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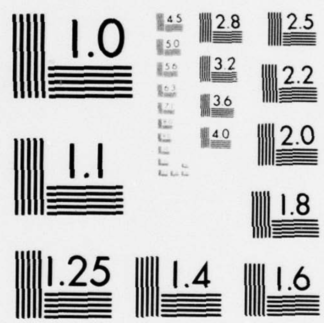

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A Feasibility Study of the Use of Radiant Energy for Fog Dispersal

MILTON M. KLEIN

6 October 1978

METEOROLOGY DIVISION PROJECT 6670
AIR FORCE GEOPHYSICS LABORATORY
HANSCOM AFB, MASSACHUSETTS 01731

AIR FORCE SYSTEMS COMMAND, USAF

This report has been reviewed by the ESD Information Office (OI) and is releasable to the National Technical Information Service (NTIS).

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FOR THE COMMANDER

John Howard

Chief Scientist

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As part of a broad effort by the Air Force to evaluate various methods of dissipating warm fogs over airport runways, a feasibility study has been made of the possible use of radiant energy to dissipate fog. The source of microwave power was considered either ground-based or airborne. For the ground-based case, the microwave beam was taken as parallel to the ground and along the runway, providing a direct source of microwave power for heating the fog. For the airborne case, the beam was taken as perpendicular to the ground, the → over

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20. Abstract (Continued)

heating of the ground by the microwave beam providing a source of infrared power for dissipating the fog.

The study showed that, for either case, very large power densities, well above the personal safety limit of 100 W/m^2 used in the U.S., would be required to dissipate the fog in a time of about 10 min. If the power density is taken as 100 W/m^2, a very long time, that is, many hours, would be required to dissipate the fog. In addition, because of the high cost of electrical energy, the large amount of energy required to dissipate a typical airport fog (about 3×10^{11} J) makes the scheme prohibitively expensive.

Preface

The author would like to thank Mr. Bruce A. Kunkel for his critical review and constructive criticism of the final manuscript.

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A Feasibility Study of the Use of Radiant Energy for Fog Dispersal

1. INTRODUCTION

For over 15 years the Air Force has been studying and evaluating various methods of dispersing warm fog. Many possibilities have been investigated, including sensible heat, helicopter downwash, hygroscopic seeding, carbon black, and electric charging of fog particles. One possible method that has surfaced in recent years is the use of microwave energy to heat the water vapor and water droplets in the fog and thereby dissipate it.

A preliminary estimate indicated that the amount of microwave energy required to vaporize the water droplets in a typical fog over an airport runway would be at least of the order of 10^{11} J. In addition, it appeared highly likely that the power density required to clear the fog in a period of several minutes would exceed the maximum power density of 100 W/m^2 that is generally employed in this country for personal safety.[1] At this power level the time of exposure recommended is 6 min or less.

Despite these preliminary findings, it was felt that a more detailed study would be useful to help assess more precisely the feasibility and utility of such a

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1. Baranski, S., and Czerski, V. (1976) Biological Effects of Microwaves, Dowden, Hutchinson & Ross, Inc., Stroudsburg, Pa., Chap. 6, pp 170-173.

scheme in the light of present-day technology. Such a study would also provide a useful reference in the event of an advance in present-day technology that significantly reduces the cost of microwave power.

The source of microwave energy was considered to be ground-based or airborne. For simplicity a one-dimensional model, that is, plane-wave propagation, was assumed. For the ground-based source, the beam was taken as parallel to the ground and along the runway; it is partially absorbed by the fog, but it does not interact with the ground. For the airborne microwave source, the beam was taken as perpendicular to the ground; here the beam is absorbed both by the fog and the ground. The reflected microwave beam provides further heating of the fog, while the microwave heating of the ground provides an additional source of heating of the fog. The airborne method obviously provides a much better utilization of the microwave energy than does the ground-based approach.

2. GROUND-BASED SOURCE: BEAM PARALLEL TO GROUND AND ALONG RUNWAY

For small wavelengths comparable in size to the liquid droplets in a fog, that is, infrared radiation, the scattering and absorption of the incoming radiation depends strongly upon the size distribution of the fog droplets. For microwave frequencies, however, the droplet size is small compared to the wavelength and, therefore, the attenuation becomes independent of the size distribution and may be specified with respect to the liquid water content of the fog.

