DEVELOPMENT OF AN OBSCURATION DATABASE FOR MODELING

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Abstract

The Combined Obscuration Model for Battlefield Induced Contaminants (COMBIC) is a standard U.S. Army computer model that is used to predict transmission through an evolving obscurant. However, the direct use of COMBIC for modeling the effects of obscurants can slow simulation time significantly. This paper presents my analysis and some of the limitations that I encountered when I used COMBIC to generate a look-up database. The generation of the database must balance the real-time requirements for the simulation with the accuracy of the transmission values through an obscurant. Initially, a set of environmental and geometrical parameters was specified. A key point in the specification was the interpretation of three terms that were used to establish the level of the obscurant: low, medium, and high. I made several calculations with COMBIC to determine how the parameters should be varied to obtain reasonable results. Once a methodical procedure was designed for generating the transmission values, a scripted program was developed that generated the entire set of values.

1. Introduction

As an aircraft flies over an object on the ground, the pilot and any sensor systems on the aircraft are able to look down and see the object. However, if smoke, munitions, or other obscurants have been deployed, the pilot and sensor system may not be able to see the object. With an obscurant present, the ability to see the object depends on the look angle, the amount of obscurant and how it is deployed, and many environmental conditions. To simulate this in a real-time model, the time available for the determination of the growth and transmission through an obscurant is extremely short. A direct approach that will make the computation time as short as possible is to supply the necessary data in a look-up table format. The data file could be indexed based on all the dependent variables and would output the values of the appropriate transmission through the obscurant.

This paper discusses the generation of a transmission database that uses the Combined Obscuration Model for Battlefield Induced Contaminants (COMBIC) [1]. A description of this model is given in the following section. The parameters that were established as an index for the database are given in section 3. In section 4, several aspects of how the U.S. Army deploys smokes are presented. Finally, some of the advantages and limitations of this database are discussed.

2. Model Description

COMBIC is a two-phase model for computing the growth of battlefield obscurants, such as dust, smoke and clouds, and the determination of atmospheric extinction along a user-determined line of sight (LOS). The model has evolved through several versions beginning in 1982, with the most recent version dating from 1992. The source code is written in Fortran 77.

As a two-phase model, COMBIC can be separated into two parts. The first phase of COMBIC computes the growth of a puff or a plume under the influence of diffusion, gravity, and external winds. A basic assumption for the computation is that the cloud is an ellipsoidal, Gaussian distribution. The physical equations that describe the growth will maintain the Gaussian form of the result, although the parameters describing the shape will deform. Results of this computation are placed into an auxiliary database that is indexed based on the time since the cloud was started. If several different types of clouds are generated, each one is accorded its own descriptive growth. This database is available and necessary for the performance of the next phase.

The second phase computes the transmittance between target and observer for the clouds defined under phase 1. For this phase, additional information about the time and location of each cloud's formation is required. If several clouds are present and growing, the transmittance through all intervening clouds is computed. These computations can be performed for multiple wavelengths. The computational speed for this phase of the algorithm is essentially real-time.

Data inputs that should be supplied by the war game model can be separated into three groups: Data that are common to both the phase 1 and phase 2 computations, data that are specific to phase 1, and data that are specific to phase 2. Default values can be assigned to most of the parameters.

The parameters that are common to all computations include

- the spectral band (specified by a start and stop wavelength, and the number of bands the region should be divided into),

- the visibility (a single value at 0.55 μm),

- the weather (this can be set initially or at a later input location and includes wind speed, atmospheric stability, and humidity), and

- some geometry values (locations of a single source, observer, receiver, and target).

Within the phase 1 parameter set, the most crucial parameter is the identification of the source of the obscurant. A default parameter set that describes the initial form of the cloud is available for many of the more standard obscurants that are used. Many of the obscurants are hygroscopic and their optical properties will change with a change in humidity. In phase 2, it is necessary to know the relative locations of all objects for which the transmission values are to be determined. In addition, it is necessary to know the time at which any obscurant cloud was started.

Output from the phase 2 computation is the aerosol transmission between a source and a detector. The computation takes into account all obscurant sources that are defined in the model inputs and that exist along the line of sight between the source and detector. This value is the primary input requirement for the sensor performance modules that are part of the war games.

A second form of the COMBIC model is available and is called PcCOMBIC. This second form is designed to run on a PC and uses the same COMBIC code described above. The advantages of this second version are that it has a user-friendly interface for both the input of the parameters and the display of the results. The output display can show the appearance of the obscurant at various times in the growth and motion of the cloud. Also, a graph of the transmission between two points versus time can be displayed. These latter two capabilities were extensively used to exhibit the results of my analysis.

3. Parameters

Seven parameters were chosen to capture the variability of smoke dispersion. These parameters and their values are shown in table 1. A discrete set of values that determines transmission was used for these seven parameters, and these parameters will be discussed in the following paragraphs.

Table 1: Parameters and their values selected for this analysis.

Parameter	Value
Smoke type	White phosphorous (WP) Hexachloroethane (HC) High explosive (HE) Fire smoke (FO) from a burning vehicle (a mixture of diesel fuel, oil, and rubber)
Smoke level	Light, medium, heavy
Wind speed (m/s)	1–2, 5, 7, 10, 20
Pasquill category	A, B, C, D, E, F
Surface temperature (°C)	–20, 0, 10, 20, 30, 40
Look angle (°)	0, 45, 55, 65, 75, 80
Wavelength (µm)	0.4 to 0.7, 3 to 5, 8 to 12

Some of these values are interrelated. A prime example of this dependence is for the Pasquill categories. The Pasquill categories are dependent on the wind speed, time of day, temperature, cloud cover, presence of more than 6 in. of snow, and latitude. Based on the flowcharts for determining stability categories [2], when the wind speed is greater than 6 m/s, only one Pasquill category occurs: D or neutral. The other two slower wind speeds of interest in our analysis can be in the Pasquill category B, C, or E. Table 2 is a summary of the related Pasquill category values.

Table 2: Pasquill categories and related values.

