of materials and applications now used worldwide in cloud modification programs. During these investigations on producing white screening smokes, Langmuir and Schaefer developed methods of controlling particle sizes. As the particles grew, they found the growth rates could be stopped at any desired point. Methods followed which surprisingly produced very small particles of extraordinarily uniform sizes. In early 1947, Dr. Bernard Vonnegut, another team member, discovered silver iodide as an effective ice nucleus. The GE Research techniques for producing hygroscopic aerosols by vaporization and subsequent condensation were applied by Vonnegut (Vonnegut, B., 1947) in the design of various prototype generators to produce silver iodide as submicron particles. Models based on these prototypes are used in present cold cloud seeding programs throughout the world.

For the next several years, research in the production of hygroscopic particles was essentially dormant. In the 1960s, specific field tests were conducted on the production of condensation nuclei smoke particles and the effects of pyrotechnic seeding devices (Henderson, 1962; Henderson, 1963). Further interest was regenerated by the Naval Weapons Center (NWC) at China Lake, California. Applications were developed to produce large numbers of cloud droplets at 75% relative humidity (Blomerth, et al., 1970). Field observations and measurements noted particles from paper mills and their effect on clouds and precipi-

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tation (Hindman, 1975). Field tests with an NWC Salty Dog pyrotechnic formulation at San Nicolas Island offshore Los Angeles demonstrated the effectiveness of droplet production in a humid marine environment (Hindman, 1978). Other field tests including CCN measurements were conducted by the NWC group to dissipate warm fog at the Arcada-Eureka airport in California (Mathews, 1974). The fog clearing tests in 1973 included hygroscopic solutions, powders, and pyrotechnic devices. Conclusions from the various field application experiments indicated that a technology was available to clear warm fogs, although the large mass of material required for treatment created practical difficulties.

In recent years there has been a resurgent interest in the use of hygroscopic particles to modify both warm and cold cloud processes. This work has largely been focused on warm-based cumulus clouds which ultimately produce precipitation through the ice crystal process. In 1990, one of the first indications of changes in cold cloud microphysical processes from seeding with a hygroscopic material suggested a dramatic broadening of the cloud droplet spectrum and a reduction in the number of smaller droplets (Mather and Terblanche, 1992). Additional field applications soon followed which have stimulated substantial new interest within the cloud seeding community (Cooper and Bruintjes, 1994). Over the past two years, further hygroscopic seeding applications have been in progress and important information from fundamental calculations and model studies is beginning to emerge. Results appear very encouraging (Biggs, 1997).

This paper summarizes one of several field tests conducted by Atmospherics Incorporated with pyrotechnic-generated hygroscopic particles applied to an orographic cumulus cell which developed over the Sierra Nevada range in California on 31 July 1996.

2.0 HYGROSCOPIC FLARE DESCRIPTION

In the course of basic research conducted in the late 1960s at the Naval Weapons Center, China Lake, California, literally dozens of hygroscopic formulations were developed and characterized. These pyrotechnic devices produced large numbers of hygroscopic particles which formed water droplets at a relative humidity near 75%. One of these pyrotechnics, dubbed "Salty Dog," was particularly effective in the production of droplets with a uniform size spectra A modification of the Salty Dog composition was prepared and manufactured by Atmospherics Incorporated for use in the 31 July 1996 field test. The composition consists of the following ingredients:

Potassium Perchlorate ($KClO_4$)	63%
Sodium Chloride (NaCl)	13%
Magnesium (Mg)	8%
Lithium Carbonate (Li_2CO_3)	5%
Organic binder	11%

Measurements conducted at the Research Department of the Naval Weapons Center revealed this general composition produces about 9.6×10^{12} particles per gram of material. The solid aerosol particles are calculated to be 78.8% KCl, 21.9% NaCl and 1.3% Li_2CO_3. Most of the mass in the effluent from the composition is found in particles between 1 and 3 micrometers diameter, with the output of these sizes approximately 1.3×10^{10} per gram. The hygroscopic flares configured for application in the test case each contained 500 grams of composition pressed in a 1.5 inch diameter linen phenolic tube.

3.0 THE SETTING

The words "complex terrain" could have been invented for the Sierra Nevada mountains in California. Geographically, the range runs *NNW-SSE.* The lower elevation begins near 100 meters and the highest peak, Mt. Whitney, is 4,677 meters above sea level. The range is covered with lakes, streams, rivers, granite peaks, deep canyons, both alpine and lush timber-surrounded meadows, Forest Service land, national parks, wilderness areas, and ridgelines that defy consistent direction. From a meteorological point of view, the area often serves as a rough baseplate for howling winds which influence endless types of cloud formations and precipitation. It is concurrently a nightmare for weather forecasters and a paradise for cloud watchers.

The San Joaquin watershed covering about 3900 km^2 is situated in the southern Sierra. The terrain features are rough and areas at the higher altitudes are chiefly designated wilderness. On average, about $2 \times 10^9 m^3$ of snowmelt water per year flow from the basin to the San Joaquin Valley. There are myriad locations for observing clouds, storm systems, precipitation, and streamflow. Tests within the San Joaquin watershed are particularly pertinent because the area boasts the longest continuously operated cloud seeding project in the world, a forty-six year program funded solely by Southern California Edison Company.

