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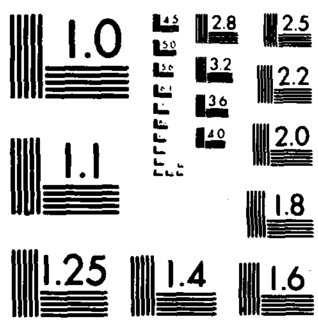

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DELIBERATE AIR POLLUTION: THE ART OF SMOKE SCREENING (U)

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INTRODUCTION

Smoke screening as a battlefield countermeasure is highly dependent upon a number of atmospheric parameters, not a function of munition expenditures alone. Consideration must be given to ambient atmospheric conditions, forecasts, and the aptly named "fog of war" and its affects upon the optical characteristics of the atmosphere. Determination of the optimum smoke density to render the atmosphere opaque to energy from the visible through the far infrared band of the electromagnetic spectrum can be accomplished by an algorithm based upon atmospheric optics and turbulent diffusion hypotheses. The algorithm KWIK was initially conceived as a munitions expenditures model but rendered versatile enough to be used for large area screening and the "seeability" on a battlefield.

The philosophy behind the design and implementation of the algorithm was to keep it simple by using conventional, well-proven formulae and calculating variables within the program from regression fits to easily obtained or measured atmospheric parameters. The model was formatted in a modular sense such that as better experimental results became available changes could be made with minimum effort.

BACKGROUND

The decision to develop a multispectral obscuration model immediately led to a straw man outline with secondary and tertiary options for the structure of the algorithm to assure flexibility. The advantages and disadvantages of atmospheric optic and diffusion postulates that could be used were weighed against the meteorological observations that would be available on a battlefield. A determination was made that eight available surface and sensible weather observations were basic to the development of a workable obscuration scheme. As a consequence, the atmospheric optics model selected was one proposed by Downs [1], being compatible with the required meteorological data. The optics model was then complemented by a diffusion approach advocated by Gifford [2]. The complementary models require a methodology for classifying atmospheric stability. The six category Pasquill [3] scheme was selected on the basis of compatibility with the input parameters. The relationships between the Pasquill categories and observational data and the eight meteorological inputs to the model are given in tables 1a. and 1b.

TABLE 1a. RELATION OF PASQUILL CATEGORIES TO WEATHER CONDITIONS

A - *Extremely unstable*	D - Neutral
B - Moderately unstable	E - Slightly stable
C - Slightly unstable	F - Moderately stable

Surface Windspeed (m/s)	Daytime Insolation			Nighttime Conditions	
	Strong	Moderate	Slight	Thin Overcast or $\geq 4/8$ Cloudiness	$\leq 3/8$ Cloudiness
< 2	A	A-B	B		
2	A-B	B	C	E	F
4	B	B-C	C	D	E
6	C	C-D	D	D	D
6	C	D	D	D	D

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TABLE 1b. METEOROLOGICAL INPUT PARAMETERS FOR STABILITY, OPTICS, AND DIFFUSION CALCULATIONS

Ceiling height (feet)	Temperature (degrees F)
Cloud cover (percent)	Dew point (degrees F)
Visibility (miles)	Wind direction (degrees)
Precipitation (yes or no)	Windspeed (knots)

The Gaussian plume and puff hypothesis chosen to model semicontinuous and quasi-instantaneous sources, uses longitudinal, lateral, and vertical dispersion parameters that are stability dependent and, in the case of vertical diffusion, a function of the aerodynamic roughness of the earth's surface. The dispersion parameters are calculated using power laws attributed to Pasquill [3]. Aerodynamic roughness is evaluated using the approach of Kung [4], based upon the height of the roughness elements, i.e., trees, bushes, grasses, etc.

The straw man approach highlighted additional factors that would influence obscuration on the battlefield including (1) relative humidity effects upon the hygroscopic characteristics of the smoke aerosols, (2) the need for optimum impact separations of artillery-delivered smoke projectiles, (3) rate of fire calculations for efficient dissemination of chemical smokes, and (4) munition expenditure estimates used for planning future operations.

