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# FOG MODIFICATION-A TECHNOLOGY ASSESSMENT

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# Fog Modification - A Technology Assessment

BERNARD A. SILVERMAN
ALAN I. WEINSTEIN





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Bernard A. Silverman
Alan I. Weinstein

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13. ABSTRACT

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# Abstract

This report is a comprehensive review of fog modification. It includes discussions of the physical structure and climatological characteristics of various types of fog. The three different methods of fog modification, that is, removal, evaporation and prevention are discussed, as are the general requirements of fog dispersal. In depth descriptions are given of the techniques used to modify supercooled, warm, and ice fog.

## Extended Summary

Fog is one of the oldest hazards to shipping and transportation. The advent of high speed transportation systems in the 20th century greatly intensified the problem, motivating an intensive search for methods of artificial fog dispersal.

From the standpoint of modification, it is most appropriate to classify fog according to its constitution and temperature. Ice fog occurs at temperatures below $-30^{\circ}C$ and is composed of up to 700 ice particles per cubic centimeter in the size range 2 to 20 $\mu m$. Supercooled fog is composed of liquid water droplets at temperatures below $0^{\circ}C$ in the size range of 5 to 65 $\mu m$, and in number concentrations of 40 to 200 $cm^{-3}$. Warm fog has, in general, the same dropsize and number concentration as supercooled fog, but occurs at temperatures above freezing.

The methods of fog modification involve consideration of the effect of fog particle size distribution on visibility. Visibility is inversely related to fog particle number concentration, and inversely related to the square of fog particle size. Hence, visibility can be improved a given percent by decreasing the number of particles by the same percent, or decreasing the size of the particles by a much smaller percent. The first method of visibility improvement, called fog droplet removal, has never been shown to be practical because of the large energy expenditure required to significantly reduce the fog particle number concentration. The second method of visibility improvement, which operates through evaporation of the fog particles, exploits the inverse square relationship between particle size and visibility. Evaporation methods are the most practical of all known fog dispersal techniques. Fog prevention techniques have not yet proven to be practical.

Supercooled fog is the most amenable to dispersal by artificial means. The modification techniques involve the creation of ice particles in the metastable water droplet fog that grow at the expense of the droplets and eventually fall out. What remains is a fog whose droplets sizes are greatly reduced and whose visibility is, thus, greatly improved. The ice particles are created by the cooling action of dry ice or liquid propane vaporization. Several operational fog dispersal programs have been undertaken by military and civilian aircraft operators, with a high level of benefit being attained for a relatively small cost.

Of the three fog types, warm fog is by far the most common in the midlatitudes where fog causes the greatest problems. Unfortunately, warm fog is in a thermodynamically stable state and thus can only be modified by "brute force" evaporative methods. Three such techniques have been proposed. Helicopters have been demonstrated to be highly effective in dispersing shallow fog, primarily to allow landing of the helicopter itself. Seeding with hygroscopic particles has been heavily investigated with, to date, only limited success. The most promising technique, but also the most expensive from the standpoint of initial investment, is the use of ground based heat to raise the air temperature and thus cause the droplets to evaporate. This technique has been the subject of several operational tests in the United States and abroad. In order to be economically sound, this technique requires careful engineering of the heat system to insure efficient distribution of heat.

Ice fog has, so far, resisted all tested methods of dispersal. The only attractive method of modification of ice fog is through its prevention. Prevention can best be achieved by very careful control of the man-made moisture sources that lead to the formation of the fog. Another prevention method, which is now being subjected to its first tests, involves the reduction of radiative cooling through the artificial creation of a stratus cloud.

The outlook for fog dispersal is bright. Supercooled fog dispersal is already an operational technology that is being increasingly applied at a substantial benefit-to-cost ratio. Warm fog dispersal has progressed to the point where several methods are becoming available, each one best suited to different operational situations. A satisfactory solution to the ice fog problem is still being sought. Optimization of existing fog dispersal techniques and the development of new methods depend strongly on the results of continued fundamental research on fog physics and dissipation concepts.

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## 1. INTRODUCTION

Fog (Figure 1), a source of inspiration to the poet, water to the farmer, and frost protection to the orchard grower, is also a major source of inconvenience to the traveler. Despite the technological advances made in electronic aids, fog continues to be the most serious hazard to navigation in the air, on land, and at sea. Modern high-speed transportation systems are periodically brought to a complete standstill by sieges of dense fog, dramatizing the fact that these sophisticated systems are no match for this insidious weather phenomenon. More important than the inconvenience it causes, fog is responsible for a large percentage of the losses in life, property, and revenue by the transportation industry.

The advent of the jet age has made the fog problem of particular concern to aviation. The ever-increasing density of air traffic, especially jet aircraft with limited endurance, is placing increasing demands on the acceptance rates of airports. Military aviation, in particular, demands the assurance of uninterrupted operations. In recent years, the Department of Transportation has found it necessary to limit the number of flights at the nation's busiest airports during periods of low ceiling and visibility. The loss of revenue by one fog at a major airport, due to aircraft diversions, delays, and cancellations, is estimated to be $100,000. The cost of one fog occurrence in the era of jumbo jets is expected to rise

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Figure 1. A Blanket of Fog Rolls Past the Golden Gate Bridge Into San Francisco Bay. The thick, murky cloud ties up transportation, slowing down automobile, ship, and airplane traffic.

to $500,000. Militarily, the cost is frequently measured in lives rather than money.

The ocean-going vessel is probably the oldest victim of fog. Modern ocean liners and freighters are as vulnerable to the perils of fog-bound harbors, canals, and sea lanes as were the Spanish galleons of old. During the winter months, as much as two hours per day of shipping through the Panama Canal are lost due to fog. When sea transportation does proceed in fog, some of the most catastrophic ship wrecks can occur. In 1956, for example, the luxury liner ANDREA DORIA collided on its maiden voyage with the STOCKHOLM off New York and sank. The toll was 51 human lives and millions of dollars in property.

The automobile is the primary land victim of fog. Some of the most spectacular multiple car collisions, involving up to 100 vehicles, have been caused by fog. Costs in excess of 300 million dollars per year are incurred by fog-associated accidents on the nation's highways. This figure is expected to rise as the number of cars and the cost of repair continue to increase.

Considering the dependence of our society on its transportation systems, it is no wonder that fog has historically been the focus of attempts to modify it. Fog was, in fact, the subject of the first scientifically-designed weather modification effort of any kind. In a milestone program that was disclosed to the public in 1938, Houghton and Radford presented several reasonably feasible methods of dissipating warm fog over airports. Some successful experiments were conducted but not followed up, because it was believed that instrument landing systems would make fog dissipation unnecessary.

The seriousness of the fog problem during World War II prompted the English to develop a thermal dissipation method called "FIDO". Further developments of the FIDO system in England and the United States were, however, abandoned after 1953, mainly because it was considered too expensive to warrant routine use by commercial aviation. With the advent of the jet age, the fog problem became acute again, and activity in warm fog dispersal research was intensified. Although the basic concepts of warm fog dispersal that are being pursued are not new, modern engineering technology is being employed in an effort to make these techniques practicable.

Another landmark event in the history of fog dispersal and, indeed, the science of weather modification in general, occurred in 1946 when Dr. V.J. Schaefer and his co-workers at the General Electric Company demonstrated that snow and subsequently clearings could be produced in supercooled stratus clouds by seeding with dry ice pellets. The theory underlying their results has formed the basis for much of the weather modification efforts that have been pursued since that time. The only reliable operational application of this theory achieved thus far is supercooled stratus clouds and fog dissipation.

Sound weather modification practice requires a thorough understanding of the natural weather phenomenon. It is, therefore, essential to review, at the outset, the state of knowledge on the morphology of fog. The physical basis and requirements of fog modification are considered against this background. The various methods of fog modification are then discussed in some detail, with the report concluding with an outlook on the future prospects of fog modification technology.

## 2. MORPHOLOGY OF FOG

According to accepted definition, the name fog is given to any cloud that envelops the observer and restricts his horizontal visibility to 1000 m or less. It is composed of numerous minute water droplets or ice crystals in colloidally stable equilibrium with their environment. Unlike most other cloud forms, fog can persist from a few hours to several days, dissipating naturally under the influence of strong vertical mixing or solar heating.

### 2.1 Fog Types

Fogs are traditionally classified according to the cause of their formation. Saturation of the air in the presence of sufficient condensation nuclei near the earth's surface is necessary for fog formation. Since condensation nuclei are abundantly available in the atmospheric boundary layer, condensation commences and fog forms when the air is brought to its saturation point either by cooling to its dew point or by increasing its moisture content. There are numerous moisture transport and cooling mechanisms in the atmosphere which give rise to fog, each process being associated with a generic fog type. Since the classification of fogs by causal mechanism is of more importance to the science of fog forecasting than fog modification, only a brief description of these fog types is presented here. The reader is referred to the treatise by Byers (1959), from which the following summary has been extracted, for a comprehensive description of the traditional classification of fogs. A categorization of fogs that is more germane to fog dispersal technology will be presented thereafter.

Fogs formed primarily by ambient air cooling are called air mass fogs. Such fogs are broken down further according to cooling mechanism into advection, radiation, and upslope fogs. More frequently than not, more than one cooling mechanism is operative, with one process being dominant.

Advection-type fogs are formed when there is a transport of air between regions of contrasting temperature. Such fogs are, by their very nature, coastal and open water phenomena. Warm, moist air moving at gentle to moderate velocities over a water surface that becomes progressively or suddenly colder downwind, provides the conditions that are favorable for its formation. Such conditions occur when (1) air from the summer-heated land is transported over cooler coastal waters on the east coast of continents or over large inland bodies of water; (2) warm ocean air is transported over a cold ocean current; and (3) warm tropical air is transported poleward over the ocean. Steam fog, on the other hand, occurs when cold air from a chilled land mass in winter is transported over the warmer water surfaces of oceans, lakes, and rivers.

Radiation fogs are formed when stagnant moist air near the ground becomes progressively cooler during a cloudless night because of an excess of outgoing radiation. Valleys are particularly subject to radiation fog. Air that is cooled at higher elevations drains into the valleys where it accumulates, resulting in dense fog as radiation cooling lowers the temperature of the air further.

Upslope fog is the air mass fog which results when stable air is adiabatically cooled to its saturation point as it is gradually orographically uplifted.

Fogs formed by bringing air to its saturation point by the addition of water vapor are called frontal fogs. When warm rain falls through cold air at a frontal surface, the air becomes saturated by the evaporation of the rain. If the air through which the warm rain falls is initially unsaturated, it will be cooled to its dew point by the evaporation process.

