Fog Dispersal: A Technology Assessment

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Fog has been a hazard to aircraft since the beginning of aviation. Intensive research and development over the past decade has led to operational implementation of several techniques for the dispersal of one type of fog and several promising concepts for the artificial dissipation of another. The dispersal of supercooled fog and stratus (i.e., liquid water clouds at temperatures below 0°C) was the objective of the most publicized early weather modification experiments and is presently the only truly operational modification technology. Recent developments in the dispersal of warm fog (i.e., clouds of droplets at temperatures above 0°C) have brought that undertaking to the brink of widespread operational implementation. The paper describes the concepts and recent developments in warm and supercooled fog dispersal and presents the evidence for recent optimism in the operational implementation of these concepts. Ice fog (i.e., clouds of ice particles) remains a rare but stubborn phenomenon whose dispersal is presently only in the conceptual stage of development.

Introduction

According to international definition, fog is a visible aggregate of minute particles suspended in the atmosphere near the earth's surface, that reduces the visibility to below one kilometer (0.6 miles). A more popular definition is that a fog is simply a cloud on the ground. This silent and sometimes inspirational phenomenon has been a source of inconvenience to man since the dawn of transportation. Despite the technological advances that have been made in electronic aids, fog continues to be the most serious hazard to navigation in the air, on land, and at sea. Normally the hazard simply results in annoying delays. Occasionally the consequences are substantial losses of property or even lives. On those occasions, fog makes the news.

Most of the time, however, fog is largely a problem for transportation specialists. In this age of large, expensive and fast moving aircraft, the problem is becoming more serious. Weinstein[1] reports that thousands of flights per year at military and civilian airports around the world can be expected to be delayed or diverted by fog. In a study done before the recent dramatic increase in prices, a 1971 Federal Aviation Administration tabulation estimated that by 1976, a typical weather caused diversion would be expected to cost approximately $2,500. The figure was anticipated to rise by more than 50% by 1981. Again before the recent inflation, Beckwith[2] estimated that the civilian domestic airlines in the U.S. lose over $75 million annually due to interruptions in service caused by fog. On those rare occasions when the severity of the problem has gone unnoticed, some of the most tragic disasters is aviation history have resulted.

The severity of the problem has motivated an intensive search for methods of artificial fog dispersal. This paper presents a review of the important concepts of fog dispersal that have been suggested and gives a current state of the science review of the operational implementation of these concepts. The paper is a condensation and update of an earlier report by Silverman and Weinstein.[3]

Basic Concepts

The most appropriate classification scheme to use in a discussion of fog modification is one that divides the phenomenon according to its constitution and temperature. According to this scheme, all fogs can be divided into one of three categories; Ice Fog, Supercooled Fog, or Warm Fog.

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Ice Fog

Ice fog, as the name implies, is a suspension of ice particles that occur at very low temperatures normally during clear, calm conditions. This phenomenon occurs at temperatures below −30°C (−22°F) and is common in the vicinity of sources of water vapor. Open water areas of streams and rivers and body fluids of herds of animals are the common natural sources of water vapor for the formation of ice fog. The most important sources of moisture for this phenomenon near inhabited areas, where the fog restricts movement of men and materials, are the activities of modern man such as power generation, automobile, and aircraft engine exhaust, and even vents from clothes driers. Because of the very cold temperatures associated with ice fog, the addition of only very small amounts of water vapor, amounts that would go totally unnoticed under other atmospheric conditions, are sufficient to bring air to its saturation point and form ice fog. Because of the extremely low temperature required for its formation, ice fog is totally restricted to Arctic and Antarctic regions of the globe and is not normally a source of problems in the mid-latitudes.

Supercooled Fog

The second type of fog, supercooled fog, is composed of liquid water droplets at temperatures colder than the normal freezing point of water (i.e., 0° C or 32°F). The reason for the water remaining in the liquid state at temperatures below 0°C is beyond the scope of this paper. The interested reader is referred to Silverman & Weinstein[3] or a much more comprehensive discourse on weather modification in general, edited by Hess,[4] for a full explanation of the phenomenon of supercooling in the atmosphere. Suffice it to say here that supercooled fogs are in a metastable state such that the introduction of a small amount of foreign material can trigger the freezing of much of the water. Without this foreign material, however, the droplets will remain in their liquid state almost indefinitely.