Pasquill category	Wind speed 2 m/s 7.2 km/hr	5 m/s 18.0 km/hr	7 m/s 25.2 km/hr	10 m/s 36.0 km/hr	20 m/s 72.0 km/hr
A					
B	X				
C	X	X			
D	X	X	X	X	X
E	X				
F					

Note: The two values that are not included in the computations, Pasquill categories A and F, correspond to a wind speed of almost zero and a very stable (A) and very unstable (F) environmental situation. They were not considered as part of our analysis.

As discussed above, the Pasquill categories for the lower wind speeds depend on additional information, including time of day, time of year, and cloud cover. These controlling parameters will be set within the simulations to select the appropriate Pasquill category.

My intention was to use the level of smokes as defined in the TARGAC (Target Acquisition Model) report [3]. This paper (see the SMOK record description in the TARGAC report, pp 88–92) uses three different values for the optical depth that depend on the degree of screening that the smoke can achieve. Terms used to describe these values are light, medium, and heavy. For a light smoke, the optical depth for a large area smoke screen or fog oil is defined as 0.25 per 100 m. For all other smokes (e.g., HC or WP), the value for a light smoke is 0.50 per 100 m. Similarly, for a medium smoke, the respective values are 0.50 per 100 m and 1.50 per 100 m, and for a heavy smoke, the respective values are 1.50 per 100 m and 3.00 per 100 m.

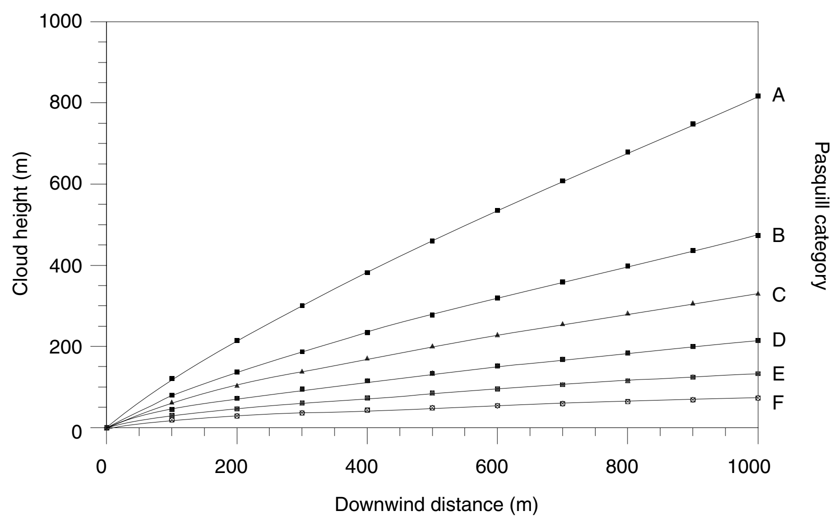
The defined optical-depth numbers for the smoke levels do not interface directly with either the input or output from the COMBIC model. The input needed for a COMBIC run includes a scaling factor for a single artillery round and the location and time of a round's placement. Output from the COMBIC model is a transmission along a line of sight between a target and an observer. These output values can be correlated with the optical-depth numbers given above. If the observer and target are separated by 100 m, the transmission through the obscurant would be 78 percent for a light fog oil, 61 percent for a medium fog oil, and 22 percent for a heavy fog oil smoke. For other types of smokes, the values would be 61 percent for a light smoke, 22 percent for a medium smoke, and 5 percent for a heavy smoke.

Before a discussion of the measurement of this transmission is presented, I make an assumption about the number and placement of the smoke from the artillery round. Initially, I assume that only a single round of variable strength is used. Also, when combined with the direction of the wind, the location of the source is such that the center of mass of the smoke will travel directly over the target during the measurement time of interest. To further discuss this assumption, I must first discuss how the Army deploys obscurants. This discussion is given in section 4 and includes the implications of my assumption.

I begin with a discussion of the geometry for a single artillery round and the assumption of a Gaussian distribution for the concentration. For this single round I need to specify where and in what orientation in the Gaussian smoke plume a transmission measurement will be made.

The shape of the obscurant cloud within the COMBIC model is not spherically symmetric. Given that the wind is in the x direction, the y direction is also parallel to the ground, and the z direction is vertically upward. Also, the shape is roughly ellipsoidal, with the x direction being the major axis of the plume. Depending on the location of the observer and the reference object, the entire LOS can be entirely within the cloud (for example, if the LOS is along the wind axis) or partly in and partly outside the cloud (for example, if the observer is vertically above the target). Because of the symmetry of this shape, the observer and the observed object are placed on opposite sides of the axis of symmetry of the cloud; that is, if $+y$ is the location of the observer, $-y$ is the location of the reference object.

I assume that the flight path of an aircraft is directly over the target at an altitude of 1000 m. Actually, any altitude can be used that exceeds the peak height of the smoke clouds. Information on the height to which a smoke cloud can rise is given in the COMBIC documentation. In figure 1, taken from that documentation, one can see that as long as we are within a downwind distance of 1000 m, the height of the smoke under all Pasquill categories does not exceed 1000 m.



Note: Formulas used to generate the data for figure 1 are taken from Alan Wetmore and Scarlett D. Ayres, *COMBIC Technical Document Users Guide*, U.S. Army Research Laboratory, ARL-TR-1831 (March 2000).

Figure 1: Cloud height dependence on Pasquill category.

The look angle that determines the line of sight from the aircraft to the target is measured with respect to the vertical. Thus, a 0° look angle occurs when the aircraft is directly above the target and the pilot or sensor system can look straight down. The values used for the look angles are ±0°, ±45°, ±55°, ±65°, ±75°, and ±80°. Figure 2 is a sketch of the positive look angles.

