SECTION 5

CLOUD SEEDING MODES, INSTRUMENTATION, AND STATUS OF PRECIPITATION ENHANCEMENT TECHNOLOGY

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5.1 INTRODUCTION

Once the decision has been made to implement a precipitation augmentation cloud seeding project or program, consideration needs to be given to the project or program design. Such a design is needed in order to systematically consider the important aspects of setting, conducting, and evaluating a project. The design should include: (1) a statement of the goals of the project; (2) definition of the project area (target and adjacent affected area) and control area, if any; (3) selection of an operational period; (4) specification of cloud seeding modes; (5) project instrumentation requirements; (6) cloud seeding criteria; (7) suspension criteria; and (8) evaluation criteria. Such a design can provide an excellent source of information for the preparation of a solicitation requesting the work to be performed. Several aspects relating to a project design are examined elsewhere in this report. The intent of this section is to provide a description of the possible cloud seeding modes and instrumentation for use in conducting cloud seeding operations. These two topics are covered separately in the following sections.

5.2 CLOUD SEEDING MODES

"Cloud seeding modes" is a term utilized to denote the choices available in selecting the appropriate cloud seeding agent, as well as the methods available for dispensing these agents. There are several decisions to

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be made in determining the best cloud seeding mode for a particular project. What cloud seeding agent to use—dry ice, silver iodide, liquid propane, or some organic compound? Should ground generators or airborne generators or a combination of the two be used? At what rate should the seeding agent be applied? How many ground generators or seeding aircraft are required to adequately seed the specified target area? Decisions such as these are best made on the basis of recommendations of knowledgeable meteorologists working in the field of weather modification. Sometimes the most desirable cloud seeding mode will prove to be too costly when compared with probable economic benefits, which will necessitate the specification of a more economical but still reliable cloud seeding methodology (Griffith et al., 1995).

5.2.1 Cloud Seeding Agents

Experiments conducted at the General Electric Laboratories in Schenectady, New York, in 1946 and 1947 by Drs. Schaefer (1946) and Vonnegut (1947) demonstrated that certain materials are quite effective in converting supercooled liquid water droplets (droplets at temperatures lower than 0°C) into ice crystals. Schaefer demonstrated that dry ice (solid carbon dioxide) particles, when dropped through a cloud, produce ice crystals due to spontaneous nucleation (Mossop, 1955). Additional experiments conducted by Vonnegut were concerned with the possible identification of materials that might serve to promote heterogeneous nucleation (Griffith et al., 1995). Heterogeneous nucleation, which is by far the dominant process in nature, can result either from direct deposition to ice from the vapor phase or the direct contact nucleation of supercooled liquid water. Foreign aerosol particles can promote both processes. In the case of supercooled liquid water, such aerosol particles can significantly raise the temperature at which the drops would otherwise freeze by homogeneous nucleation. Among the most effective freezing nuclei identified by Vonnegut were silver iodide and lead iodide (AgI and PbI). The temperature threshold at which particles of these substances began to produce a few ice crystals was in the range of −3°C to −4°C, much higher than with most naturally occurring substances in the atmosphere.

Later research (Fukuta, 1963, 1966) demonstrated that several organic materials can also provide effective freezing nuclei. Two examples of such materials are 1,5-dihydroxynaphtalene and metaldehyde. *Pseudomonas syringae* (Ward and Demott, 1989), a bacteria thought to reduce frost damage in plants, has also been shown to be an effective heterogeneous nucleating agent. Different classes of cloud seeding agents (homogeneous, heterogeneous, and organic, either homogeneous or heterogeneous) will be examined separately. A fourth class of cloud seeding agents, which consists of an array of hygroscopic (water absorbing) materials, will also be covered.