THE FOG OF WAR

The visual range in the atmosphere is directly affected by natural aerosol concentrations and particle size distributions occurring over any optical path. Visibility may be reduced by dry haze, wet or relative humidity haze, fog, or air pollution. Battlefield visibility can be compromised by the additive effects of the fog of war, i.e., pollution induced by deliberate smoke screening, dust thrown up by the mass movement of heavy vehicles and intense artillery barrages, or smokes from burning vehicles. The reduction of visibility by natural aerosols plus the fog of war had a direct effect upon countermeasure obscuration used to deny target acquisition.

Battlefield pollution coupled with the liquid water content of the atmosphere control the aerosol scattering and water vapor absorption of visible light and infrared radiation in the

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atmosphere. The attenuation of an optical path by scattering and absorption results in a higher threshold level of detection. The net effect is a need for less smoke to render an optical path opaque. The KWIK algorithm was designed to take these phenomena into account, i.e., aerosol mass concentrations with respect to battlefield visiblity and attenuation by water vapor as a function of relative humidity.

The inclusion of visibility in the determination of extinction coefficients for finite optical paths is a major factor in the reduction of munitions expenditures necessary to establish and maintain obscuring screens on a battlefield. Conversely, as discussed below, the KWIK algorithm, with some modifications, can be used to estimate the degradation of visibility by the products of a dirty battlefield.

SMOKE SCREENING AND OBSCURATION

Countermeasure obscuration may be considered from two viewpoints, the first being the attenuation of near horizontal optical paths where the crosswind integrated concentration of smokes such as white phosphorous or zinc chloride is of prime importance. The second is large area screening whereby detection of ground targets by airbone observers or remotely piloted vehicles is denied. Here the vertical or slant path integrated concentration is the prime parameter. The determination of the horizontal or vertical integrated concentrations necessary to obscure an optical path to the threshold level is almost wholly dependent upon the basic optical calculations. The optics portion of KWIK is adapted from an approach to atmospheric transmission suggested by Downs [1]. Transmittance of light at various wavelengths through a path is determined by calculating the attenuation due to absorption by water vapor, scattering by haze or fog, and precipitation. When the attenuation due to atmospheric conditions is known, the attenuation due to smoke that is required to lower tansmittance to a threshold contrast can be computed.

Absorption is attributable to the amount of precipitable water in a path, assuming the water vapor concentration in the atmosphere is well behaved and exhibits a scale height of about 2 km. The water vapor concentration expressed in centimeters per kilometer of path length may then be given as:

$$W = W_o e^{-(L \sin \theta)/2} , \quad (1)$$

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where W_o is the precipitable water along a path L and θ is the angle between the horizontal and the height of a target above or below an observer. W_o is computed from a regression equation relating precipitable water and dew point temperature (T_d):

$$W_o = 0.4477 + 0.0328T_d + 1.2(10)^{-3} T_d^2 + 1.84(10)^{-5} T_d^3 \quad (2)$$

Equation (2) was fit to data extracted from Downs [1] and is considered valid for any meteorological condition.

The amount of water vapor in the path, W, is given by:

$$W = W_o \int_o^L e^{-(L \sin \theta)/2} \, dL . \quad (3)$$

Transmission through the absorbing component of the atmosphere is calculated by using an error function absorption law developed by Elsasser [5]

$$T = 1 - \text{erf}(z) , \quad (4)$$

$$\text{erf}(z) = \frac{2}{\sqrt{\pi}} \int_o^z e^{-z^2} \, dz , \quad (5)$$

where $z = 0.5 \ \beta \ \sqrt{\pi W}$, and β is the error function absorption coefficient as a function of wavelength.

