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determine seeding material concentrations produced as the result of dispensing material into the downwash. Continuous seeding while hovering, pulse seeding while hovering, and the effect of helicopter movement are examined. These cases are studied in conjunction with results generated from earlier hygroscopic seeding studies. It is determined that, for the purpose of utilizing both techniques simultaneously, it is not possible to effectively combine helicopter downwash and hygroscopic seeding. A helicopter can be used as a reasonable platform from which seeding material can be dispensed. However, before downwash efforts are initiated, sufficient time must be permitted for the hygroscopic mechanism to work.

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**A NUMERICAL STUDY OF CLEARING WARM FOG
BY USING HYGROSCOPIC SEEDING
IN CONJUNCTION WITH HELICOPTER DOWNWASH**

by

PAUL M. TAG

MAY 1974



ENVIRONMENTAL PREDICTION RESEARCH FACILITY
NAVAL POSTGRADUATE SCHOOL
MONTEREY, CALIFORNIA 93940

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I. INTRODUCTION

Several techniques have been investigated for the purpose of dissipating warm fog. Cold fogs, those in which the air temperature lies below 0°C, have proven fairly amenable to modification and are being dissipated operationally (Fletcher, et al., 1970). It is warm fog, however, which most commonly affects the primary areas of man's environment and the Navy's areas of operational interest. Because of the severe impact it can have on land, air, or sea operations, much effort has been devoted to developing techniques for warm fog dissipation which are relevant to military operations.

To consider a fog dissipating technique to be "relevant" is perhaps somewhat premature when one realizes that no warm fog dissipating technique has yet proven fully reliable or successful. The Air Force is actively pursuing a thermally driven system as the potential solution for fixed-base airfields (Weinstein, 1973). Such a technique, while very satisfactory for a fixed airfield, is, however, not very applicable to Navy or Marine Corps operations where carrier or battleground landings are necessary. Permanently installed clearing equipment is of no use, except possibly on board a large carrier.

A technique more applicable to such operations and which showed some promise of success for fogs of limited depth was that of helicopter downwash. The Army and Air Force (Plank, et al., 1970) and the Marines (Leipold, 1972) conducted field experimentation to determine the limitations of this method. Plank, et al., concluded that cleared zones large enough for helicopter landings could be effected under naturally occurring fog situations when the fog depth is less than 300 ft. A recent numerical study of downwash-induced clearings by Johnson, et al., (1973) defines several parameters which are key indicators of the depth to which a clearing can be produced.

At about the same time that field tests of downwash clearings were being conducted, the investigation of hygroscopic seeding as a fog dispersal technique was being enthusiastically pursued. Theoretical studies, including those of Silverman (1970), Tag, et al. (1970), and Tag (1971), demonstrated a sound basis for the technique. Consequently, in an attempt to augment the clearing capability of helicopter downwash, field tests were conducted in which hygroscopic seeding material was dispensed into the downwash of a helicopter (Leipold, 1972).

It was the purpose of this study to investigate, primarily by means of a two-dimensional model, the ramifications of dispensing seeding material from a helicopter. The path of the material in response to a hovering and a simulated-moving helicopter was considered. In addition, the implications of combining downwash and hygroscopic seeding to clear fog were analyzed.

2. BACKGROUND AND THEORY

Clearing warm fog by means of helicopter downwash depends on mechanisms very different from that of hygroscopic seeding. A clearing produced by helicopter downwash is essentially the result of two mechanisms. One is simply the physical blowing away of fog droplets by the downwash wind. The other is evaporation of fog droplets in response to warmer and dryer air being forced into fog laden air from above. The air may be warmer as a result of the typical inversion characteristic of a radiation fog sounding or because of heat addition from the helicopter engines. Johnson, et al. (1973) concluded that both mechanisms (advection and evaporation) were important in their numerical simulations of downwash-induced clearings.

The effect of direct advection of fog droplets is almost immediate. The velocity of air movement below a helicopter is on the order of from 1 to 20 meters per second. Consequently, advection proceeds on the order of seconds or, at the most, tens of seconds.

Similarly, the effect of heat is just as immediate as that of advection. Figure 1 shows the effect of an instantaneous temperature rise on the visibility and liquid water content of a moderately dense fog. These results were generated by the one-dimensional model used in earlier hygroscopic studies (Tag, et al., 1970; Tag, 1971). The figure makes quite clear the point that the effect of heat is also an immediate one.

On the other hand, the mechanism at work as the result of hygroscopic seeding is a relatively slow one. Instead of seconds, as with the above examples, time-lags on the order of minutes are required. Table 1, taken from Tag (1971), shows the minimum time required to produce a clearing as a function of the treatment size. Figure 2 (taken from Tag (1971) and applicable to the fog discussed in the previous paragraph),

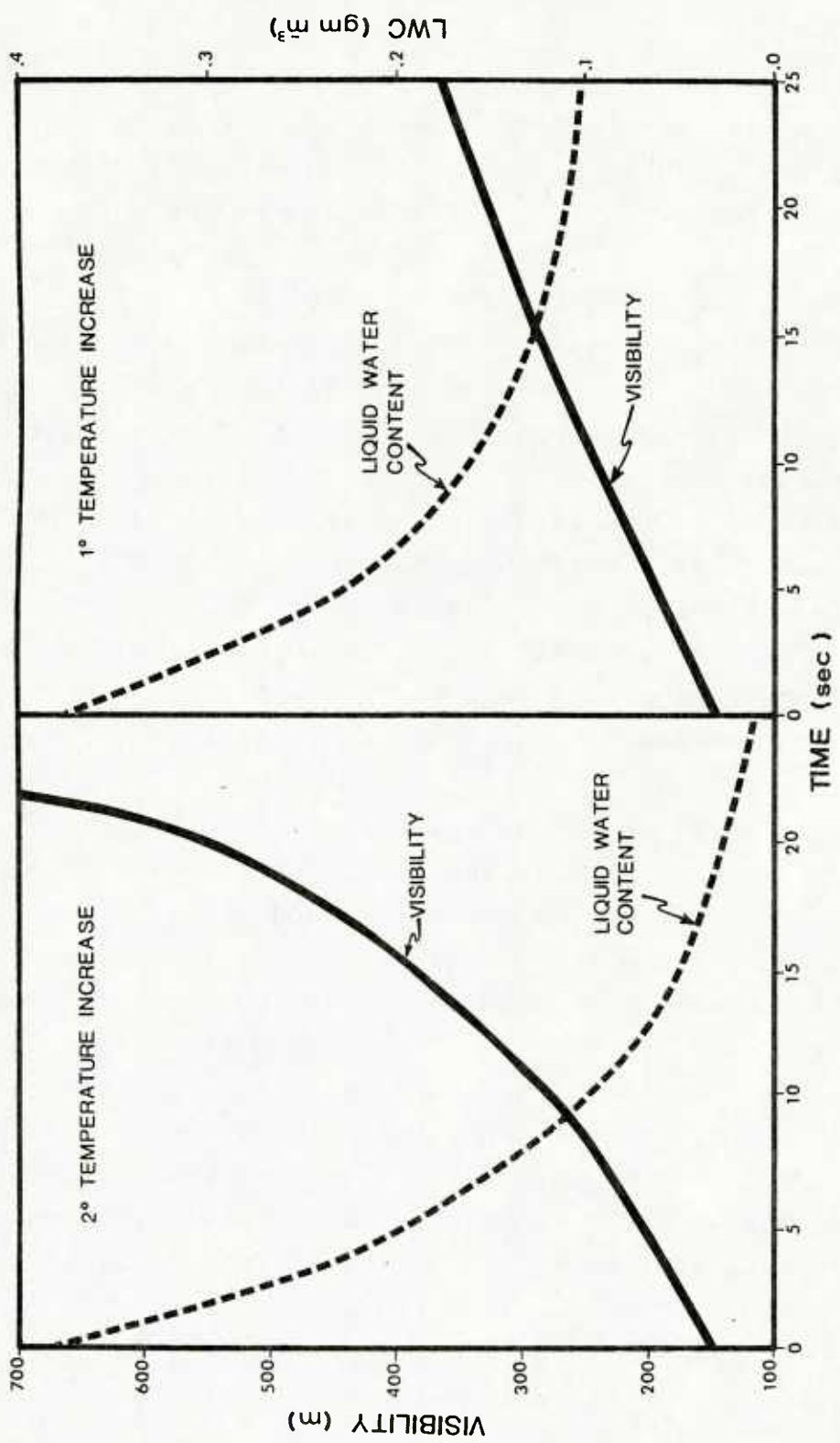


Figure 1. Visibility Increase and LWC Decrease in Response to an Instantaneous Temperature Increase.

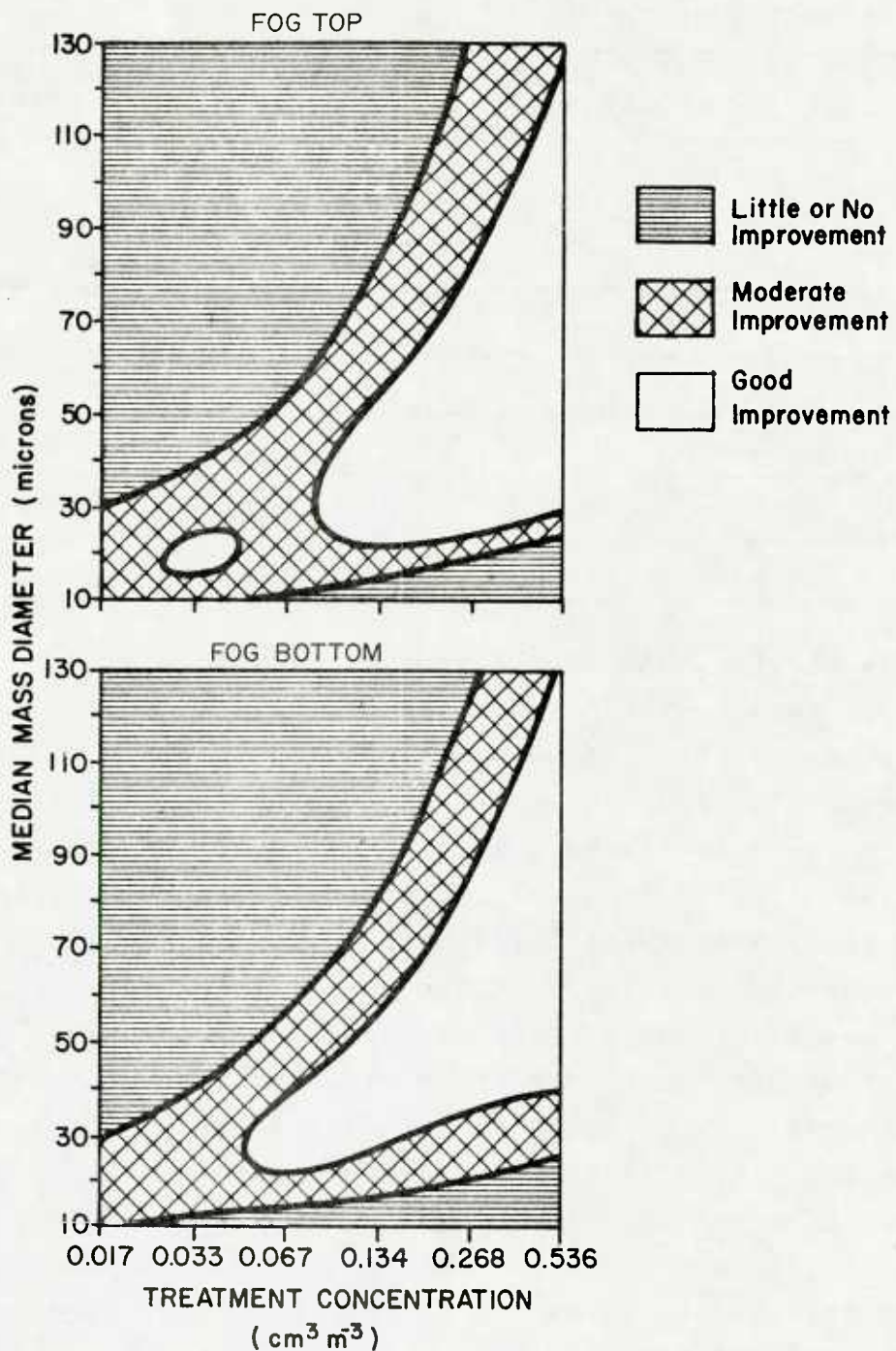


Figure 2. Visibility improvement (30 minutes after seeding) as a function of treatment drop size and concentration (Fog LWC = 0.39 gm m⁻³; fog depth = 150 m).