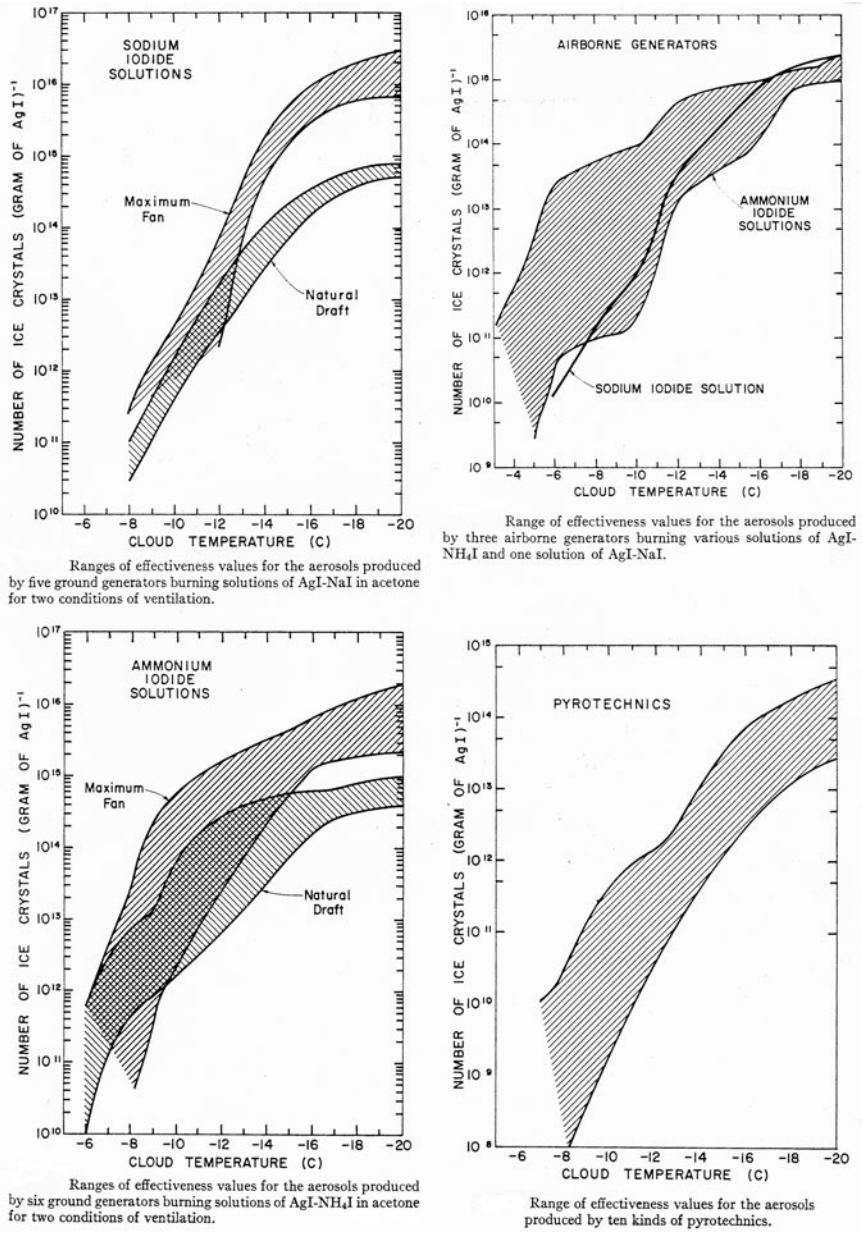
5.2.1.1 Homogeneous Nucleating Agents. Dry ice (solid CO_2) is an effective ice-nucleating agent producing 2×10^{11} to 8×10^{11} ice crystals per gram of dry ice dispensed, and its effectiveness is relatively independent of temperature in the range from −1°C to −11°C (Holroyd et al., 1978). Other research, (e.g., Horn et al., 1983) indicates that these numbers may be several orders of magnitude low, with definite temperature dependence. While dry ice has a number of advantages, such as rapid transformation of supercooled cloud water droplets and vapor to ice, good effect near the melting level, a total lack of any toxic residuals, and low cost, it must be dispensed directly into the supercooled region of the cloud—thus usually requiring an airborne delivery system. Dry ice was frequently used in cloud seeding projects in the United States in the 1950s and early 1960s but was slowly replaced by silver iodide as convenient storage and dispensing capabilities for generation of silver iodide particles were developed. Dry ice has received some attention again in recent years, especially for research projects.