From the standpoint of dispersal, fog can be classified into three general types according to its constitution and temperature; that is, ice fog, supercooled fog, and warm fog. This classification system is more relevant to fog dispersal than that based on causal mechanism since the method of modifying each type is quite different. The differences in a given fog type due to the various ways that it forms may only require some variation in the application of the modification method.

Ice fog is a suspension of ice particles that occur at very low temperatures during clear, calm conditions. Ice fog is rare at temperatures warmer than -20°F (-28.9°C) and increases in frequency and density with decreasing temperature until it is nearly always present to some degree at air temperatures of -50°F (-45.5°C) in the vicinity of water vapor sources. Such sources are the open water areas of streams and rivers, herds of animals, but especially the multiple sources of moisture associated with man-made activities. Because of the very cold temperatures, the addition of only very small amounts of water vapor are sufficient to bring air to its saturation point and form ice fog.

Supercooled fog is composed of water droplets that exist at below-freezing temperatures. Although bulk water freezes at 32°F (0°C), water droplets have been observed to remain in a liquid state at temperatures as cold as -40°F (-40°C), the temperature at which pure water droplets freeze. Ice crystal formation is inhibited by the lack of suitable ice embryos in the atmosphere. It has been found that more than 80 percent of the clouds warmer than 15°F (-9.4°C) contained liquid, but about half of them were mixed liquid and ice. By -5°F (-20.5°C), only 10 percent were liquid clouds, although 30 percent contained both supercooled drops and ice crystals.

Warm fogs consist of water droplets at above-freezing temperatures. They are both colloidally and thermodynamically stable. They are the most common type of fog and the most difficult to artificially disperse.

### 2.2 Climatology

Fog is largely a localized weather phenomenon. The moisture and cooling that are required for its formation are greatly influenced by local geographical and meteorological conditions. The spatial distribution of fog frequency is, therefore, highly discontinuous, with great changes in fog frequency occurring over small distances. A reasonably true account of fog occurrence can be attained only through observation. Because of a pilot's and ship captain's need to see in order to navigate, fog occurrence is best documented at airports, lighthouses, and harbors, and in ships' logs.

Figure 2, taken from recently published data by Guttman (1971), shows the worldwide frequency of fog days. A fog day is here defined as occurring whenever the visibility falls below 5/8ths of a mile some time during the day. It can be seen that fog is primarily a coastal phenomenon. With the notable exception of Western Europe, the regions of the world where fog occurs most frequently are almost all coastal. They form mainly as a result of cooling of the warm, moist ocean air as it passes over cold ocean currents. The two foggiest regions of the world, the west coasts of South America and Africa, are dominated by the cold Humboldt and Benguela currents, respectively. To a lesser degree, the Canaries and West Australian currents create fog conditions off the northwest coast of Africa and the western coast of Australia, respectively. All of these regions experience the same frequency of fog in each season. The California current is

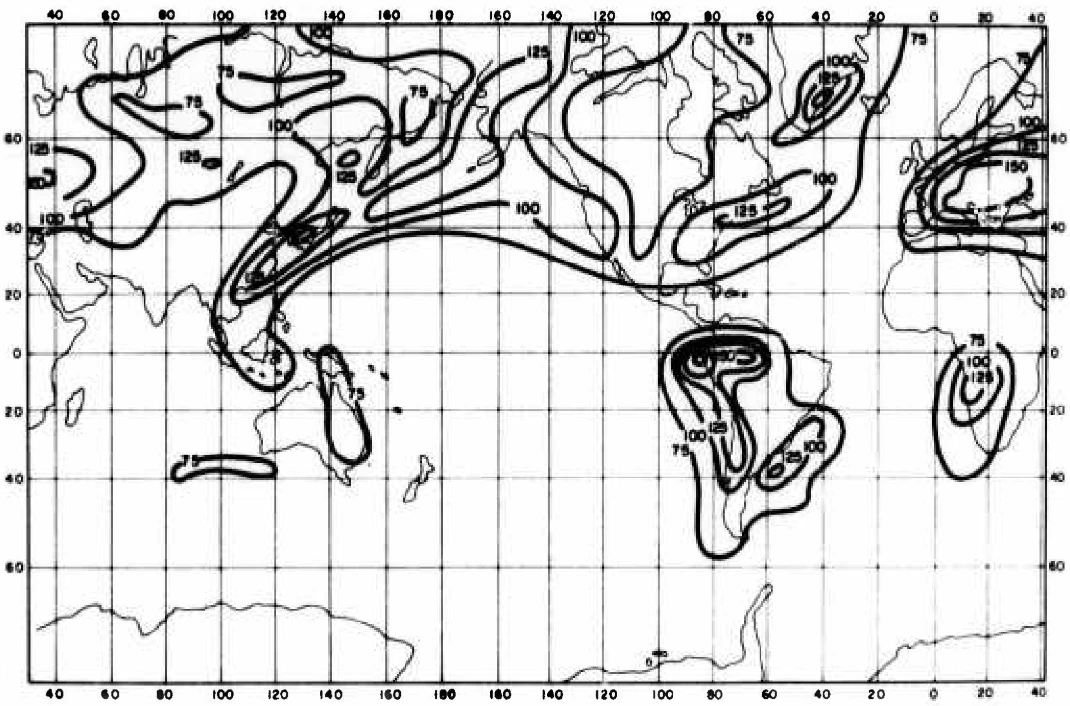


Figure 2. Worldwide Fog Climatology. Isopleths represent the number of days per year on which the visibility falls to $\leq 5/8$ mile some time during the day

responsible for the high fog frequency on the California coast in the summer months. In all cases, the fog occurs almost exclusively as warm fog.

The prevalent summer sea fogs in the Grand Banks area of Newfoundland are caused by the passage of air from the warm Gulf Stream waters to the cold ocean currents in the vicinity of the Banks. A similar juxtaposition of the warm Japan current and the cold currents from the Bering Sea produce an area of high fog frequency in the sea between Japan and Korea during the summer months. Similar conditions are also found off the southeastern coast of South America where the warm Brazil current meets the colder waters from the west. In all of these cases, the fog is also predominantly warm.

Tropical air fogs occur over western Europe in winter when the warm marine air is cooled as it passes over the cold continent. Radiation fogs also occur in the valleys of western Europe during winter. Both types of fog are generally supercooled. Other areas where fog occurs frequently and the temperatures are below freezing are the northwestern United States, Alaska, and Greenland. Some of the fogs in the far northern latitudes are undoubtedly ice fogs.

Figure 3 shows the frequency of occurrence of days with fog in the United States. In Figure 3, fog is defined as restricting visibility to 1/4 mile or less. It can be seen that the regions having the highest frequency of fog are the Pacific

Figure 3. United States Fog Climatology. Isopleths represent the number of days per year on which the visibility falls to $\leq$ 1/4 mile. (After Court and Gerston, 1966)

Coast, the New England Coast, the Appalachian valleys, and the Pacific Coast valleys, all of which experience more than 60 days of fog per year on the average. The mean fog frequency per reporting station for 256 first-order weather stations, approximately 50 percent of which are air terminals, is 27 days per year. The 20 airports in the United States having the greatest number of air carrier operations experience an average of 2700 hr of below-minimum visibility weather per year, nearly all of which is due to fog.

Fog that occurs at below-freezing temperatures accounts for only 5 percent of the fog occurrences in the United States. These fogs are restricted to the northern latitudes in winter. Warm fog accounts for the other 95 percent of the cases.

### 2.3 Physical Structure

Despite the research interest in fog phenomena during the past three decades, the amount of consistent data on fog structure is generally meager. Measurements of the vertical structure of fog are particularly sparse. The deficiency stems partly from the lack of adequate instrumentation and partly because of the great variability in fog properties with fog type and age. While statistically valid measures of the physical characteristics of fog are not available, the specification of representative or typical fog values is possible. For the purposes of this discussion, the fogs are categorized according to their constitution; that is, ice and water fogs. Table 1 summarizes the physical properties of these fogs.

Table 1. Fog Characteristics

| Fog Parameter | Ice Fogs | Water Fogs | |
|---|---|---|---|
| | | Radiation | Advection |
| Average Particle Diameter (μm) | 8 | 10 | 20 |
| Typical Particle Size Range (μm) | 2 - 30 | 5 - 35 | 7 - 65 |
| Equivalent Water Content ($gm/m^3$) | 0.10 | 0.11 | 0.17 |
| Particle Concentration ($cm^{-3}$) | 150 | 200 | 40 |
| Horizontal Visibility (m) | 200 | 100 | 300 |

Most of the published observations on ice fog were obtained at various locations in Alaska (Ohtake, 1970). The ice fog was concluded to result almost entirely from water vapor discharged into the atmosphere by human activity; that is, heating plants, power plants, moist air vents, vehicle exhausts, and the exhausts of oil and coal space heaters. The concentrations, size distributions, and solid water content of the ice fog particles varied from place to place, depending upon the local temperature, humidity, and moisture supply rate. The ice particles that formed were of three principal types: hexagonal plates, prisms, and droxtals. A droxtal is a tiny spherical ice particle, about 3 to 10 $\mu m$ in diameter, that is formed by the direct freezing of supercooled water droplets at temperatures colder than $-22^{o}F$ ($-30^{o}C$). The concentration of ice crystals increased from about a few particles per $cm^3$ at $-22^{o}F$ ($-30^{o}C$) to 700 particles per $cm^3$ at $-49^{o}F$ ($-45^{o}C$). The range of equivalent water content of ice fogs was found to be 0.01 to 0.18 $gm/m^3$ with a mean value of 0.1.

When the air temperatures are in the upper range for ice formation, that is, $-4^{o}F$ ($-20^{o}C$) to $-22^{o}F$ ($-30^{o}C$), the water vapor condenses rapidly as relatively large ice crystals which soon fall out. The concentration of the ice crystals is usually too low to reduce the visibility significantly. At temperatures lower than $-22^{o}F$ ($-30^{o}C$), small ice crystals and droxtals are formed which remain suspended for longer periods. The relative number of droxtals increases rapidly with decreasing temperature and are responsible for the low visibilities associated with ice fog.

There is no distinction between the physical properties of supercooled and warm fogs in the atmosphere. The physical properties of a water droplet fog (Jiusto, 1964), whether it be warm or supercooled, are, however, related to the method of formation. Radiation fogs that are characteristic of inland valleys tend to have a high concentration of small droplets. Advection fogs that are typical of coastal and oceanic regions have, on the other hand, lower concentrations of relatively large droplets. It is not uncommon to find drizzle falling out of advection fogs that have existed for several hours. These differences between advection and radiation fogs are consistent with the nature and concentration of condensation nuclei in marine and continental environments. The thickness of a fog layer can range from a few tens of meters for a radiation fog to several hundreds of meters for advective type fogs. The winds are generally lighter and the visibility lower in radiation fogs. There is also usually more heterogeneity in space and time in radiation fog, with conditions changing significantly during a 10-min period.