For a cloud at $10^{o}C$ with liquid water content, $M = 1\ gm/m^3$, Battan[2] quotes the attenuation coefficient K, dB/km, for several values of the wavelength λ:

$\lambda = 0.9$ cm, $K = 0.681$

$\lambda = 1.24$ cm, $K = 0.406$

$\lambda = 1.8$ cm, $K = 0.179$.

For inland fog at $18^{o}C$, $M = 1\ gm/m^3$, Chen[3] gives:

$\lambda = 0.3$ cm, $K = 4.6$

$\lambda = 1$ cm, $K = 0.43$

$\lambda = 1.25$ cm, $K = 0.25$.

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2. Battan, Louis J. (1973) Radar Observations of the Atmosphere, University of Chicago Press, Chicago and London, Chap. 5, p. 70.

3. Chen, C. C. (1975) Attenuation of Electromagnetic Radiation by Haze, Fog, Clouds and Rain, The Rand Corporation, Santa Monica, CA, R-1694-RR, p. 12.

For small droplets of water at 18°C, M = 1 gm/m^3, Goldstein[4] gives:

λ = 0.2 cm, K = 7.14

λ = 0.5 cm, K = 1.65

λ = 1.25 cm, K = 0.280.

The attenuation coefficient increases with a decrease in temperature. At λ = 1.25 cm, the increase is 93 percent in going from 18°C to 0°C. The variation with wavelength is far more sensitive, a decrease in wavelength by a factor of 3 increasing the attenuation coefficient by an order of magnitude. For the purpose of absorption, a short wavelength is desirable. However, in order to generate a fairly large amount of power, the wavelength cannot be much less than 1 cm. Based on the foregoing data, we shall use a value K = 0.5 dB/km per unit value of M, for wavelengths near 1 cm, as a representative value for fog.

We now consider the attenuation of a microwave beam, parallel to the ground and along the runway, passing through a fog 100 m high, 100 m wide, and 4000 m long. We shall assume a liquid water content M = 0.5 gm/m^3 for which K = 0.25 dB/km. Since the wavelength is large compared to the size of the droplets, the absorption is large compared to the scattering, and we take the attenuation of the beam as due to absorption only. The intensity of the transmitted beam relative to the incident beam is given by

$$\frac{I}{I_o} = 10^{-KL/10} \qquad (1)$$

where

I_o is the incident energy flux

I is the transmitted energy and

L is the path length.

For a path L of 4000 m, corresponding to the length of the runway and approach zone, the attenuation or fractional energy absorbed is

$$\frac{\Delta I}{I_o} = \frac{I_o - I}{I_o} = 0.2 \quad , \qquad (2)$$

so that only 20 percent of the incident beam is absorbed by the fog.

4. Goldstein, H. (1951) in Propagation of Short Radio Waves (Kerr, Editor), McGraw-Hill Book Co., Inc., New York, Chap. 8, p. 677.

With a liquid water content $M = 0.5\ gm/m^3$, the mass of liquid water encountered in a unit area of the beam is

$$ML = 2000\ gm/m^2 \quad .$$

For water at 20°C, the heat of vaporization V is 2450 J/gm; therefore, the energy density G required to vaporize the fog is

$$G = \frac{VML}{0.2} \quad , \tag{3}$$

which yields

$$G = 2.45 \times 10^7\ J/m^2 \quad .$$

The temperature rise required to accommodate the additional water vapor is about 1°C, with a corresponding heat input roughly equivalent to that required to vaporize the fog. Thus, the total energy density required is about $4.9 \times 10^7\ J/m^2$.

If the time allowed to clear the fog is taken as 10 min, the required power density S is

$$S = \frac{4.9 \times 10^7}{600} = 82,000\ W/m^2 \quad . \tag{4}$$

This is a very large power density, well above the safety limit in the U. S. of $100\ W/m^2$. Assuming the fog is cleared to a depth of 60 m, the cross sectional area normal to the beam is $6 \times 10^3\ m^2$. Accordingly, the total power P required during this period of 10 min is

$$P = 6 \times 10^3 \times 82,000$$
$$= 492\ MW \quad .$$

This represents a total energy requirement of about 3×10^{11} J.