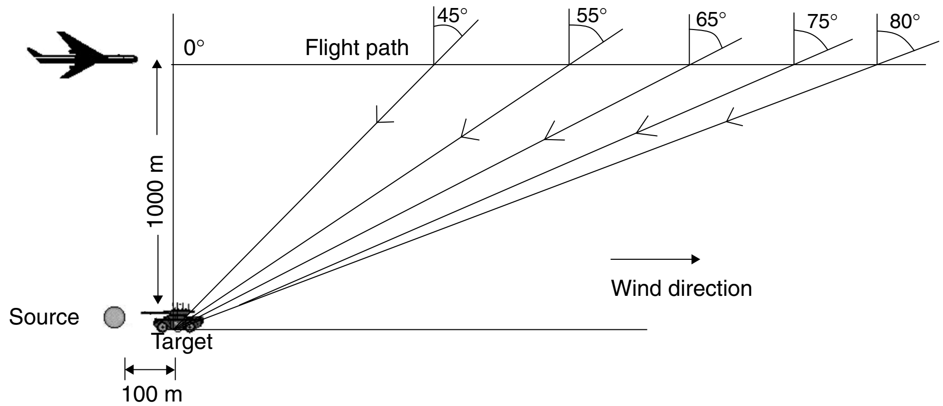


Figure 2: Positive look angles for line of sight from aircraft to target.

An initial upwind offset distance of 100 m is assumed between the source and the target. This allows the obscurant to grow and diffuse. Also, if the source and the target are collocated, the wind will blow the obscurant away from the observation at the very start of any analysis. During the data runs, this offset is allowed to increase if the transmission is less than 61 percent for the length of the run.

Another effect of the shape of the cloud is that transmission will vary depending on whether the observer is approaching the target or looking back after passing the target. For example; as shown in figure 3, if the cloud has just started to pass over the target, the transmission from a look angle of 80° may be 100 percent, while from the other side (–80°) the transmission could be minimal. Thus, when the computation of transmission is considered both situations need to be taken into account.

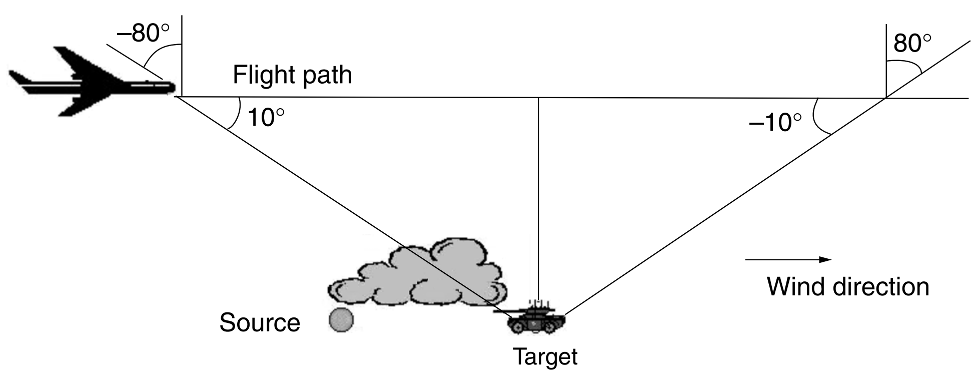


Figure 3: Aspect effects of obscurant on line of sight to target.

Wind speed is the most important environmental parameter that must be supplied, as it determines both the dispersion and downwind transport of the obscurant. It also is a significant input for determining the value of the Pasquill category. The Pasquill category also is a significant factor for determining the evolution of the size of an obscurant cloud. The wind speed values that have been chosen as important are 2 m/s, 5 m/s, 7 m/s, 10 m/s, and 20 m/s.

The wavelength bands for which the transmission is computed are the visual band from 0.4 µm to 0.7 µm, the near infrared from 3 µm to 5 µm, and the infrared from 8 µm to 14 µm. These bands are standard COMBIC choices. In the database, a single wavelength is used to represent each of these bands: 0.5 µm, 4 µm, and 10 µm.

The format of the data that will be assembled depends on how the user intends to access the data. For example, it can be formatted as a flat ASCII file. That is, a record will consist of eight alphanumeric entries. The first seven entries correspond to the seven parameters listed in table 1, and will be entered in the same sequence. A comma will delimit each entry. The last or eighth entry for a record will be the value computed by COMBIC for the transmission through the obscurant and it will be delimited by an ASCII CR for a carriage return. The general appearance of the file is as follows:

Smoke Type	Smoke Level	Wind Speed	PASQUILL Category	Surface Temp	Zenith Angle	Wave-length	Smoke Transmission

An example of a record would be

HC, L, 2, C, –20, 0, 0.5, 0.635.

This record would be interpreted as a light hexachloroethane smoke, in the presence of a 2-m/s wind at –20 °C, with a Pasquill category of C. It would have a transmission of 0.635 when a ground target is viewed at a look angle of 0° (straight down) for a visual wavelength band centered at 0.5 µm.

A second example would be

FO, H, 7, D, 20, 45, 4, 0.445.

This record would be interpreted as a heavy fog oil smoke in the presence of a 7 m/s wind at 20 °C, with a Pasquill category of D. It would have a transmission of 0.445 when a ground target is viewed at a look angle of 45° for a near infrared wavelength band centered at 4 µm.

4. Army Smoke Operations

The Army uses smokes and obscurations as a tactical weapon [4]. Early consideration for the use of smoke (although not used) dates back to the Civil War, and serious employment of smoke dates back to applications during World War II. Depending on the missions that are to be carried out, the resources that are available, and the environment within which the mission is to be carried out, many different battlefield smoke operations can be used, and their effectiveness will differ. Some of these smoke operations are discussed in the following paragraphs.

Modern battlefield planning considers two general categories of smoke operations: hasty and deliberate. Hasty smoke operations are conducted with minimal planning. These operations generally cover a small area for a short duration. On the other hand, deliberate smoke operations are conducted with detailed planning. These operations will normally cover large areas over long periods.

Smoke has four battlefield applications: obscuring, screening, protecting, and marking. Obscuring smoke is delivered directly on or immediately in front of enemy positions. A screening smoke is delivered in areas between friendly and enemy forces or in friendly operational areas; there are three categories of this type discussed below. Protecting smoke is used to defeat enemy guidance systems or attenuate energy weapons. Finally, marking smoke is used to mark targets, identify friendly positions, and provide for prearranged battlefield communications.