Table 1. Clearing times required for various median mass treatment spectra.

MEDIAN SPRAY-SIZE DIAMETER (MICRONS)	MINIMUM TIME REQUIRED FOR A CLEARING (MINUTES)
< 10	Impractical for Field Use
10 - 20	30 - 60
20 - 30	20 - 30
30 - 40	15 - 20
40 - 60	10 - 15
60 - 100	5 - 10
> 100	< 5

shows, however, that decreased clearing time is not realized without cost. As clearing time decreases, treatment size increases, necessitating corresponding treatment concentration increases in order to effect a given degree of improvement.

Because an aircraft is usually the platform from which seeding material is dispensed, there is a physical limitation to treatment quantity that can be carried aloft. Consequently, smaller treatment particle or spray sizes have been necessary and, indeed, are the more economical. This criterion has forced a minimum clearing time on the order of 15 minutes. Thus, compared with the effect of heat or advection, the effect of hygroscopic seeding is one to two orders of magnitude slower. A fundamental purpose of this paper is to make some relevant suggestions with regard to using together two clearing techniques which operate on such a disparity of time scales.

3. MODEL DESCRIPTION AND INPUT

1. BASIC MODEL DESCRIPTION

The numerical model used for this study is a variation of the warm precipitation version of the RAND cumulus dynamics model (Murray and Koenig, 1972). A general description of the model and a specific explanation of how inert seeding material is placed into the flow of a simulated helicopter will be covered. However, for the specific equations and computational procedure the reader is referred to Murray and Koenig (1972) or Johnson, et al. (1973).

The model is a two-dimensional vorticity model. Computations at the centerline are treated as though they have axial symmetry. The other boundaries of the domain are treated as rigid and free-slipping. Utilizing a 10-meter grid spacing, the modeled volume is a cylinder 350 m in radius and 500 m in height.

The equations of motion, which utilize the Boussinesq approximation and the continuity equation, provide the basis for the model. The thermodynamics of the model include temperature changes resulting from warm phase changes of water. Water is partitioned into vapor and suspended cloud water. The work of Johnson, et al., utilized the complete thermodynamic equation in order to simulate the downwash effect on the fog liquid water. Because the purpose of this study is, however, merely to follow inert material dispensed into the downwash, there is no need to include a fog -- consequently, there is no need for the liquid water partitioning.

No attempt is made at simulating the effect of the hygroscopic material on the fog. The effect of treatment quantities and sizes had already been ascertained from the one-dimensional model of Tag, et al., (1970) and Tag (1971).

2. DOWNWASH SIMULATION

The method used by Johnson, et al., whereby a fixed region of the computational domain was constrained to a certain value of vorticity, is again utilized to simulate the downwash from a helicopter. By prescribing certain values of vorticity in this region, a downwash or velocity profile (largest near the constrained region and diminishing downward) is achieved.

Figure 3 illustrates the constrained zone of the computational domain. Shear between the downwash and the environment occurs along the $J = 2$ column and, as a result, the velocity of the downwash is specified by the strength of vorticity of the $J = 2$ column. The points in the column adjacent to the $J = 2$ column, the $J = 3$ column, as well as the top-point (in the constrained region) of the $J = 2$ column, are constrained to zero. At the model's centerline (recalling that the $J = 1$ column is the center of a cylindrical domain) vorticity is also set to zero, as well as on the free-slip boundaries of the domain.

Leipold (1972) described several field tests utilizing hygroscopic seeding in conjunction with a CH-46 helicopter. This medium size, twin-rotor helicopter was mounted with internal and external (hanging) seeding pods. In an attempt to model the downwash profile for this helicopter, the velocity profile in the model, which is a function of the vorticity prescription, was tuned to an observational profile. Plank, et al., (1970) provided a two-dimensional circulation structure (complete with isotachs) from which a centerline velocity profile could be taken. This observed profile, along with the simulated one used for the numerical experiments to be described, is shown in Figure 4.

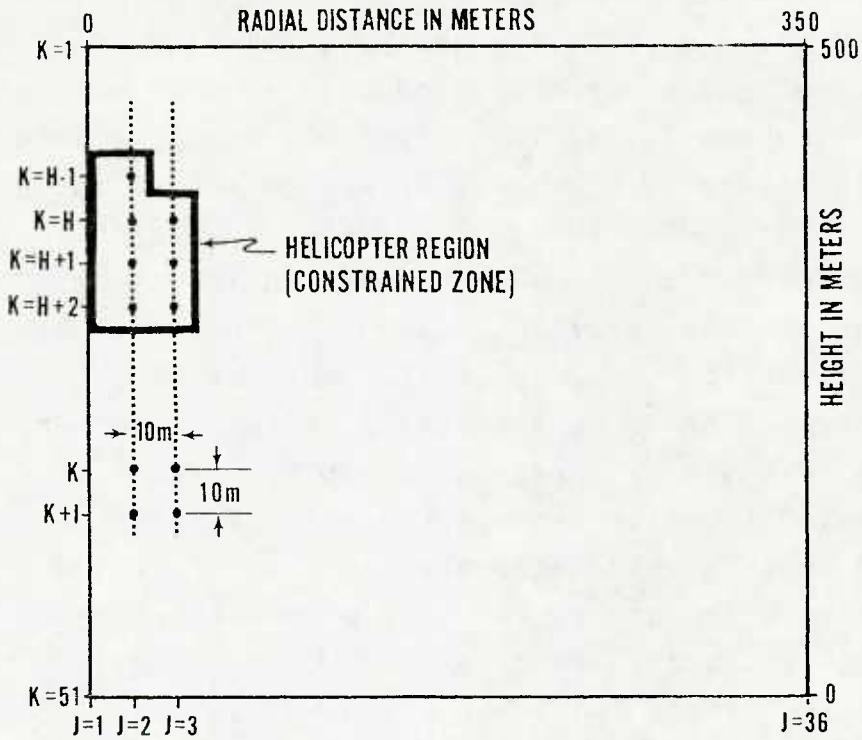


Figure 3. Computational domain (assuming axial symmetry) of two-dimensional model.

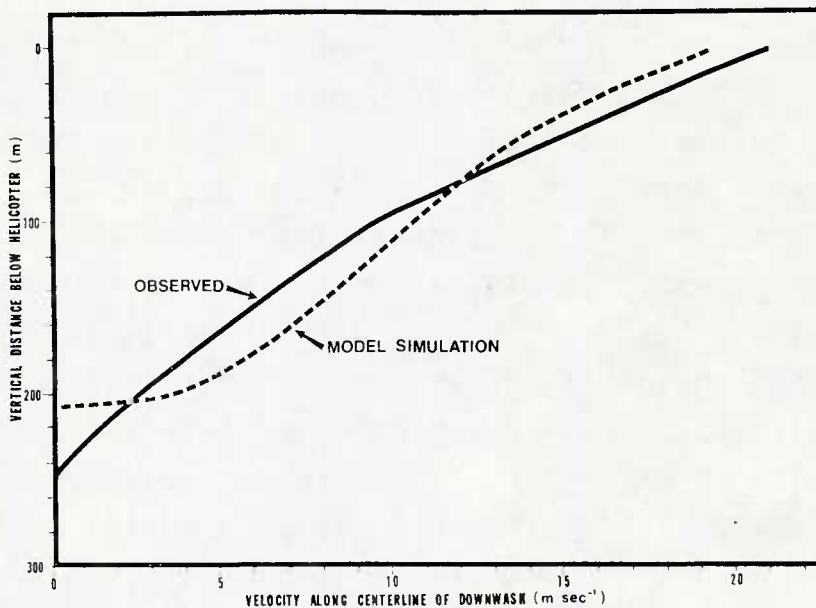


Figure 4. Observed and model approximation of CH-46 helicopter downwash profile.

As one would expect, the observed velocity is at a maximum very near the helicopter. In producing a model simulation, the first step was to adjust the value of the vorticity center so as to duplicate this maximum speed. Although the duplication near the top was very good, it was discovered that another change had to be made in order to improve the correlation along the total profile. Such an adjustment was achieved by means of varying the eddy coefficient for momentum. The coefficient that produced the best profile simulation, and represents that shown in Figure 4, was $5 \text{ m}^2 \text{ sec}^{-1}$.

In making the test profile comparisons it was also discovered that the simulated profile, as a function of a constant vorticity center, was very much a function of the height of that center. This point is to be expected, however, because of the effect the lower boundary has on the downwash. For this reason, a model vorticity height (helicopter height) was chosen for initial calibration purposes to be approximately the same as that for the observed profile.

3. SEEDING SIMULATION

Once the downwash profile had been simulated, the remaining step necessary for the present study was to incorporate a means of dispensing seeding material into the downwash. For this purpose a special array for inert material was set up. A value in the array (representing a point on the grid) is permitted to change as the result of advection and turbulent mixing. At the start of the program or as required, a source term allows for the introduction of material at helicopter level.

Leipold (1972), in his description of helicopter seeding, gave specifications regarding the external seeding pods. Each of the 66 ft^3 pods could carry 2000 lbs of material. When pressurized to 5 psi, the material could be released at rates ranging from 50 to 500 lbs per minute.

For the purpose of the experiments it was decided to simulate the maximum flow rate. Since the possibility of visibility improvement is much greater under conditions of large concentrations (see Figure 2), this specification seemed reasonable. Consequently, a seeding rate of 8.36 lb sec^{-1} or 3.8 kg sec^{-1} is used. Referring to Figure 3, this amount is evenly distributed over a volume appropriate to the two grid points $k = H, J = 1$ and $k = H, J = 2$.

4. HELICOPTER HEAT AND MOISTURE INPUT

In an attempt to realistically simulate the helicopter's presence, heat and moisture appropriate for the CH-46 are added to the downwash in the same location as that of the seeding material. The introduction of either, but particularly the heat, causes changes in the buoyancy, and thus the depth to which the downwash penetrates. Although not mentioned previously, these terms were included for the comparison with the observed profile. Johnson, et al. varied the amount of heat and moisture introduced into the downwash in order to determine the effect on the fog. For the present study the only purpose of the moisture and heat is to more correctly describe the downwash into which the seeding material is introduced.

5. MODEL SOUNDING

The sounding shown in Figure 5 is the one utilized for the experiments to follow. The inversion is typical of a radiation-type fog.

