A Modern Thermo-Kinetic Warm Fog Dispersal System for Commercial Airports

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ABSTRACT

An extensive investigation has been made to arrive at near-optimum specifications for a thermo-kinetic warm fog dispersal system. This study included passive heat tests, subscale heat/momentum tests, and tests with a single full-scale runway combustor and an approach zone combustor. These tests were augmented with extensive analytical modeling of buoyant jets under co-flowing and counter-flowing wind conditions. The approach category and the minimum volume to be cleared within each category are the primary factors affecting the size of the thermal fog dispersal system (TFDS). Based on these studies and the clearing geometries defined by the International Civil Aviation Organization, it is shown that a Category II TFDS employs 16% fewer combustors and uses 63% less fuel than a Category I TFDS. A Category III TFDS uses 35% fewer combustors and 78% less fuel than a Category I TFDS. The combustor specifications and orientation are presented for the three approach categories.

1. Introduction

Delays and diversions due to fog have plagued aviation since the first scheduled flights. The advent of jumbo jets with their huge cargoes and heavy fuel consumption has elevated the problem from a single inconvenience to a serious economic concern. Weinstein (1974) has shown that fog can be expected to affect up to several percent of the annual flights, with the absolute number of flights sometimes running into the thousands per year. Seven years ago Beckwith (1971) estimated that fog was costing civilian domestic airlines over $75 million annually and was expected to increase yearly. On occasions the losses are measured in lives as well as dollars. These economic and human factors have motivated an intensive search for methods of artificial fog dispersal.

The most recent review of the current state of the art of fog dispersal technology has been given by Weinstein (1976), drawing heavily on an older but more detailed survey by Silverman and Weinstein (1974). It is not appropriate to review these in detail here. Suffice it to say that dispersal of supercooled fog (i.e., temperature <0°C) is generally recognized to be an operational technology with programs existing in the United States (Fletcher, 1971; Beckwith, 1971) and Europe (Serpolay, 1960). Warm fog (i.e., temperature >0°C), however, is by far the most common visibility obscuration worldwide. This phenomenon has been the subject of the most intense weather modification research over the past few decades. Helicopter downwash mixing as described by Plank *et al.* (1971), hygroscopic particle seeding as originally described by Houghton and Radford (1938) and more recently by Weinstein and Silverman (1973), electrical charging, some of which has been described by Tag (1976, 1977), and the application of heat as originally described by Walker and Fox (1946) are the four methods of warm fog dispersal that have been most vigorously pursued. The first three techniques have not been found to be well-suited to routine operational implementation at large airports.

2. Thermal fog dispersal

The only operationally proven technique for dispersing warm fog is the use of thermal energy. The application of heat to disperse fog is accomplished with an array of ground-based heat sources. These sources are used to warm the air, thereby raising its capacity to hold water vapor. If the air temperature is raised sufficiently, the fog droplets will evaporate and the visibility will increase above takeoff or landing minimums.

Considerable attention has been paid to this method of warm fog dispersal. Unfortunately, since little material has been published in the formal literature, it is difficult to document the work in a systematic way. I attempt here to briefly review the major efforts by subdivision into two categories according to the method of directing the heat.

a. Passive systems

The first method of thermal fog dispersal that was investigated involved the simple liberation of heat from parallel lines of heat sources on both sides of a runway. This technique depends on the dynamic circulation induced by the two lines of burners to merge the plumes over the runway. The most well-known example of a passive thermal fog dispersal system is the English system that came to be known as Fog Investigations and Dispersal Operations or FIDO. The FIDO program is described in great detail (unfortunately, in a rather obscure publication) by Walker and Fox (1946). Important, independent, subscale studies relating to this effort were described by Rankine (1950) and Rouse *et al.* (1953). It was said by Walker and Fox that FIDO systems were operated at 12 installations in England between 1943 and 1945 and were responsible for 2500 landings.

Following the success of the English FIDO, a variation on this technique was developed at Arcata, California, by the Landing Aids Experiment Station (LAES, 1950). A system patterned after the LAES work was installed at Los Angeles International Airport (LAX) in 1949. Called LAX FIDO, that system was finally abandoned in 1953 after it was found to be too expensive to operate successfully for the traffic load and size of aircraft LAX in the 1950's.

Approximately a decade after the LAX FIDO activities, some passive thermal fog dispersal experiments were conducted in Japan. As described by Magono (1972), these experiments verified the practical feasibility of operational thermal fog dispersal.