Liquid propane is a freezing agent much like dry ice. It produces almost the same number of crystals per gram as does CO_2 (Kumai, 1982). It cannot be dispensed from aircraft because it is a flammable substance. However, it can be dispensed from the ground if released at elevations which are frequently within supercooled clouds. The U.S. Air Force has used liquid propane dispensed from ground-based sites to clear supercooled fog at military airports for more than 30 years. It has recently been applied as a cloud seeding agent for winter snowpack enhancement through development of a remotely operated ground-based dispenser (Reynolds, 1991, 1992). Liquid propane seeding experiments were also conducted on the Utah/National Oceanic & Atmospheric Administration's Atmospheric Modification Project (Super, 1999). Future experimentation needs to demonstrate that this technique can increase precipitation over a fixed target area for a significant period of time (e.g., a winter season).

5.2.1.2 Heterogeneous Cloud Seeding Agents. Both silver iodide (AgI) and lead iodide (PbI) particles, in size ranges of 0.1 micron to 1 micron are very effective freezing nuclei. Due to environmental concerns related to the release of lead into the atmosphere, PbI has generally not been utilized as a cloud seeding agent. However, silver iodide does not suffer from these environmental constraints and has been the preferred seeding agent in many cloud seeding projects. This has been the case for projects and/or programs conducted in the United States and in other countries, such as Australia and Canada, for decades. Correctly sized particles of AgI are usually produced through some combustion process followed by rapid quenching, which forms literally billions of effective freezing nuclei/gram of AgI consumed if temperatures are lower than −4°C. Methods of generating properly sized particles of AgI are covered in Section 5.2.2.

Cloud chambers have been constructed at several research facilities, such as Colorado State University (1969–2004), in order to test, among other things, the effectiveness of different generating techniques in producing freezing nuclei. Figure 5-1 provides plots of the number of effective freezing nuclei produced per gram of AgI consumed in a variety of seeding material generation methods as a function of the temperature of the cloud chamber (Garvey, 1975). All of the curves in Figure 5-1 exhibit an increase in activity with decreasing temperatures. Similar studies of naturally occurring freezing nuclei exhibit this same characteristic with even fewer active nuclei in the regions warmer than −10°C. Note the relative increase in effectiveness of silver iodide-ammonium iodide mixtures over that of silver iodide and sodium iodide. The presence of either ammonium or sodium iodide in solutions of AgI and acetone mixtures is prompted by the need for a catalyst to allow dissolving AgI in acetone. The differences in activity from solutions involving sodium and ammonium iodide have been studied extensively and are attributed to more hygroscopic complexes being formed using sodium iodide solutions. This decreases the effectiveness of AgI particles produced from these solutions (Donnan et al., 1970). Following this research, conducted by the Naval Weapons Center, the South Dakota School of Mines and Technology, and other groups, most operations utilizing AgI acetone solutions in that era (1970s) switched from sodium iodide to ammonium iodide as the catalyst. Differences also occur due to the difference in airflow past the cloud seeding generator. This effect is shown in the upper left hand figure, where maximum fan production is greater, and this might be expected to occur under cloud seeding conditions.

Later research by DeMott et al. (1983) in cloud chamber tests indicates that the addition of ammonium perchlorate (NH_4ClO_4) to the standard silver iodide, ammonium iodide, acetone solution increases the number of effective freezing nuclei produced per gram of silver iodide. Other research (DeMott, 1988) indicates that the addition of sodium perchlorate ($NaClO_4$) to the above solution apparently produces a hygroscopic nucleating agent. The complex produced through the burning of these mixtures exhibits significantly faster reaction times in producing ice crystals than other means of producing AgI freezing nuclei. Finnegan (1999) provides further documentation that the addition of chlorine to seeding solutions provides increased activity at higher temperatures and, perhaps more important, faster rates of nucleation than solutions that generate pure AgI. These results suggest that there are choices available in the design of cloud seeding projects that utilize AgI in terms of the potential number of ice crystals that can be produced per gram of AgI utilized and also in the rates at which these ice crystals are produced. Different cloud seeding project designs may be able to effectively utilize these choices to a definite advantage.