The vast majority of supercooled fog that creates problems for transportation in the mid and upper latitudes occurs at temperatures between −10 and 0°C (14 and 32°F) although this phenomenon has been observed down to near −30°C (−22°F). Parts of Canada, Northern U.S., and Northern Europe are the regions in the west that are the most seriously plagued by supercooled fog.

Warm Fog

The last, and by far most common, type of fog is called warm fog. This phenomenon is composed of water droplets at temperatures above the nominal freezing point of water. In part because most of the globe experiences above freezing temperatures most of the time, and in part because most of the world's industrial developement, whose progress is closely related to modern transportation, has taken place in the mid-latitudes, warm fog is by far the most important fog phenomenon. Unfortunately, it is also very difficult to modify because it is in a stable state and consequently resists all but the most intensive efforts at dispersal.

Dispersal Concepts

The objective of fog dispersal is visibility improvement. It can be shown that the visibility, V, in a fog is inversely proportional to the number of particles in the fog, N, and the square of their radius, r. This can be stated quantitatively by Eq. (1)

$$V = K/Nr^2 \tag{1}$$

where K is a constant of proportionality that depends upon many factors not appropriate for this discussion.

From Eq. (1) it can be seen that the visibility in a fog can be improved by either decreasing the number of particles, decreasing their size, or both. In addition, it can be seen that a decrease in radius has a stronger effect than a decrease in number. A factor of 3 reduction in radius raises the visibility nine-fold. A similar reduction in the number of particles only raises the visibility by a factor of 3.

Methods of fog dispersal aimed at decreasing the size of the particles are commonly called evaporative methods since the particles shrink by evaportation. Modification techniques that are designed to reduce the number of fog particles are generally called removal methods.

Removal Methods

The methods that have been proposed for the physical removal of fog particles fall into one of three categories: a) methods leading to the removal of the particles by collecting them on some physical surface such as a screen or baffle; b) methods promoting the fallout of the particles under the force of gravity after agglomeration amongst themselves or by foreign particles; and c) methods that replace a volume of fog laden air with a similar volume of clear air.

Generally, physical removal methods are most successful on shallow or patchy fog where the volume of fog that must be treated is relatively small. Fog dispersal by seeding with electrically charged particles , a type b) removal method, is the only one of these methods that is designed to treat deep fogs.

Evaporative Methods

The most heavily investigated and most promising fog dispersal techniques fall into the category of evaporative methods. Since fog is a colloidally stable suspension of particles that are in vapor equilibrium with the surrounding air, these particles can only be made to evaporate either by removing some of the vapor from the air or by increasing the capacity of the air to hold additional vapor. In either case, the relative humidity of the air is temporarily reduced below 100%. The first method is the basis of the method commonly known as chemical seeding. The second method is achieved by raising the temperature of the fog and is the basis of the method known as thermal fog dispersal. An additional method that could either reduce the vapor content of the fog or raise its temperature is a method of mechanically mixing in drier and possibly warmer air into the fog from above or from the sides. The use of helicopter rotors is an example of this method. Often the mixing in of dry air also physically pushes the fog away, thus, involving the removal concept as well as the evaporative one.

Because of the decreasing ability of air to hold water vapor as the air temperature decreases, evaportative methods are largely restricted to warm and supercooled fogs. To date, ice fog has not been effectively treated by evaporative methods.

Prevention Methods

The final method of fog dispersal that has been suggested involves the prevention, rather than dissipation of the fog. Prevention methods depend upon keeping the moisture out of the fog, keeping the air warm enough to prevent saturation, or removal, or modification of the foreign particles (called condensation nuclei) on which water droplets or ice crystals can form. In all cases, large amounts of air must be treated and the formation of the fog must be anticipated. The logistics of the former and inability to accurately forecast the latter have kept prevention methods from being practical under most conditons, particulary for aviation applications.

Fog dispersal Geometry at Airports

The overwhelming majority of fog dispersal operations are aimed at improving visibility at airports. Although harbors and highways are also often plagued by fog, these areas are only rarely and sporadically the subjects of fog dispersal programs or proposals.