Recently, Kunkel *et al.* (1974) described a series of passive thermal fog dispersal experiments conducted in California which confirmed the earlier findings of the FIDO program with respect to the characteristic pattern of temperature rise in a crosswind situation. The program also documented visibility improvements in the heat plumes that could only be inferred from the published FIDO data on temperature rise. Tag and Lowe (1974) recently reported on numerical simulations of passive thermal fog dispersal that could lead to extension of the past field results to a wider range of meteorological conditions.

b. *Thermo-kinetic systems*

The alternative to a passive system is one that uses thrust to direct the heat plume over its intended target. The best known system that uses this technique is a French one called Turboclair. As described by Sauvalle (1976), this thermo-kinetic system uses surplus jet aircraft engines aligned on one side of the runway to supply the heat and thrust. Turboclair systems were credited with assisting 128 low visibility landings during the 1976/77 winter fog season at Orly and Charles De Gaulle airports near Paris.

The first experience with thermo-kinetic fog dispersal in the United States was described by Appleman and Coons (1970). In this pilot project the exhausts from four C-141 aircraft were used to raise the visibility from 300 m to well over 800 m along the runway at Travis AFB, California.

Starting in 1971 the Air Force Cambridge Research Laboratories (now the Air Force Geophysics Laboratory) initiated a program to develop an efficient and effective thermokinetic fog dispersal system. This paper describes that program and presents a set of specifications for a thermo-kinetic fog dispersal system for use at commercial airports. A similar report by Kunkel (1978) describes the requirements for a fog dispersal system for U. S. Air Force bases. The primary difference in the requirements is the narrower approach zone clearing width specified by the Air Force, thus resulting in slightly smaller combustors in the approach zone.

3. Clearing geometry

Before specifying the amount of thermal and kinetic energy required, the volume to be cleared must be

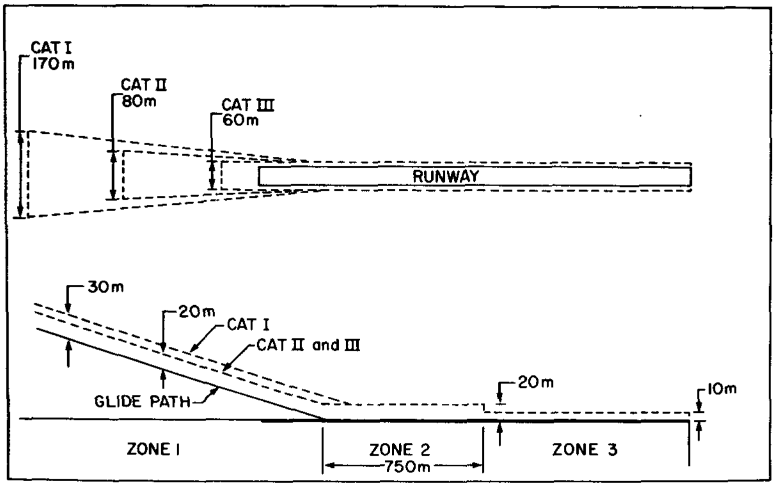


FIG. 1. Volume of space to be cleared of fog (reprinted from ICAO, 1977).

TABLE 1. Minimum volume of space to be cleared and RVR to be provided (reprinted from ICAO 1977)

Type of approach	Before the ILS touchdown point Zone 1—approach					After the ILS touchdown point Zone 2—touchdown				Zone 3—roll out and taxi			
	Length* (m)	Outer width (m)	Inner width (m)	Height above glide path (m)	RVR (m)	Length (m)	Width (m)	Height (m)	RVR (m)	Length** (m)	Width (m)	Height (m)	RVR (m)
Category I	100	170	60	30	800	750	60	20	800	—	60	10	200
Category II	100	80	60	20	400	750	60	20	400	—	60	10	200
Category III	100	60	60	20	200	750	60	20	200	—	60	10	200

* Before decision point.
** To runway end.

defined. The size of the clearing volume is defined by the type of instrument landing approach and the operational requirements within each approach category. The International Civil Aviation Organization (1977) has defined the minimum clearing volume for three types of approaches: Category I [Decision Height (DH) = 60 m, Runway Visual Range (RVR) = 800 m]; Category II (DH = 30 m, RVR = 400 m), and Category III (DH = 15 m, RVR = 200 m). Most major airports and commercial aircraft have Category II capability, while the smaller commercial airports have Category I approaches. As the microwave landing system comes into being Category III approaches will undoubtedly become routine at the larger airports. The minimum volumes to be cleared for the three types of approaches are shown in Fig. 1. Table 1 shows the minimum dimensions of the clearing volumes and the RVR's for the three landing categories. For a $2\frac{1}{2}°$ glide slope and a 2000 m long rollout (zone 3), the total length of zone 1 including the 100 m before the decision point and the total minimum volume to be cleared are shown in Table 2.