## 3. FOG MODIFICATION CONCEPTS

The objective of fog dispersal is visibility improvement. Equation (1) defines the Meteorological Visibility, V, as the distance at which a black target can be just detected against a horizon sky in daytime with a contrast threshold of 2 percent; that is

$$V = 3.912/\pi \sum_{i=1}^{M} (K_i n_i r_i^2) \tag{1}$$

where N is the number concentration of fog droplets or ice crystals, r is the fog particle radius, K is the scattering efficiency of a fog particle, and the summation, Σ, is taken over all fog particles. For visible light and spherical fog droplets, the scattering efficiency has a constant value of approximately 2.

It can be seen from Eq. (1) that the visibility can be improved by either decreasing the number concentration of fog particles, decreasing their radius, or both. Because of the inverse square relationship between visibility and radius, a decrease in radius by, for example, a factor of 3 results in a nine-fold increase in visibility. A similar decrease in the number concentration, on the other hand, results in only a three-fold increase in visibility.

Methods designed to decrease the radii of the fog particles do so by evaporation. Modification techniques that are aimed at decreasing the number concentration of fog particles involve their physical removal.

### 3.1 Physical Removal Methods

A number of ways to accomplish the physical removal of fog particles have been proposed. In general these methods can be divided into those in which (1) fog droplets or ice crystals are removed from suspension in air by precipitating them onto suitable surfaces; (2) those in which fog particles are caused to fall out by gravity after agglomeration amongst themselves or after collection by larger particles that have been introduced for this purpose; and (3) those in which the volume of fog laden air is totally replaced by a similar volume of clear air. Electrostatic precipitation of the fog particles and filtration by screens, baffles, and forests are examples of the first type of physical removal method. Examples of the second type are coalescence of the fog particles induced by ultrasonic sound waves and scavenging of the fog particles by electrically charged or neutral seeding particles, or by organic chemicals known as polyelectrolytes. Use of large fans on patchy ground fog is an example of the third type of physical removal method.

All of the air to be cleared of fog by the physical removal methods must, of necessity, be acted upon directly. Due to the low number concentration of fog particles, the scavenging and agglomeration methods are inefficient. The size of the apparatus required for the application of the filtration and replacement methods are so large as to render them impractical. For these reasons, none of the physical removal methods has thus far proven to be operationally feasible.

### 3.2 Evaporation Methods

Evaporation methods are among the most promising approaches to fog dispersal. Since fog is a suspension of water droplets or ice crystals that are in equilibrium with the water vapor in the air, the fog particles can be induced to evaporate either by removing some of the water vapor from the air or by increasing the capacity of the air to retain additional water in vapor form. Removal of water vapor can be achieved by condensation on hygroscopic materials; that is, materials that have a particular affinity for water vapor in subsaturated atmospheres. Chemical dessicants such as calcium chloride, sodium chloride, and urea are examples of hygroscopic materials that have been proposed for this purpose. Raising the temperature of the fog environment by the application of heat is the most obvious way of increasing the water vapor capacity of the foggy air. Mixing of the fog with drier air of natural or man-made origin is another way of achieving the subsaturated environment that is required to promote the evaporation of the fog particles.

It is important to note that the water vapor content of saturated air decreases with decreasing temperature. Table 2 illustrates the impact that this physical fact has on the magnitude of the reduction in relative humidity that must be achieved by the two evaporative methods, as a function of temperature, to accommodate a fog having a water content of 0.17 gm/m$^3$. At a temperature of 68$^{\circ}$F (20$^{\circ}$C) the water vapor content of saturated air is 100 times larger than the fog water content and, therefore, the relative humidity of the air need be reduced only slightly to accommodate the evaporating fog particles. At 32$^{\circ}$F (0$^{\circ}$C) the ratio of saturation vapor content to fog water content is only 5 and the required relative humidity reduction is consequently higher. At -40$^{\circ}$F (-40$^{\circ}$C) the saturation vapor content is comparable to the fog water content, causing the required reduction in relative humidity to be extremely large.

At temperatures below about 5$^{\circ}$F (-15$^{\circ}$C), the required relative humidity falls below 90 percent and the energy and logistical requirements of the evaporative methods become prohibitively large. These methods are, therefore, only feasible for warm and some supercooled fog conditions.

Table 2. The Relative Humidity as a Function of Temperature That Must be Achieved to Accommodate a Fog Water Content of 0.17 $gm/m^3$ by the Water Vapor Removal and Increased Vapor Capacity (air heating) Evaporation Methods

| Temperature | | Relative Humidity (%) | |
|---|---|---|---|
| °F | °C | By Water Vapor Removal | By Heating |
| 68 | 20 | 99.0 | 99.0 |
| 50 | 10 | 98.2 | 98.2 |
| 32 | 0 | 96.5 | 96.6 |
| 14 | -10 | 92.8 | 93.3 |
| -4 | -20 | 84.2 | 86.3 |
| -22 | -30 | 62.5 | 72.7 |
| -40 | -40 | 3.2 | 50.8 |

### 3.3 Prevention Methods

All of the modification techniques described thus far involve dissipation of existing fog. Another appealing fog modification concept is fog prevention. The prevention of fog involves control of the moisture, nuclei, and/or cooling that are required for its formation. The use of evaporation inhibiting chemicals on open water surfaces and the reduction of moisture pollution from man-made sources are examples of possible moisture control methods. It has been suggested that fog could be prevented by treating the natural nuclei with condensation-retardant chemicals. It has, however, been shown that this method only delays fog formation by approximately 10 min and that when it does eventually form, it is considerably more dense than it would have been otherwise. It has also been suggested that the nocturnal cooling required for the formation of radiation fog could be suppressed by the artificial creation of a cloud layer to greatly reduce the outgoing radiation.

Fog prevention operations must be conducted on a scale that is generally one to two orders of magnitude larger than those required by the physical removal and evaporation methods which attempt to clear only a portion of the fog. Fog prevention methods are, therefore, only feasible for application in those situations where the dispersal methods are not feasible and/or the sources of moisture and nuclei are limited in size and number.

## 4. GENERAL REQUIREMENTS OF FOG DISPERSAL

Since the majority of all fog modification efforts are aimed at improving visibility at airports, the rest of this section will address this problem. Similar factors are important for other applications such as visibility improvements on highways or shipping lanes. The only difference in most cases is the dimensions of the clearing and the level to which the visibility must be improved. In the latter respect aircraft operations, because of the high speeds involved, have the most stringent requirements.

The size and shape of the region in which visibility must be improved, and the level of improvement necessary to permit landing operations depends upon the level of sophistication of the electronic landing aids present at the airport. The least sophisticated systems, called Category I landing systems, require a minimum visibility of 2400 ft and a decision height of 200 ft. The more elaborate Category II systems require visibilities of $\geq$ 1200 ft and a decision height of 100 ft. The most sophisticated systems, Category III, are further subdivided into three categories, reflecting the difficulty in achieving the goal of very low visibility systems. Category IIIa systems require a minimum visibility of 700 ft to a decision height of 50 ft. Category IIIb and c systems have no decision height specification but require minimum visibilities of 150 ft and zero ft, respectively. As of 1 January 1971 all major airports in the United States had Category I landing systems, 14 civilian airports in the continental United States had Category II systems, but no airports had any Category III systems although one or two test facilities were being planned.

Aircraft generally land on a $3^{\circ}$ Glide Slope. The distance from the decision height to the touchdown point for Category I and II landing systems are 3900 ft and 1900 ft, respectively. The general dimensions of the volume that must be cleared for Category I and II landing systems are shown in Figure 4. The volume of fog to be cleared for Category I and II landing systems are approximately 280 million and 130 million $ft^3$ respectively.

It should be noted that a pilot need not see his touchdown point upon reaching his decision height, rather he must be able to identify the approach lights to decide if he is properly aligned for a safe landing. During rollout after touchdown, the pilot must have sufficient visibility to maintain alignment on the runway. Since the aircraft is rapidly

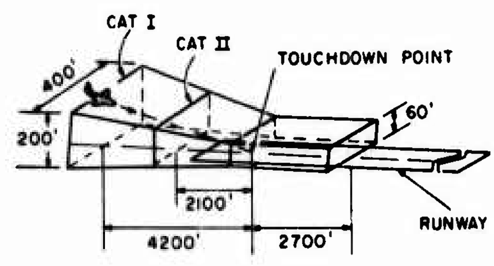



Figure 4. Regions to be Cleared by Fog Dispersal Techniques at Airports. Dimensions are in ft

decelerating during rollout, the visibility need not be as good as that required on approach and, of course, it need only exist up to the height of the cockpit (less than 50 ft for most aircraft). Under most conditions, aircraft can taxi to the terminal in unmodified fog under the guidance of radar or follow-me vehicles.

In consideration of fog dispersal methods the wind condition, particularly the variability in wind speed and direction, is a very important factor. The wind velocity not only determines the volumetric dissipation rate required to create and maintain a clearing over an airport but it also dictates the quantity and configuration of the necessary apparatus. Fog is never found in absolutely calm air, the wind velocity usually being from 1 to 20 miles/hr. Thus, even for fogs having only relatively little mean motion with respect to the runway, any modification method would have to be applied either continuously to all air entering the volume of interest or in a single operation throughout a considerably larger volume. To keep an airport clear of fog in the presence of, for example, a 5 mile/hr cross-runway wind, it is necessary to renew the cleared zone once every 40 sec as new fog is continuously being introduced on the upwind side. The energy and logistic requirements of a fog dispersal system generally increase with increasing wind velocity.

The extent and duration of a clearing produced by some fog dispersal methods depend to a large extent on the intensity of turbulence in the fog layer. If a fog dispersal method is to be operationally effective the clearing must be produced in substantially less time than it takes the fog to refill the cleared volume by turbulent diffusion. The relative rates of the opposing processes determine the usable life time of the clearing. Evaporation methods are, in general, superior to physical removal methods with respect to this factor because the limiting effects of turbulence are partially reduced by the lowered relative humidity of the cleared air. Since the characteristic diffusion time is directly proportional to the square of the width of the cleared zone, the influence of this factor becomes less important as the size of the clearing is increased.