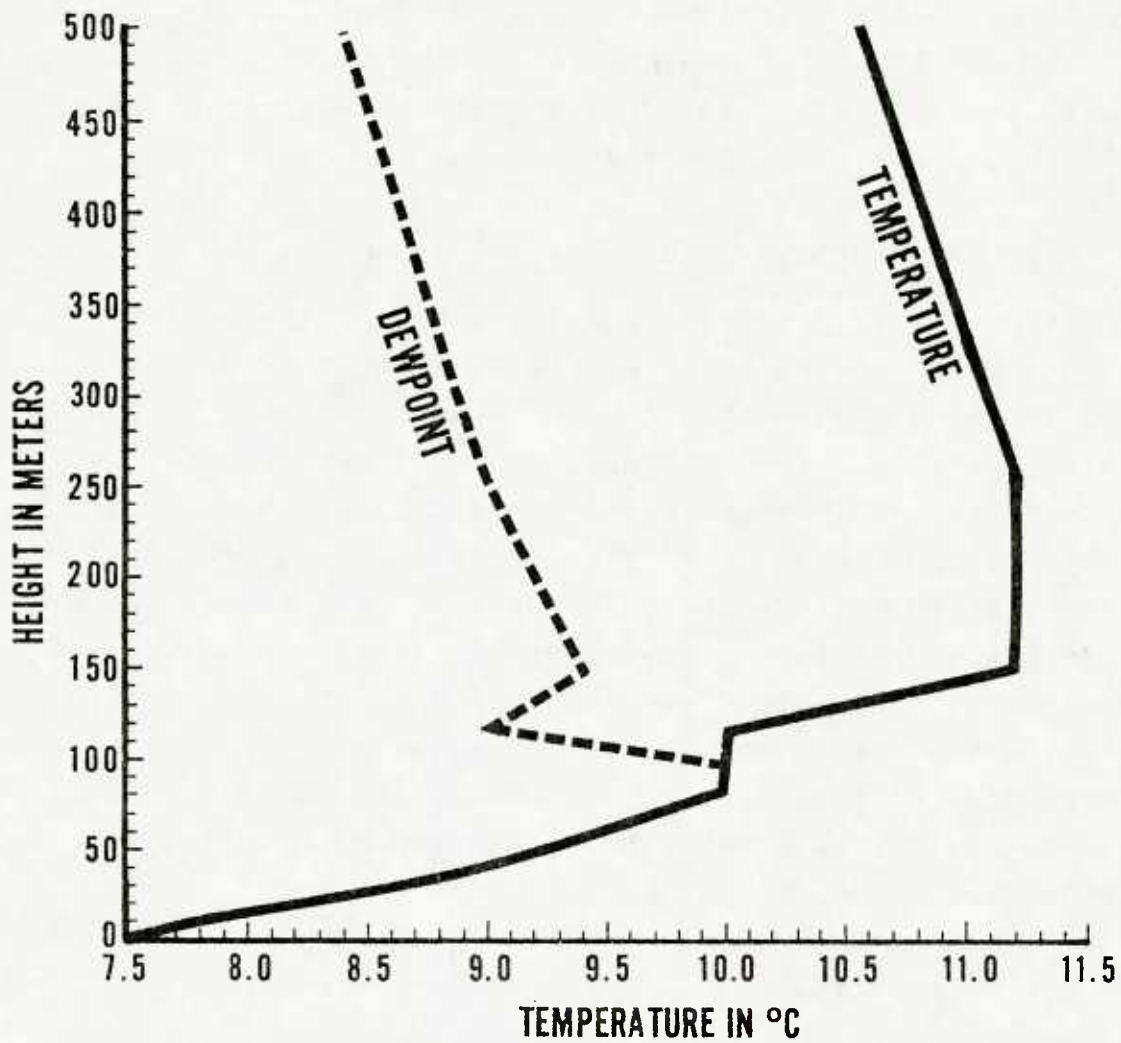


Figure 5. Sounding utilized for two-dimensional simulation of seeding.

4. OBJECTIVES AND MODEL RESULTS

1. SPECIFIC OBJECTIVES

A number of experiments were run in order to provide answers to the following questions:

(a) Can helicopter downwash be successfully combined with hygroscopic seeding in the hover mode? It was mentioned earlier that the two techniques work in completely different time frames. Consequently, such a disparity of scale might make the two uncombinable.

(b) When operating from the continuous hover mode, would pulse seeding be more advantageous than continuous seeding?

(c) To what depth can seeding material be forced by a CH-46 helicopter? Does ground effect have an influence?

(d) If (a) above should indicate that the hover mode is not a feasible way to combine hygroscopic seeding and helicopter downwash, is horizontal speed of the helicopter a critical parameter with regard to using a helicopter only as seeding vehicle? What advantage would a helicopter have over a fixed-wing aircraft?

The following series of experiments were run to provide insight to the questions listed above. The description of each will be accompanied by a sequence of graphical VARIAN plots of treatment concentration and velocity vectors for the flow field. These vectors are logarithmically scaled. The isolines of treatment concentration depict a minimum concentration of 0.05 gm m^{-3} with increasing increments of 0.05 gm m^{-3} . The threshold of 0.05 gm m^{-3} is based on Figure 2. Notice that 0.05 gm m^{-3} (assuming a treatment material density of 1 gm cm^{-3}) is the minimum concentration (with any median-size distribution) required to produce a significant visibility improvement in that particular, moderately dense fog. The time given in each illustration is in minutes.

2. CONTINUOUS HOVER AND SEEDING

Figure 6 represents continuous seeding from a hover mode at 150 m. Notice that in response to the large downward velocities in the downwash center, seeding material reaches the ground in less than 24 seconds (Figure 6(b)). From then on, the only change in the distribution of material is seen in the horizontal spreading of material at the surface.

It would appear that, at one minute (Figure 6(e)), a nearly steady-state condition is reached. Material is being mixed and advected outward (horizontally at the surface) into areas where the concentration is less than that represented by the threshold isoline, at nearly the same rate as it is being inserted at 150 m. No removal of material is permitted at the surface. Consequently, all seeding material inserted into the downwash remains airborne.

The obvious conclusion provided by Figure 6 is that continuous seeding from a hover mode only 150 m from the surface is extremely wasteful of seeding material. It is not necessary to force seeding material throughout the entire depth of a fog. The very mechanism of hygroscopic clearing relies on the fallout of material after seeding particles or droplets have grown in size as a result of their own hygroscopicity.

The above point is illustrated quite well in Figure 7, taken from the numerical microphysical studies of hygroscopic seeding mentioned earlier (Tag, 1971). Relative visibility improvement versus height (in this case for a 300 m deep fog) is plotted as a function of seeding height. Material is inserted only once at this level and moves only in response to terminal velocities of the droplets. Notice that material inserted in the upper half of the fog results in the most total clearing. Of course, if material is initially distributed throughout the entire fog depth, more fog dissipation will occur but at the expense of considerably more seeding material.

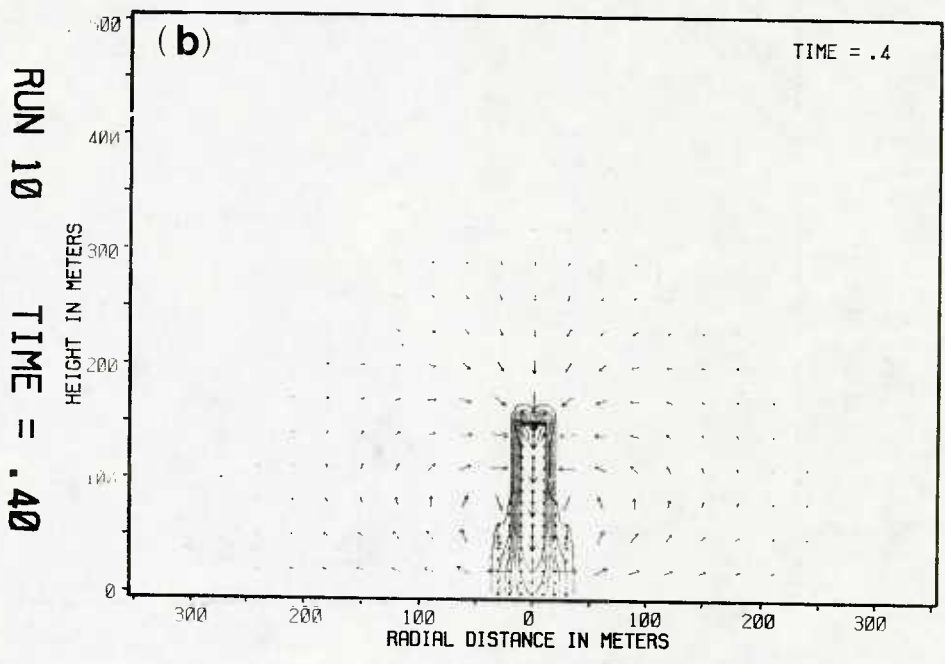
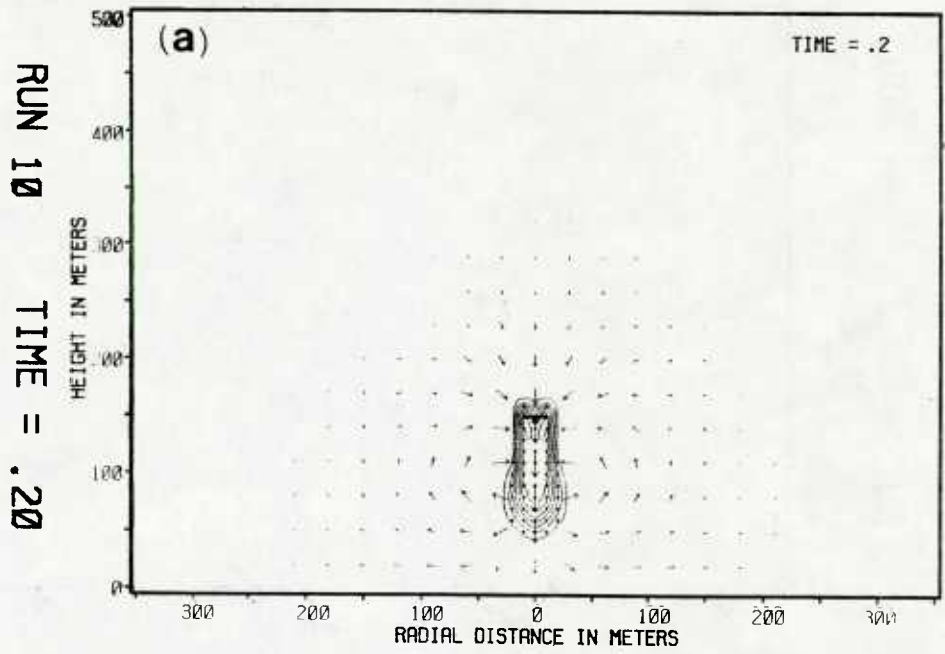


Figure 6. Continuous seeding from a hover mode at 150 m. (Treatment concentration isolines are in increments of 0.05 gm m^{-3} , with a minimum of 0.05 gm m^{-3}).

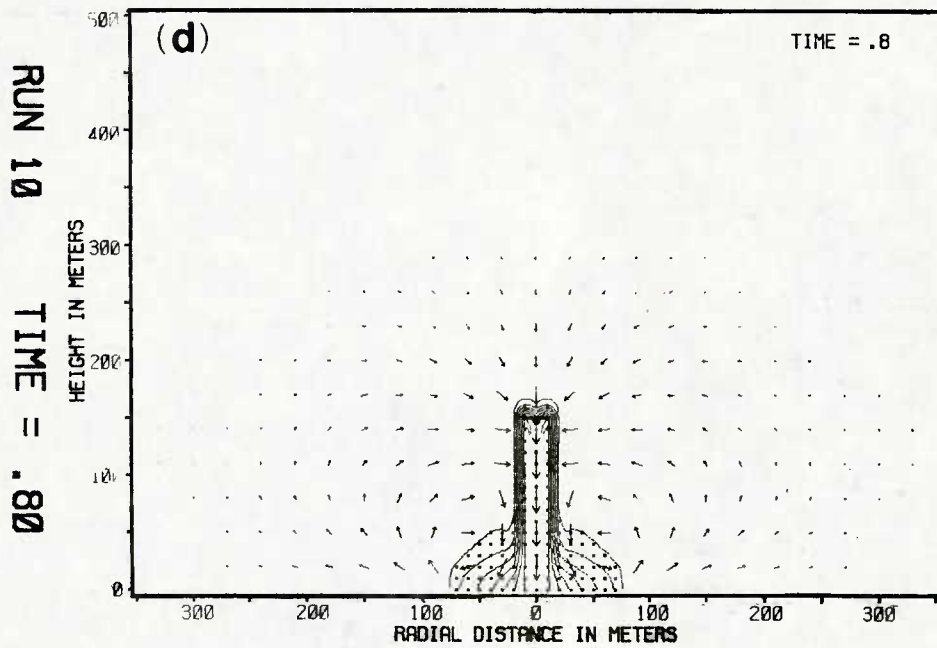
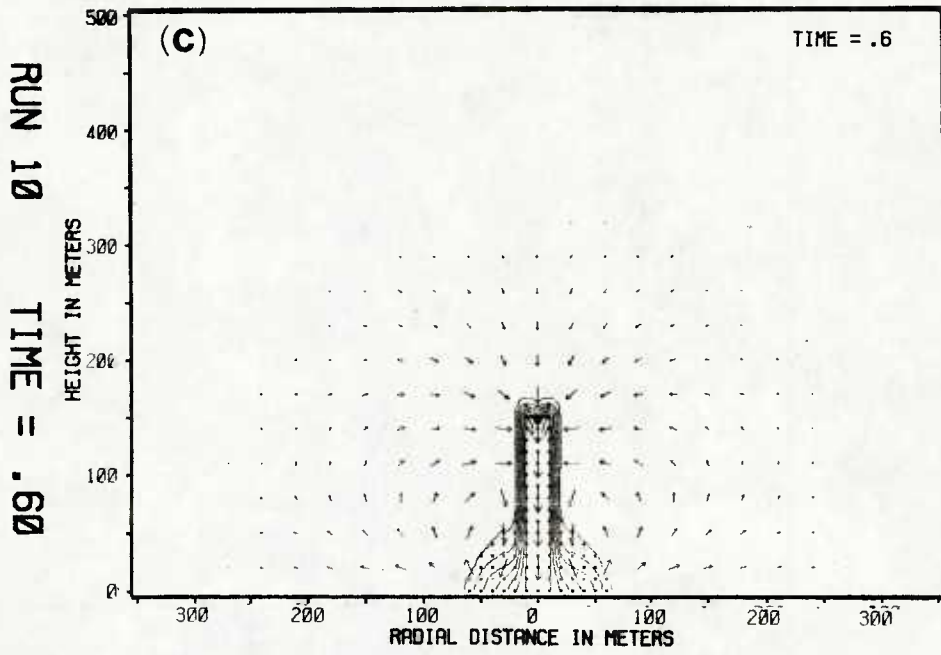