Since the heat requirements, and thus fuel consumption, are directly related to the size of the clearing volume, there is no question that a Category III thermal fog dispersal system (TFDS) would be the least expensive to build and operate. However, to determine the most cost effective TFDS, the costs of the dispersal system must be weighed against the costs of the different instrument landing systems and the frequency of fog with RVR less than the minimum for the particular landing category. A cost tradeoff analysis is beyond the scope of this report.

TABLE 2. Approach zone length and volume to be cleared.

Type of approach	Zone 1 length (m)	Total clearing volume (m^3)
Category I	1474	14 672 700
Category II	787	4 116 200
Category III	444	2 802 600

4. Theoretical heat and fuel requirements

In order to clear fog in a given volume of air, sufficient heat must be provided to evaporate the fog droplets and to accommodate the evaporated water in the vapor state. The amount of heat required to accomplish the former is directly proportional to the fog liquid water content. The amount of heat required for the latter is related to the temperature of the fog as well as the liquid water content.

Fig. 2 shows the amount of heat required to completely clear fogs of different liquid water contents and temperatures. Any hydrocarbon fuel that would be burned to create the heat would also produce some water vapor. The solid lines in Fig. 2 represent the heat requirements taking into account the water vapor from

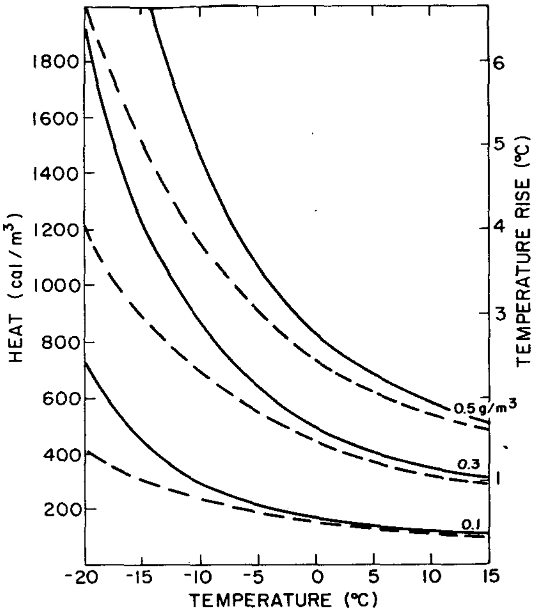
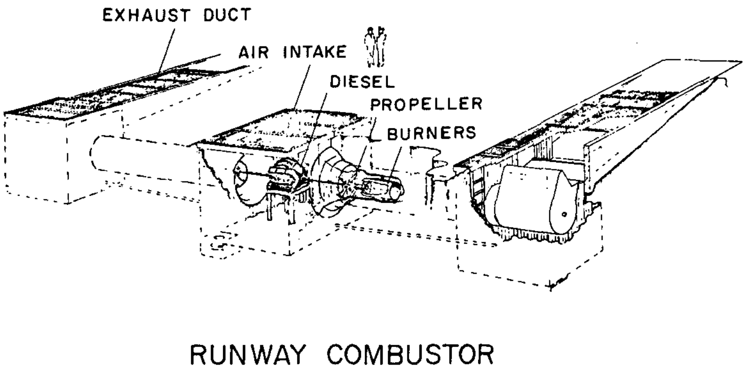


FIG. 2. Heat required to dissipate fog as a function of air temperature and liquid water content. Solid curves represent heat requirements taking into account the water vapor added to the air by the burning fuel. Dashed curves neglect the added water vapor.



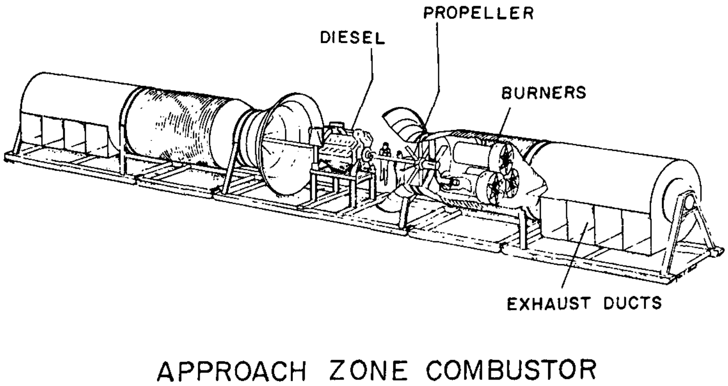


FIG. 3. Artist conception of runway and approach zone combustors.

the burning fuel. The dashed lines show the heat requirements if the added water vapor from the fuel is neglected. The temperature rise scale is approximate (±7%) since the temperature rise produced by a given quantity of heat is a function of the air density which varies slightly with temperature. The curves are based on an atmospheric pressure of 1000 mb.