## 5. SUPERCOOLED FOG DISPERSAL

The simplest of all weather phenomena to modify is supercooled fog or stratus clouds. The reason for this relative simplicity lies in the fact that supercooled fog, although colloidally stable, is in a thermodynamically metastable state. The supercooled water droplets exist at an energy level above that of the more stable ice phase. The addition of only a small amount of energy is required to induce their transition to the more stable ice phase, the final result of which leads to the dispersal of the fog.

The artificial dissipation process is based on the physical fact that the equilibrium vapor pressure over ice is less than that over water at the same temperature. When ice crystals are introduced into a supercooled, water saturated fog, they grow by vapor deposition and thereby cause the water droplets to evaporate. As the ice crystals grow, they are disseminated throughout the fog under the action of turbulent mixing which is intensified locally by the latent heat of fusion that is released as the affected volume is transformed from water to ice. The ice crystals spread laterally at a rate of about 1 m/sec, stopping only when the ice crystal concentration is significantly reduced by fallout. After 10 to 20 min, crystals start reaching the ground. Fallout continues up to an hour or more after the initial introduction of the ice crystals. Usable clearings form within 30 to 60 min, depending on fog thickness, temperature, and wind conditions. A single line of ice crystals generally produces a clearing that is about 1. 5 to 2. 0 miles wide.

### 5.1 Seeding Technology

Two techniques can be used to create the ice crystals necessary to initiate the artificial dissipation process.

The first technique is based on seeding with tiny particles about 1$\mu$m in diameter which have a crystal structure that is very similar to that of ice. These particles serve as embryos on which ice can grow. The particles are called ice or freezing nuclei, and the initiation of the ice growth process is known as heteorogeneous nucleation. Silver iodide is the most commonly used artificial ice nucleus. Lead iodide and some organic materials have also been found to be effective nucleating agents. They are active at tempertures that are colder than 23$^{o}$F (-5$^{o}$C).

The second technique by which ice crystals are introduced into a supercooled fog, involves homogeneous nucleation. The ice crystals are formed by the local cooling of the air to below -40$^{o}$F (-40$^{o}$C), the critical temperature at which nucleation of ice occurs spontaneously without the aid of special nuclei. The cooling necessary to initiate homogeneous nucleation is produced by seeding with dry ice, that is, solid carbon dioxide that exists at temperatures as low as -112$^{o}$F (-80$^{o}$C), or by the instantaneous vaporization and expansion of refrigerants, such as liquid propane, that are sprayed into the fog. This technique is effective in producing ice crystals at temperatures as warm as 30$^{o}$F (-1$^{o}$C).

The reader is referred to Knight (1967) for a review of the physics of the heteorogeneous and homogeneous nucleation processes.

### 5.2 Operational Programs

The technology required to carry out operational, supercooled fog dissipation programs has been available since the early to mid 1950's. Operational programs at airports did, however, not come into practice until the early 1960's. At present, they are being conducted in the United States, France, and the Soviet Union. Both airborne dry ice seeding and ground-based propane systems are being used. Due to the high frequency of occurrence of supercooled fog at temperatures warmer than 23°F (-5°C), the airborne silver iodide seeding technique is not routinely used on an operational basis.

5.2.1 DRY ICE SEEDING SYSTEM

In a typical operation, the seeding of the fog is accomplished with an aircraft that has been fitted with a dry ice crusher/dispenser (Figure 5). Dry ice cakes

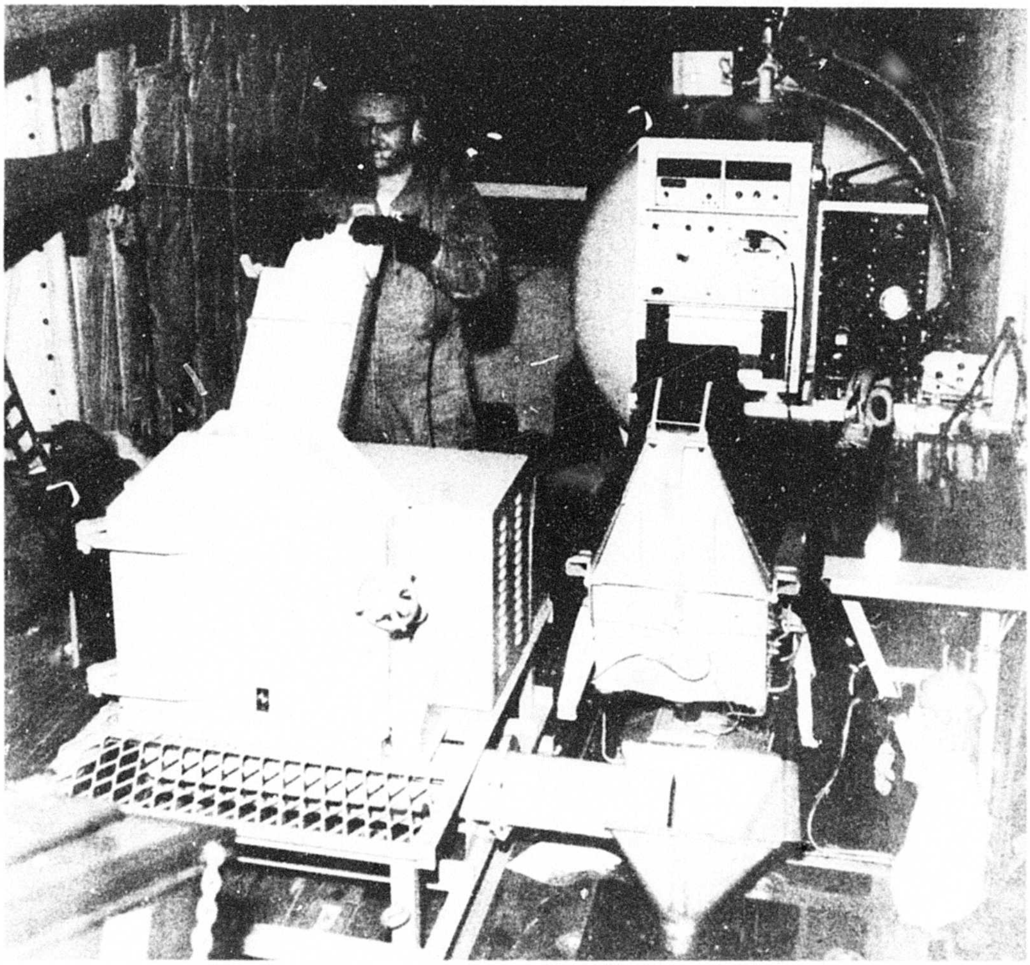


Figure 5. Dry Ice Crusher/Dispenser Installed in an Air Weather Service WC-130 Aircraft

are stored on board the aircraft and are loaded into the crusher, as required, during the seeding operation. The usual seeding pattern consists of 5 to 30 parallel lines, 5 to 6 miles long and about 1.5 to 2.0 miles apart, flown just above the fog at a distance between 45 and 60 min upwind of the airport to be cleared. The dispensing rate is generally about 15 lb/mile. Since about half the crushed dry ice is in the form of powder that probably vaporizes before reaching the fog deck, the effective seeding rate is about 7 lb/mile.

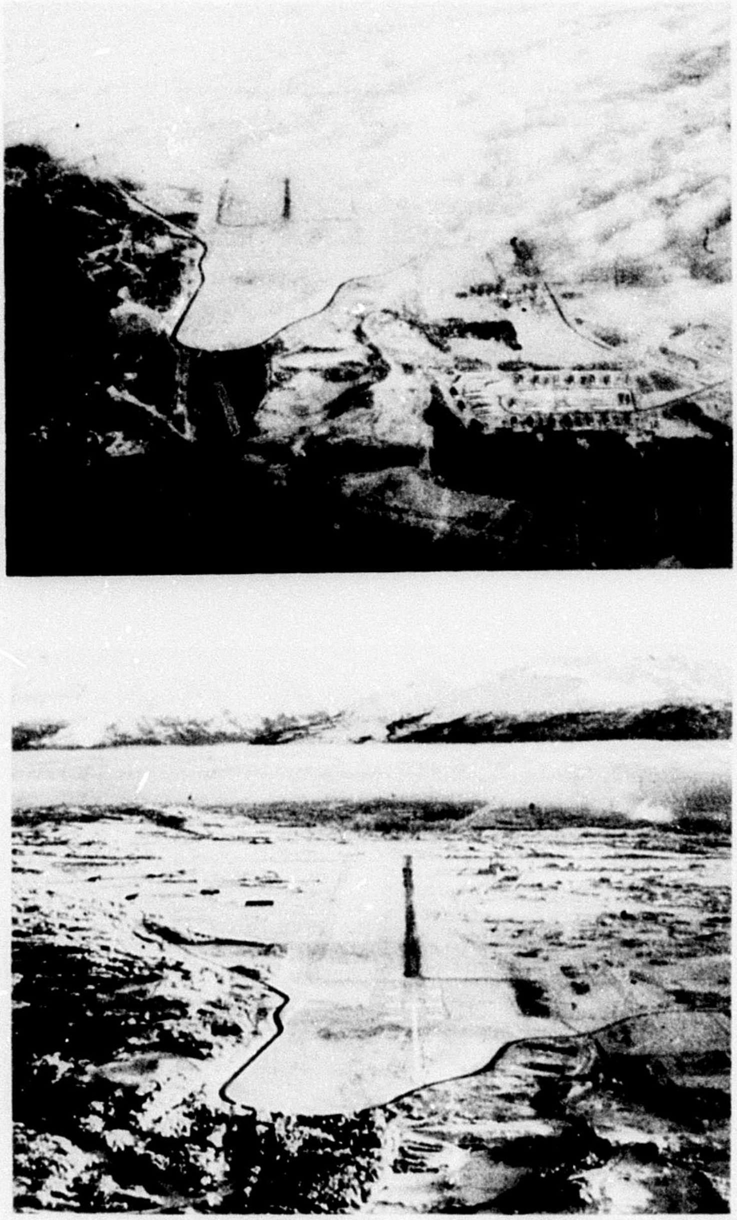
The airborne dry ice seeding technique is employed in airport fog dispersal operations conducted by the Air Weather Service (AWS) at Air Force bases in Alaska and Western Europe, by the Air Transport Association (ATA) at commercial airports in the United States, and by the appropriate Soviet authorities at airports in Russia. During the years 1968-1972, AWS fog dispersal operations assisted or expedited 736 aircraft departures and 686 arrivals at Elmendorf AFB, Alaska. They were also responsible for the successful completion of 256 aircraft departures and 172 arrivals at nine operating locations in Europe during the years 1970-1972. The clearing effects produced by one of the dry ice seeding operations at Elmendorf AFB is shown in Figure 6.