Because of air movement, a dispersal time of 10 min would have to be taken as the maximum practically allowable. From a realistic point of view, a system capable of dispersing fog under most observed wind conditions would have to be able to disperse the fog in a period of 1 to 2 min. Thus, the time requirement for the fog dispersal system considered here makes the amount of power required unrealistically large and incompatible with the maximum power density dictated by personal safety regulations.

3. AIRBORNE SOURCE: BEAM PERPENDICULAR TO GROUND

3.1 Analysis of Amount of Beam Reflected by Ground

In this situation the microwave beam passes through a 100-m-deep fog before reaching the ground. Using Eq. (1) we obtain a small absorption of about 1 percent. The beam reaching the ground is partially absorbed by the ground, the remainder being reflected back through the fog. The surface of the ground will heat up, the temperature rise becoming negligible when the heat transferred by radiation and convection balances the energy flux in the incident beam.

A study of the reflection characteristics of microwave radiation shows a wide variation in the amount absorbed, depending on the polarization and frequency of the beam, the type of material, amount of moisture present, and whether the surface is rough or smooth. However, in general, a large fraction of energy ranging from 50 to 100 percent is absorbed. For the purposes of this investigation, we shall assume that 100 percent of the energy is absorbed. It will be seen that the precise amount chosen has no qualitative effect upon the conclusions drawn from this study.

3.2 Determination of Temperature of Ground

Although the solution to the problem of determining the temperature history of a surface both radiating and subject to an incoming flux is not given directly, the problem may be reduced to one of surface radiation only, for which the solution is known, by a suitable change of variable. We shall, as is customary in problems of this type, where the temperature rise is not excessive, assume the linear Newtonian radiation law rather than the more complicated Stefan-Boltzmann 4th power law (Carslaw and Jaeger[5]). It may be noted here that use of the Newtonian law is equivalent to using an average value of the coefficient of convective heat transfer, H, which may be too low when the temperature rise is not negligible. It will, therefore, be useful to obtain the effect of changes in H upon the solution.

We then wish to solve the heat conduction equation

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2} , \qquad (5)$$

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5. Carslaw, H. S., and Jaeger, J. C. (1959) Conduction of Heat in Solids, Oxford University Press, London, Chap. I, pp 18-19.

where

$\alpha = \frac{k}{\rho C_p}$ is the coefficient of thermal diffusivity

ρ is density

C_p is specific heat

k is the coefficient of thermal conductivity

x is the distance measured normal to the surface, and T is temperature.

At the surface, x = 0, we have the boundary condition

$$k \frac{\partial T_s}{\partial x} = H(T_s - T_a) - F, \ x = 0 \quad , \tag{6}$$

where T_a is the ambient temperature, T_s the surface temperature, and F is the incoming power flux density. We assume here initial equilibrium, that is, the initial surface temperature is the same as the ambient.

We may write Eqs. (5) and (6) in the form

$$\frac{\partial v}{\partial t} = \alpha \frac{\partial^2 v}{\partial x^2} \tag{7}$$

and

$$\frac{\partial v}{\partial x} = h v \quad , \quad x = 0 \quad , \tag{8}$$

where

$$v = T - T_a - \frac{F}{H} \tag{9}$$

and h = H/k. Thus, a solution for v immediately yields the temperature T since F and H are known quantities.

To solve Eqs. (7) and (8) we utilize the Laplace transform,

$$\overline{v} = \int_0^\infty v e^{-pt} \, dt \quad , \tag{10}$$

which, when applied to Eqs. (7) and (8), yields

$$\frac{d^2\bar{v}}{dx^2} - q^2\bar{v} = -\frac{V}{\alpha} \tag{11}$$

and

$$\frac{d\bar{v}}{dx} = h\,\bar{v} \quad , \quad x = 0 \quad , \tag{12}$$

where

$$q^2 = p/\alpha$$

and V is the initial value of v. Solving Eq. (11) we obtain

$$\bar{v} = A\,e^{-qx} + \frac{V}{p} \quad , \tag{13}$$

where A is an arbitrary constant. The positive exponential does not appear in Eq. (13) because the temperature v is bounded for large x. To determine A, we utilize the radiation condition, Eq. (12), which gives:

$$A = -\frac{V}{P}\,\frac{h}{h+q} \tag{14}$$

and

$$\bar{v} = -\frac{V}{p}\,\frac{h}{h+q}\,e^{-qx} + \frac{V}{p} \quad . \tag{15}$$