Figure 6. (continued)

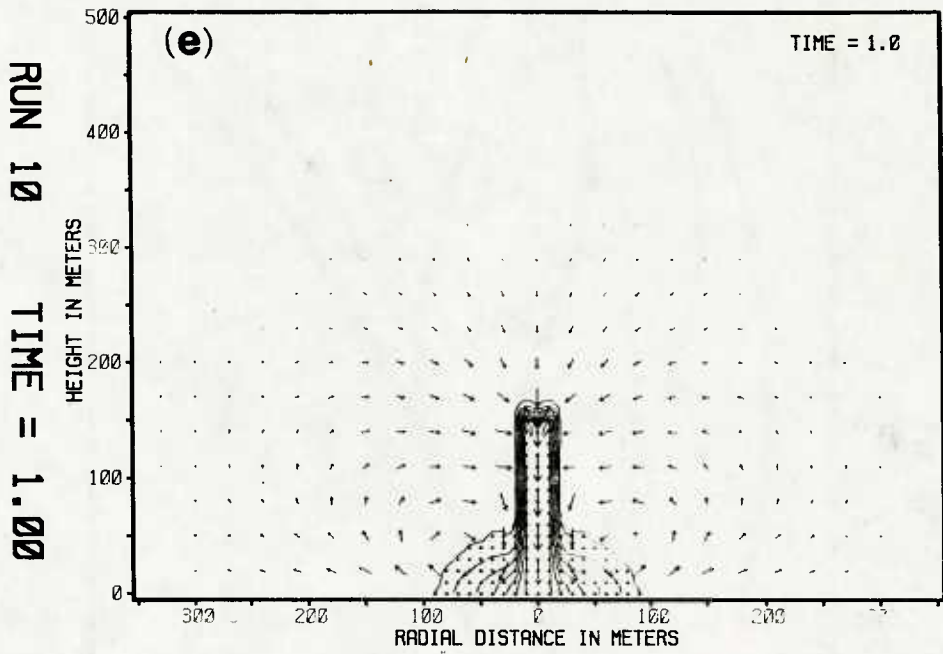


Figure 6. (continued)

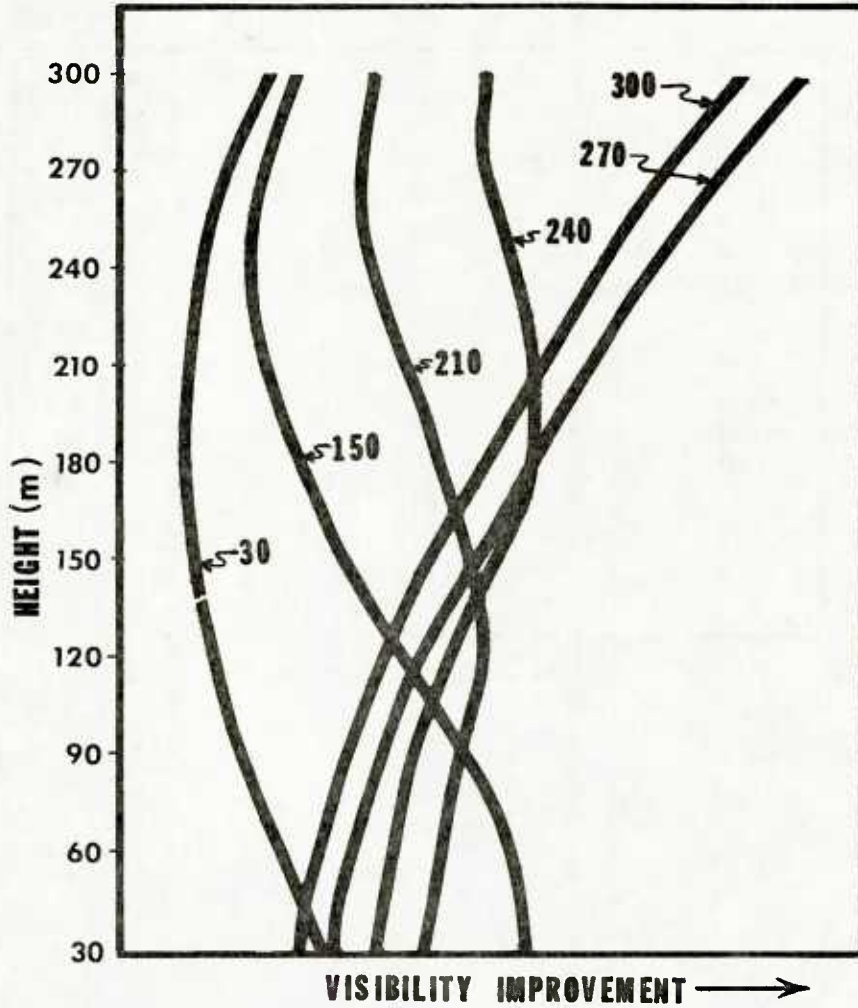


Figure 7. Typical visibility improvement pattern achieved by hygroscopic seeding at various heights within a 300 m deep fog.

The reason that seeding material is "wasted" if inserted too near the bottom of the fog is one of inefficiency. The material indeed does remove moisture from the air, grow, and fall out. The inefficiency results from the fact that a droplet falls onto the ground before its hygroscopicity is "used up." A droplet inserted higher into the fog has enough time during its descent to grow to where it becomes dilute. Assuming that the initial treatment droplet or particle size is not too small, its size after growth will be such that it is easily carried from the fog without further growth.

In order to observe continuous seeding with minimum initial ground effect, the first experiment was repeated with the simulated helicopter hovering at 300 m. The resultant time sequence is shown in Figures 8(a) through 8(e). Notice that there is horizontal spreading of the plume long before the ground effect is felt. Such spreading results from the circulation pattern induced by the downwash, a circulation that splits from the initial vertical position and moves downward. This movement is evident from the time sequence and allows the spreading to continue as the seeding plume is advected downward through the entire 300 m. Although horizontal spreading does occur, the 0.05 gm m^{-3} threshold isoline moves outward only to about 50 m from the centerline. Beyond that seeding material is present, but in a more diffuse concentration.

In both of the above cases, maximum treatment concentrations are approximately 0.35 gm m^{-3} in the center of the downwash. Figure 2 and Table 1 indicate that if the proper size of treatment material is used, an initial treatment concentration of 0.35 gm m^{-3} can produce a clearing in five to ten minutes. Such large concentrations, unfortunately, are produced inefficiently and cover only a relatively small horizontal area. Because there is a finite limitation to the amount of material that can be carried aloft, the latter restriction limits the total area that can be seeded and thus increases targeting difficulties.

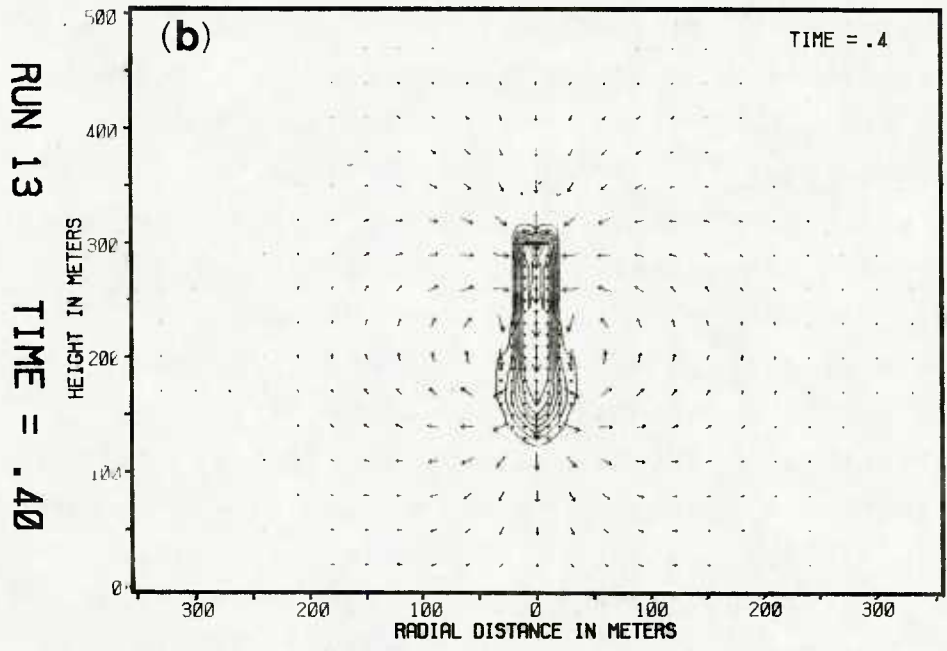
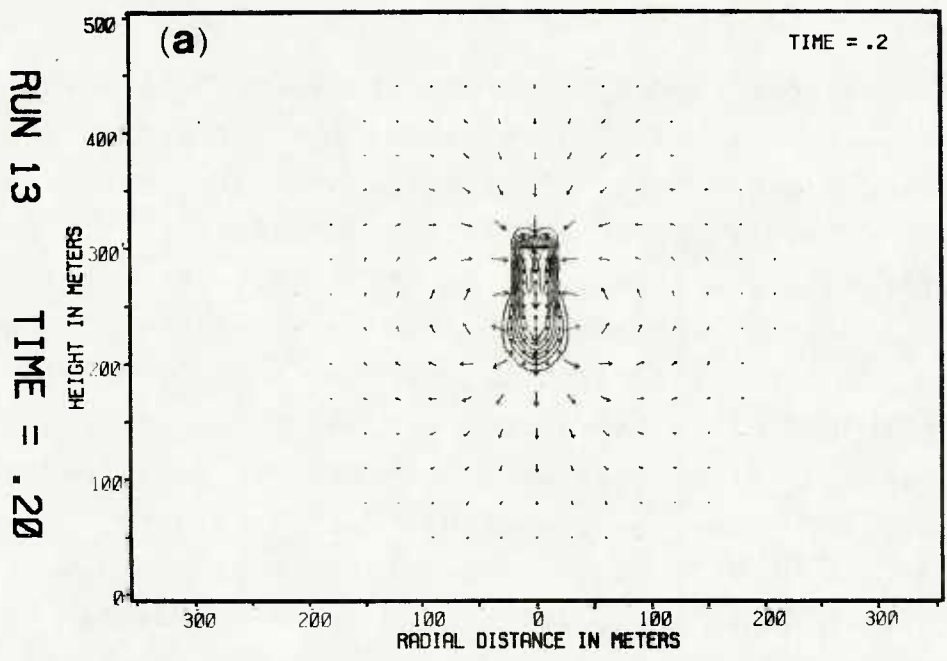


Figure 8. Continuous seeding from a hover mode at 300 m.