Dry ice seeding operations have been used to disperse supercooled fog at 13 airports in the North-Central and Northwestern sections of the United States. A considerable reduction in revenue losses due to fog has been achieved ever since the initiation of the fog dispersal operations in 1963. During the winter 1969-1970, for example, fog dispersal operations costing approximately $80,000 resulted in a saving of over $900,000 in airline operating expenses.

Supercooled fog dispersal operations are conducted at approximately fifteen of the largest airports in Russia. They reported that 80 percent of their operations at the Moscow airport were successful between 1964 and 1967. Fog dispersal operations were credited with permitting 284 take-offs and 143 landings that would not have otherwise been possible. An even higher success rate was achieved in later years.

### 5.2.2 LIQUID PROPANE SYSTEM

Supercooled fog dispersal operations using a ground-based liquid propane system are conducted by the AWS at Fairchild AFB, Washington and by the Paris Airport Authority at Orly Airport, Paris, France. The AWS system consists of 21 dispensers, four near the airport for calm-wind situations and the rest placed at various distances upwind along the most common wind directions. Each unit is capable of dispensing 10 gallons of propane per hour. Since its installation in 1969, fog dispersal operations have been responsible for 97 aircraft departures and 49 aircraft arrivals that would not have been possible otherwise.



(a)

(b)

Figure 6. Supercooled Fog Dispersal Operation Using Airborne Dry Ice Seeding as Carried Out by the Air Weather Service at Elmendorf AFB, Alaska on 20 December 1968. (a) Before dry ice seeding, and (b) after dry ice seeding

Figure 7. Liquid Propane Dispenser at Orly Airport, Paris, France. This unit is part of a ground-based supercooled fog dispersal system operated by the Paris Airport Authority

The French system has been operating at Orly Airport since 1964. A centrally-controlled ground installation consisting of 60 dispensers of the type shown in Figure 7 is used at an operating cost of 20 dollars per hour. During the winter of 1970-1971, 340 aircraft arrivals and 284 departures were made possible by the operation of the Orly Airport system.

## 6. WARM FOG DISSIPATION

Warm fogs are among the most stable cloud systems in the atmosphere. In contrast to supercooled fog, there is no latent phase instability in warm fog that can be exploited to promote the artificial dissipation process. Warm fog dispersal methods are necessarily "brute force" in character. Any energy required to dissipate the fog must be supplied by the dispersal method. Careful engineering is required to make any warm fog dispersal technique reliable, cost-effective, and free of detrimental side effects.

The development of warm fog dispersal methodology in the past few years has been based on an interactive program of computer model simulation of the artificial dissipation processes and field experimentation. The acceleration of progress in the engineering of warm fog dispersal techniques can be attributed to this approach. Three techniques, all designed to promote the evaporation of the water droplets, have been found to be effective in improving the visibility in warm fog: (1) mechanical mixing of the fog with drier, warmer air from above, (2) drying of the air with hygroscopic chemicals, and (3) heating of the air.

### 6.1 Helicopter Downwash Mixing

The physical basis of warm fog clearing with helicopters rests primarily on the principle of downwash mixing. The helicopter, during the clearing operation, either hovers or moves slowly forward in the clear air above the fog layer. The downwash action of the helicopter forces this relatively dry, clear air downward into the fog. The wake air, on descending, entrains and mixes with the fog. If the relative humidity of the air above the fog is approximately 90 percent or less, the resulting air mixture becomes subsaturated and the fog droplets are, thereby, caused to evaporate. The dimensions of the clearings created by the helicopter wake are much larger than the helicopter itself, usually by a factor of 10 to 20. In shallow fogs, the wake of large helicopters may be strong enough to physically push the foggy air aside and replace it with the clear air from above.

The dimensions of the rotor downwash wake of a helicopter and, therefore, its fog clearing capability depends primarily on its weight, its forward speed, and the thermal stability of the fog layer. The wake of a medium size helicopter weighing approximately 25,000 lb, such as a CH-3E helicopter, in the hover and forward motion flight modes has the general appearance indicated in Figure 8. The dimensions of the wake, particularly its penetration depth, increases with the weight of the helicopter. Under otherwise analogous conditions, the wake is deep but narrow when the thermal structure of the fog layer is relatively unstable and shallow but wide when the layer is relatively stable. Fog layers of thickness greater than the penetration distance of the wake cannot be effectively cleared by helicopters. If, however, the wake penetration distance exceeds the fog thickness, the dimensions of the clearing will be enhanced because the bottom part of the wake impinges on the ground and spreads laterally.

The typical appearance of a hover-produced clearing in a fog is as shown in Figure 9. When the helicopter is flown in forward motion above the fog at an airspeed of 15 miles/hr, a cleared trail, as shown in Figure 10, is produced behind the helicopter. The clearings usually appear within 30 to 45 sec and persist for 3 to 8 min after the helicopter clearing operation is terminated.

The most extensive, quantitative tests of the helicopter downwash mixing technique of fog dispersal were carried out jointly by the United States Air Force and United States Army during September 1969 at Lewisburg, West Virginia. The results of these tests and subsequent theoretical analyses have demonstrated that (1) cleared zones large enough to permit helicopter landing operations can be created by the downwash of single, medium size helicopters in most fog situations where the fog depth is less than 300 ft; and (2) single or multiple helicopters can create and maintain continuous clearing of fog over airports in situations where the fog is 200 ft in depth, the refilling diffusion velocity is less than 1 ft/sec, and the cross-runway component of the wind is less than 2.5 miles/hr. The reader is

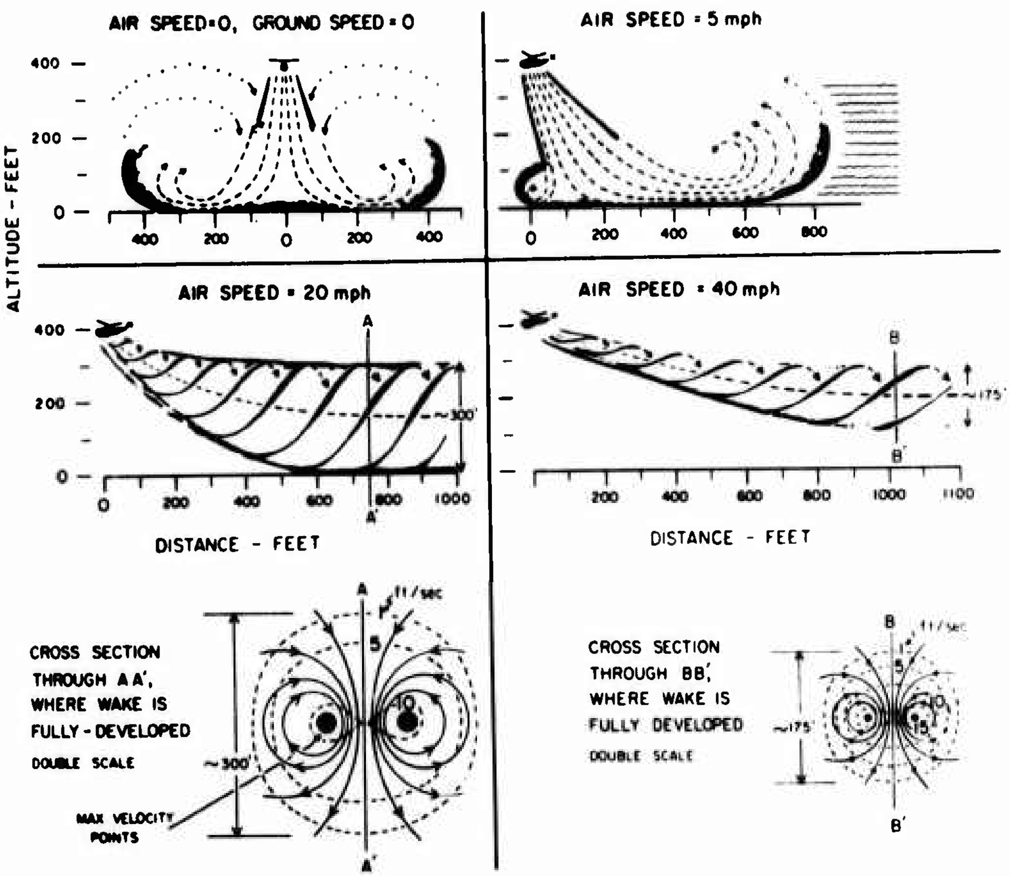



Figure 8. Schematic Representation of a Helicopter Rotor Wake at Different Forward Air Speeds. (After Plank et al, 1970)

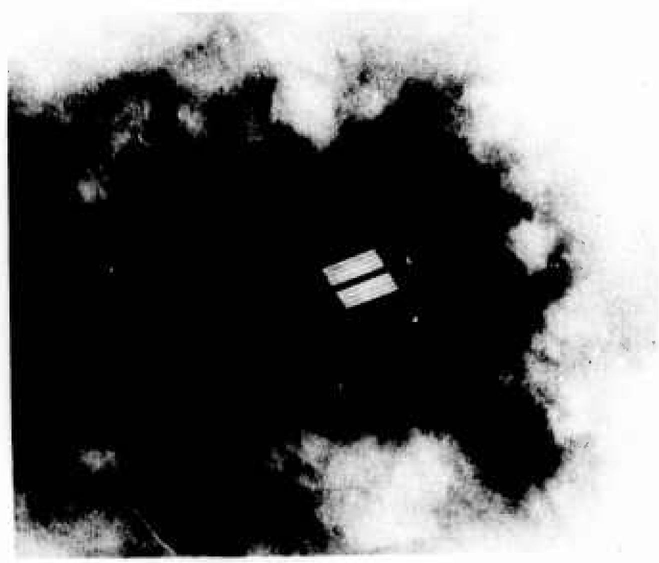


Figure 9. Fog Clearing Created by a CH-47a Helicopter Operating in the Hover Mode. (After Plank et al, 1970)

