complexes being formed using sodium iodide solutions. This decreases the effectiveness of AgI particles produced from these solutions (Donnan et al. 1970). This finding caused a switch from sodium iodide to ammonium iodide as the preferred catalyst. Differences also occur due to the difference in airflow past the cloud seeding generator. This effect is shown in the upper left-hand image of the figure, where maximum fan production is greater, which might be expected to occur under cloud seeding conditions.

Later research by DeMott et al. (1983) in cloud chamber tests indicated that the addition of ammonium perchlorate (NH_4ClO_4) to the standard silver iodide, ammonium iodide, acetone solution further increases the number of effective freezing nuclei produced per gram of silver iodide. Other research (DeMott 1988) indicated that the addition of sodium perchlorate ($NaClO_4$) to the aforementioned 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 by 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. Finnegan indicated that the addition of chlorine can be accomplished by adding sodium or potassium perchlorate or paradichlorobenzene to silver iodide-acetone seeding solutions. These results suggest that choices are 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.

It has been shown that field observations of nucleation efficiency from aircraft wingtip acetone generators or ground-based silver iodide generators in clouds with temperatures below 0 °C may exhibit even higher efficiencies (Finnegan and Pitter 1987). This is because of the production of water vapor in the combustion process providing transient supersaturations. Deshler et al. (1990) reported 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 (CardoENTRIX 2011; Williams and Denholm 2009; Klein 1978; Cooper and Jolly 1969; Douglas 1968). Findings indicate little concern over the short term (measured in decades), with some possible impact in the long term (hundreds of years). The Weather Modification Association issued a “Position Statement on the Environmental Impacts of using Silver Iodide as a Cloud Seeding Agent” (WMA 2009).

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 ice-forming nuclei (Fukuta 1966, 1963; 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 probably will 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 dry ice (Griffith et al. 1995).

Several potential advantages are associated with organic nucleants, which should encourage consideration for testing in research projects. These plentiful materials are biodegradable, have lower costs (especially when compared with 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 used AgI complexes as their primary nucleating agent since the 1950s (ASCE 2004). Nevertheless, the injection of hygroscopic agents that 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 a 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). A two-season, follow-on experiment was conducted in Mexico (Bruintjes et al. 2001). A three-season experiment was conducted in Thailand (Silverman and Sukamjanaset 2000). Following these experimental programs, hygroscopic seeding began to be applied on more operationally oriented programs such as those in Texas (Rosenfeld et al. 2010) and India (Krishna et al. 2009).

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 μm. The hygroscopic flares contained about 1 kg 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 cloud condensation nuclei (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. These flares do, however, potentially offer an opportunity to increase precipitation from clouds whose temperatures are entirely above 0 °C, temperatures at which freezing nuclei (e.g., silver iodide) are ineffective.

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 on plausible physical principles and may offer potential (though yet to be proven through modeling and 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 because of urban pollution or heat island effects. Research performed by Rosenfeld and Lensky (1998) 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."

An increase in the aerosol burden within a cloud may retard the precipitation process unless the infusion is accompanied by a direct or indirect amount of water vapor to accommodate the additional loading (see Chapter 4). For example, substantial reduction in the rainfall efficiency of clouds observed when plumes of smoke caused by biomass burning due to agricultural practices or forest fires (e.g., Rosenfeld 1999; Andreae et al. 2004), cooking and heating, and industrial processes

(Rosenfeld 2000; Ramanathan et al. 2001) were entrained into these clouds was manifested as actual loss of 15 to 25% of the winter precipitation from orographic clouds downwind of major coastal urban areas (Givati and Rosenfeld 2004). Air pollution was observed to mask the added rainfall because of 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.

Clouds formed in polluted air with suppressed precipitation processes could regain their rain-producing ability once they incorporate sufficient additional water vapor, 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 mixed into the clouds may override the detrimental effect of the smoke particles. Dust in Saudi Arabia also was found to modify convective clouds. Under dusty conditions, when a large concentration of coarse-fraction mineral particles was in the aerosol, cloud drop concentrations were lower and droplet diameters larger than under regional background conditions when the aerosol was dominated by submicrometer sulfate particles (Posfai et al. 2013).