Below 0°C the heat requirements begin to rise dramatically, especially at the higher liquid water contents. Above 0°C, the water vapor added by the burning fuel has little effect on the heat requirements. However, below 0°C the added water vapor becomes increasingly more important. Because of the higher heat requirements for below freezing temperatures, thermal fog dispersal is normally considered a warm rather than a supercooled fog dispersal technique.

The curves in Fig. 2 represent the heat requirements for total clearing. In reality, total evaporation need not be accomplished. Rather, only enough evaporation is needed to reduce the number and/or size of the droplets sufficiently to raise the RVR above the particular landing category requirement.

It would appear from Fig. 2 that a temperature rise of 2°C would be sufficient to disperse most warm fogs. Fogs with liquid water contents >0.3 g m^{-3} are quite rare and would normally not be suitable for a thermal fog dispersal system because the extremely low visibilities would impede the taxiing of aircraft. For most visibility and wind conditions, a 2°C temperature rise would provide a sufficiently rapid clearing as shown by Kunkel *et al.* (1974). This is below the 3.3°C (6°F) found during the FIDO experiments but is close to the 1.6°C assumed by Magono (1972) and the 2–3°C reportedly aimed for by the Turboclair system.

Table 3 shows the amount of aviation fuel required to raise the air temperature 2°C throughout the clearing volume for the various types of approaches.

The actual amount of fuel burned during a 5 min operation (the estimated time to land one aircraft) would be considerably greater since some heat will escape the clearing volume because of its own buoyancy and the wind. Also, in practice, the heat cannot be distributed uniformly, thus requiring a certain amount of overheating.

5. Review of USAF program

In 1971, the Air Force Cambridge Laboratories (now the Air Force Geophysics Laboratory) initiated a program to develop an efficient and effective thermal fog dispersal system (TFDS) that would be compatible with Category I operations. The objective was to design a system that would efficiently distribute the heat as uniformly as possible throughout the clearing volume, thus minimizing fuel consumption. Passive, heat tests

TABLE 3. Theoretical fuel requirements to raise air temperature 2°C for various types of approaches.

Type of approach	Fuel (liters)
Category I	995
Category II	279
Category III	190

described by Kunkel *et al.* (1974), pointed out the inefficiency of a passive type system which depends quite heavily on the winds and requires large amounts of energy in order to insure adequate heating in the clearing volume. As a result, subscale tests conducted on a 1:6 distance scale (Kunkel, 1975) were performed in 1974. Blowers were used to project the heat from propane burners over a hypothetical runway. Tests were conducted in clear air and an array of thermistors and wind sensors were used to measure the heat plume profile under a variety of heat, thrust and wind conditions. Froude number scaling laws were used to determine the heat and thrust requirements and combustor spacing for a full scale TFDS. In the meantime, theoretical studies on the behavior of buoyant round and planar jets in a wind field were being conducted and were summarized in a series of publications (Klein and Kunkel, 1975a,b; Klein, 1977a,b, 1978). As a result of these studies, combustor specifications were derived for a full scale TFDS. A contract was awarded to Ultrasystems Inc., Irvine, California, to design, fabricate and test one runway combustor and one approach zone combustor. Because of the inherent uncertainties in scaling up to full scale, the two combustors were designed with 50% more heat and 30% more thrust than the estimated required amounts.

An artist's conception of the two combustors designed by the contractor is shown in Fig. 3. Each combustor produces two exhaust flows of heated air directed toward the runway at a prescribed elevation angle. Each unit consists of a central diesel engine with propellers at each end to produce the combustion air and the thrust air. The air is heated as it passes by a burner located in front of each propeller, and then enters an elbow where it is turned 90°. The elbows rotate in the vertical to allow the thrust to be projected out at different elevation angles.

TABLE 4. Combustor design and performance specifications.