The three different categories of screening smokes are smoke haze, smoke blanket, and smoke curtain. Smoke haze is a light concentration of smoke placed over friendly areas. A smoke blanket is a dense, horizontal concentration of smoke used over friendly areas. A smoke curtain is a dense, vertical concentration of smoke. It is placed between friendly and enemy positions.

These screens can be deployed in many different ways. Battlefield smoke can be generated by individual munitions (such as grenades, projectiles, and bombs), by control of the exhaust from moving vehicles, and by smoke generators. It can be done by a single source or by combined sources. The major limitation to the deployment of smoke is the amount of resources that can be devoted to a smoke mission. If artillery is being used to fire smoke projectiles, it is not being used to fire explosives that could destroy enemy targets. If soldiers are used to drive smoke-generating vehicles, they are not being used to attack the opposing force. Thus, deploying smoke is a difficult command and control issue. In most situations, the choice will probably be to deploy less smoke.

Here, I look at how a single round of smoke would appear on the battlefield. The following tables show selected results of a single computer run using the COMBIC model. Other than default values, the only run-specific choices that were made are that the smoke is generated by a 155-mm white phosphorous artillery round and that the wind speed is 2 m/s. This information shows how a cloud from a single round grows in size. The standard deviation given in the table is, in effect, a measure of the size of the Gaussian cloud. Remember from the earlier definitions that the x-direction is along the downwind direction of the wind, the y-direction is in the horizontal plane and perpendicular to the x-direction, and z is in the vertical direction.

Table 3: Subcloud trajectory.

Downwind distance (m)	Time (s)	Centroid height (m)	Gaussian cloud standard deviations (m)		
			Direction		
			x	*y*	*z*
1.00	1.06	1.41	17.21	17.31	2.03
5.24	4.38	1.91	17.21	17.47	2.29
14.92	11.15	2.42	17.21	17.82	2.85
27.50	19.29	2.42	17.21	18.95	3.78
47.89	31.79	2.42	17.21	20.77	5.15
67.82	43.42	2.42	17.21	22.53	6.41
85.54	53.43	2.42	17.21	24.08	7.46
96.06	59.26	2.42	17.21	24.99	8.07
107.88	65.72	2.42	17.21	26.02	8.74
121.15	72.87	2.42	17.21	27.16	9.47
136.06	80.80	2.42	17.21	28.44	10.28
152.80	89.58	2.42	17.21	29.87	11.16
171.60	99.30	2.42	17.21	31.46	12.13
192.71	110.07	2.42	17.21	33.25	13.19
216.42	122.01	2.42	17.21	35.23	14.36
272.94	149.88	2.42	17.21	39.92	17.03
344.23	184.11	2.42	17.21	45.75	20.25
386.58	204.05	2.42	17.21	49.18	22.09
487.55	250.67	2.42	17.21	57.24	26.33
614.89	308.02	2.42	17.21	67.23	31.41
870.90	419.87	2.42	17.21	86.85	40.99
1098.37	516.52	2.42	17.21	103.88	49.00
1555.67	705.59	2.42	17.21	137.22	64.10
2203.37	965.44	2.42	17.21	182.99	83.92
3120.74	1323.38	2.42	17.21	245.75	109.94
4420.06	1817.46	2.42	17.21	331.74	144.09
7030.52	2782.78	2.42	17.21	497.75	206.75
9957.67	3838.91	2.42	17.21	676.78	271.11
11182.72	4275.28	2.42	17.21	750.08	296.76

Several interesting observations can be made based on the results of this simulation. The first is the height of the centroid of the cloud; the maximum height is 2.42 m. This is slightly above the height of a 2-m high visual observer but well below the *standard* meteorological height of 10 m used for wind measurement. The second observation is the horizontal dimensions of the cloud at 100 m. The cloud has spread to about 50 m across (the standard deviation in the *y* direction is about 25 m). The first observation is significant when the measurement for the values of the cloud level (light, medium, or heavy) are considered. A height of 2 m for measurement of the transmission is reasonable, while a height of 5 m or 10 m is too high. The second observation is important when more than a single round has been deployed.

The data in this table can also be used to portray how the cloud will appear as time elapses. In figure 4, the appearance of a single white phosphorous round is shown at three points in time: 10 s, 30 s, and 60 s after the cloud is started. These figures were derived from the PcCombic graphical routines and show a top-down view with the wind blowing to the right.

The distribution of the deployed smoke will generally not be the result of a single round placed at a single point. Rather it will be the result of several rounds that have started a cloud at different times and different places. For an artillery battery firing 155-mm white phosphorous rounds to cover a 1,200-m × 50-m area for 15 min, an estimated 128 rounds need to be fired [4]. These rounds are fired at a sustained rate of 1 round per minute by each tube in the battery. The current battery structure has 6 tubes. These tubes are deployed in various arrangements to take advantage of the 50-m shrapnel radius of 155-mm munitions. When fired in a linear sheaf, the artillery rounds will be separated on impact by 100 m. A single volley will more than cover a 50-m × 600-m area (recall the 50-m cloud width discussed above). After aim-point adjustments are made, a second volley covers the remainder of the targeted region. At a point in the center of this linear sheaf on the battlefield, as the smokes are blown by the wind along the line of the sheaf, they begin to overlap and reinforce each other. Another point about the Army's smoke practices is that white phosphorous is used to start smoke coverage quickly. After the white phosphorous is deployed, the Army switches to a felt wedge round that maintains a smoke cloud closer to the ground. I presumed the use of this latter round in the following simulations.