Rosenfeld and Givati (2006) established that reductions in precipitation in mountainous areas located downwind of large cities are occurring in the western United States. The authors attributed these reductions to artificially made aerosols interfering with the natural precipitation formation processes. Griffith et al. (2005) demonstrated similar reductions are occurring in mountainous areas downwind of Salt Lake City, UT. A field experiment in the California Sierra Nevada mountains found that the aerosols transported from the coastal regions are augmented greatly by local sources in the Central Valley, resulting in high concentrations of aerosols in the eastern parts of the Central Valley and Sierra foothills, consistent with the detected patterns of suppressed orographic precipitation in the southern and central Sierra Nevada. The precipitation suppression occurs mainly in the orographic clouds that are triggered from the boundary layer over the foothills and propagate over the mountains (Rosenfeld et al. 2008).

Rosenfeld et al. (2012) claimed, "Dust and pollution aerosols, through their effect on precipitation forming processes, redistribute latent heat in a way that weakens tropical cyclones. Therefore, incorporating these aerosol effects in models has the potential to improve the predicted storm intensities."

Another example of inadvertent weather modification revolves around the question of what happens to precipitation outside the intended cloud seeding target areas. This issue is frequently raised during the conduct of weather modification programs. A recent paper (DeFelice et al. 2014) examined this question. The conclusion was that the results summarized in the paper made a strong case for enhanced precipitation, or a direct seeding effect, in extra-area regions from the conduct of precipitation enhancement seeding programs.

5.2.2 Delivery Systems

Two broad options, ground-based and aerial, exist regarding cloud seeding delivery systems. Most systems currently in use are designed to dispense silver iodide nuclei, hygroscopic particles, 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 conditions and requirements of a given project area. This requires a good climatology of the target areas clouds.

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 that burn a solution of silver iodide dissolved in acetone, or through pyrotechnic devices (flares), either ejectable 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 byproducts into the atmosphere (ASCE 2004; Griffith 2006).

Pyrotechnics are similar to ordinary highway flares that are typically ignited at one end and designed to burn for periods varying from several seconds to several minutes. Silver iodide cloud seeding pyrotechnics (often referred to as flares) are impregnated with varying amounts of silver iodate ($AgIO_3$); $AgIO_3$ is used because this compound provides the oxygen needed to burn the flare formulation. Other flares can be utilized that burn some type of salt (e.g., calcium chloride) to produce small hygroscopic particles. These flares are classified as Class 1.4 s explosives, which require some restrictions in the way they are transported. Cloud seeding pyrotechnics (silver iodide and hygroscopic) can be burned from racks mounted on an aircraft near the trailing edge of the wing or can be ejected (silver iodide) 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 on the designed burn time) before being completely consumed. An aluminum casing containing the ejectable 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 g of active seeding agent per minute of burn, whereas aerial acetone generators typically produce 2 to 3 g of active seeding agent

Fig. 5-2. Example of an acetone-silver iodide generator mounted on a wing tip
Source: Courtesy of North American Weather Consultants, Inc.

per minute. 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 10 times as many effective ice nuclei per gram of AgI burned as do pyrotechnics. In addition, the activation temperatures and nucleation mechanisms also may 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 highly informative in this regard. Figures 5-2 through 5-4 provide common installations of a silver iodide acetone dispenser, a pyrotechnic burn-in-place rack, and a rack for ejectable silver iodide pyrotechnics.

Dry ice is frequently dispensed through openings located through 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, available commercially in some of the larger cities of the United States, with 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 dispensers have been developed that either dispense precrushed dry ice or actually crush dry ice slabs onboard the aircraft. Figure 5-5 provides a

Fig. 5-3. Example of a wing-mount silver iodide pyrotechnic rack
Source: Courtesy of Weather Modification, Inc.