Downs [1] states that the Elasasser approach is unable to correctly address long wavelengths and suggests using an approach described by Fisher [6] for the far infrared wavelengths, with the computation of transmission due to absorption by water vapor given by:

$$T = e^{-0.0681W} . \quad (6)$$

Reduction in transmittance due to attenuation by haze and fog can be calculated by using Mie theory. Downs [1] indicates that the Mie scattering coefficient decreases with altitude such that its

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behavior can only be estimated. The following expressions for σ_M (Mie scattering coefficient) are, at best, an approximation to the behavior of the σ_M versus altitude relationship

$$\sigma_M = \sigma_{hf} e^{-L \sin \theta / 4.1} ; \; V_R \geq G(\lambda) \; , \qquad (7)$$

$$\sigma_{M_1} = \sigma_{hf} e^{L \sin \theta \ln (0.1/\sigma_{hf})} \; ; \; V_R < G(\lambda) \; , \; 0 < L \sin \theta \leq 1 \text{ km}$$

$$\sigma_{M_2} = 0.128 e^{-L \sin \theta / 4.1} \; ; \; V_R < G(\lambda) \; , \; 1 \text{ km} \leq L \sin \theta < \infty$$

$$\sigma_M = \sigma_{M_1} \left(\sigma_{M_2} \right) \; , \qquad (8)$$

where σ_{hf} is the extinction coefficient determined from a linear regression as a function of visibility and wavelength, based upon Downs' evaluation. V_R is visibility, and $G(\lambda)$ is the scale height of σ_M. $G(\lambda)$ is not constant; rather it is a function of altitude, visibility, and wavelength. Transmission along a path with attenuation σ_M can be determined by the equation

$$T = e^{-\int_o^L \sigma_M(L) \, dL} \; , \qquad (9)$$

after substituting a value for σ_M according to equations (7) and (8). If precipitation is indicated (by input parameter), then the value for transmittance in equation (8) is set to one and a calculation is made for attenuation by precipitation instead.

Reduced transmittance owing to attenuation by precipitation can be obtained from

$$T = e^{-\int_o^L \sigma_r(L) \, dL} \; , \qquad (10)$$

where L is the path length and σ_r is an attenuation coefficient determined from a regression equation as a function of visibility and wavelength. The total transmittance along an optical path is the product of the partial transmittances

$$T_{total} = T_a T_{hf} T_p T_s \,, \qquad (11)$$

where

T_a = Transmittance due to attenuation by absorption

T_{hf} = Transmittance due to attenuation by haze and fog

T_p = Transmittance due to attenuation by precipitation

T_s = Transmittance due to attenuation by smoke

T_s is then calculated from equation (11), and the desired threshold contrast of transmittance for a particular wavelength can be determined from:

$$T_s = \frac{T_{tc}}{T_a T_{hf} T_p} \,, \qquad (12)$$

where T_{tc}, *the threshold contrast, is based upon the Koschmieder* [7] theory but set equal to 0.10 for visible wavelengths and 0.05 for infrared.

The approach used to determine the line of sight integrated concentration, CL, of the smoke screen necessary to attenuate an optical path to a threshold level is based on the transmittance of equation (12) as a function of CL. The CL-value necessary to attenuate an optical path to deny target acquisition may be determined from the Bouguer-Beer law written as

$$T_s = \frac{I}{I_o} = e^{-\alpha CL} \qquad (13)$$

where I is the illuminance at a target, I_o is the illuminance at the light source, α the extinction coefficient, and T_s the reciprocal of attenuation. Rearranging and solving equation (13) yields

$$CL = \frac{\ln Ts}{-\alpha} \qquad (14)$$

where CL is the minimum integrated smoke conc ntration.

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Equation (14) is applicable to both visible and infrared wavelengths, if values of α are known. Listed in table 2 are average extinction coefficients for the two screening chemical smokes considered by the KWIK algorithm, i.e., bulk white phosphorous (WP) and hexachloroethane (HC) (zinc chloride) for the indicated spectral bands.