Ranges of effectiveness values for the aerosols produced by five ground generators burning solutions of AgI-NaI in acetone for two conditions of ventilation.

Range of effectiveness values for the aerosols produced by three airborne generators burning various solutions of AgI-NH_4I and one solution of AgI-NaI.

Ranges of effectiveness values for the aerosols produced by six ground generators burning solutions of AgI-NH_4I in acetone for two conditions of ventilation.

Range of effectiveness values for the aerosols produced by ten kinds of pyrotechnics.

FIGURE 5-1. Ranges of Effectiveness Values for Aerosols Produced by Various Methods (Griffith et al., 1995).

It has been shown that field observations of nucleation efficiency from wingtip acetone generators or ground-based silver iodide generators may exhibit even higher efficiencies (Finnegan and Pitter, 1987). This is due to the production of water vapor in the combustion process, providing transient supersaturations. Deshler et al. (1990) report on such a phenomenon from aerial seeding in clouds over the Sierra Nevada.

The potential toxicity of AgI and possible environmental impacts have been investigated extensively (Cooper and Jolly, 1969; Douglas, 1968; Klein, 1978). The results of this research indicate little concern over the short term (measured in decades), with some possible impact in the long term (hundreds of years).

5.2.1.3 Organic Cloud Seeding Materials. Several organic materials (compounds of carbon) have been identified as effective freezing nuclei. Phloroglucinol appears to have been the first organic freezing nucleant identified (Langer et al., 1963). Several other compounds, including trichlorobenzene, raffinose, trimesic acid, melamine, 1-leucine, 1-tryptophane, metaldehyde, and 1,5-dihydroxynaphtalene have been shown to provide effective freezing nuclei (Fukuta, 1963 and 1966; Langer et al., 1963; Power and Power, 1962). Some of these compounds exhibit higher threshold activation temperatures, which hold promise for potential future applications where activation near the melting level is advantageous. Most organic nucleants have received little field-testing to date; therefore, their acceptance for use in operational precipitation enhancement projects will probably be delayed until tested in research-oriented cloud seeding projects. The exception is liquid propane, which has been previously mentioned. Its efficiency is similar to that of solid carbon dioxide (Griffith et al., 1995).

There are several potential advantages associated with organic nucleants, which should encourage consideration for testing in research projects. These many materials are biodegradable, have lower costs (especially when compared to silver iodide), and have comparatively high temperature activation thresholds. Some organic materials, unlike dry ice, can undoubtedly be adapted to ground generation techniques (similar to propane).

5.2.1.4 Hygroscopic Materials. Numerous precipitation enhancement projects have been using AgI complexes as their primary nucleating agent since the 1950s (ASCE, 2004). Nevertheless, the injection of hygroscopic agents which may alter the initial cloud droplet spectra or create raindrop embryos immediately may be an efficient method for treating warm-based continental cumulus clouds, in which the vertical distance from cloud base to the melting level can be as much as a few kilometers. Ludlam (1958) and Appleman (1958) described the concepts involved in hygroscopic seeding with salt particles by dropping large numbers of salt particles into cumulus clouds. Salt seeding was used experimentally in the North Dakota Pilot Project, a combination hail suppression and rainfall enhancement project, in 1972. In that experiment and others conducted in South Dakota, finely ground salt particles were released near the bases of moderate sized cumulus clouds to create raindrop embryos around the salt particles. Experiments carried out in South Africa in the early 1990s underscored the potential effectiveness of seeding with hygroscopic agents in increasing precipitation from cumulus clouds (Mather and Terblanche, 1994).