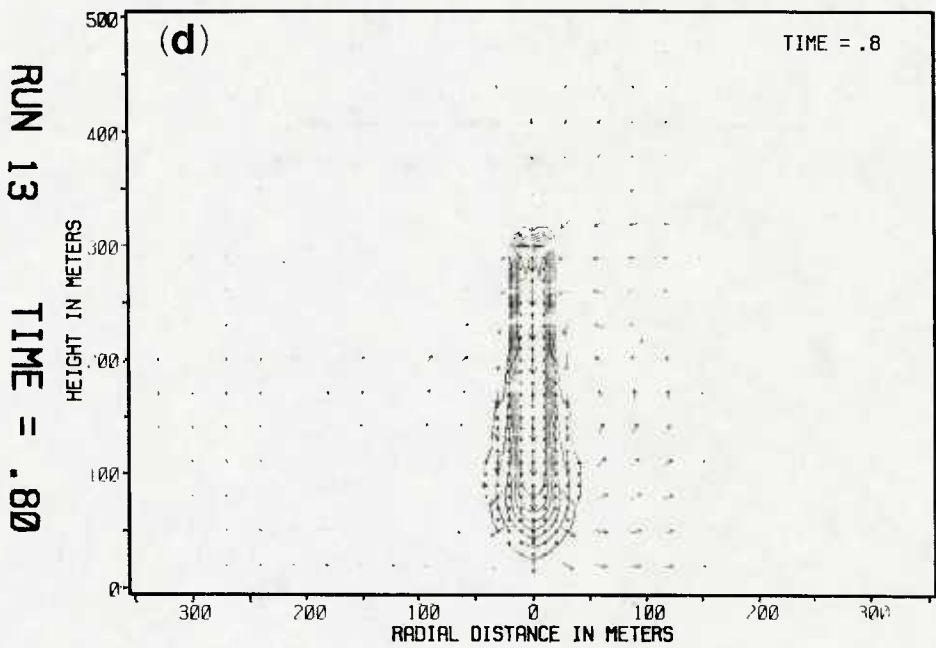
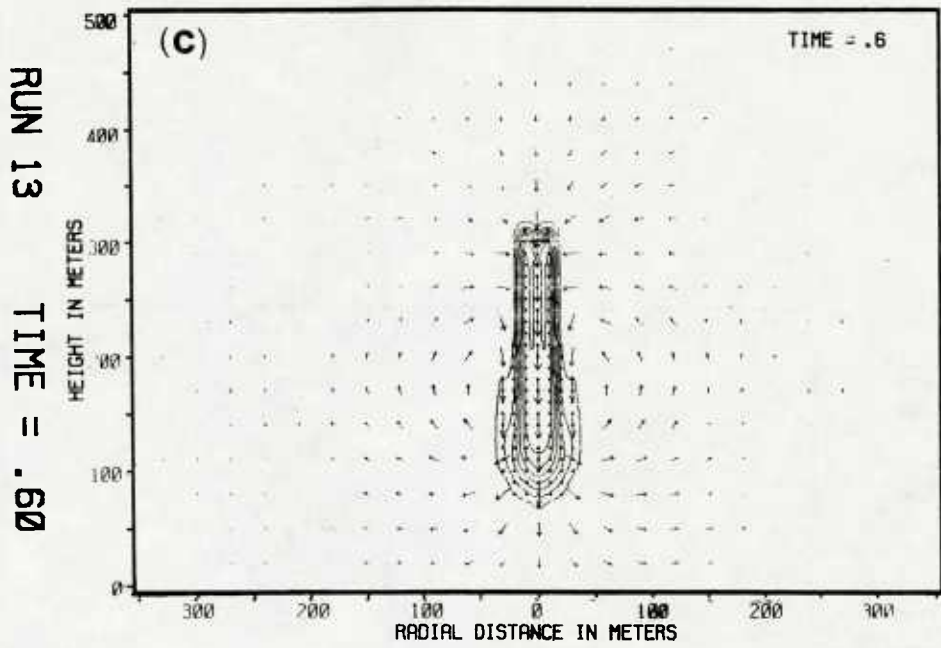


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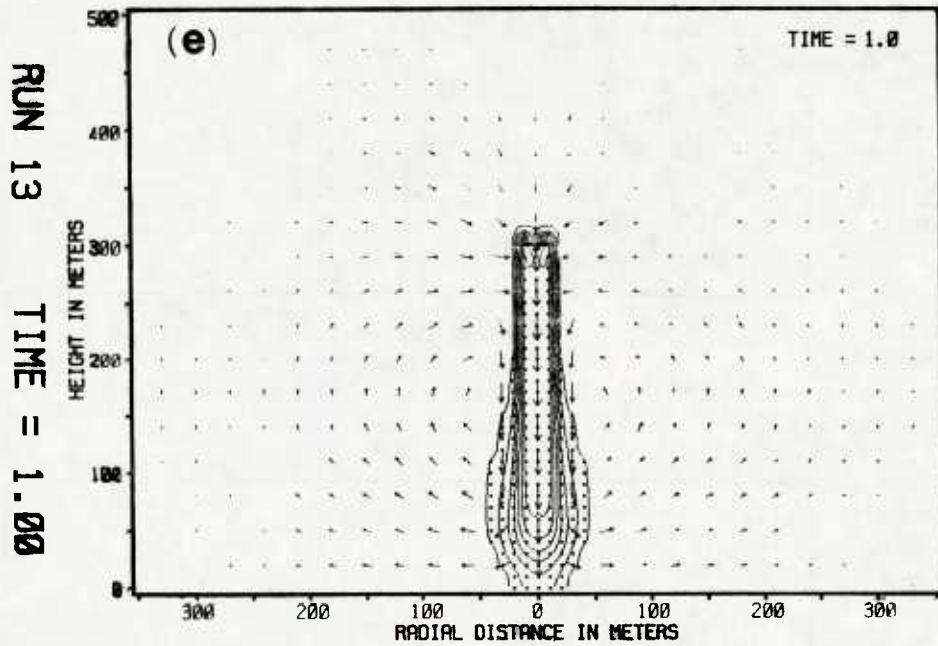


Figure 8. (continued)

3. CONTINUOUS HOVER WITH PULSE SEEDING

Acknowledging that both of the first two experiments simulated the use of a large amount of seeding material inefficiently, it was decided to simulate a pulse seeding with a continuous hover. Such an experiment would determine if seeding material, although being advected to a different locale, could remain in a concentration dense enough to be a viable seeding agent. The answer is quite evident in Figures 9(a) through 9(d) which display the results of a 12-sec (.2 min) seeding pulse. Although concentrations as large as 0.40 gm m^{-3} are seen at the termination of seeding, within 48 seconds the threshold isoline is no longer visible. Another experiment (not shown) in which the helicopter hovered at 150 m produced nearly the same results. The material is advected and mixed into small concentrations. Figure 2 indicates that such concentrations are ineffective, at least for short lag times. Consequently, pulse seeding in the hover mode is essentially useless.

4. SEEDING FROM A MOVING HELICOPTER

It has been conclusively shown that using a helicopter in the hover state is an inefficient method of dispensing material. If seeding is continuous, material is wasted; if pulse seeding is attempted, treatment material becomes too diffuse to be effective.

The remaining questions that need to be answered concern the use of a moving helicopter for dispensing seeding material. Obviously, horizontal movement would allow for decreased periods of downwash and thus alleviate (depending on the horizontal speed) the difficulty of forcing material too far into the fog. Unfortunately, as horizontal speed increases, the quantity of material dispensed over one point decreases.

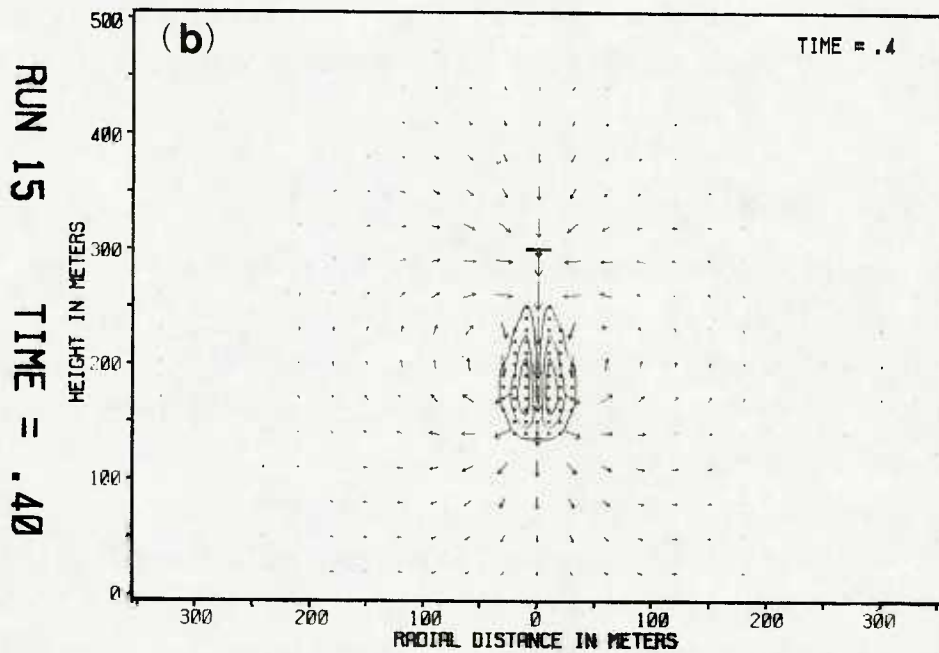
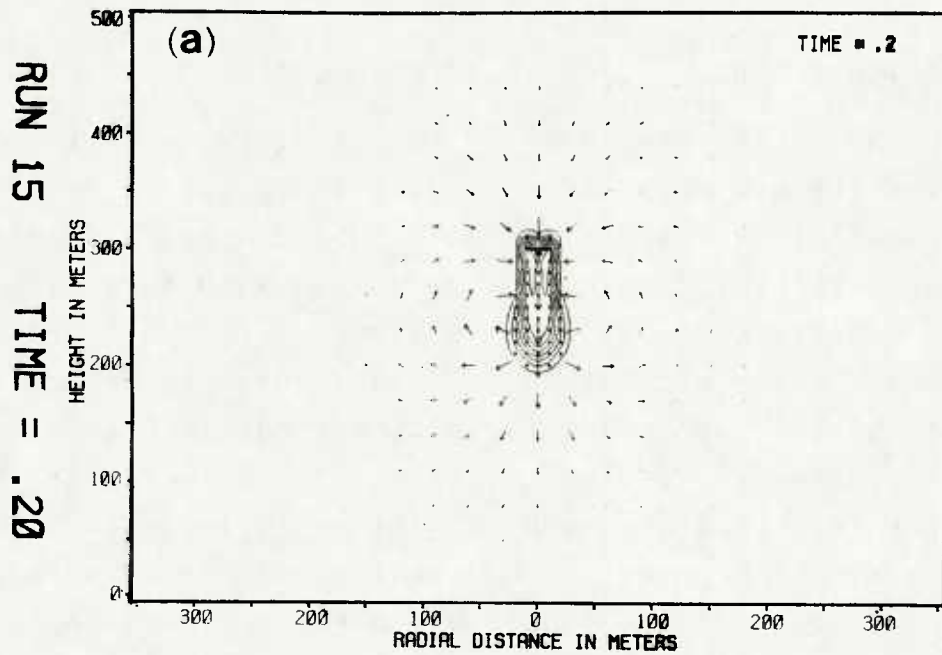


Figure 9. Pulse seeding (0.2 min duration) from a hover mode at 300 m.