Figure 1 shows the clearing geometry for landing aircraft in the vicinity of runways. The clearing is divided into an approach zone clearing (A) and a rollout zone clearing (R). The dimensions of the former depend upon the level of sophistication of the electronic landing aids of the airport and the incoming aircraft. On its final approach, an aircraft flies down a glide slope that is generally 2½-3°. The point where a pilot must make a final decision as to continuing down or pulling out (i.e., executing a "missed approach") is the intersection of the glide slope and the decision height (DH). The decision height depends upon the level of sophistication of the electronic landing aids. The least sophisticated of the landing aids, category I aids, require a DH of 60 m (200 ft) and a runway visual range (RVR) of not less than 600 m (1800ft). Category II landing systems require a DH of 30 m (100 ft) and an RVR of 400 m (1200 ft). The length of A for category I and II landing systems are 2160 m (7100 ft) and 1460 m (4800 ft), respectively. This includes 300 m (1000 ft) before the DH point and 500 m (1500 ft) beyond the touchdown point shown as the ground plane indicator (GPI) in Fig. 1. This extra clearing provides a margin of safety that is valuable when operating in fog.

The dimensions of the rollout zone depend upon the length of the runway and the avaiability of taxiways. The depth of R is 15m (50 ft). The width of the cleared zone is 150 m (500 ft) in the approach zone and the width of the runway in the rollout zone.

Supercooled Fog Dispersal

Supercooled fog or stratus was the subject of what is often regarded to be the beginning of modern weather modification. To this day, this remains as the simplest of all weather phenomenon to modify. The reason for this simplicity lies in the fact that supercooled fog is thermodynamically metastable. The supercooled water droplets exist at an energy level above that of the more stable ice phase. As explained and demonstrated by Schaefer[5] and his co-workers, the introduction of a small amount of energy either in the form of foreign particles called ice nuclei or as strong local cooling, can induce the transition of the supercooled water droplets into ice crystals. In the end, the introduction of the correct number of ice crystals into a supercooled fog, can result in the initiation of an evaporative fog dispersal mechanism that has been understood for over three decades. The basis of this dispersal process was originally thought to be the basis of all rainfall in the world and has been known since the early 1900's.[4] The long history of supercooled fog dispersal is repeated to emphasize the fact that the physics behind

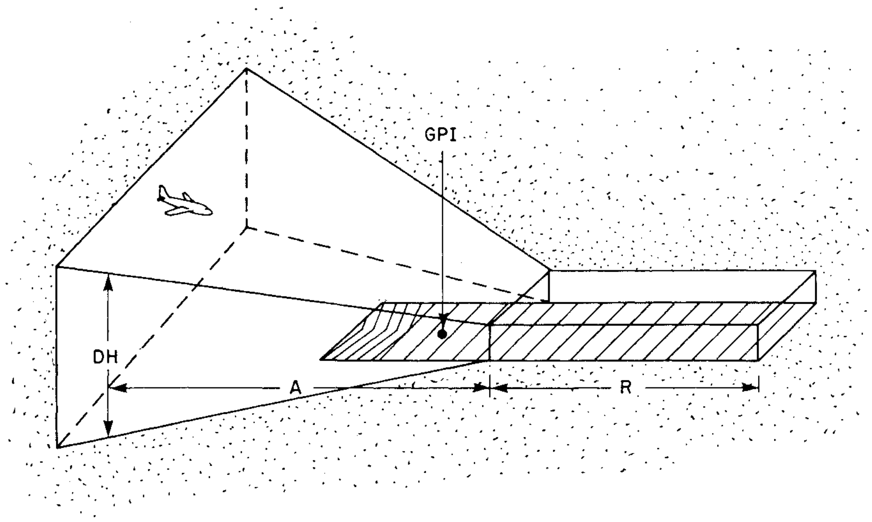

Fig. 1 Clearing geometry. The regions depicted by the symbols R&A are the approach and rollout zone clearings, respectively, as described in the text. DH is the decision height.

the technique has been known for many years. Operational programs, however, have taken a while because of the need to develop practical methods of producing the required ice crystals in the appropriate numbers, in the correct places, at the right time.