Hygroscopic agents deliquesce (that is, become liquid by absorbing moisture from the air) at relative humidity values significantly less than 100%. Mather et al. (1997) made use of flares containing primarily potassium perchlorate, which when burned produced potassium chloride (KCl) particles with mean diameters of about 0.5 microns. The hygroscopic flares contained about 1 kilogram of seeding material. These flares were burned near the base of cumulus clouds in an attempt to alter the cloud droplet spectra through the "competition" effect. Although there are many naturally occurring hygroscopic substances, KCl particles have an advantage of only requiring a relative humidity on the order of 70% to 80% to deliquesce, and readily act efficiently as CCN.

Project planners should bear in mind that the hygroscopic flare method is relatively new and is not yet used as widely as the AgI complexes, although it has shown considerable promise (Cooper et al., 1997; Mather et al., 1996, 1997). Additional experimentation utilizing this technique has been conducted in Mexico for rain enhancement (Bruintjes et al., 1999). Future experimentation needs to demonstrate that this technique can increase precipitation over a fixed target area for a significant period of time (e.g., a summer convective season).

5.2.1.5 Other Seeding Methods and Inadvertent Weather Modification. Over the years, there have been a number of proposed techniques to produce increases in precipitation. Some of these techniques are based upon plausible physical principles, and may offer potential (though they are yet to be proven) through field-testing. An example could be the alteration of the albedo of an area through the installation of a surface that absorbs the sun's energy, thereby creating increased convection near the earth's surface, possibly leading to enhanced cloud development. An inadvertent effect appears to have been detected during the Metromex project (Changnon et al., 1971) conducted in the St. Louis area, although, in this case, the effect was hypothesized to have been due to urban pollution or heat island effects. Recent research (Rosenfeld and Lensky, 1998) has indicated that "natural and anthropogenic aerosols can substantially modify clouds not only in pristine environments, as was already demonstrated by the ship tracks, but they can also produce a major impact on cloud microstructure and precipitation in more continental environments, leading to substantial weather modification in densely populated areas."

Substantial reduction in the rainfall efficiency of clouds was observed to be induced by plumes of smoke caused by biomass burning due to agricultural practices, forest fires (Rosenfeld, 1999; Andreae et al., 2004), cooking and heating, and industrial processes (Rosenfeld, 2000; Ramanathan et al., 2001). This was manifested as actual loss of 15% to 25% of the winter precipitation from orographic clouds downwind of coastal major urban areas (Givati and Rosenfeld, 2004). Air pollution was observed to mask the added rainfall due to cloud seeding (Givati and Rosenfeld, 2005). Therefore the opposing effects of air pollution and cloud seeding need to be separated for proper assessment of the anthropogenic impacts on precipitation amounts.

Polluted clouds with suppressed precipitation could regain their raining ability once they incorporate large hygroscopic particles originating as sea spray (Rosenfeld et al., 2002) or salt dust particles from salt flats such as the anthropogenically dried Aral Sea (Rudich et al., 2002) because large hygroscopic particles were then mixed into the clouds and overrode the detrimental effect of the smoke particles.

5.2.2 Delivery Systems

A number of alternatives exist regarding cloud seeding delivery systems. A basic division exists between these alternatives, consisting of ground-based or aerial generating systems. Most systems currently in use are designed to dispense either silver iodide nuclei or particles of dry ice. The choice of the delivery system (or systems) should be made on the basis of the project design, which should establish the best system for the specific requirements and the topographic configuration of a given project (Griffith et al., 1995).

5.2.2.1 Aerial Application. Commonly available aircraft can be modified to carry an assortment of cloud seeding devices. Silver iodide nuclei dispensers include models which burn a solution of silver iodide dissolved in acetone, or through pyrotechnic devices (flares), either droppable or burn-in-place units. A typical silver iodide solution burner has a solution tank and a nozzle configuration. The silver iodide acetone solution is forced through the nozzle into a combustion chamber where the atomized solution is ignited, and the silver iodide crystals formed through combustion are expelled along with the other combustion by-products into the atmosphere (Griffith et al., 1995; ASCE, 2004).