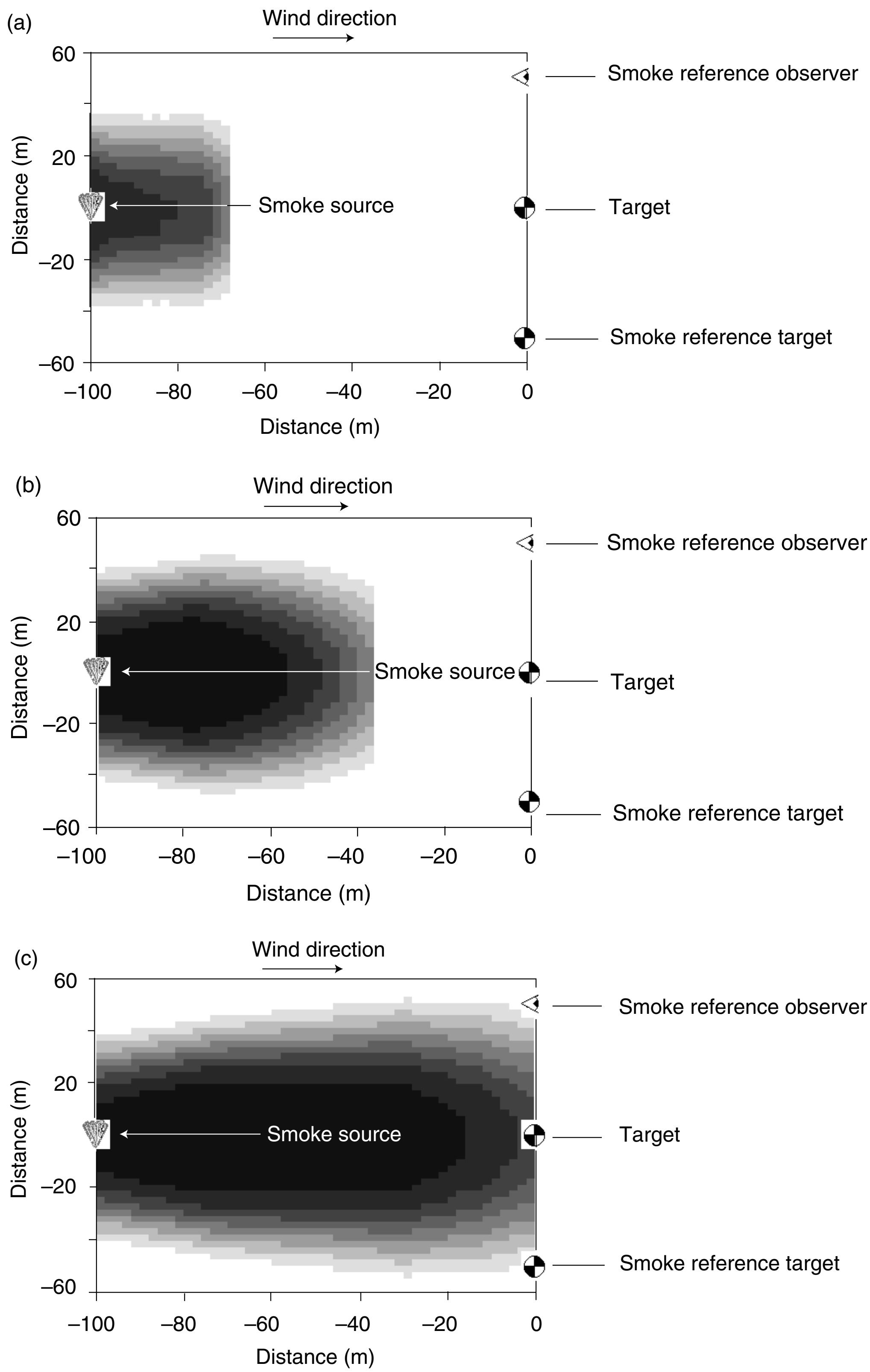


Figure 4: *x*, *y* plots of smoke concentration growth for 155-mm white phosphorus round in 2-m/s wind at (a) 10 s, (b) 30 s, and (c) 60 s.

Before I examine the effect of 6 rounds, I consider the effects of a single round deployed in a 2-m/s wind. The transmission versus time is shown in figure 5.

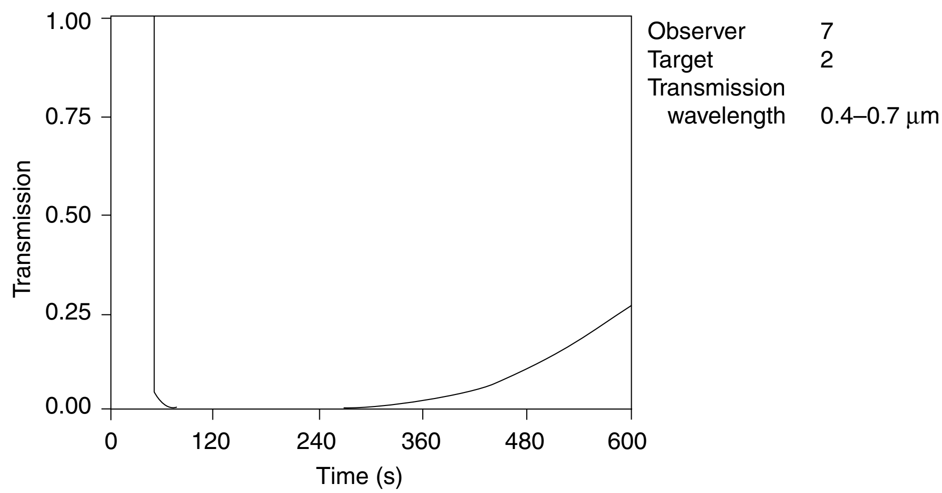


Figure 5: Transmission versus time for one white phosphorous round.

The transmission for a single round is less than 5 percent for a substantial amount of time. To observe the higher transmission levels, one has to wait until the smoke cloud has almost blown past the target. If we add more rounds upwind from the observation point, the effect of these rounds located further from the target will not be as extensive as the round that is close to the target. However, the total effect of the multiple rounds will be additive. The transmission versus time is shown in figure 6 for 6 white phosphorous rounds in a 2-m/s wind. These rounds are placed along a straight line that is in the same direction as the wind, separated by a distance of 100-m, and the *y* direction transmission measurements are made in the middle of the array. The transmission does not become as high as 5 percent until the smoke again (as with a single round) begins to pass the target.