	Approach	Runway
Center–center outlet distance (m)	23	18
Diesel engine horsepower	750	230
Outlet area (m^2)	4.67	1.17
Thrust range (kg)	118–593	26–133
Heat range (kcal s^{-1})	472–4720	126–1260
Max exhaust temperature (°C)	222	264
Max exhaust velocity (m s^{-1})	37.8	36.6

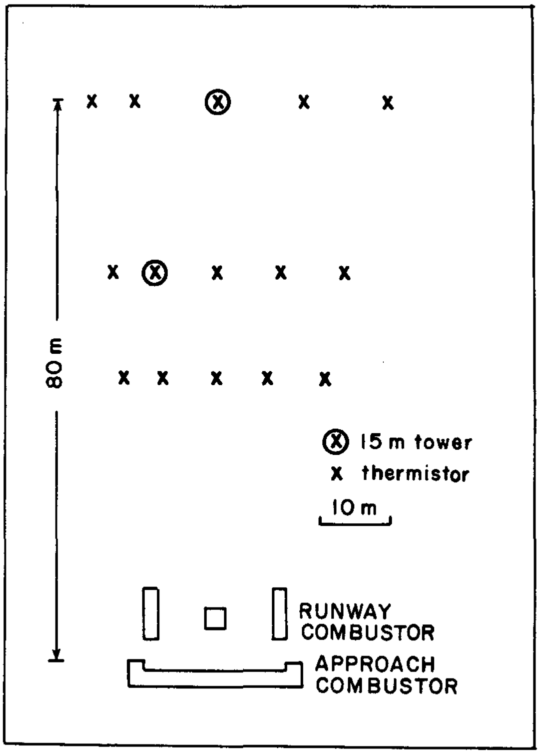


FIG. 4. Layout of combustors and thermistors at the El Toro test facility.

The runway unit is designed to be flush with the ground so as not to be a hazard to aircraft that might accidently veer off the edge of the runway. The approach zone combustor was designed for above ground use. Table 4 lists the design and performance parameters of the two combustors. Thrust is specified instead of velocity or momentum because theory shows that the plume projection distance is a function of the outlet area and the square of the outlet velocity. Thrust is also related to the area and velocity squared such that

$$\text{Thrust} = V^2 A\rho/g,$$

where V, A, ρ and g are outlet velocity, outlet area, air density and gravitational acceleration, respectively.

In June 1978, tests were conducted with the two combustors to verify or improve on the heat and thrust requirements as determined from the subscale tests conducted in 1974. The tests were conducted at the Ultrasystems test facility at El Toro, California. An array of 24 thermistors, as shown in Fig. 4, was installed downstream of the combustors. Fifteen thermistors were installed in a horizontal array 3 m above the ground. Five thermistors and single-component R. M. Young wind sets were mounted every 3 m on each of the two 15 m towers. The closer tower is positioned at the near edge of a hypothetical runway and the far tower at the centerline of a 45 m wide runway. A reference wind set and thermistor were mounted about 150 m from the site

Fig. 5. Photograph of runway combustor heat plume illuminated by smoke and searchlight.

and outside the area affected by the combustors. Although it would have been desirable to place thermistors more than 80 m from the large combustor, this was not practical because of the extremely hilly terrain beyond this point. All data were fed into a 100-channel data acquisition system and recorded on magnetic tape. In many of the tests that were conducted at night, smoke was introduced into the plume, illuminated with a search light, and then photographed. These pictures, an example of which is shown in Fig. 5, provided a means of determining the areal extent of the heat plume. Subjective measurements of lift-off distances were also made for each test by physically feeling the heat plume and determining where it appeared to lift off the ground. By combining these three forms of data, a reasonable picture of the heat plume from the runway and approach zone combustors can be obtained, as illustrated in Figs. 6 and 7. The shaded area in the upper portion of the figures represents the vertical cross-sectional area outlined by the smoke. The bottom portion shows the temperature rise contours for the 3 m level. The temperature rises represent 1 min averages, whereas the lift-off distance and plume profile, as defined by the smoke, represent 10–15 s averages.

Tests were conducted at night in clear air under a variety of heat, thrust, thrust angle and wind conditions. Tests were restricted to times when the winds were generally <2 m s^{-1}. Crosswinds, or winds perpendicular to the combustor flow, were restricted to 0.5 m s^{-1} or less. As it turned out, 95% of the tests were conducted with a headwind as opposed to a tailwind. There were 127 tests conducted with the runway combustor and 165 tests with the approach zone combustor. Each test lasted for a period of 3–5 min.

To determine the appropriate heat output for fog clearings the combustors were operated at various heat settings and the temperature changes (ΔT) were observed. It was assumed that temperature rises of 2–3°C were adequate to clear the fog. Since temperature measurements were made only up to 15 m height one can only conjecture as to the heat requirements for clearing higher than 15 m. The subscale tests indicated heat requirements of 283 and 420 kcal s^{-1} per runway combustor outlet for clearing depths of 15 and 30 m, respectively, and 1589 kcal s^{-1} per approach zone combustor outlet for a clearing depth of 60 m. These values assume combustors on both sides of the runway and approach zone. Operating the runway combustor