4.0 WEATHER SYNOPSIS

On 31 July 1996, the early morning surface maps noted weak thermal low pressure centers near Yuma, Arizona, and Redding, California, connected by an inverted surface trough. A strong high pressure center was plotted 700 *nm* off the California/Oregon coast. The upper level charts indicated strong high pressure continuing over California with similar high pressure areas over north-central Mexico, the northern Sea of Cortez, and 200 *nm* west of Vandenberg. These features were combined to form a single broad flat ridge over the western states to east of the Rockies.

The area forecast suggested that residual moisture over the higher elevations in late afternoon was likely to produce a few isolated cumulus cells which would move rapidly northeastward over the Sierra Crest to the Owens Valley. Winds would be light southwesterly. The freezing level was expected to be near 4,700m *msl* with the -5°C level near 5,600m *msl*. Precipitable water was 19.8mm inches with the K-index 25, total-totals at 48, and the Sweat Index 110.

As the day evolved, small individual cumulus cells appeared at 1130 PDT over the mid-elevations of the San Joaquin watershed. These continued to grow throughout the early afternoon. At this time the decision was made to activate an airborne seeding flight for the application of hygroscopic particles at the cloud base of a single cumulus cell near the South Fork of the San Joaquin River.

5.0 OPERATIONS

By 1530, small individual cumulus cells appeared over the mid-elevations of the San Joaquin watershed and a meteorologist was dispatched to a cloud observation point (3,109 m. msl) overlooking the San Joaquin Basin. Shortly thereafter, an airborne seeding flight was activated for the application of hygroscopic particles at the cloud base of a single cumulus cell above the South Fork of the San Joaquin River. The 5 cm weather radar system dedicated to the cloud seeding program was activated at 1600. No precipitation echoes were logged at this time. As the small cumulus cells continued to evolve, a photographic sequence was initiated (*Photo 1*, 1645 PDT).

The aircraft lingered at cloud base for a few moments, measuring cloud base altitude (3,810 m. msl), temperature (+5°C), and updraft velocities (3m s^{-1}). At this time the target cloud appeared stationary (*Photo 2*, 1655), although a small merging cumulus was approaching from the south. Seeding with a sequence of 500-gram hygroscopic flares began at 1655. No precipitation echoes were logged at the radar site.

Within eleven minutes, the first radar echo aloft appeared. Evidence of ice crystal formation was apparent in the mid-layers of the target cloud (*Photo 3*, 1708). The temperature at the center of this layer was estimated to be near -6°C at 4,877 m. msl. The cloud was growing both vertically and horizontally but no precipitation was observed near cloud base at this time.

In another fourteen minutes the cloud merger was complete but the seeded cloud remained stationary. Radar information was now indicating a vertical expansion of the echo and precipitation was observed falling below cloud base (*Photo 4*, 1722). During an aircraft penetration of the precipitation core, the pilot reported a substantial amount of soft snow pellets and small, very hard hailstones. Seeding continued in the strengthening inflow area (5m s^{-1}). A total of 1500 grams of hygroscopic material from three flares had now been dispersed since seeding began at 1655.

As the aircraft continued an oval seeding track in the updraft region on the south side of the target cell, precipitation intensity increased and spread in all directions over a much larger area. Approximately one hour after seeding was initiated (*Photo 5*, 1747), the pilot reported an extended area of graupel and hard hail at ground level. Updraft velocities had further increased to 7.6m s^{-1} and penetrations of the precipitation noted a substantial increase in graupel concentration and hard hail approximately 7mm in diameter.

Some thirty-seven minutes passed before a second "daughter" cloud moved into the area from the south (*Photo 6*, 1826) and began to merge with the target cloud. Some minor subsidence was in progress, although an expansive area of precipitation was still providing a strong radar echo. Icing at lower and mid-levels of the treated cloud was clearly visible from the camera site. A total of 4500 grams of hygroscopic material had been dispersed when seeding was terminated at 1826. Adjacent small cumulus cells 20-30 km from the target cloud had produced weak but far less intense radar echoes than the seeded cloud. At this juncture, all other clouds in the watershed had completely dissipated.

It was now almost two hours since seeding had been initiated. The present cloud merger was complete by 1846 and the precipitation area continued to expand (*Photo 7*, 1846). Glaciation was very pronounced in the downwind volume of the target cloud. The production of graupel and small, very hard hail persisted, covering a still larger area beneath the stationary seeded cloud.

The final photograph (*Photo 8*, 1909) shows yet another "daughter" cloud entering the seeded area. Some forty-three minutes after the seeding was terminated, graupel and hail persisted below the seeded cloud volume.. All other clouds in the San Joaquin watershed had totally disappeared. The target cloud continued to produce precipitation for an additional thirty-five minutes before the tops began a rapid collapse. By this time, an area of approximately 60 km^2 was white with graupel and hail.

6.0 CONCLUSIONS

Seeding small cumulus during the summer months over complex mountain terrain has produced unexpected results. The case described above is only one of several tests conducted in the past several years which produced similar curiosities. The two results which appear unique are:

- The seeded cloud was in motion prior to seeding but remained stationary for more than four hours during and following the termination of seeding, even though "daughter" clouds moving from other locations merged with the target cloud.
- Seeding was followed by substantial precipitation which contained large amounts of 5-7 mm diameter graupel and clear, hard hailstones. Because of their size, these graupel and hail particles could well serve as embryos for much larger hailstones in cumulus clouds which are more massive and aggressive.

Because of these findings, it seems evident that the inclusion of hygroscopic flares applied during hail suppression programs postulates further examination.

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