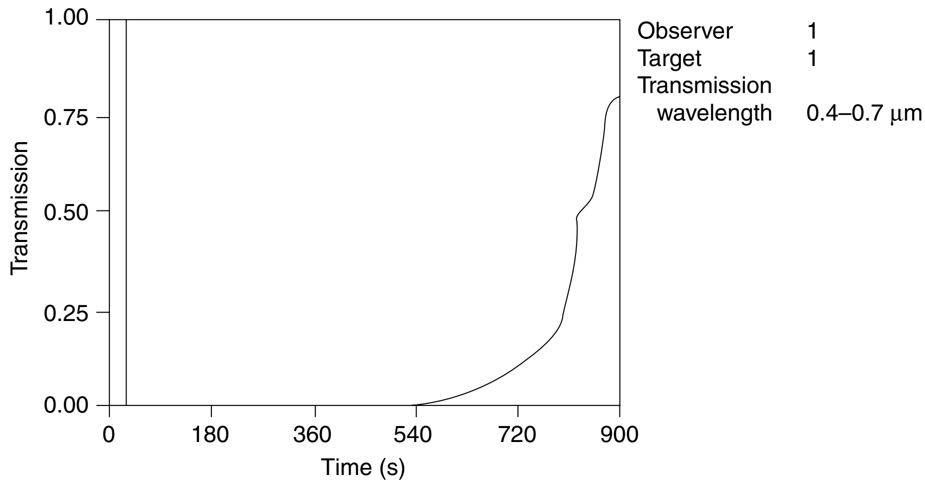


Figure 6: Transmission versus time for 6 white phosphorous rounds.

When we compare the effects of a single round with 6 rounds for the various look angles, we see a slight difference for small look angles. Large differences occur when the geometry is such that the line of sight passes under the cloud; for example, with a single round at a high look angle as compared with 6 rounds at a high look angle. The data for this comparison are given in table 4. The reference transmission is for a horizontal path while the other transmissions are for a vertical path through the smoke.

Table 4: Transmission through cloud from 155-mm white phosphorous round.

Reference transmission	Look angle (°)	1 round	6 rounds	Percent difference
0.049	–80	0.040	0.041	–2.47
0.049	–75	0.106	0.101	4.83
0.049	–65	0.238	0.232	2.55
0.049	–55	0.341	0.335	1.78
0.049	–45	0.413	0.406	1.71
0.049	0	0.540	0.539	0.19
0.049	45	0.398	0.395	0.76
0.049	55	0.316	0.313	0.95
0.049	65	0.201	0.198	1.50
0.049	75	0.062	0.061	1.63
0.049	80	0.011	0.010	9.52
0.223	–80	0.203	0.210	–3.39
0.223	–75	0.331	0.321	3.07
0.223	–65	0.493	0.477	3.30
0.223	–55	0.586	0.569	2.94
0.223	–45	0.645	0.628	2.67
0.223	0	0.738	0.734	0.54
0.223	45	0.637	0.614	3.68
0.223	55	0.569	0.543	4.68
0.223	65	0.459	0.426	7.46
0.223	75	0.260	0.227	13.55
0.223	80	0.114	0.087	26.87
0.606	–80	0.677	0.594	13.06
0.606	–75	0.729	0.664	9.33
0.606	–65	0.801	0.745	7.24
0.606	–55	0.842	0.791	6.25
0.606	–45	0.868	0.819	5.81
0.606	0	0.905	0.880	2.80
0.606	45	0.860	0.803	6.86
0.606	55	0.827	0.759	8.58
0.606	65	0.769	0.679	12.43
0.606	75	0.634	0.499	23.83
0.606	80	0.482	0.270	56.38

These results are not identical for other sources of obscuration. When a high-explosive round generates dust in a COMBIC model, the transmission becomes close to 0 very quickly and does not produce a cloud that is very large. The dimensions of the cloud from a single high-explosive round are given in table 5.

Table 5: High-explosive round subcloud trajectory in 2-m/s wind.

Downwind distance (m)	Time (s)	Centroid height (m)	Gaussian cloud standard deviations (m) Direction x	y	z
1.00	0.74	0.03	5.30	5.29	2.55
2.84	2.10	0.02	5.44	5.41	2.64
8.09	5.94	0.01	5.82	5.76	2.88
14.92	10.85	0.00	6.32	6.20	3.19
23.02	16.54	–0.02	6.90	6.72	3.54
32.24	22.83	–0.04	7.56	7.31	3.93
42.44	29.61	–0.06	8.28	7.95	4.35
53.78	36.94	–0.08	9.07	8.66	4.80
67.82	45.78	–0.11	10.04	9.53	5.34
85.54	56.64	–0.14	11.25	10.62	6.01
96.06	62.96	–0.16	11.97	11.26	6.39
107.88	69.96	–0.18	12.76	11.97	6.82
121.15	77.71	–0.20	13.64	12.76	7.29
152.80	95.80	–0.26	15.73	14.64	8.37
192.71	117.95	–0.32	18.32	16.96	9.69
243.04	145.07	–0.41	21.53	19.85	11.28
344.23	197.59	–0.56	27.83	25.51	14.30
487.55	268.81	–0.78	36.49	33.31	18.30
690.54	365.54	–1.07	48.38	44.02	23.58
978.04	497.17	–1.46	64.71	58.71	30.53
1385.25	676.72	–2.00	87.08	78.87	39.68
1747.06	831.69	–2.47	106.43	96.30	47.33
2474.45	1134.58	–3.37	144.23	130.36	61.77
3504.68	1550.48	–4.62	195.98	176.99	80.73
4963.84	2122.90	–6.34	266.81	240.83	105.63
7030.52	2912.54	–8.71	363.75	328.19	138.32
8866.81	3600.23	–10.77	447.48	403.66	165.60
11182.72	4454.34	–13.33	550.68	496.67	198.31

When the cloud is 100 m from its source, the standard deviation in the *y* direction of the cloud is about 25 m. To have multiple rounds interact laterally, the sources will have to be laterally located within 25 m of one another. An artifact of the use of a Gaussian ellipsoid to represent the distribution of the cloud is the appearance of negative values for the centroid height of the cloud; the cloud does not actually penetrate the ground.

The duration of this cloud, determined by the CL value being non-zero, is given in table 6.