Using a table of Laplace transforms, we obtain

$$\frac{v}{V} = \text{erf}\left[\frac{x}{2(\alpha t)^{1/2}}\right] + e^{hx+h^2\alpha t}\,\text{erfc}\left[\frac{x}{2(\alpha t)^{1/2}} + h(\alpha t)^{1/2}\right] \quad , \tag{16}$$

where erf denotes the error function and erfc the complementary error function. The surface temperature v_s, corresponding to x = 0, is then given by

$$\frac{v_s}{V} = e^{h^2\alpha t}\,\text{erfc}\,[h(\alpha t)^{1/2}] \quad . \tag{17}$$

For the case of no convective heat transfer (H = 0), the temperature history is given by (Carslaw and Jaeger[6])

$$\Delta T = T - T_a = 2 \frac{F}{k} \left(\frac{\alpha t}{\pi}\right)^{1/2} \quad . \qquad (18)$$

For the purposes of this study, we have chosen earth and concrete as typical surface materials for which the thermal data are (average representative values have been utilized):

earth:

$\alpha = 0.002\ cm^2/sec$

$k = 0.002\ cal/cm\ sec\ ^oC$

concrete:

$\alpha = 0.01\ cm^2/sec$

$k = 0.005\ cal/cm\ sec\ ^oC$.

Since, as will be evident from the calculations, the solution is more sensitive to H than to α or k, a range of values has been chosen for H. Schneider[7] gives as a typical value for earth, $H = 5\ Btu/ft^2\ hr\ ^oF = 6.8 \times 10^{-4}\ cal/cm^2\ sec\ ^oC$, while for concrete and sandstone a representative value is $0.65\ Btu/ft^2\ hr\ ^oF = 8.8 \times 10^{-5}\ cal/cm^2\ sec\ ^oC$ (Brown and Marco[8]). When using the linear radiation law, Eq. (6), the coefficient H, as indicated by Carslaw, is an overall value including the effects of radiation and convection. Since these effects are, in general, of the same order of magnitude, the coefficient H may attain values as high as $10^{-3}\ cal/cm^2\ sec\ ^oC$. We have, therefore, chosen a range of values of H from 10^{-4} to $10^{-3}\ cal/cm^2\ sec\ ^oC$.

The temperature histories for earth and concrete are given in Figures 1 and 2 where the temperature rise $\Delta T = T - T_a$ is plotted against time for several values of H. An incident flux, F, of 1000 W/m^2 was chosen for the calculations. Since the temperature rise is proportional to F, the solution for any other value of F can easily be obtained from these results. The results for earth and concrete are very close, so very little difference in the temperature rise may be expected because

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6. Carslaw, H.S., and Jaeger, J.C. (1959) Conduction of Heat in Solids, Oxford University Press, London, Chap. II, p. 75.

7. Schneider, P.J. (1955) Conduction Heat Transfer, Addison-Wesley Publishing Co., Inc., Cambridge, MA, Chap. 10, p. 265.

8. Brown, A.I., and Marco, S.M. (1958) Introduction to Heat Transfer, McGraw-Hill Book Co., Inc., New York, Chap. 11, p. 194.