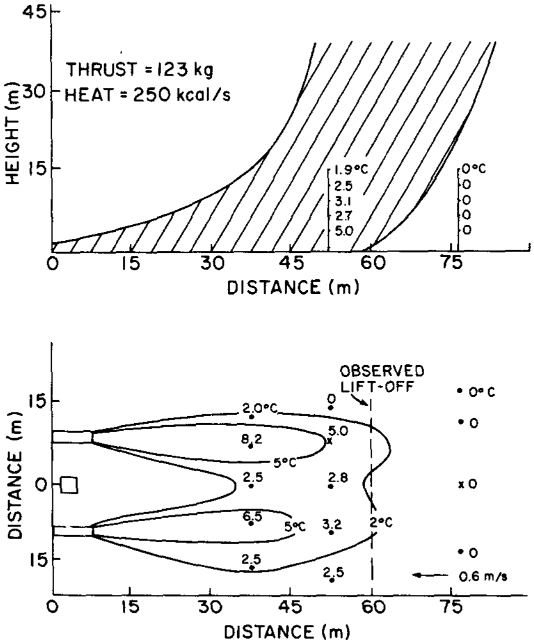


Fig. 6. Top and side views of runway combustor heat plume as depicted by the smoke and thermistors.

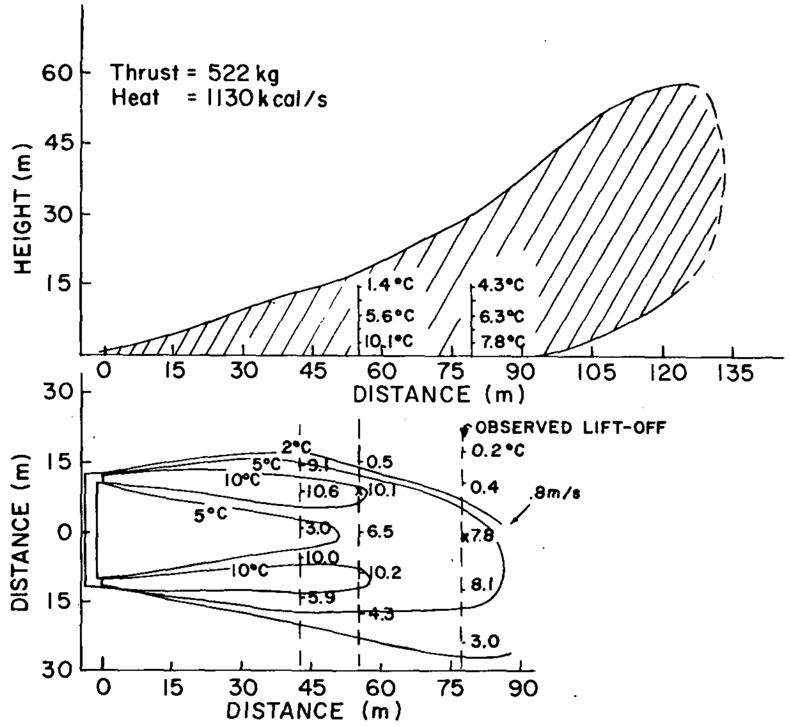


FIG. 7. Top and side views of approach zone combustor heat plume as depicted by the smoke and thermistors.

near the two heat outputs produced temperature rises of 4–5°C at the near tower and 2°C at the far tower when the plume reached that far. Operating the approach zone combustor at the above heat output resulted in maximum ΔT's of approximately 11 and 7°C at the near and far tower, respectively. In both cases, this would appear to be adequate heat for clearings to depths of 30 and 60 m. Therefore, based on the restricted measurements of the full-scale tests, the heat requirements derived from the 1974 subscale tests appear to be reasonably valid.

Thrust settings were also varied to determine the appropriate thrust settings for various heat outputs and wind conditions. The observed lift-off distances were compared with the subscale and theoretical results. It was determined from the tests that the lift-off point D occurred when plume centerline height Z was approximately equal to $0.17D$. These distances were compared with the trajectories derived from the round jet model described by Klein and Kunkel (1975b) and with the subscale projection distances, defined in full scale as the plume distances when the centerline heights are equal to 7.8 m.

Fig. 8 shows a comparison of the full-scale, subscale and theoretical lift-off distances for both the small and large combustors. The full-scale test results are an average of all tests in which the heat outputs were close to the optimum heat settings described above. In most cases the wind was a headwind and averaged 0.5 m s^{-1}. Five different thrust settings on each combustor were used during the tests. Since lift-off points beyond 80 m were difficult to measure because of the hilly terrain, the lift-off distances at the three higher thrust settings on the large combustor are approximate. The subscale results are based on a 0.5 m s^{-1} headwind. However, the theoretical results are based on zero wind since the model is not designed for headwind cases.