There are two methods of producing the ice crystals. The least commonly used technique for supercooled fog dispersal is the most commonly used one for the more popular weather modification activity, i.e., precipitation augmentation or rainmaking. This technique involves the introduction of artificial particles known as ice nuclei to cause heterogenous nucleation (i.e., nucleation by foreign particles). Generally these particles are silver iodide or lead iodide, that are effective in freezing water droplets at temperatures as warm as $-4°C$ (25°F).

A more commonly used technique for supercooled fog dispersal involves the chilling of the small parts of the fog down to temperatures colder than $-40°$. At this cold temperature, the droplets will freeze spontaneoulsy by a process known as homogenous nucleation (i.e., nucleation without foreign particles). Several methods have been employed or suggested to bring about this local cooling.

The only operational method of *airborne* supercooled fog dispersal involves the dropping of small pellets of dry ice (i.e., solid CO_2). As these particles fall through the fog, they chill the air in their immediate vicinity to temperatures well below $-40°$, leaving behind a trail of frozen water droplets that initiate the dispersal process. The airborne dry ice seeding technique has been employed by the U.S. Air Force on operational programs in the U.S. and Europe, by civilian aircraft authorities at several commercial airports in the United States and by the appropriate Soviet authorities at airports in Russia.

During the years 1968-1972, Air Force programs in airborne supercooled fog dispersal using dry ice have been credited with assisting almost 1,000 departures and over 750 arrivals at airports in Alaska and Western Europe. Similar efforts have been mounted at 13 airports in the North-Central and Northwestern sections of the U.S. by civilian aviation interest on programs that date back to 1963. Soviet interests report that 80% of their dry ice operations at Moscow Airport were successful between 1964 and 1967, resulting in 284 takeoffs and 143 landings that would otherwise not have been possible.

The second method of supercooled fog dispersal that has been gaining increasing acceptance involves chilling the air from a ground based array of devices. The operational programs to date have employed the chilling caused by the evaporation of liquid propane spray as described by Hicks and Vali,[6] as the mechanism to cause homogenous nucleation. Recent work by Weinstein & Hicks[7] has suggested that the substitution of adiabatic expansion of compressed air might be a more economical way of producing the same number of ice crystals.

Presently the Air Force conducts highly successful operational supercooled fog dispersal operations using liquid propane spray at Elmendorf AFB, Alaska, Fairchild AFB, Washington and Hahn AB, Germany (see Lininger[8]). A similar French system described by Serpolay[9] has been in operation at Orly Airport near Paris since 1964. During the winger of 1970-1971 it was reported that 340 arrivals and 284 departures were made possible by the operations of the propane spray system at Orly Airport.

It is clear that methods for the operational dispersal of supercooled fog are available and, if desired, need only be adapted to the local meterological and topographic conditions existing at an airport that is plagued by this meterological phenomenon.

Warm Fog Dispersal

In stark contrast to the simplicity of supercooled fog dispersal, warm fog dispersal is one of the most difficult accomplishments in weather modification. The reason for this is that in contrast to the metastable state of supercooled fog, warm fog is one of the most stable cloud systems in the atmosphere. Because of this, warm fog dispersal techniques must be "brute force" in character. Any energy required to disperse the fog must be supplied by the dispersal method itself as there is no latent phase instability to capitalize upon. Detailed understanding of the physics of the dispersal method must be combined with careful engineering to make any warm fog dispersal technique reliable, cost-effective, and free of detrimental side effects.

Because of its occurrence in those areas of the world where high speed transportation is most common, warm fog dispersal has been the subject of some very intensive research. The first published work in this area was by Houghton and Radford.[10] Most of the intensive efforts, however, have taken place since the mid 1960's.

Most of the methods of warm fog dispersal fall into one of four general areas; a) mechanical mixing of drier, warmer air from above down into the fog by means of helicopter rotors; b) drying of the air with hygroscopic chemicals; c) heating of the air, and d) introduction of electrical forces to stimulate coalescence and rainout of the water droplets.