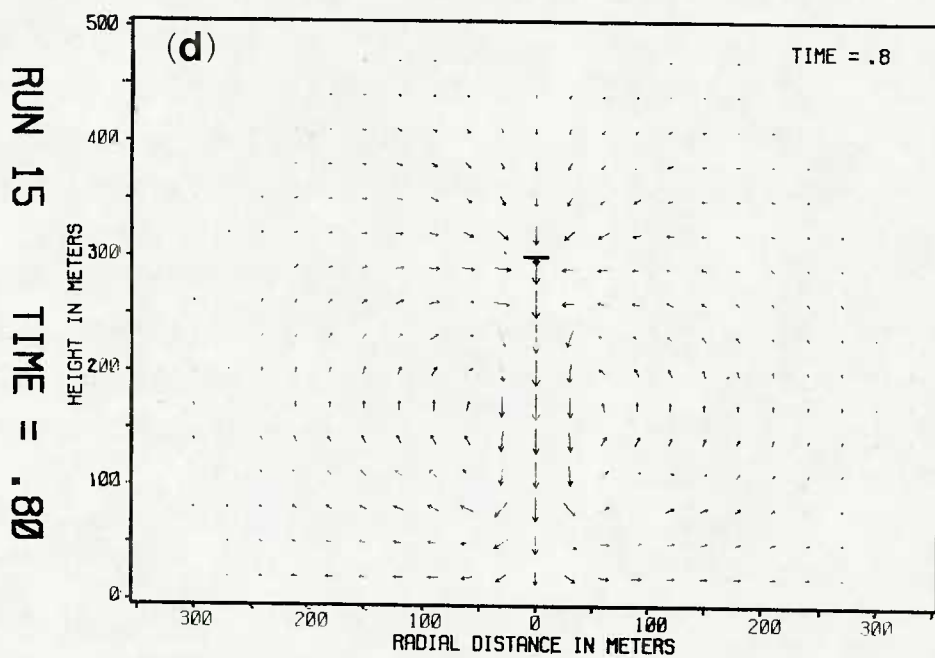
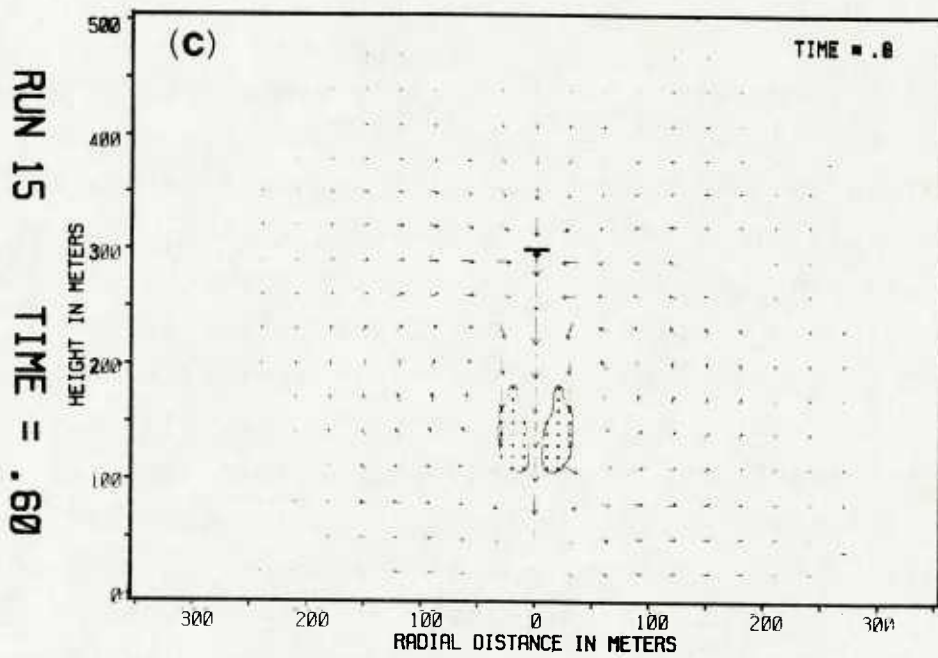


Figure 9. (continued)

Utilizing the model in the axially-symmetric (cylindrical) manner for the downwash simulation precludes moving the vorticity source (and thus simulating movement of the helicopter) since, by definition, the helicopter is always located in center. Consequently, helicopter movement simulation is not really possible. A way of determining relative effect of helicopter movement, however, is through variation of both the vorticity and seeding pulse duration. For example, although probably not exact, a three-second pulse could qualitatively be said to simulate a speed five times faster than a 15-sec pulse. Although not extremely useful in an absolute sense, a comparison should provide some qualitative information regarding the effect of speed on the shape and concentration of the seeding plumes.

Figures 10(a) through 10(f) and 11(a) through 11(e) represent seeding and downwash impulses lasting 15 and 3 sec (.25 and .05 min) respectively. Because the circulation takes longer to reach steady-state, Figure 10 is plotted through 1.2 min. A comparison of the two experiments reveals facts which one would qualitatively expect and which are consistent with the observational data of Plank, et al., (1970). The slower moving helicopter, because of a longer lasting downwash pulse, forces material deeper. A comparison of the two plumes shows that a two-fold increase in depth is gained with the five-fold increase in pulse persistence.

The longer downwash pulse is accompanied by a correspondingly longer seeding pulse. The most interesting comparison of the two steady-state final pulses lies in the fact that the maximum internal treatment concentration is approximately the same for each. In other words, although more material is dispensed in Figure 10, the additional material is spread over additional depth so as to make the maximum concentrations approximately the same. It should be

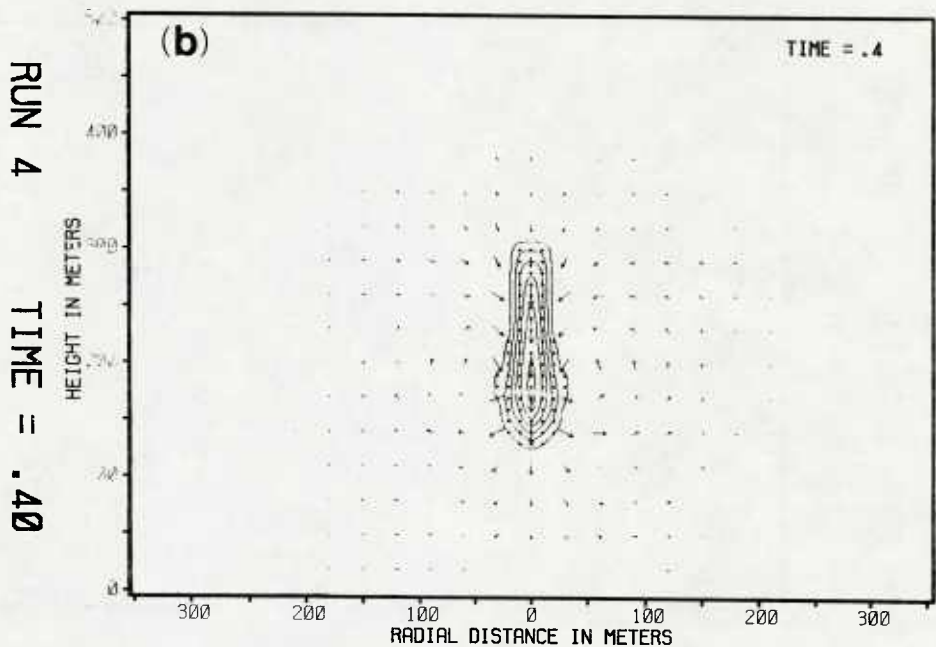
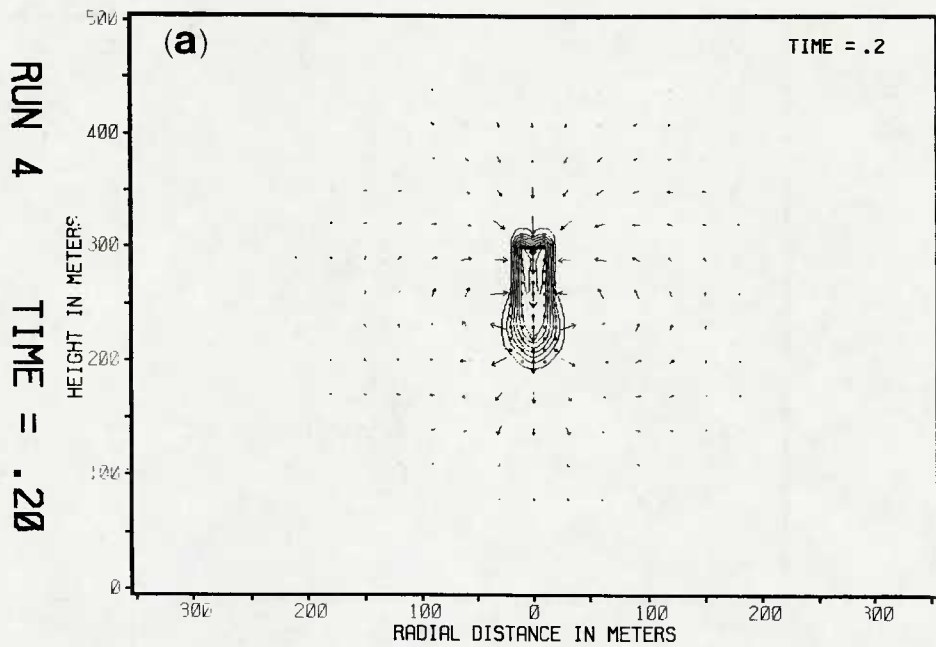


Figure 10. Seeding and downwash pulse of 0.25 min duration at 300 m.

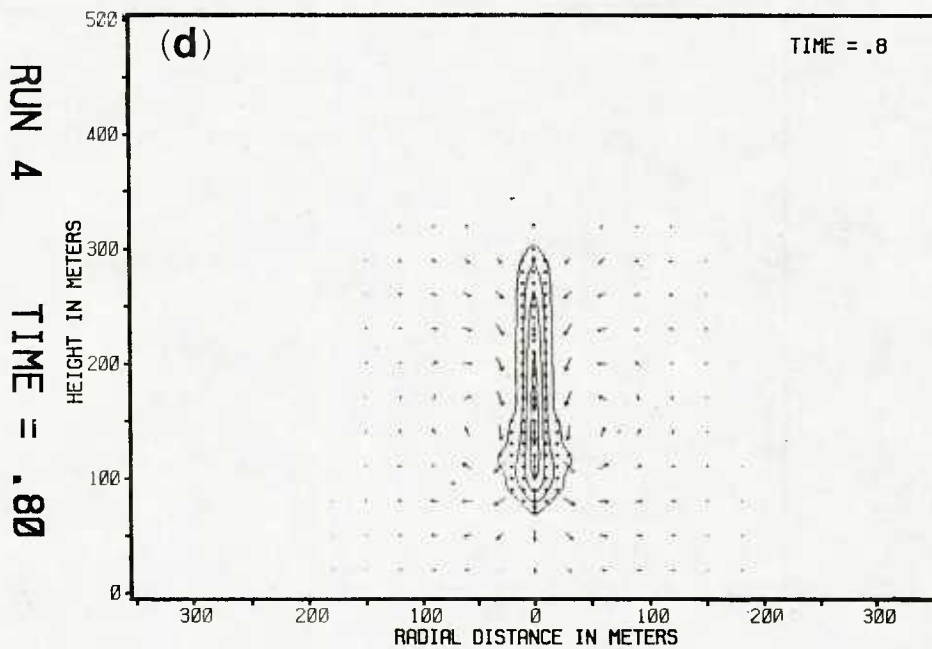
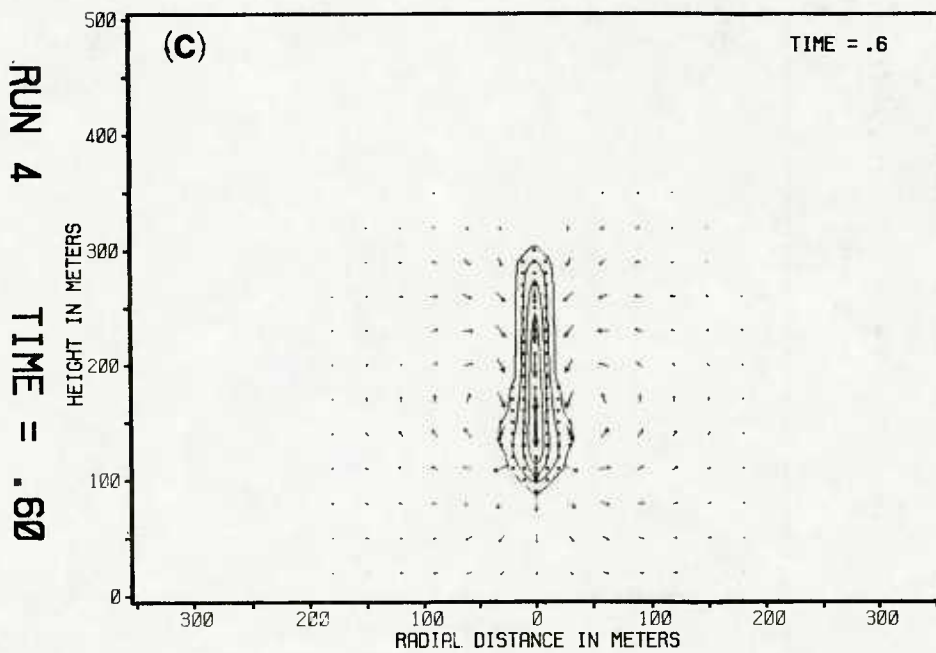


Figure 10. (continued)