The plume from the larger combustor shows shorter distances than the plume from the smaller combustor for a given thrust because of its larger heat output and consequently, greater buoyancy. In general, the three approaches show reasonably good agreement. However, the full-scale results show a steeper slope at the higher thrust levels. In other words, greater thrust increases are required to increase the distance by a given amount. In fact, during some test sequences, little change was noticed in the plume behavior when going from 60 to 100% thrust. It is believed that if a line of combustors were used, as they were in the subscale tests, that the lift-off distances at the greater distances would be increased because of the merging of the plumes and the thrust/distance slope would be similar to that of the subscale tests.

The effect of wind speed on the plume trajectory was also determined. In general, the effect was less than that indicated by the subscale tests and the model, as shown in Table 5. The 35% reduction in plume lift-off distance as the headwind increased from 0–1.5 m s^{-1} is considered a maximum change. At several combustor settings, wind appeared to have no or very little effect.

Some of the scatter and apparent inconsistencies in the data are believed to be due to the fact that, because of the hilly terrain, the reference wind was at times not representative of the wind affecting the plume.

The effect of heat output on the plume trajectory was also compared with that predicted by the subscale tests and the model. Again, as with the wind, the effect due to varying heat was less than expected. As illustrated in Table 5, as the heat increases tenfold, the plume lift-off distance decreases 25% while both the model and the subscale tests show a 65% decrease.

There is no apparent explanation of this relatively insensitive behavior of the plume to changes in wind and heat. In any case, the reduced dependency on wind and heat is encouraging because it means a more stable plume and, therefore, more persistent clearings than one would have thought possible based on theory and the subscale results.

The combustors were also operated at different vertical thrust angles to determine the effect of the thrust angle on the plume trajectory. Thrust angles could be varied in 15° increments. These tests were conducted only in tailwind situations. It became quite apparent that raising the thrust angle only 15° raised the plume some 15 m off the ground over the target area, at least in tailwinds up to 1.5 m s^{-1}. Greater thrust angles placed the plume well above the two 15 m towers. It would appear that only at those airfields that experience high crosswinds in fog would there be a need to vary the vertical thrust angle, and then probably only in a Category I approach zone, where clearings must extend up to 90 m.

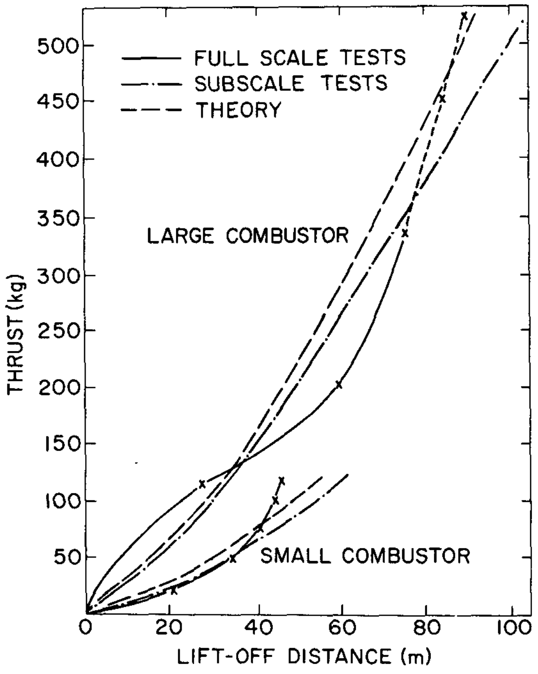


Fig. 8. Lift-off distance as a function of thrust for both combustors as derived from full-scale and subscale tests and from theory.

Table 5. Percentage reduction in plume lift-off distances as headwind component increases from 0–1.5 m s^{-1} and heat output increases tenfold.

	Percent reduction	
	Wind increase (0–1.5 m s^{-1})	Heat increase (10×)
Subscale	65	65
Theory	55*	65
Full scale	35	25

* Represents the percentage change as tailwind decreases from 1.5–0 m s^{-1}.

6. Thermal fog dispersal system specifications

A modern thermal fog dispersal system (TFDS) should consist of three major components—the combustors, the fuel distribution subsystem and the control subsystem. The TFDS should be fully automated so that it can be operated and monitored from one central control point, thus minimizing the number of operators and providing fast turn-on and turn-off capability in order to conserve fuel. For most efficient and reliable operation, meteorological data should be fed into the control center and used to optimize the combustor settings.