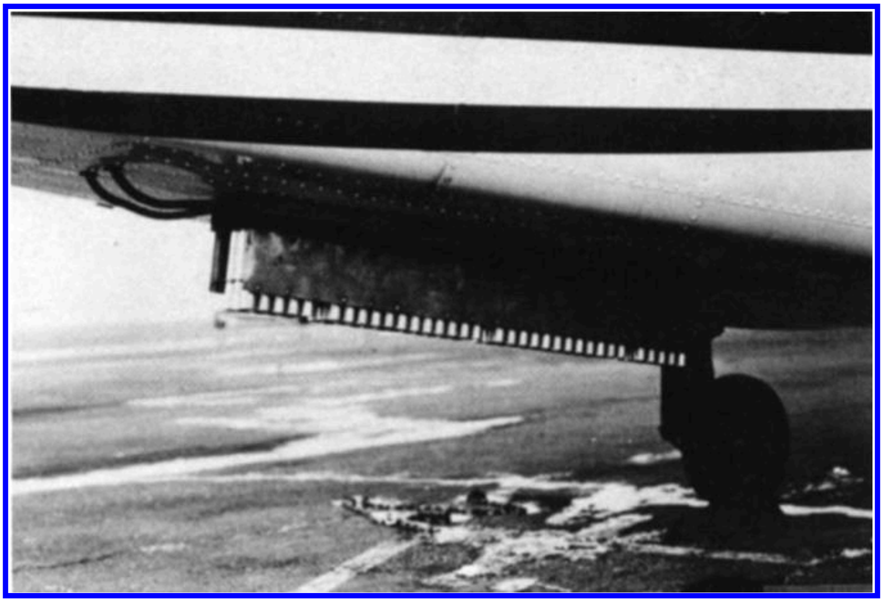

Fig. 5-4. Example of an ejectable silver iodide pyrotechnic rack
Source: ASCE (2004); © ASCE.

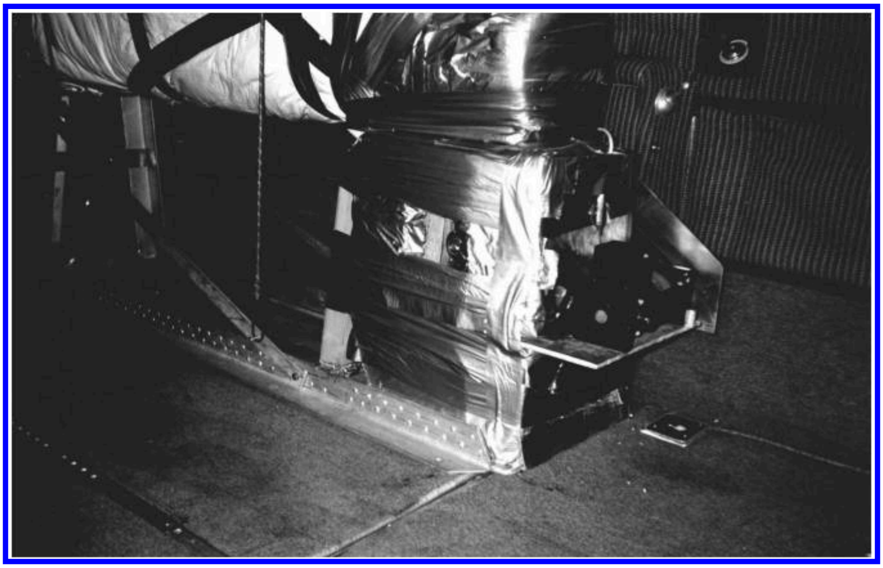

Fig. 5-5. Example of a dry ice dispenser mounted in an aircraft
Source: ASCE (2004); © ASCE.

photograph of a dry ice dispenser mounted in an aircraft. A third type of dispenser developed for Air Force research in the 1960s (Vickers and Church 1966) manufactured dry ice pellets from containers of pressurized liquid carbon dioxide.

Some prototype organic and hygroscopic dispensers have been developed on various projects. Fukuta et al. (1977) reported on an organic dispenser that received some field testing in South Dakota. Some agricultural spray dispensers have been modified to dispense hygroscopic materials. One disadvantage of most hygroscopic materials is that they are corrosive, requiring special care to avoid damage to the cloud seeding aircraft. They also tend to clump in humid conditions, requiring careful storage and handling techniques.