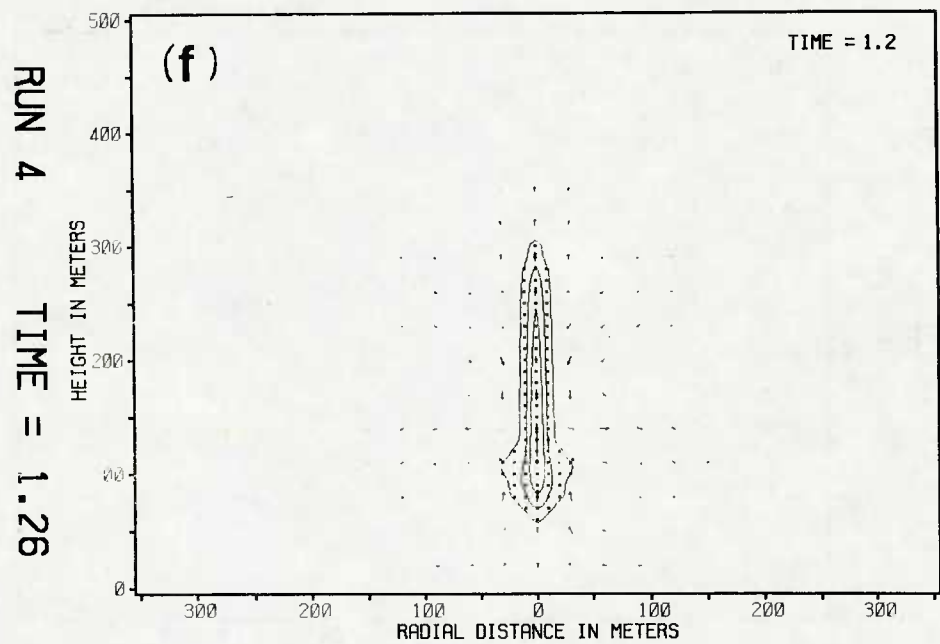
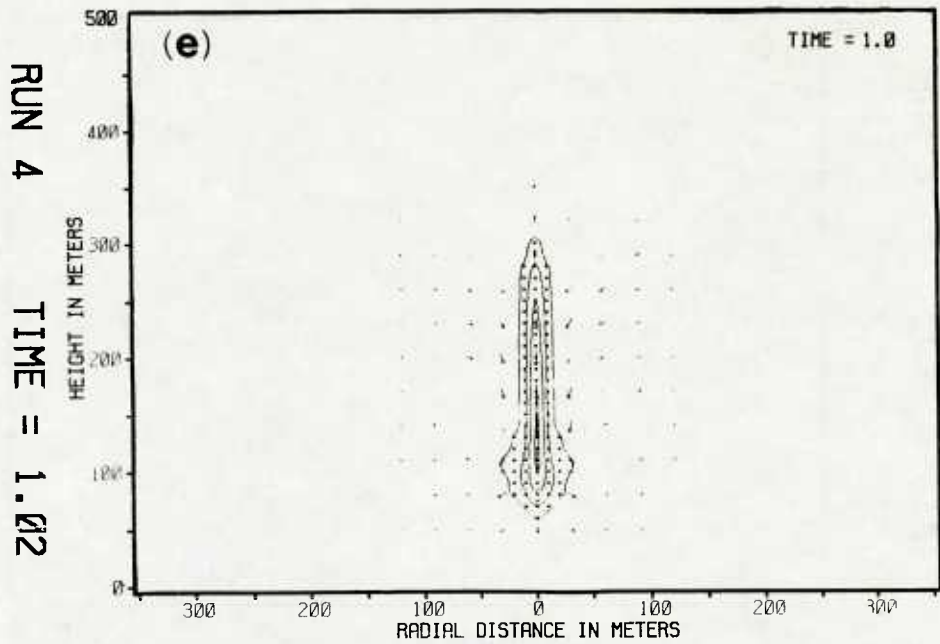


Figure 10. (continued)

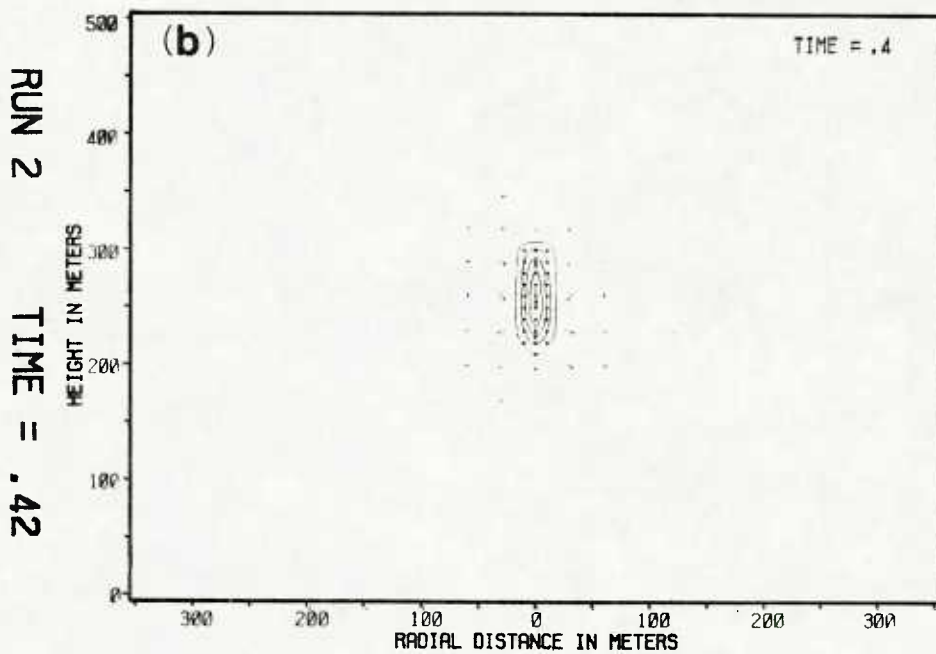
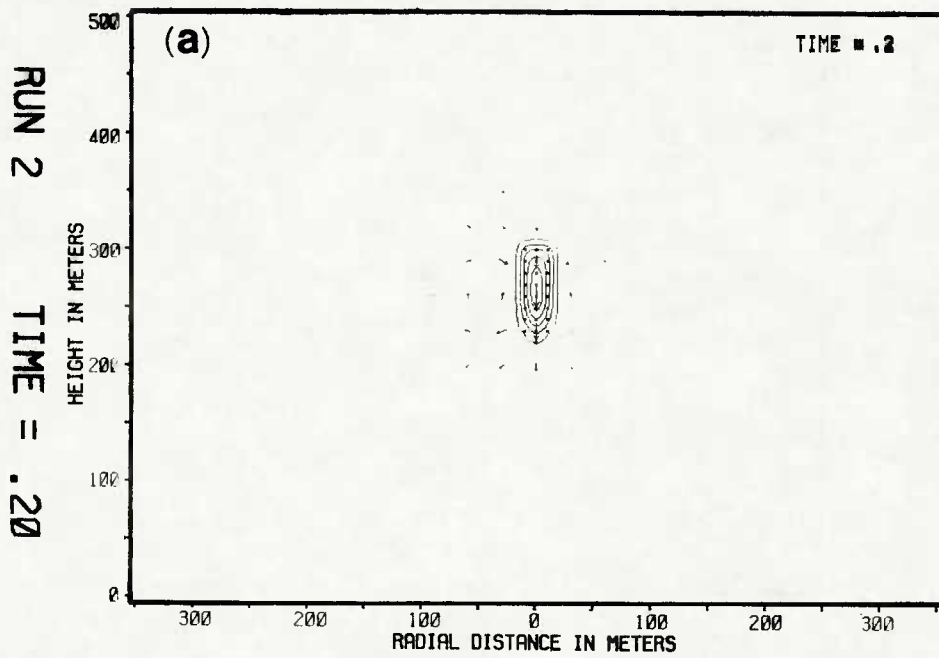


Figure 11. Seeding and downwash pulse of 0.05 min duration at 300 m.

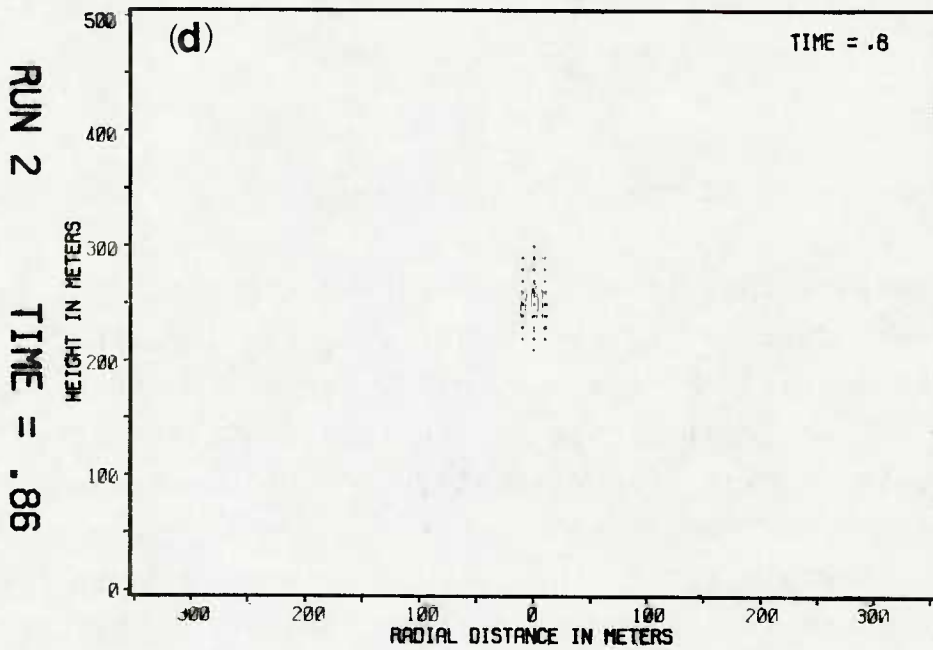
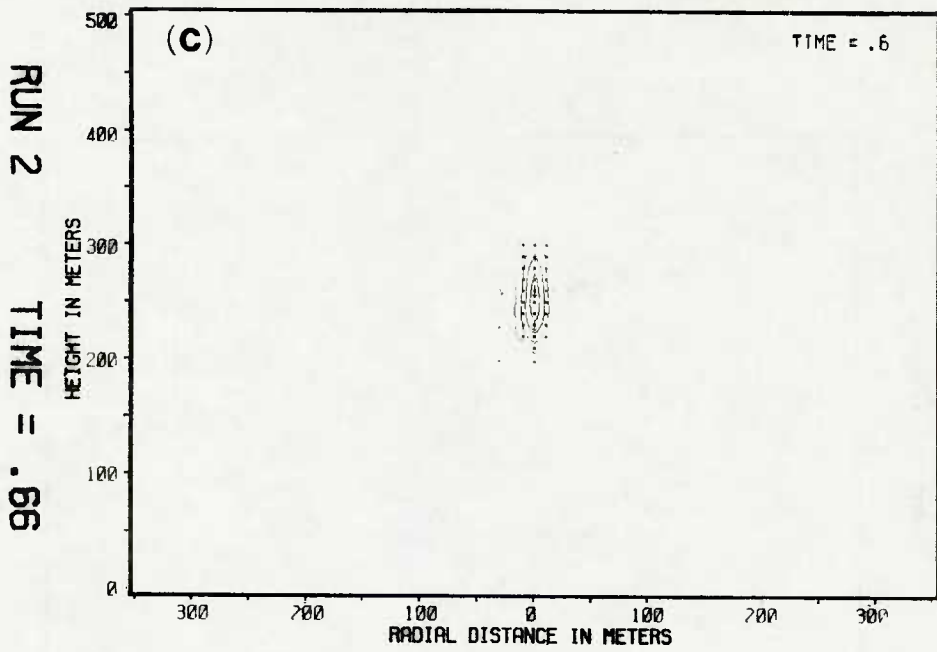


Figure 11. (continued)

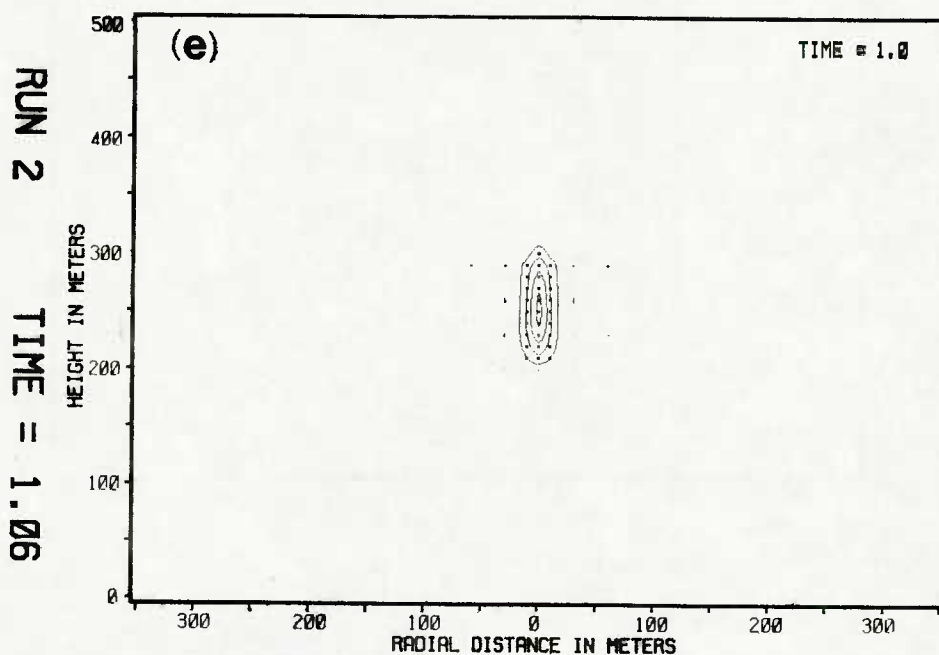


Figure 11. (continued)

noted, however, that in other experiments in which the pulse duration was further decreased (implying still faster speeds) maximum concentration does eventually decrease. Such a decrease is a natural result of the fact that the vortex does not decrease in size proportionately to the decrease in horizontal seeding concentration.