The number and size of combustors will vary depending on the approach category and the expected winds in fog at the particular location. Since more than one size combustor is required, because of the varying geometry, there are certain tradeoffs that should be considered which would have an impact on costs and complexity. At airfields with light crosswinds or crosswinds from one predominant side, the most economical system may be one which employs one line of larger combustors on the upwind side rather than two lines of small combustors. In the approach zone where the cross-sectional area expands, the most effective system would be one in which the combustors increase in size as the cross-sectional area increases. However, this type of system would not be practical from a production and maintenance standpoint. A more realistic approach would be to vary the spacing between outlets, the spacing decreasing with increasing cross section, thus in effect increasing the heat output per unit length of approach as the cross section increases. In this study we will assume a maximum of three different sized combustors.

Based on the results of the full-scale and subscale tests and the theoretical work, combustor specifications were derived for the various geometries of the three approach categories as shown in Fig. 1. These specifications are shown in Table 6 along with the fuel consumption required to produce the specified heat. It is assumed that combustors are placed on both sides of the runway.

It should be emphasized that there could be many variations to the specifications in Table 6. Various tradeoffs, depending primarily on costs, can be made in the

TABLE 6. TFDS combustor specifications for different approach categories.

Zone	Average heat output (kcal s^{-1})	Maximum thrust (kg)	Spacing (m)	Number of outlets	Distance from centerline (m)	Length (m)	Fuel consumption (ℓ min^{-1})
				CATEGORY I			
1	3000	750	18–32	42	150	515	952
	1500	500	16–28	46	115	515	520
	500	150	11–18	60	80	444	224
2	350	150	18	84	80	750	220
3	250	150	30	134	80	2000	252
Total				336		4224	2168
				CATEGORY II			
1	1150	500	20–32	24	115	343	208
	350	150	13–21	52	80	444	140
2	350	150	21	72	80	750	200
3	250	150	30	134	80	2000	252
Total				282		3537	800
				CATEGORY III			
1	350	150	18–30	36	80	444	96
2	350	150	30	50	80	750	132
3	250	150	30	134	80	2000	252
Total				220		3194	480

spacing and distance of combustors from the centerline and in segment length, all of which have an affect on the heat and thrust output and number of outlets.

The maximum thrust is that thrust required to project the heat into the volume on the near side of the centerline in calm or parallel wind conditions. In a crosswind situation the heat from the upwind combustors will cover more of the clearing volume, while the heat from the downwind combustors will cover less. At some point, $\sim$2 m s^{-1}, the downwind combustors can be shut off and all the clearing can be done by the upwind combustors. In this situation, the heat output of the upwind combustors should be about double the average heat output, thus maintaining a constant heat output per unit length of runway. To allow for crosswind situations, the maximum heat output of each outlet should then be twice the average output. It will be noted that there are five different heat output specifications for a Category I system. However, one burner could be designed to operate at the three lower heat settings, thus maintaining the requirement of no more than three different-sized combustors.

The spacing of the combustors was adjusted to take into account the less stringent RVR requirements for Categories II and III and for the rollout of a Category I approach system. Using the relationship between extinction coefficient and drop size and concentration, and Allard's law, which relates visual range with the extinction coefficient, and assuming a worse case of 100 m RVR, it can be shown that most of the drops must be evaporated to achieve 800 m RVR while 84% must be evaporated to achieve 400 m RVR and 60% to achieve 200 m RVR. For higher initial RVR's the percentages would be lower. To achieve 84 and 60% clearing, the number of combustors can be decreased 16 and 40%, respectively, thus resulting in an increase in spacing of 19 and 67%, respectively.

The distance between the line of combustors and the centerline was based on the fact that the distance between the combustors and the edge of the clearing zone should be at least 2.5 times the spacing between outlets in order to assure adequate merging of the plumes. This, however, would not be required for achieving 400 m or 200 m RVR where complete merging is not necessary.

Table 6 clearly shows the advantages of a Category II TFDS over a Category I TFDS. The need for large thrustors is eliminated, the number of combustors is reduced by 16% and, probably most importantly, the fuel consumption is reduced by 63%. Additional fuel savings can be realized with a Category III TFDS. However, the low frequency of sustained fogs with RVS's $<$200 m would probably not warrant the construction of a TFDS.

It should be emphasized that the specifications given in Table 6 are based on subjective interpretation of rather limited tests and on theoretical studies. The ultimate test would be with a full-scale system at an airport. However, additional testing in fog, using two rows of combustors with a minimum of six to eight outlets per row and adequate visibility and wind instruments, would be desirable in order to further optimize the size and orientation of the combustors. Without this additional testing, it is recommended that the heat and thrust specifications be increased ~20% to provide an adequate safety margin. This amount of reserve would be sufficient to produce a noticeable change in the plume characteristics, but would not be so large as to significantly increase the costs of the system.

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