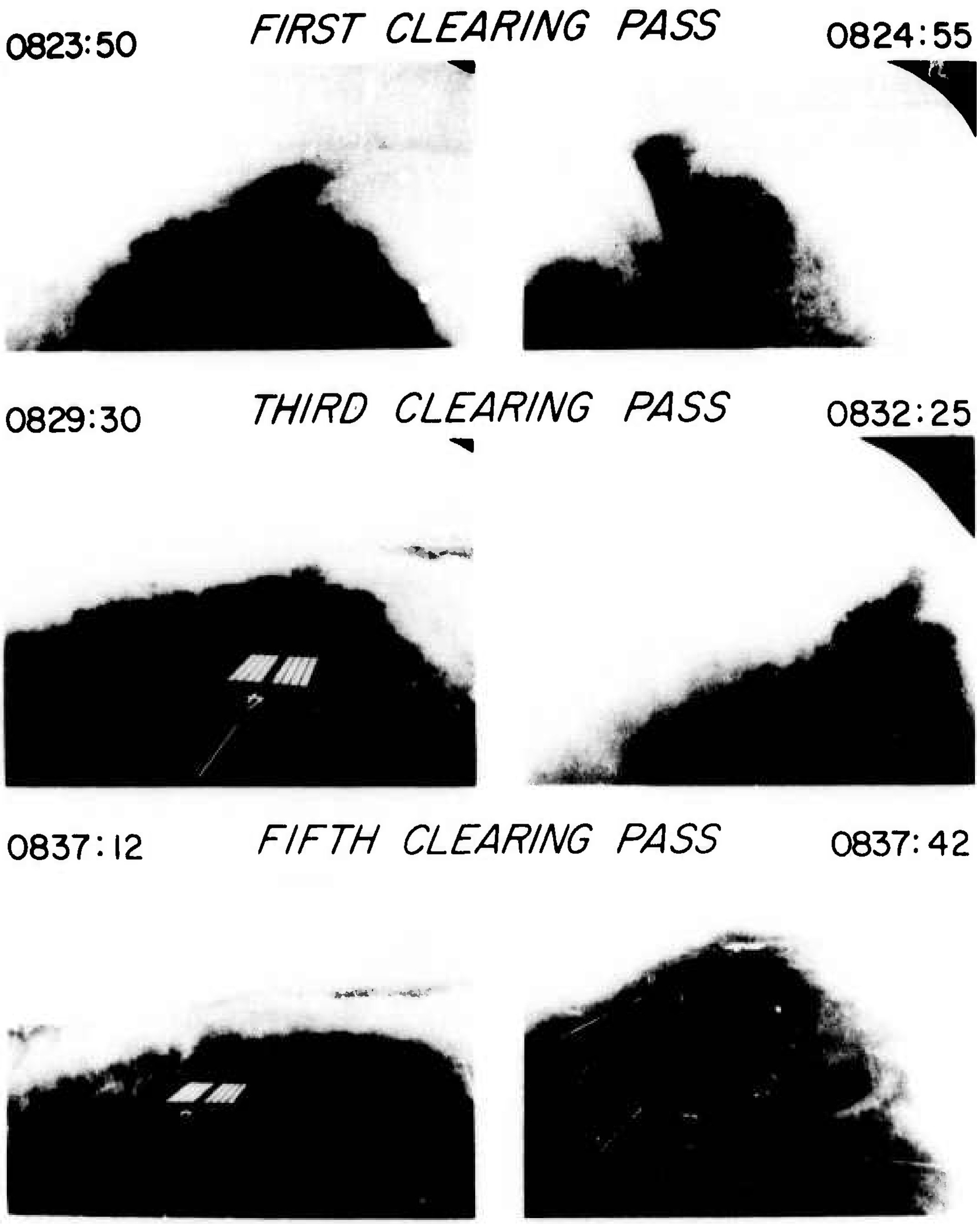



Figure 10. Cleared Trail Created in Fog by a CH-47A Helicopter at a Forward Air Speed of 15 miles/hr. (After Plank et al, 1970)

referred to the report on the West Virginia experiments by Plank et al, (1970) for a more complete discussion of the fog clearing capability of helicopters.

Fog clearing with helicopters has, to date, only been used in military operations in Southeast Asia. The evacuation of 29 wounded personnel was made possible by helicopter fog clearing operations. It was also instrumental in permitting the resupply of 2 outposts and the landing of 42 aircraft.

### 6.2 Hygroscopic Particle Seeding

When hygroscopic substances in the form of either dry particles or solution droplets are released within a fog they absorb water vapor, and the air, in drying, causes the fog droplets to evaporate. Figure 11 illustrates the four phases that characterize the artificial clearing process. During the seeding phase, carefully sized hygroscopic particles are introduced into the fog above and upwind of the intended target zone, usually an airport runway. If the seeding particles are introduced from the ground, they must be blown up to the altitude to which clearing is desired. Because of their great affinity for water vapor, the hygroscopic particles grow rapidly by condensation as they fall under the action of gravity. Most of the hygroscopic particles grow about three times larger than their initial size before falling out of the fog layer in approximately 5 min. The visibility improves as the fog droplets evaporate in response to the vapor deficit that is created. The clearing first appears at the seeding level and spreads, in time, to the ground. The maximum visibility improvement on the ground occurs approximately 10 min after seeding. The clearing is advected past the target zone by the wind field and eventually refills under the action of turbulent mixing. If further clearing of the target zone is required, additional applications of seeding material are required.

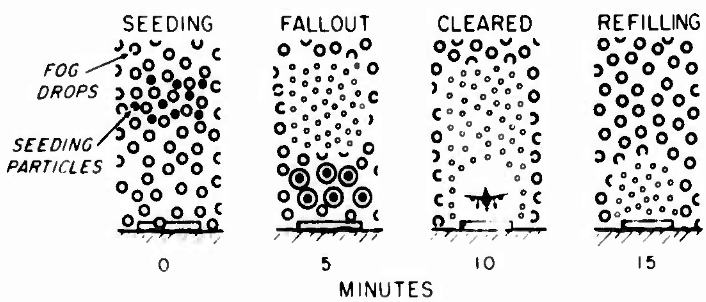



Figure 11. Schematic Representation of Warm Fog Modification by Airborne Hygroscopic Particle Seeding

The quantity of seeding material that is required to produce an operationally useful clearing by the process described above is dependent upon the size and chemical nature of the hygroscopic material, the fog water content, and the environmental wind field. The influence of these parameters on the clearing process has been evaluated by means of interactive computer simulation studies and field experimentation. The reader is referred to the work of Kunkel and Silverman (1970), Kocmond et al (1970), and Silverman (1972) for a more complete discussion of the results of these investigations.

The clearing effectiveness of the hygroscopic treatment is critically dependent on the size of the seeding particles. As the seeding particle size decreases, the quantity of hygroscopic material to attain a given visibility improvement decreases but the residence time of the particles in the fog increases. If the hygroscopic particles are too small, however, they will remain in suspension and contribute to lower visibility. Excessively large particles, on the other hand, fall out too rapidly for water to condense on them efficiently. The optimum size particle is one that can grow large enough to fall out of the fog and produce the required visibility improvement in reasonable times using as small a quantity of hygroscopic material as possible. Figure 12 shows the maximum visibility produced by seeding a fog, having an initial visibility of 85 m, with various sizes and concentrations of urea particles. It can be seen that the optimum size seeding particle in this case is 30 μm in diameter. Hygroscopic particles approximately 30 μm in diameter are, in general, most efficient.

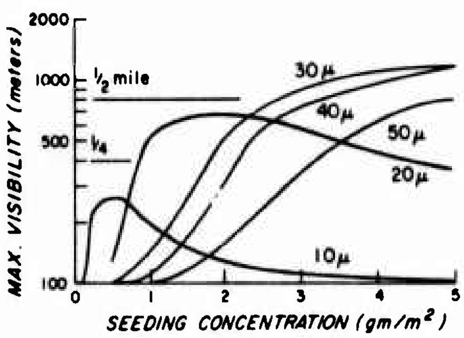



Figure 12. Computed Maximum Visibility at the Ground as a Function of Urea Seeding Concentration and Particle Diameter. The initial visibility was 85 m

It should be pointed out that the urea concentrations shown in Figure 12 are based on seeding with uniform size particles. The generation of monodispersed size distributions of hygroscopic particles is, however, not practicable. The seeding concentrations required to produce operationally significant improvements in visibility with realistic, commercially-available size distributions of hygroscopic particles are two-to-three times greater than those required for idealized uniform size distributions having the same modal diameter.

The most important property of an effective seeding agent is that it maintain its affinity for water vapor when the material concentration gets progressively more dilute as the particle grows by condensation. Since the clearing of the fog near the ground is of greatest practical value, the seeding agent must be able to continue to remove water vapor after it has fallen through some depth of fog and becomes quite dilute. Some materials, such as calcium chloride, take on water at a very low relative humidity (45 percent) but rapidly lose their affinity for water vapor after becoming dilute. Other materials, such as lithium hydroxide, require a higher relative humidity (83 percent) before they take on water but maintain a relatively high growth rate as they become dilute. Table 3 lists some of the more effective hygroscopic materials and their efficiency. Fog clearing efficiency is herein defined as the ratio of the maximum vertical visibility from the ground produced by a given mass of hygroscopic material to that produced by sodium chloride. Sodium chloride is taken as the standard because it has been the most widely used in fog clearing experiments. With the exception of acetamide, which is prohibitively expensive, all of the hygroscopic materials that are more effective than sodium chloride, are also highly toxic to plants and animals and/or corrosive to metal surfaces. As is the case with sodium chloride, these materials cannot be used operationally at airports and other populated areas. Of these materials, only ammonium nitrate-urea-water has been actively pursued for limited operational use where corrosion and/or ecological factors are not critical. The primary technical problem with this material is that it is disseminated in liquid form through high pressure nozzles. Generation of the required seeding concentrations in the correct particle size distribution is beyond the current state-of-the art of spray technology.

Table 3. Some of the More Effective Hygroscopic Chemicals and Their Fog Clearing Efficiency

| Hygroscopic Chemical | Fog Clearing Efficiency |
|---|---|
| Lithium Hydroxide | 4. 10 |
| Ammonium Chloride | 2. 06 |
| Lithium Chloride | 1. 88 |
| Sodium Hydroxide | 1. 85 |
| Potassium Hydroxide | 1. 31 |
| Ammonium Nitrate-Urea-Water | 1. 17 |
| Acetamide | 1. 02 |
| Sodium Chloride | 1. 00 |
| Urea | 0. 93 |
| Disodium Phosphate | 0. 85 |
| Ammonium Nitrate | 0. 84 |
| Calcium Chloride | 0. 62 |

Urea is the best, safe hygroscopic seeding material. Raw urea cannot, however, be used to seed warm fog because it has a soft, friable crystalline structure which fragments easily during handling, producing large numbers of submicron particles that contribute to a degradation rather than to an improvement in visibility. Conventional sizing methods such as mechanical milling and sorting are, therefore, not suitable for urea. Microencapsulation technology whereby single crystals are chemically packaged inside thin, harmless shells has been exploited to provide for the sizing and stabilization of the urea particles, thereby optimizing its efficiency as a warm fog seeding agent. The microencapsulation process produces a narrow size distribution that is completely devoid of the very small particles. Microencapsulation technology is widely used in industry to produce such consumer products as timed-release cold capsules and carbonless multiple copy paper.