Thus it would appear that one cannot continue to increase treatment concentration by decreasing horizontal helicopter speed, except in the case of hover. Even by utilizing a maximum seeding rate, concentrations after steady-state is reached are no larger than 0.2 gm m^{-3} for the 15 sec pulse duration.

The question was earlier raised as to how a downwash-produced concentration would compare to a fixed-wing aircraft produced concentration. Smith and MacCready (1963) state that the flow field of an aircraft wake is contained in an oval area of $A = 1.69b^2$, where b is the aircraft wingspan. Consequently, the degree of concentration will be very much a function of the size of aircraft. Based on the above formula, nomograms were produced for the B-26 ($b = 20$ m) and the DC-7 ($b = 39$ m), Figures 12 and 13 respectively. These figures were originally intended for seeding of a liquid agent and, as a result, flow rates are given in terms of gal min^{-1} .

Utilizing the maximum flow rate used in the downwash experiments (assuming for convenience a treatment material density of 1 gm cm^{-3}), 3.8 kg sec^{-1} is converted to 60 gal min^{-1} . Such a flow rate produces concentrations of 0.1 gm m^{-3} and 0.026 gm m^{-3} respectively, for the B-26 and the DC-7 at 110 kts. Faster speeds produce lesser concentrations. Because the nomograms are based on average concentrations, however, larger concentrations could be found in the aircraft wake.

Based on these concentration comparisons it appears that, if seeding rates are the same, a helicopter can equal or exceed material concentrations produced by a fixed-wing aircraft. If the aircraft is of the DC-7 or larger size, concentrations generated by a helicopter will be several times larger. If faster clearings are necessary, a helicopter would thus be more desirable than fixed-wing aircraft. Other factors, including the required clearing size and aircraft payload capability, are important considerations, however.

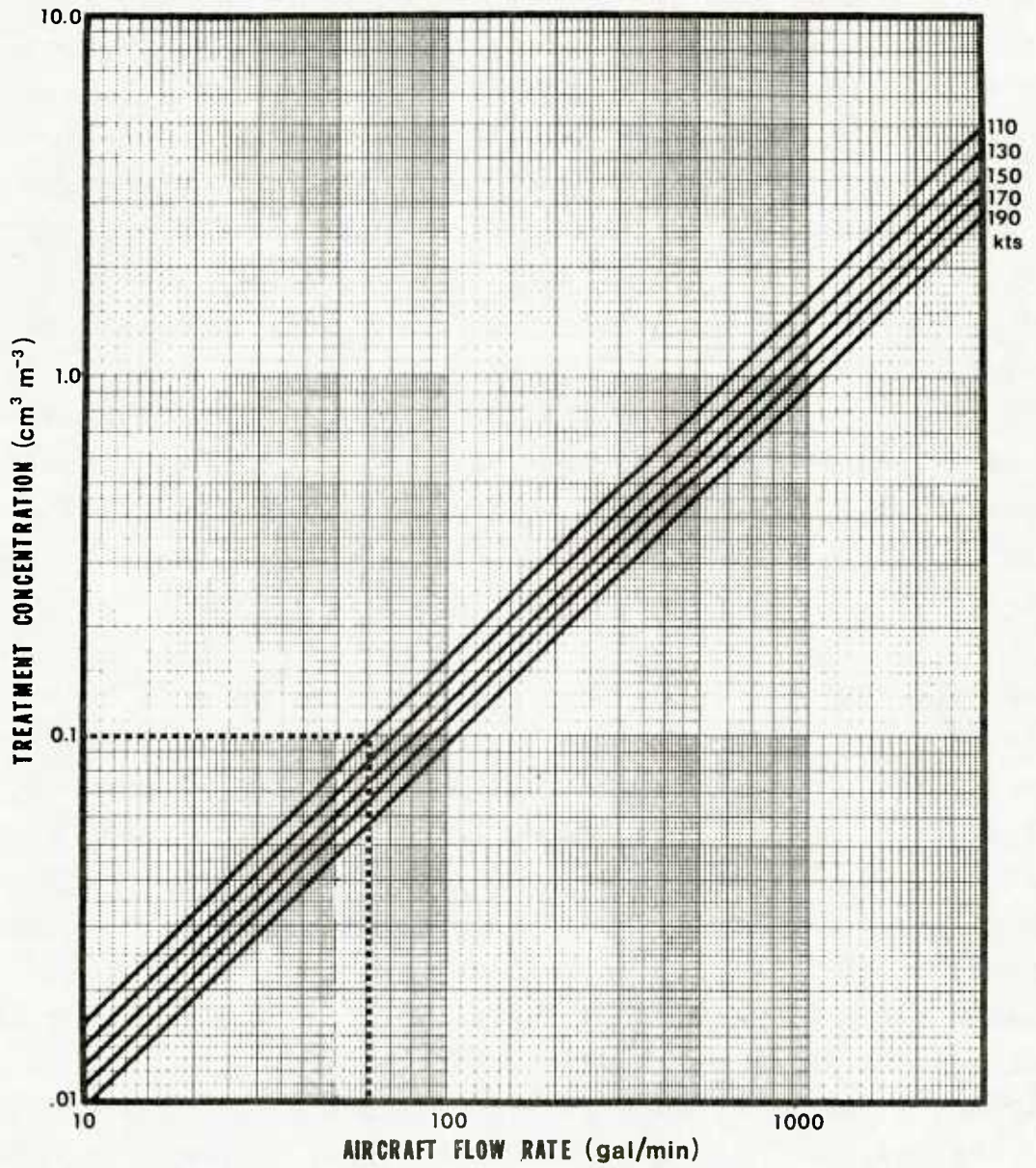


Figure 12. Seeding rate and corresponding treatment concentration for B-26.

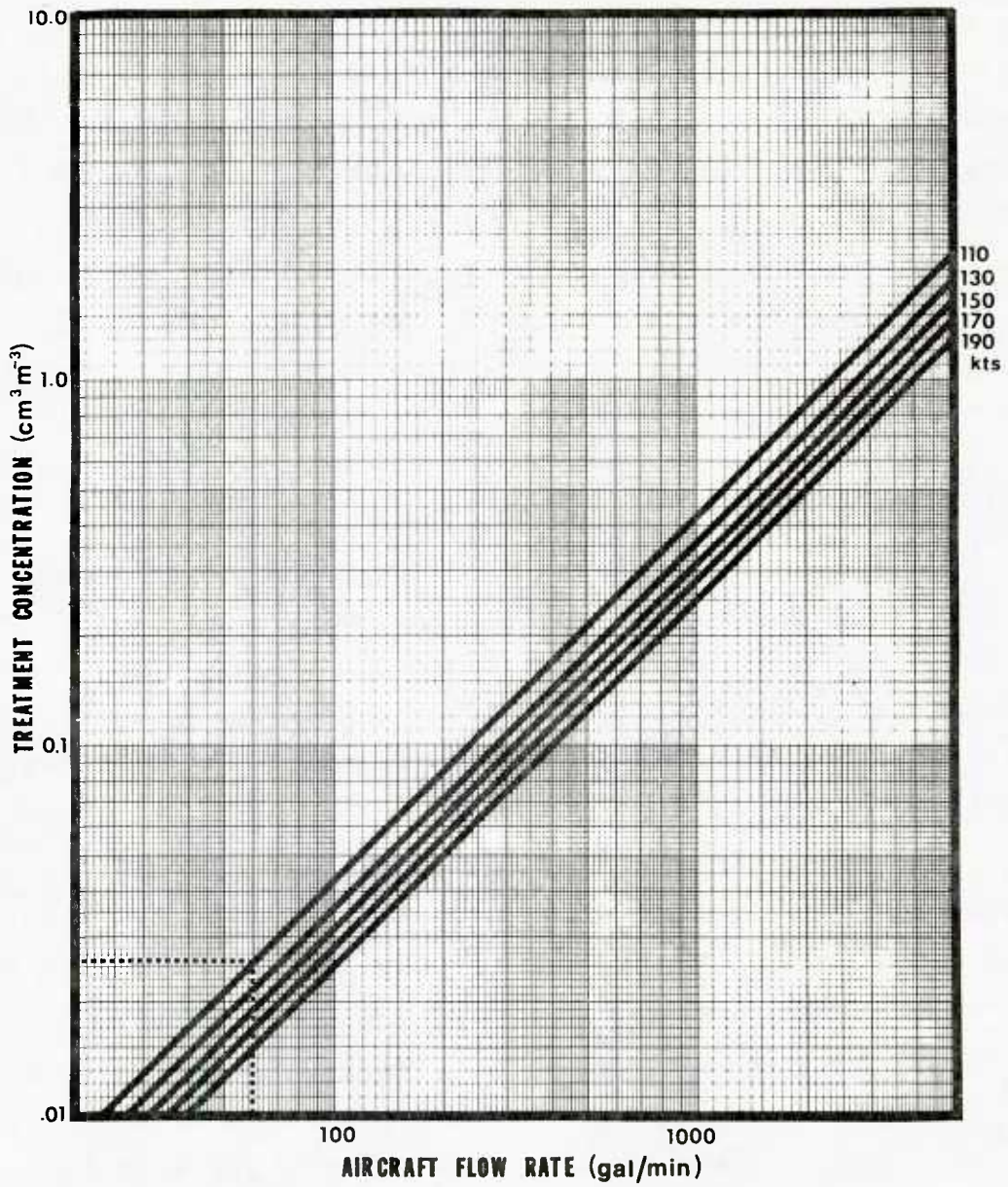


Figure 13. Seeding rate and corresponding treatment concentrations for DC-7.

5. CONCLUSIONS

Based on model simulation of downwash-produced seeding concentrations, supplemented with microphysical simulation of heat-produced visibility improvement and earlier hygroscopic treatment studies, several pertinent observations and conclusions applicable to fog dissipation tests involving helicopters can be made:

1. The basic mechanisms involved in downwash-produced clearings operate in a time frame one to two orders of magnitude faster than the mechanisms responsible for clearings produced by hygroscopic seeding. Consequently, a successful combination of the two techniques can be achieved in only limited ways.

2. Continuous seeding from the hover state is very inefficient. Large treatment concentrations which can produce clearings in relatively short times can be achieved; however, seeding material is wasted because it is driven through the fog within a time frame less than is required for the hygroscopic mechanism to be effective.

3. Pulse seeding from the hover state is completely ineffective. Because of continuous advection and mixing, seeding material concentration becomes too dilute to be an effective seeding reagent.

4. A helicopter can be an effective vehicle for the dispensing of hygroscopic material if the horizontal speed of the helicopter is not so slow that material is driven too deeply into the fog.

5. In comparison with a fixed-wing aircraft the slower speeds of a helicopter generally allow for larger concentrations of seeding material.

6. For the purpose of utilizing both techniques simultaneously, it is not possible to effectively combine helicopter downwash and hygroscopic seeding, either while hovering or moving. A helicopter can be used as a reasonable platform from which seeding material can be dispensed. However, before downwash efforts are initiated to supplement the hygroscopic mechanism, sufficient time must be permitted for the hygroscopic mechanism to work. That amount of time is determined by the quantity and size of the treatment material.

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