TABLE 2. EXTINCTION COEFFICIENTS FOR WHITE PHOSPHOROUS AND HEXACHLOROETHANE GENERATED SMOKES

Spectral Band	Wavelength (μm)	α, $m^2\ g^{-1}$	
		Zinc Chloride	White Phosphorous
Visible	0.4 to 0.7	3.30	2.46
Near IR	0.75 to 1.2	1.50	1.50
Mid IR	3 to 5	0.12	0.21
Far IR	8 to 14	0.05	0.28

The development of diffusion formulae for predicting the obscuring power of chemical smokes starts with the assumption of an instantaneous point source of material diffusing in three dimensions. For a Gaussian distribution of diffusion taking place independently in the three coordinate directions, the equation can be stated as

$$\chi_{(x,y,z)} = \frac{(2\pi)^{-3/2}\, Q_T}{\sigma_x\, \sigma_y\, \sigma_z} \exp\left\{-\frac{1}{2}\left[\left(\frac{x - \overline{V}t}{\sigma_x}\right)^2 + \left(\frac{y}{\sigma_y}\right)^2 + \left(\frac{z}{\sigma_z}\right)^2\right]\right\} \tag{15}$$

where χ is concentration in g m^{-3}, Q_T the total release of material in g, x, y, z the coordinate directions, $\overline{V}$ the mean windspeed in m s^{-1}, t is time, and σ_x, σ_y, σ_z the dispersion parameters.

Integration of equation (15) yields the continuous source equation for sources and receptors near the ground as

$$\chi = \frac{Q}{\pi\, \overline{V}\, \sigma_y\, \sigma_z} \exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2 + \left(\frac{z}{\sigma_z}\right)^2\right] \tag{16}$$

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where Q is a time rate of release. If equation (16) is integrated, the result is the crosswind integrated concentration (CWIC) of the plume

$$\chi_{CWIC} = \left(\frac{2}{\pi}\right)^{1/2} \frac{Q}{\overline{V}\,\sigma_z} \exp\left[-\frac{1}{2}\left(\frac{z}{\sigma_z}\right)^2\right] \tag{17}$$

which is the basic form for estimating obscuration from sources generated by the HC smoke mix. The vertical dispersion parameter σ_z is determined using the Pasquill [3] power law in the form

$$\sigma_z = cx^d \; . \tag{18}$$

The coefficient and index values will be discussed at the end of the section.

Screening and obscuration are not restricted to the along wind case of equation (16); consequently, a wind direction correction factor must be considered for head, tail, and quartering wind conditions. The correction factor may be derived from considerations concerned with finite line sources, cumulative effects of multiple sources, and discrete point line sources. The correction factor is eliptical and given by

$$\delta^2 = \frac{m^2\, n^2}{m^2 \sin^2\theta + n^2 \cos^2\theta} \tag{19}$$

where m = 3.71 and n = 1, the eliptical semi-axes, and θ the angle between the mean wind direction and the optical path.

The exponential term on the right hand side of equation (17) is only partially sensitive to stability and downwind travel distances associated with smoke screening. Consequently, numerical evaluation for the six stability categories and along wind distances of 50 to 150 m shows that $\exp[-1/2(z/\sigma_z)^2]$ may be taken as constant and set equal to 0.916.

The assumption can be made that the line of sight integrated concentration CL of the screening aerosol calculated from equation (14) is equal to the value of χ_{CWIC} evaluated from equation (17). This allows equation (17) to be rearranged, after substitution of equation (18) and consideration of the ramifications of equation (19) and solved for the along wind travel distance x. Included in the solution are the source efficiency term λ and the relative humidity-related yield factor Ω, which serve to modify the source strength Q. Thus

$$\chi = \delta^{-1}\left[\frac{0.731\ \lambda\ \Omega\ Q}{C\ \overline{V}\ CL}\right]^{d^{-1}} \tag{20}$$

after combining all the constants. The integrated concentration required for obscuration reaches a minimum at the distance x downwind from the source. Accordingly, x is the calculated impact separation of the smoke projectiles.