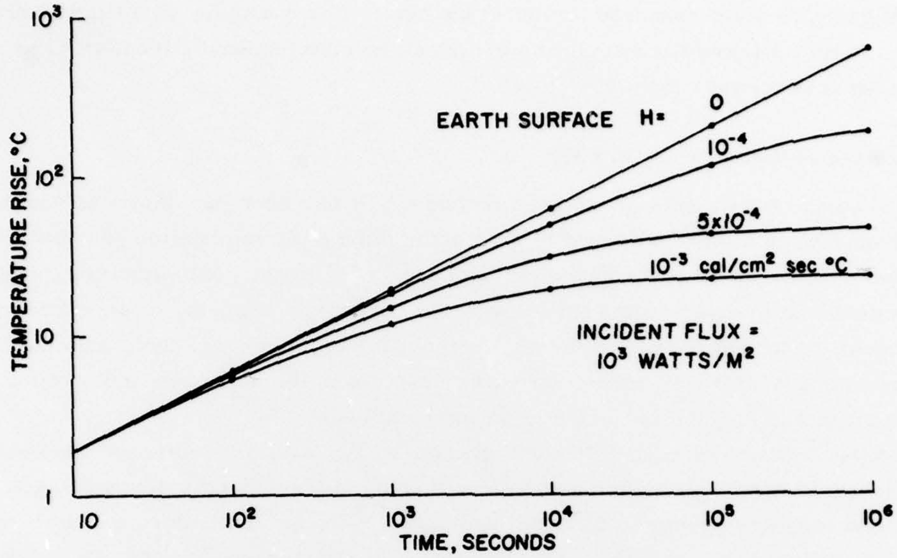

Figure 1. Temperature Rise of an Earth Surface for an Incident Flux of 1000 W/m^2, and Several Values of the Convective Heat Transfer Coefficient H

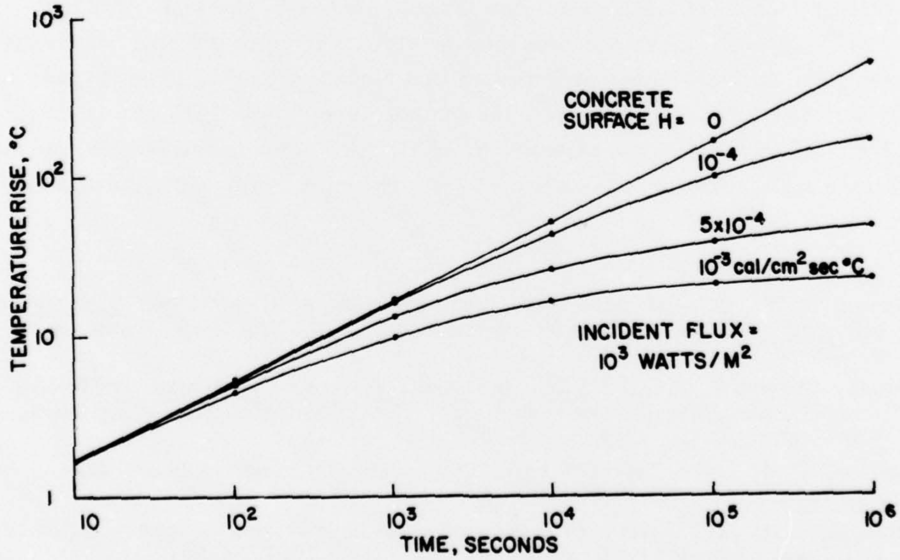

Figure 2. Temperature Rise of a Concrete Surface for an Incident Flux of 1000 W/m^2, and Several Values of the Convective Heat Transfer Coefficient H

of variations in the thermal properties of the surface. Changes in H have a much more significant effect upon the temperature rise. For example, in a time interval of 1 hr, Figure 1 (earth) indicates the temperature rise increases from 16°C to 32°C when H decreases from 10^{-3} to 10^{-4}.

3.3 Interaction of Radiant Energy With Fog

In standard treatments of infrared technology it has been customary to assume that absorption is small compared to scattering during the interaction of infrared radiation with water droplets in the atmosphere.[9, 10] Hence, only scattering has been considered in determining the attenuation, by water droplets, of an infrared beam passing through the atmosphere. Recent studies, however, have indicated that absorption of infrared energy by water droplets in the atmosphere may be a significant factor in the attenuation of an infrared beam.[11, 12]

Hodges[12] shows that from 20 to 50 percent of the total attenuation of the beam is due to absorption, the higher amounts occurring at wavelengths beyond 10 μ. Since most fogs are opaque to infrared radiation,[13] we shall assume, for the purposes of this study, that the total attenuation is 100 percent and that 40 percent of the incident beam is absorbed by the fog.

As indicated previously, the maximum safe power density in the U.S. is 100 W/m^2. For this incoming flux, the amount absorbed by the earth is, assuming 100 percent absorption, also 100 W/m^2 (for convenience, we neglect here the small fraction of the incident microwave beam absorbed by the fog). Taking $H = 5 \times 10^{-4}$ cal/cm^2 sec as a representative value for the convective heat transfer coefficient, the temperature rise for earth in a period of 1 hr is, from Figure 1, $\Delta T = 23^oC$. For a flux of 100 W/m^2, the temperature rise is 1/10 of this amount, or 2.3°C. At an ambient temperature of 18°C = 291°K the corresponding surface temperature is $T_s = 293.3^oK$. Since a fog of high liquid water content and a depth

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9. Kruse, P.W., McGlaughlin, P.D., and McQuistan, R.B. (1962) Elements of Infrared Technology, John Wiley and Sons, Inc., New York, Chap. 5, p. 186.