An example of a clearing in warm fog that was produced by seeding with microencapsulated urea particles is shown in Figure 13. A fog over McClellan AFB, California that was 100 ft in depth was seeded with 1200 lb of microencapsulated urea particles over a distance of 1800 ft. The seeding operation was carried out by a C-130 aircraft that was fitted with a specially constructed motor-driven augur-feed dispenser (Figure 14). At 7 min after seeding, the 700 ft wide by 1500 ft long clearing appeared over the approach end of the runway; and 36 min after seeding, the hole was completely refilled by turbulent mixing.

This experiment demonstrated the inhibiting effects of one meteorological variable, turbulence, on fog clearing effectiveness. Another variable that influences the effectiveness of seeding is fog water content. The quantity of seeding material required to produce a given percentage increase in visibility increases linearly with increasing fog water content. Because visibility is inversely related to the water content—that is, fogs of high liquid water content have very low initial visibility—the quantity of seeding material required to raise the visibility to an operationally useful level increases almost as the square of the increase in liquid water content.

As a result of the counteracting influences of turbulence and vertical wind shear, and the great difficulty in targeting the clearing, single line hygroscopic particle seeding is not operationally feasible. Application of the seeding material over a wide area is required to produce operationally useful clearings. The size of the clearing and, therefore, the quantity of seeding material to produce it increases as the speed of the wind and its variability in direction increases. For the normal range of wind conditions in fog, a seeding area of 1 to 10 square miles is required to ensure proper targeting of the clearing. Approximately eight-to-ten passes by one or more seeding aircraft must be made to cover areas of this size. Wide area seeding patterns can be executed under the guidance of standard airport aircraft control radar, provided that the wind at the seeding level and its expected variability during the 15 min period required for clearing can be determined.

Figure 13. Fog Clearing at McClellan AFB, California Created by Airborne Seeding With Microencapsulated Urea Particles

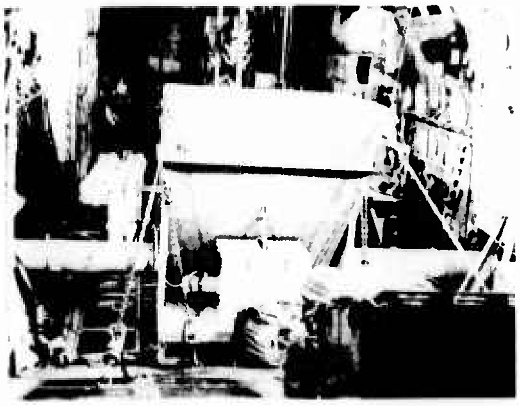


Figure 14. Hygroscopic Particle Dispenser Installed in a U.S. Air Force WC-130 Aircraft

Table 4. Requirements for Operational Warm Fog Modification by Airborne Seeding With Microencapsulated Urea

| | Category I | Category II | | Category IIIa | |
|---|---|---|---|---|---|
| Visibility Goal (miles) (m) | 1/2<br>800 | 1/4<br>400 | | 1/8<br>200 | |
| Fog Type | Both | Radiation | Advection | Radiation | Advection |
| Seeding Conc. ($gm/m^2$) ($lb/miles^2$) | 2.25<br>12.8 K | 1.0<br>5.7K | 1.6<br>9.2K | 0.6<br>3.4K | 0.4<br>2.3K |
| Total Material (lb/hr) (lb/landing) | 80 K<br>6.7K | 36K<br>3.0K | 58K<br>4.8K | 22K<br>1.8K | 14K<br>1.2K |
| Cost ($/hr) ($/landing) | 40 K<br>3.3K | 18K<br>1.5K | 29K<br>2.4K | 11K<br>0.9K | 7K<br>0.6K |

Table 4 gives model computations of the seeding material and cost requirements of operational warm fog dissipation for average radiation and advection fog conditions that are associated with a 3 knot cross-runway wind. The seeding concentrations and costs shown in Table 4 should be multiplied by approximately 0.5 and 2.0 to account for the range of fog conditions likely to be encountered. The cost figures are based upon a cost of $0.50 per pound for microencapsulated urea, the supplier's projected cost if the material is purchased in large quantities. The costs per aircraft landing are based on assisting one aircraft operation during a 5-min seeding period and are, therefore, considered to be conservative. Even though technically feasible, operational warm fog dissipation by airborne hygroscopic particle seeding, is nevertheless costly.

### 6.3 Ground-Based Heating

One of the oldest and most successful methods of dissipating warm fog is by ground based heating through the combustion of hydrocarbon fuels. Sufficient thermal energy must be provided to evaporate the fog droplets and to raise the temperature of the air sufficiently to accommodate the additional water. This quantity of heat is easily calculated from the basic laws of physics. Figure 15 shows how the required amount of heat varies as a function of air temperature and fog liquid water content.

The energy requirements given in Figure 15 are theoretical minimum values needed to completely dissipate the fog. In practice the values have to be increased to account for the need for rapid, but not necessarily complete, evaporation of the drops, the additional water vapor introduced into the air by the combustion of the fuel, and the uneven spatial distribution of heat. The first two factors can readily be incorporated into the calculations used to produce Figure 15. The effect of the last factor—the uneven heat distribution—cannot, however, be as easily evaluated because the physics of heat plume systems is not completely understood. In order to insure adequate heat to account for all of the uncertainties described above, the values given in Figure 15 are generally multiplied by a factor of 2 or more, in designing operational warm fog dispersal systems.

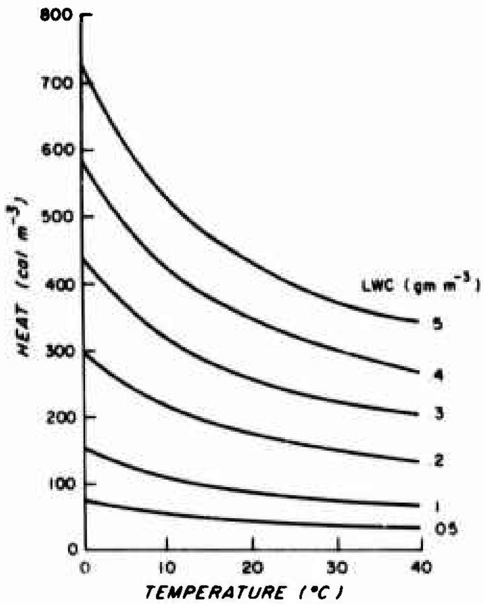



Figure 15. Heat Required to Dissipate Fog as a Function of Air Temperature and Fog Water Content

The rate at which the heat must be applied is primarily a function of the wind speed. Except for the near calm condition, the heating rate increases with increasing wind speed. Large heating rates are, however, required during very light wind conditions to compensate for the vertical heat losses due to buoyancy.

Based on extensive tests conducted since 1936, thermal fog dissipation systems were installed at 15 airfields in England during World War II to ensure the safe arrival of RAF aircraft following offensive sorties in Europe. The thermal fog dissipation systems, called FIDO (Fog Intensive Dispersal Of), consisted of pipelines along the runways through which aviation fuel was pumped under low pressure and burned as it escaped through small holes in the pipes. Despite problems of smoke and ignition failure, the FIDO systems were highly successful. The first operational landing by an aircraft returning from a mission was made in November 1943. By the end of the war, over 2500 aircraft containing approximately 10,000 airmen had landed with the aid of FIDO. On one occasion, 85 aircraft were landed with the aid of FIDO in an 8 hr period. The reader is referred to the report of Walker and Fox (1946) for the most comprehensive review of the FIDO work.

After World War II, further development of FIDO was pursued by the United States Navy at the Landing Aids Experimental Station (LAES), Arcata, California.

Advances were made in the mechanical, electrical, and combustion design of FIDO. A high-pressure, fuel-flow system was used to avoid the preheating required by the old low-pressure system and to permit the use of cheaper diesel fuel or fuel oil. Special burner heads were used to reduce the unwanted production of smoke, and heat-coil igniters were used to minimize ignition failure. The improved FIDO system was tested at the Arcata Airport during the period 1946 to 1950 as a component of the other integrated landing aids which were also being evaluated. In 94 percent of the test cases, minimum visibility and ceiling conditions were produced by the FIDO system in dense advection fog that occurred in association with a moderate onshore wind.

As a result of the successful fog dispersal operations at Arcata, a FIDO system was installed at Los Angeles International Airport (LAX) in 1949 to serve commercial aviation. The LAX FIDO system, which cost about $ 1, 325, 000 to install, was improved further by providing for automatic ignition and monitoring of visibility and wind from a central location. Operation of the system was, however, still plagued with problems of fuel leakage, ignition, dirt, and smoky burners. Fog dispersal operations were abandoned in December 1953 when it was realized that the FIDO system, as installed, was not capable of clearing fog conditions more severe than 1/8th mile visibility. This limitation was largely due to inadequate maximum heat outputs and gaps in the burner lines at cross-runways and at the ends of the runway. It was generally concluded that an effective FIDO system was too expensive to warrant routine use by commercial aviation. Advances in electronic landing aids made at that time permitted the lowering of visibility and ceiling minima to such an extent as to considerably reduce the amount of air traffic disrupted by fog.

In 1947, the United States Air Force undertook the development of a thermal fog dissipation system that would overcome the main disadvantages of FIDO in military operations; that is, the permanence of the installation and the inherent objection to mixing fire and aircraft. A mobile or transportable system, which employed the exhaust heat from jet engines to dissipate the fog, was developed. In response to a request by Berlin Airlift Operations, a system consisting of seven J-33 jet engines combined with afterburning in an aspirator was constructed in 1949. Preliminary tests of a single engine at Arcata were favorable. With the closing of the Arcata test facility after the 1949 fog season, the full jet engine system was sent to Alaska for testing in ice fog during 1950 and 1951. The system failed to dissipate the ice fog. The combustion of the fuel produced a liquid water content of 0.02 $gm/m^3/^oF$ rise in temperature which at -40$^o$F (-40$^o$C) actually intensified the fog. Not realizing that this was the true reason for the failure of the J-33 tests, the discouraging results on ice fog were generalized and all activity on the development of the jet engine system was discontinued.

Interest in the jet engine exhaust heat approach was revived in 1958, when it was realized that this technique should be successful in dissipating fog at above-freezing temperatures. Development efforts were initiated in both the United States and France. After conducting tests in 1958 to determine the fog clearing capability of a jet engine, United States Air Force scientists recommended that the jet engine fog dispersal technique be used as an emergency capability at all airbases where jet aircraft are available. Use of jet engines in a fixed underground installation was not recommended at that time because it was not considered to be cost-effective. In the early 1960's, France conducted experiments using jet aircraft parked alongside a runway which were successful in clearing the fog. In 1968 the AWS conducted similar tests using four C-141 four-engine aircraft, and again demonstrated the feasibility of this technique.