Helicopter Downwash Mixing

One of the most dependable, straight-forward methods of creating small holes in shallow fog is to hover a large helicopter over the intended clear zone. As described by Plank et

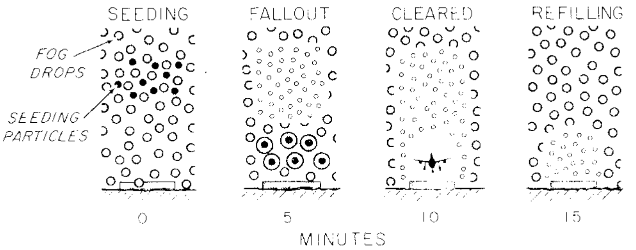

Fig. 2 Schematic representation of warm fog dispersal by hygroscopic particle seeding.[12]

al.,[11] the imposed downward thrust of dry air from above the fog top will either completely replace the fog with clear air or will mix in enough dry air to evaporate the fog droplets. Such clearings are useful for rescue operations, and, in fact, have been applied to this activity in the past. Unfortunately, if the fog is more than 60-100 m (200-300 ft) deep, and the clearing that is desired is more than two to three times the size of the helicopter rotor, the dependability of the technique seriously deteriorates.

Hygroscopic Particle Seeding

Hygroscopic particle seeding was one of the most heavily investigated warm fog dispersal techniques during the 1960's and early 1970's. Consequently, the technique is well understood. As described by Weinstein and Silverman[12] and illustrated in Fig. 2, the technique can be divided into four stages. During the seeding stage, hygroscopic particles (i.e., particles with a strong affinity for water) are introduced into the fog at an elevated altitude. Because of their affinity for water, these particles grow rapidly by condensation, removing water vapor from the air surrounding the natural fog droplets. In time, during the fallout stage, the hygroscopic droplets grow large enough to drop out of the fog, leaving behind a vapor deficit in the air surrounding the droplets. Eventually, the fog droplets evaporate to fill that vapor deficit and a clearing develops. This is the cleared stage during which aircraft can be landed or dispatched. In time, the combined effects of wind and turbulence refill the fog and additional applications of the hygroscopic particles are needed if more clearing is required.

In order to be effective, the seeding particles must be precisely the right size. This ideal size depends upon the material used for the seeding as well as other features of the fog. Large particles fall out of the fog before they can remove enough water vapor. Small particles never grow large enough to fall out of the fog. The most commonly used materials for hygroscopic seeding are urea, sodium chloride (salt) and a solution of ammonia nitrate and urea in water.

Probably the single greatest drawback to the use of hygroscopic material for operational warm fog dispersal is the problem of targeting. The clearing takes approximately 10-20 min to appear following the dispersal of the material. Since the winds are normally light and variable in fog, it is difficult to estimate where to insert the material so as to insure that the clearing will occur over a pre-determined location such as an airport runway and approach zone. Methods of overcoming this problem involve seeding over a very large area in order to ensure that some portion of the clearing will be over the intended target. This solution to the problem requires the use of very large quantities of seeding material. Since the only noncorrosive hygroscopic material, urea, is also an expensive chemical fertilizer, the economics of seeding in such large quantities becomes marginal. It has been estimated by Weinstein and Silverman[12] that a clearing up to category I landing levels would require almost 7,000 lb of urea. The cost would be over $6,000 today. The price of the material is so high because of the special handling required to ensure that the correct particle sizes would be dispensed.

To date there have been a few reported operational hygroscopic particle seeding operations conducted at a few civilian airports in the U.S. It has never been possible to properly document the success or failure of these operations.

Thermal Fog Dispersal

The only method of warm fog dispersal that has ever been operationally successful for long periods of time is thermal fog dispersal (i.e., the application of heat from an array of ground based combustors). The program that is being referred to was called FIDO, Fog Investigations and Dispersal Operations. FIDO systems were installed at 15 airports in England near the end of WW II and were credited with helping in the landing of over 2,500 aircraft returning from bombing sorties over Continental Europs. Walker and Fox[13] give a description of taht system. It is a classic example of a passive thermal fog dispersal system (i.e., the heat is applied with no thrust and the dynamic circulation is applied with no thrust and the dynamic circulation that is caused by the two line sources of heat is depended upon to move the plume over the runway and approach zone).