Table 6: Duration of high-explosive round cloud in 2-m/s wind.

Time (s)	Observer No.	Target No.	Total CL (g/m^2)	Number of clouds	Transmission 0.4–0.7 µm	Transmission 3.0–5.0 µm	Transmission 8.0–12.0 µm
41	1	1	0.050	1	0.978	0.983	0.986
43	1	1	2.437	1	0.860	0.880	0.883
45	1	1	3.981	1	0.773	0.805	0.811
47	1	1	5.739	1	0.644	0.692	0.703
49	1	1	7.259	1	0.517	0.578	0.594
51	1	1	8.425	1	0.384	0.454	0.473
53	1	1	9.297	1	0.257	0.326	0.347
55	1	1	10.055	1	0.154	0.214	0.233
57	1	1	10.832	1	0.086	0.132	0.147
59	1	1	11.607	1	0.049	0.082	0.093
61	1	1	12.161	1	0.031	0.056	0.065
63	1	1	12.266	1	0.025	0.046	0.054
65	1	1	11.786	1	0.025	0.047	0.054
67	1	1	10.256	1	0.033	0.059	0.068
69	1	1	8.976	1	0.051	0.084	0.095
71	1	1	7.398	1	0.086	0.130	0.144
73	1	1	5.772	1	0.148	0.204	0.220
75	1	1	4.292	1	0.241	0.306	0.324
77	1	1	3.060	1	0.361	0.429	0.447
79	1	1	2.095	1	0.496	0.560	0.576
81	1	1	1.385	1	0.628	0.680	0.694
83	1	1	0.890	1	0.740	0.780	0.791
85	1	1	0.473	1	0.860	0.880	0.884
87	1	1	0.281	1	0.914	0.927	0.929
89	1	1	0.163	1	0.949	0.957	0.959
91	1	1	0.092	1	0.971	0.975	0.976
93	1	1	0.000	0	1.000	1.000	1.000

The length of time for the cloud to cross the line of sight was about 50 s (91 s–41 s). A plot of the time variation for these data is shown in figure 7.

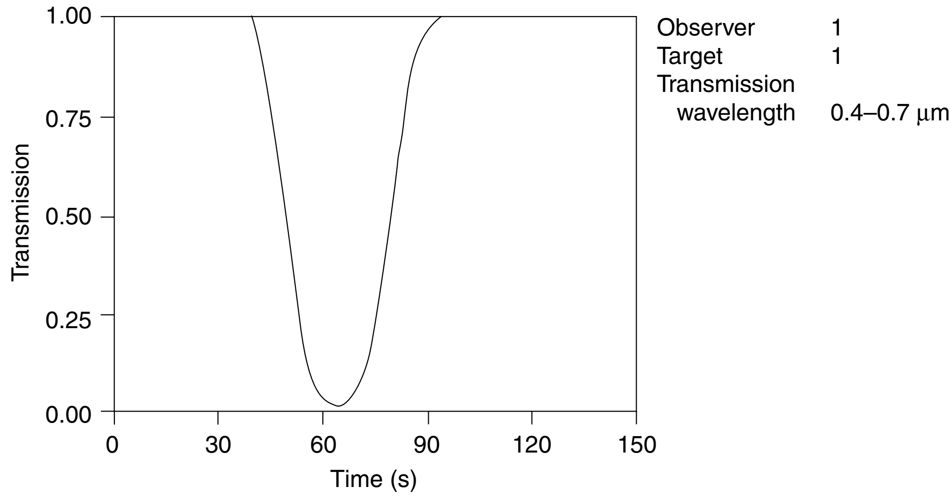


Figure 7: Transmission versus time for high-explosive dust cloud.

As can be seen from these data, if there is any wind moving the cloud, the effect is very short-lived since the cloud formed by a single round is not very extensive. When multiple rounds strike a large area and the possibility exists for the rounds to overlap, the entire cloud can be considered as a unit that travels with the wind to pass over the observation point. Except for lines of sight that look under the external edge of the cloud, the transmission through this cloud from all look angles can be considered to be zero. A plausible scenario for this event is to have the battery of 155-mm artillery fire a sheave of 9 rounds (typically, a second battery would be coordinated with the first) to cover a 150-m × 150-m area. These rounds would be fired every minute and impact the area at 50-m separations. The numbers that are used are based on the effective shrapnel range of a 155-mm round and the sustained firing rate of a 155-mm cannon. The effect of this scenario is to have a target completely obscured whenever the cloud passes over. Otherwise the transmission to the target is 100 percent.

Obscuration by smoke from a burning vehicle causes a different analytical problem. This smoke tends to rise well above the 2-m observation height used to measure the level of obscurant. Table 7 shows the COMBIC prediction for the smoke rise as well as the growth of the cloud.

Table 7: COMBIC prediction for various parameters of cloud from burning vehicle.

Downwind distance (m)	Time (s)	Centroid height (m)	Gaussian cloud standard deviations (m) Direction		
			x	*y*	*z*
0.15	0.47	0.77	1.23	1.25	0.35
0.60	1.40	2.87	1.25	1.24	0.35
1.38	2.33	5.12	1.50	1.41	0.48
2.47	3.26	7.18	1.92	1.66	0.68

Table 7: COMBIC prediction for various parameters of cloud from burning vehicle (cont'd).