The increased losses in revenue with the advent of the jet age made fixed installation heating systems economically attractive for at least those airports having a high volume of air traffic. Further development of the jet engine technique by the French led to the installation of a sophisticated thermal fog dissipation system, called Turboclair, at Orly Airport, Paris in 1970 . The initial Turboclair installation consisted of eight jet engines in underground chambers alongside the upwind edge of the runway as shown in Figure 16. Each unit was equipped with a remotely controlled, directional outlet grid to distribute the exhaust heat over the desired part of the runway. The installation was capable of clearing fog over a distance of 300 m in the approach zone and 300 m along the runway. In 1972, another four engines were installed to clear an additional 600 m in the touchdown and rollout zones of the runway. The complete installation cost about three million dollars to install and costs about $3400 per hour to operate. Tests of the Turboclair system showed that it was capable of improving the visibility in the approach and touchdown zones of the runway from below minimum to at least Category II landing conditions. The turbulence generated by the jet engines did not create any problems for the landing of the test aircraft, even with automatic pilot on during their approach. Based on the results of these tests, in 1972 the French Ministry of Transportation authorized French air carriers to use Turboclair to assist in landings in fog in accordance with established airport minima criteria. The reader is referred to the report of Fabre (1971) for a review of the history of the development of the Turboclair system.

In 1970, development of fixed installation thermal fog dissipation systems in the United States was also resumed. By the application of modern heat and meteorological engineering technology, the United States Air Force is developing a thermal fog dissipation system that promises to be cost-effective, meet air quality standards, and safe for aircraft operations. The Federal Aviation Agency is sponsoring the development of a similar system for application at civilian airports.

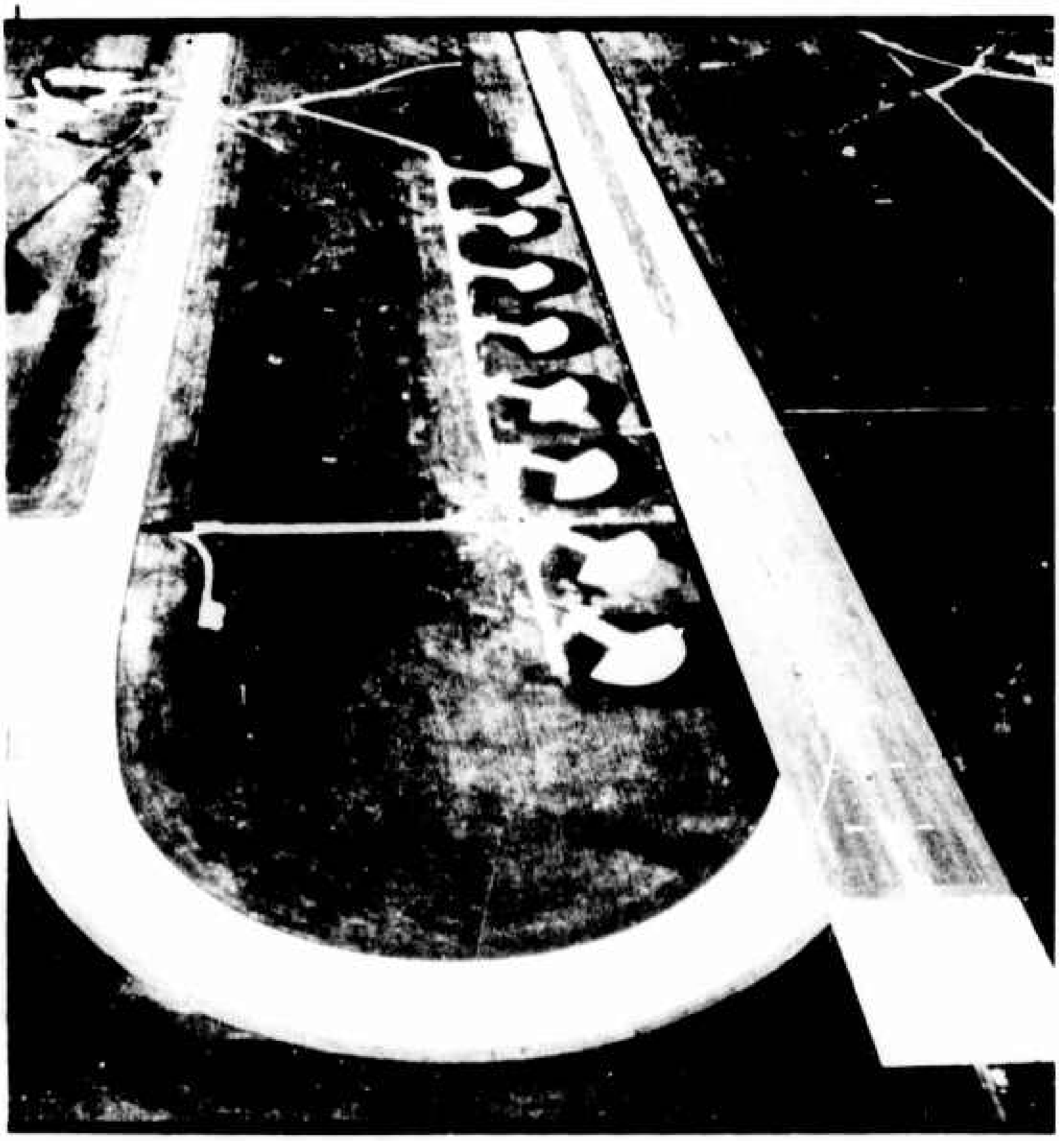


Figure 16. Turboclair Fog Dispersal Installation at Orly Airport, Paris, France. The installation was constructed by Bertin et Cie for use by the Paris Airport Authority in dissipating warm fog

## 7. ICE FOG ELIMINATION

At present, there is no practical method of dispersing ice fog once it has formed. Although the methods of warm fog dispersal are, in principle, applicable to ice fog, the extremely large energy and logistic requirements to make them effective at very cold temperatures make them economically unsound. Ice fog can, however, be prevented by controlling the man-made nuclei and moisture sources which lead to its formation. Various suppressive and corrective measures have been devised to alleviate the ice fog problem at Eielson AFB, Alaska. Many of the unnecessary moisture sources have been eliminated. Emission of moisture from many of the remaining sources has been greatly reduced by use of condensate return systems. A modern central power plant was constructed which permitted the shutting down of three diesel- or oil-fired power substations on the base. Combustion studies resulted in revised operating procedures for the coal burners used in the laundry, mess halls, motor pools, and power station which increased the coal burning efficiency of its boilers and decreased the amount of moisture by about 10 to 15 percent. Less successful engineering attempts have been made to eliminate the large amount of moisture from the stack effluents of the central power plant, its cooling pond, and the exhaust of vehicles.

Despite the engineering attempts to eliminate major moisture sources at Eielson AFB, it is probable that there will always be some ice fog to hamper base activities. Even the small moisture inputs that result from the operation of clothes driers, exhaust fans, vehicles, aircraft, etc., will continue to produce local pockets of ice fog on the base. Ice fog has not been eliminated completely, but its severity has been lessened.

Conditions favoring the formation of ice fog could largely be avoided at new air bases. The runways should be located as far as possible from the remainder of the base and should be placed upwind of water vapor sources. The only source of moisture would then be the aircraft. Aircrews report that the visibility reduction due to departing aircraft is drastic, lowering the visibility to near zero, but in 5 to 10 min the visibility is restored to its original value.

## 8. OUTLOOK

Limited operational systems to dissipate supercooled fog at airports are being successfully employed in the United States and Europe. Large airports are increasingly favoring fixed, ground based systems using propane over airborne dry ice seeding systems. The initial investment in ground based installations is larger than that for airborne systems, but the relative ease of operation makes it worthwhile. Smaller airports and locations, where supercooled fog is an infrequent but costly phenomenon, will tend to favor the airborne dry ice system. The airborne dry ice system will also be used to increase the amount of winter sunshine over cities that are plagued with persistent supercooled stratus clouds. In any case, the investment necessary to implement either system is unquestionably less than the losses suffered by users due to fog.

Inasmuch as warm fog is the most prevalent and, therefore, the most troublesome fog type, considerable effort has been invested in developing methods for its dispersal. This investment is rapidly approaching the point where returns will be forthcoming. Recognizing that the clearance of large areas of warm fog with the expenditure of small amounts of energy is incompatible with physical reality, current efforts are primarily concerned with the application of modern technology to the engineering of proven "brute force" techniques. Each of the three techniques seriously considered for operational implementation appears to have its applications. Helicopter downwash mixing is simple and inexpensive, but is restricted to shallow radiation fog. It is most dependable for application in situations where relatively small clearings are needed, such as those required to facilitate helicopter landing or rescue operations, or small but congested sections of roadways. Wide-area hygroscopic particle seeding is applicable to deeper, but not all, warm fogs. The seeding equipment is inexpensive, but the seeding material is costly and the seeding operation is relatively difficult to execute. It is most appropriate for use in applications where the fog must be dissipated and mobility of operation is essential. The thermal technique is effective in all warm fog situations. Although relatively simple and inexpensive to operate and maintain, it is extremely costly to install. Its use is, therefore, economically justifiable only for urgent military purposes or in cases, such as Los Angeles International Airport, where its frequency of operation will rapidly amortize the cost of the initial installation.

Ice fog can be prevented by controlling the man-made sources of moisture and nuclei that lead to its formation. It is, however, not within the present state-of-the-art to dissipate ice fog once it has formed. A promising new approach to ice fog dissipation, that is presently being investigated, is based on the hypothesis that a widespread stratus cloud can often times be artificially created in an arctic atmosphere and that such cloud decks will radiationally induce sufficient surface level warming to evaporate the ice fog. Continued research on ice fog and new dispersal concepts such as this one may, in time, result in the development of an effective dissipation technique.

There is no doubt that fog can be eliminated by artificial means. Further experimentation with existing techniques to establish criteria that can be used to make the techniques more successful as well as to decrease the cost and the hazards of operation is desirable. There is still room for new ideas in both methods and equipment. Empirical testing will, in time, lead to standardization of fog dispersal techniques. Optimization of these techniques and the development of new methods, however, depend strongly on the results of fundamental research on fog physics and dissipation concepts. Computer modeling of the evolution of fog will play an important role in this research.

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