The opposite extreme to a passive system is the heavy jet engine concept that is employed in a French thermal fog dispersal system called Turboclair. This system as described by Sauvalle[14] uses large jet engines, usually one side of the runway and approach zone, to advect the heat over the intended target. Turboclair systems to allow category II landings are operational at Orly and Charles De Gaulle Airports outside Paris.

A third approach to thermal fog dispersal has been developed by scientists and engineers of the Air Force Cambridge Research Laboratories (now Air Force Geophysics Laboratory). It is illustrated in Fig. 3. In this case, the best features of both the passive and jet engine concepts are combined into a system called the Momentum Augmented Thermal (MAT) System. As described by Weinstein et al.,[15] the MAT System has been carefully engineered to conserve fuel while creating the required clearing. The key component of the MAT System is a sophisticated control system that senses the wind and visibility and moderates the output from the combustors to insure the correct location, intensity and depth of the clearing. An operational MAT system is anticipated to be working at an Air Force base by the end of this decade.

Other Techniques

Some other techniques that have been seriously suggested for the dispersal of warm fog include electrical charging methods as described by Gourdine et al.[16] and Tag,[17] and the use of lasers as described by Sedunov et al.[18] Both of these are examples of physical removal techniques and have never been demonstrated to be effective on fog in the atmosphere. Although these, and possibly other, methods might deserve further attention, none of them can even be considered close to operational implementation at the present time.

Ice Fog Prevention

This section uses the word prevention rather than dispersal because the best way to overcome ice fog appears to be to prevent it rather than to disperse it. After extensive tests by the Air Force in Alaska, it has been concluded that the best way to alleviate the problems associated with ice fog is to control the moisture sources and thus prevent the fog from forming in the first place. This is practical for ice fog near airpost runways because in almost all cases the source of the moisture for the fog are man made. Consequently, the proper positioning and engineering of things like power plants, laundries, motor pools, etc., can prevent the fog from forming over the runways more effectively than dispersal methods can dissipate it.

The two methods of ice fog dispersal that hold the best promise for eventual success are laser techniques and the

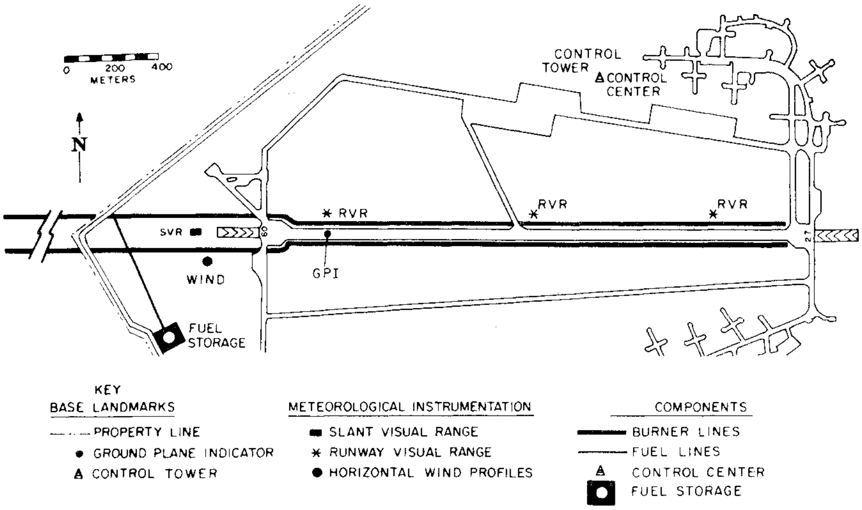

Fig.3 Schematic representation of the Air Force Momentum Augmented Thermal (MAT) warm fog dispersal system.

production of a high or mid level cloud layer. The former would break up the ice particles. The later would modify the radiation balance of normally clear Arctic areas so as to warm up the ground level and allow the air to hold more moisture before a fog forms. Both methods hold some promise but as in the case of the other techniques for warm fog dispersal, considerably more research is required before they can be seriously considered for operational implementation.

Outlook

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 or possibly compressed air 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. 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. 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 the 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. Promising new approaches to ice fog dissipation are presently being investigated. Continued research on ice fog and new dispersal concepts could and 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.

Acknowledgments

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