Types of aircraft utilized in operational cloud seeding projects range from single engine aircraft (such as a Cessna 182 or Piper Comanche) to larger twin-engine aircraft (Piper Twin Comanche, Aztec, Navajo, Seneca, and Cheyenne; Cessna 310, 340, 411, 414, and 421; or Aero Commander 690). Any modification of an aircraft incorporating cloud seeding equipment must be certified by the relevant aviation authority. This certification usually places them in a restricted category. As the name implies, certain restrictions govern the use of such aircraft including a limitation on the type of personnel authorized to fly in such aircraft.

The type of cloud seeding agent and delivery system used may dictate the type of aircraft used. Dry ice or ejectable AgI flares usually are dispensed at cloud top. However, this is only possible if cloud tops are accessible to seeding aircraft, tall enough to contain supercooled water (0 °C to −10°C), and positioned such that proper targeting of the cloud seeding effects is possible. Cloud seeding flights that are likely to entail flying through supercooled portions of clouds should be conducted with aircraft with de-icing capabilities.

For AgI acetone burners and end burning flares (AgI or hygroscopic), the aircraft can be operated in updraft regions below cloud base. However, when using silver iodide as the seeding agent it is advantageous to inject the seeding agent directly into supercooled clouds. With possible flight durations of 4 h or more, the aircraft should be fully de-iceable or frequent descents below the melting level will be required to shed ice buildup.

Research in winter orographic cloud seeding utilizing aircraft suggests that AgI acetone wingtip generators provide the simplest and most effective way to seed from aircraft. This is because (i) a 30-L solution tank holds enough cloud seeding solution for a 5 h flight; (ii) silver iodide solutions with a chlorine additive can effectively seed at temperatures near −5°C, with the silver iodide becoming more effective as the seed line rises to higher levels in the cloud; and (iii) the cloud seeding agent can be released outside a supercooled cloud, and when the seeding plume subsequently encounters the supercooled cloud, nucleation can occur (ASCE 2004).

5.2.2.2 Ground Applications Most ground generators utilized in the United States to date have relied on the generation of silver iodide freezing nuclei. Several different techniques have been developed to generate correctly sized silver iodide particles, including electric arc generators (a technique that is no longer used operationally), acetone solution generators, and pyrotechnics. Electric arc generators produce silver iodide particles by passing electricity through an electrode of silver in the presence of iodine. The most common type of ground generator in use today consists of a tank that holds an acetone solution with a given concentration (usually in the range of 1 to 5% by weight) of silver iodide. Other components include a means of pressurizing the solution tank, a nozzle, and a combustion chamber. Frequently, such systems employ a propane tank with a pressure reduction regulator to pressurize the solution tank and serve as a combustible material into which the silver iodide-acetone solution is sprayed. Other systems have been developed that utilize nitrogen to pressurize the solution tank, which directly burns the silver iodide-acetone solution.

Ground-based generating systems have been developed that are operated either manually or by remote control. Manually operated units often are sited at local residences at lower elevations upwind of the target area.

Fig. 5-6. Example of a manually operated, ground-based silver iodide generator
Source: Courtesy of North American Weather Consultants, Inc.

Local residents are instructed in the operation of these units and then are called from a central location to turn the generators on or off. Figure 5-6 provides an example of a typical installation. Remotely controlled units are often desirable if suitable residences are not located upwind of the target area and to facilitate location of units in higher elevations upwind of the target to ensure the seeding agent reaches elevations cold enough for nucleation to occur. Both acetone burners and pyrotechnic systems have been developed for remote control applications using radio, cell phone, and satellite communications systems. Figure 5-7 provides an example of a remotely controlled system.

Pyrotechnics, similar to the end-burning type described for aerial applications, also can be used at surface sites. Again, these units dispense silver iodide nuclei. Racks are built to hold a number of pyrotechnics, which can be ignited via an automated control system to burn units at a predetermined rate. These units can be operated remotely using the same communications systems as those used to operate the remotely controlled acetone generators. Figure 5-8 provides an example of a typical installation.

The following comments are oriented toward winter programs, but some of these concepts apply to summer clouds as well. Defining the