Pyrotechnics are similar to ordinary highway flares that are typically ignited at one end and designed to burn for varying periods of time from several seconds to several minutes. Cloud seeding pyrotechnics (often referred to as flares) are impregnated with varying amounts of silver iodate ($AgIO_3$); $AgIO_3$ is used since this compound provides the oxygen needed to burn the flare formulation. They are classified as Class 1.4 pyrotechnics, which require some restrictions in the way they are transported. Cloud seeding pyrotechnics can be burned from racks mounted on an aircraft near the trailing edge of the wing or can be dropped from the underside of the aircraft. In the latter case, the flare is ignited as it leaves the aircraft and then falls for approximately 600 to 1,800 m (depending upon the designed burn time) before being completely consumed. An aluminum casing containing the droppable pyrotechnic mixture remains in the dispensing rack on the aircraft when the cloud seeding mixture is expelled by a propellant charge. Pyrotechnics typically produce 10 to 100 grams of active seeding agent per minute of AgI, while aerial acetone generators typically produce 2 to 3 grams of active seeding agent per minute of AgI (ASCE, 2004). The rate at which the seeding agent is dispersed is not the only important factor, however. Cloud chamber tests indicate that, in general, acetone generators produce about ten times as many effective ice nuclei per gram of AgI burned as do pyrotechnics. In addition, the activation temperatures and nucleation mechanisms may also vary. All of these factors should be considered when selecting the type of generation method to be used. Laboratory cloud chamber test results can be very informative in this regard. Figures 5-2 through 5-4 provide common installations of an acetone dispenser, a pyrotechnic burn-in-place rack, and a rack for droppable pyrotechnics.

FIGURE 5-2. Acetone-Silver Iodide Generator Mounted on a Wing Tip (ASCE, 2004).

FIGURE 5-3. Wing-Mount Silver Iodide Pyrotechnic Rack (ASCE, 2004).

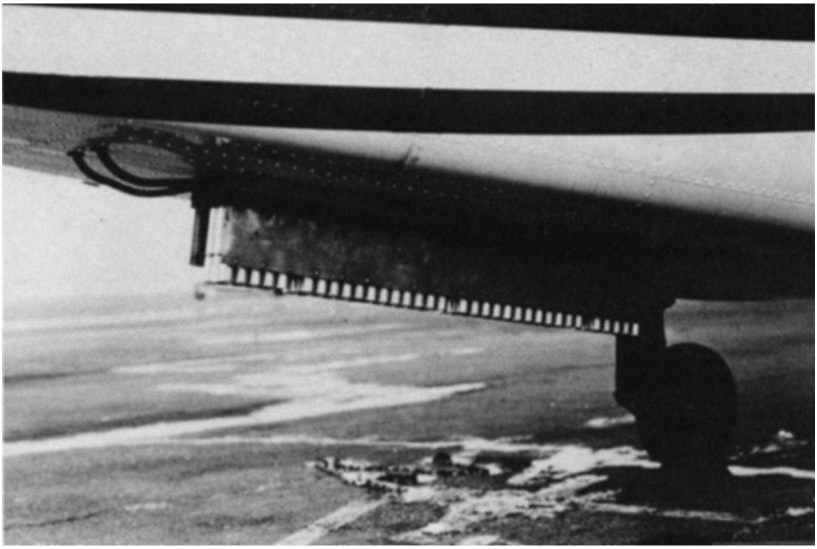


FIGURE 5-4. Droppable Silver Iodide Pyrotechnic Rack (ASCE, 2004).

Dry ice is frequently dispensed through openings in the floor of baggage compartments or extra passenger seat locations on modified cloud seeding aircraft. Dispensers have been designed to disperse "pelletized" or small particles of dry ice. Dry ice pellets are available commercially in some of the larger cities of the United States. Diameters of 0.6 to 1 cm and 0.6 to 2.5 cm in length are the appropriate size. The goal of dispensing dry ice is to have the particles fall 1 to 2 km before they sublime completely, thereby creating a sizable "curtain" of seeded cloud area. Other dis-