Obscuration calculations for quasi-instantaneous sources, i.e., as generated by bulk WP munitions requires that the integrated concentration equation be written in the form

$$\chi_{CWIC} = \frac{\lambda\ \Omega\ Q_T}{\pi\ \sigma_{x_I}\ \sigma_{z_I}}\ \exp\left\{-\frac{1}{2}\left[\left(\frac{x - \overline{V}t}{\sigma_{x_I}}\right)^2 + \left(\frac{\overline{Z} - z}{\sigma_{z_I}}\right)^2\right]\right\} \tag{21}$$

where the dispersion parameters σ_{x_I} and σ_{Z_I} are not to be confused with those associated with a continuous source. The term $\overline{Z}$ represents the height of the puff centroid above the surface. Owing to the nature of the exponential on the right hand side of equation (21) which requires knowledge of two downwind travel distances and three heights for solution, the integrated concentrations were determined for a unit downwind distance of 100 m.

Bulk WP is an exothermal smoke source, with only a fraction of the total material available for screening. The major portion of the phosphorous smoke is transported vertically in the thermal plume. An analysis of available data yielded the efficiencies or percent of payload available shown in table 3. Also tabulated in table 3 are numerical evaluations of the exponential term of equation (21) for each stability category (K factors).

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TABLE 3. EFFICIENCIES AND K FACTORS FOR BULK WHITE PHOSPHOROUS SMOKE MUNITIONS AS A FUNCTION OF PASQUILL STABILITY CATEGORY

Pasquill Category	K Factor	Efficiency
A	0.4633	0.07
B	0.3631	0.10
C	0.2056	0.14
D	0.0647	0.28
E and F	0.0725	≈ 0.30

This allows equation (21) to be restated as

$$\chi_{CWIC} = \frac{K \lambda \Omega Q_T}{\pi \sigma_{x_I} \sigma_{z_I}} . \qquad (22)$$

Projectile impact separations can now be determined from

$$x = 100 \frac{\chi_{CWIC}}{CL} \qquad (23)$$

where the constant is the unit screen length and CL is calculated from equation (14).

Large area screening can be treated by integration of equation (16) in the vertical yielding

$$\chi_{VIC} = \left(\frac{2}{\pi}\right)^{1/2} \frac{Q}{\overline{V} \sigma_y} \exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right] \qquad (24)$$

which is applicable to the use of fog oil generators. The rendering opaque of large areas such as air fields is dependent upon the inherent and apparent contrast between two objects on the ground with respect to the sky-ground ratio and the threshold contrast of the objects. The problem of vision looking downward from aircraft has been discussed by Duntley [8] and Middleton [9]. Middleton suggests that the threshold contrast over a slant

range $\overline{R}$ is given by

$$\varepsilon = C_o \left[1 - \left(\frac{B_m}{B_o} \right) \left(1 - \exp 3.912 \, \overline{R}/V_r \right) \right]^{-1} \tag{25}$$

where C_o is the inherent contrast, B_m/B_o the sky-ground ratio, and V_r the visual range. Values of ε so determined may be used in equation (14) to evaluate slant range integrated concentrations. Sherwood [10] found that χ_{VIC}'s of 0.33 g m^{-2} were necessary to screen a large area from aerial observation.

The obvious use of equations (24) and (25) is the determination of the number and separation of oil fog generators required to screen a large area. Equation (24) can be manipulated to yield the separation distance y_s as

$$y_s = 2 \, \sigma_y \left[\ln \left(\frac{2}{\pi} \right)^{1/2} \frac{Q}{\overline{V} \, \sigma_y \, \chi_{VIC}} \right]^{1/2} \tag{26}$$

and the number of generators N_g required by dividing the screen width L by y_s plus one, or

$$N_g = \frac{L}{y_s} + 1 \; . \tag{27}$$

The dispersion coefficients σ_y, σ_z, σ_{x_I}, and σ_{z_I} are based upon the Pasquill [3] power laws and given by

$$\sigma_y = ax^b \tag{28}$$

$$\sigma_z = cx^d \tag{29}$$

$$\sigma_{x_I} = \sigma_{x_o} + 0.74 \, ax^b \tag{30}$$

$$\sigma_{z_I} = \sigma_{z_o} + 0.667\ cx^d \qquad (31)$$

where σ_{x_o} and σ_{z_o} are the initial dispersion or burst functions. Downwind dispersion parameters for the quasi-instantaneous sources are approximately two-thirds of those for continuous sources as shown by Pasquill [3], which is reflected by equations (30) and (31). The coefficients and indices for the dispersion parameters as a function of stability and aerodynamic roughness are tabulated in table 4 for three roughness lengths.