10. Plass, Gilbert N. (1965) Handbook of Military Infrared Technology (Wolfe, Editor), Superintendent of Documents, U.S. Government Printing Office, Washington, D.C., Chap. 6, p. 206.

11. Carlon, H.R. (1970) Infrared emission by fine water aerosols and fogs, Applied Optics 9(No. 9):2000-2006.

12. Hodges, J.A. (1972) Aerosol extinction contribution to atmospheric attenuation in infrared wavelengths, Applied Optics 11(No. 10):2304-2310.

13. Chen, C.C. (1975) Attenuation of Electromagnetic Radiation by Haze, Fog, Clouds and Rain, The Rand Corporation, Santa Monica, CA, R-1694-RR, p. 18.

of 100 meters or more is opaque to infrared radiation, we may consider it as a radiating blackbody. The net power density flux S_r radiating from the surface to the fog is then

$$S_r = \sigma \left(T_s^{\;4} - T_a^{\;4} \right) \quad , \tag{19}$$

where

$\sigma = 5.67 \times 10^{-8}\ W/m^2\ {}^oK^4$ is the Stefan-Boltzmann constant.

We then obtain

$$\begin{aligned} S_r &= 5.67 \times 10^{-8}\ [(293.3)^4 - (291)^4] \\ &= 13.1\ W/m^2 \quad . \end{aligned} \tag{20}$$

The flux absorbed by the fog, ΔS_r, assuming 40 percent absorption, is then

$$\begin{aligned} \Delta S_r &= 0.4(13.1) \\ &= 5.24\ W/m^2 \quad . \end{aligned} \tag{21}$$

For a fog depth of 100 m and a liquid water content of 0.5 gm/m^3, the heat G required to vaporize the liquid droplets in a unit area of the fog, as shown in Section 2, is

$$G = VML = 1.22 \times 10^5\ J/m^2 \quad .$$

As in the previous case, the amount of heat required to raise the temperature of the air sufficiently to accommodate the additional water vapor is about the same as G. Thus, the total required energy density is twice this value, or $2.45 \times 10^5\ J/m^2$.

The time Δt required to vaporize the fog by infrared radiation is, therefore,

$$\begin{aligned} \Delta t &= \frac{2.45 \times 10^5}{5.24} \\ &= 0.47 \times 10^5\ sec \\ &= 13\ hr \quad . \end{aligned}$$

Since the absorption for microwave energy is only 1 percent, the direct effect of microwave power at a density of 100 W/m^2 upon the fog dispersal may be neglected. We then see that the time required to vaporize the fog, when limited by a power density of 100 W/m^2, is unrealistically long. Even if the amount absorbed by the fog were assumed to be 100 percent rather than 40 percent, the time required would still be over 5 hr.

At a power density of 100 W/m^2, the total power required for a runway 4000 m long by 100 m wide is 40 MW, an extremely large amount of power for airborne equipment. Thus, even where limited by the maximum power density imposed by personal safety factors, the use of microwave power by airborne equipment to clear a fog is unfeasible with regard to the amount of power required.

4. SUMMARY AND CONCLUSIONS

A feasibility study has been made of the possible use of radiant energy to clear a fog over an airport. The source of microwave power was considered either ground-based or airborne. For the ground-based case, the microwave beam was taken as parallel to the ground and interacting only with the fog. For the airborne case, the beam was taken as perpendicular to the ground, the heating of the ground by the microwave beam providing a source of infrared power for dissipating the fog.

The study showed that, for either case, unrealistically large amounts of power, well above the personal safety limits prevailing in the U. S., were required to dissipate the fog in a reasonable length of time, that is, about 10 min. To conform to the maximum power density determined by safety requirements, 100 W/m^2, imposes unrealistic times, that is, many hours, to dissipate the fog. In addition, because of the high cost of electrical energy, the large amount of energy required to dissipate a typical airport fog (about 3×10^{11} J) makes the scheme prohibitively expensive.

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