TABLE 4. COEFFICIENT AND INDEX VALUES FOR THE POWER LAW DISPERSION PARAMETERS

Stability Category	a	b	c	d	c	d	c	d
			z_o = 1 cm		z_o = 10 cm		z_o = 100 cm	
A	0.40	0.90	0.154	0.94	0.279	0.90	0.615	0.83
B	0.32	0.90	0.133	0.89	0.225	0.85	0.539	0.77
C	0.22	0.90	0.121	0.85	0.213	0.81	0.533	0.72
D	0.143	0.90	0.108	0.81	0.195	0.76	0.456	0.68
E	0.102	0.90	0.078	0.78	0.139	0.73	0.348	0.65
F	0.076	0.90	0.062	0.72	0.117	0.67	0.309	0.58

SEEABILITY ON THE BATTLEFIELD

A battlefield may be considered as being mesometeorological in scale, i.e., areas ranging from hundreds to thousands of square kilometers. If the density of meteorological observations is large and timely, the optics portion of KWIK may be used to calculate the attenuation of optical paths for each weather observational site. The attenuations may be plotted and analyzed much like synoptic data to prepare "seeability" charts for a battlefield. Battle plans for future engagements with estimates of munition expenditures anticipated number of burning vehicles and vehicular dust conditions can be used to predict visibility conditions which may be used for attenuation forecasts. Seeability, prognostications can be used for planning purposes, i.e., what weapons system will be effective on the next day's predicted dirty battlefield.

DISCUSSION

The complete KWIK smoke obscuration model has been discussed by Umstead, Peña, and Hansen [11], including the development of the scheme to establish rates of fire, impact separations in adverse wind conditions, and the special considerations for munitions expenditures in the mid and far infrared regions of the spectrum. Owing to space limitations, these subjects are beyond the scope of this paper.

The basic scheme developed for artillery delivered smoke projectiles assumes that smoke obscuration operations will be conducted with batteries or battalions firing in an open sheaf rather than parallel or normal sheaf patterns. This concept, coupled with relative humidity dependent yield factors in the smoke model, will result in a more efficient use of smoke on a battlefield. Preliminary studies suggest savings in munitions up to 20 to 30 percent over current methods.

The use of the KWIK algorithm for large area screening operations and predicting attenuation degradation on the dirty battlefield does not detract from the original intent of the model, but enhances its capabilities. The outputs of these offshoots of the primary model can be utilized to improve the munition expenditure estimates generated for countermeasure obscuration purposes. Large area screening systems utilizing oil fogs are only usable in the visible portion of the spectrum. Consequently, the portion of KWIK expressed by equations (24), (25), and (26) only apply to the 0.4- to 0.7-µm band.

Owing to the extinction characteristics of HC smoke, the approach personified by equation (20) is valid only in the visual and near infrared portions of the electromagnetic spectrum. The superior characteristics of WP allow it to be utilized to countermeasure devices operating in the mid and far infrared regions.

CONCLUSIONS

The KWIK obscuration model is highly versatile and has been programmed to operate on a variety of machines ranging from programmable desk calculators to digital computers. Three versions are in existence: the Fortran, the real-time with three options, and a deferred-time version for generating munition expenditure estimate tables based upon climatological input data. The algorithm may be used in threat analysis studies or as a subroutine in force on force

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scenarios. The modular concept used to develop KWIK allows greater flexibility than found in predecessor smoke models.

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