Downwind distance (m)	Time (s)	Centroid height (m)	Gaussian cloud standard deviations (m) Direction		
			x	*y*	*z*
4.52	4.66	9.77	2.74	2.09	1.03
End of vertical rise phase					
5.52	5.26	10.72	2.85	2.28	1.24
12.61	9.08	15.43	2.85	3.33	2.52
23.34	14.32	20.14	2.85	4.55	3.99
36.75	20.54	24.70	2.85	5.86	5.56
52.40	27.56	29.12	2.85	7.25	7.20
72.34	36.29	33.99	2.85	8.91	9.12
90.06	43.90	37.85	2.85	10.33	10.72
100.58	48.37	39.99	2.85	11.16	11.63
112.40	53.36	42.27	2.85	12.07	12.63
157.32	72.04	50.18	2.85	15.48	16.22
220.93	97.96	59.90	2.85	20.19	20.89
311.04	133.94	71.89	2.85	26.74	26.97
438.66	183.91	86.71	2.85	35.87	34.86
619.41	253.37	105.08	2.85	48.62	45.04
875.42	349.97	128.03	2.85	66.37	58.15
1102.89	434.57	146.53	2.85	81.89	68.89
1238.01	484.07	146.53	2.85	94.43	74.63
1751.58	670.53	146.53	2.85	132.14	89.88
2478.96	932.63	146.53	2.85	183.63	110.32
3509.19	1301.71	146.53	2.85	253.95	137.58
4968.36	1821.06	146.53	2.85	350.05	173.78
7035.04	2550.73	146.53	2.85	481.40	221.71
9962.18	3574.33	146.53	2.85	660.99	285.01
11187.24	3999.82	146.53	2.85	734.48	310.32

The width of the cloud is still less than 25 m when the cloud is 100 m away from its source. If there are stronger winds, this 25-m lateral separation will occur even further away from the source. As the distance from the source increases, the validity of the model becomes of greater concern. Within the simulations, the downwind distance has been allowed to increase to 300 m to increase the transmission values.

For a ground-level observer and target, the transmission is always high. I doubt whether one can ever generate a plausible scenario to be able to measure the required lower transmission levels along a horizontal path. Instead, the recommended measurement is made when the observation point is 100 m above the target and the look angle is vertically downward. The modeled scenario consists of burning vehicles initially located uniformly on a 100-m × 100-m target area. The central point in this target area is the observation point for the aircraft flying overhead. However, if a burning vehicle is at this point, the model predicts a transmission of significantly less than 4.9 percent. Therefore, no burning vehicle is located at the center of the array. The other vehicles are separated by 50 m. An additional characteristic of this array is the use of downwind sources. The logic for this choice is based on what an observer in an aircraft could expect to see on the battlefield after an attack had destroyed and left a number of burning vehicles. The appearance of this 100-m × 100-m array is shown in figure 8.

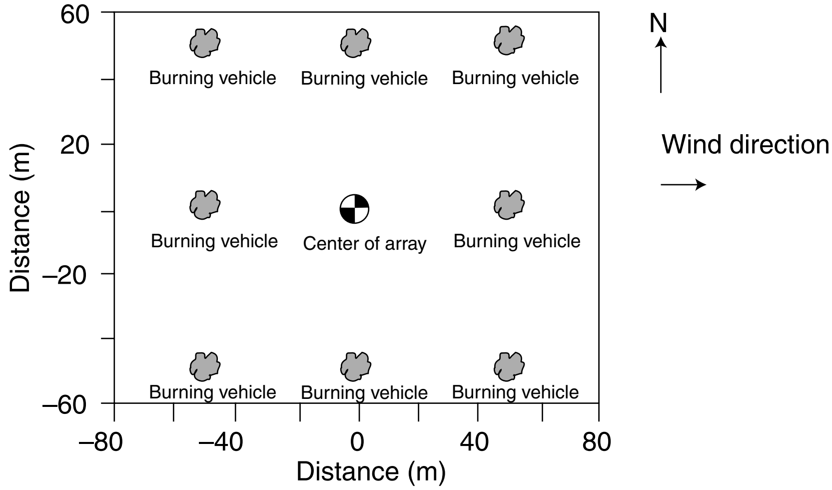


Figure 8: Deployment of burning vehicles after an attack.

When the simulation is performed, two parameters can be modified. The first parameter is the strength of the source. A value of 1 roughly corresponds to the value for a burning truck. A value of 3 corresponds to a burning tank, and values around 0.3 correspond to a burning high-mobility multipurpose wheeled vehicle (HMMWV). The second parameter is the location of the vehicles to the left of the center of the array. This value is incremented in 50-m steps and is needed to achieve the higher values of transmission through the smoke.

The transmission through the smoke as a function of time is shown in figure 9. The parameters include a source strength of 1, all sources are 50 m from one another, and the wind speed is 2 m/s. All other parameters are default values.

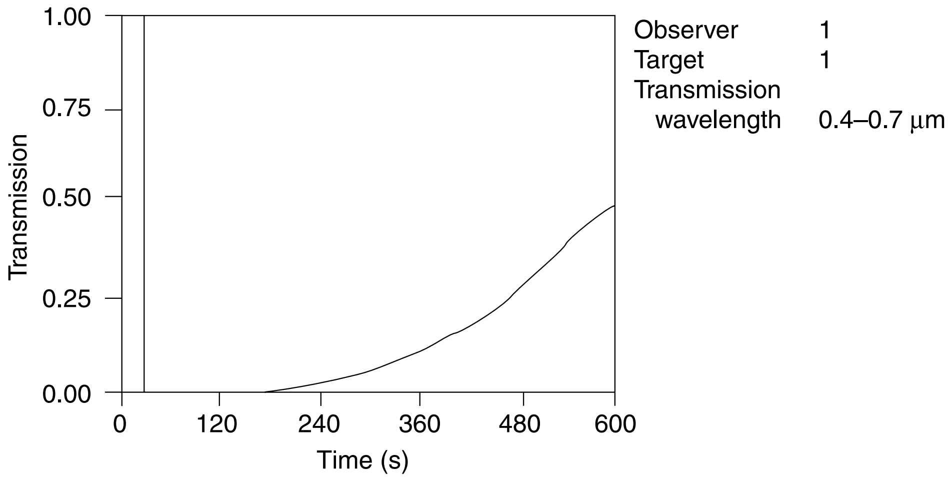


Figure 9: Transmission versus time for 8 burning vehicles with 2-m/s wind.

The transmission is not zero from the beginning of the run. It is at zero about 25 s after the start of the run. The scale of this curve may be confusing; the front edge of the cloud arrives within the line of sight about 25 s downwind from the source. This corresponds to the 50-m distance that the cloud will move in a 2-m/s wind. To reach the specified values for transmission, the fire and consumption of the vehicle must begin to decrease and the cloud must pass by the observation point.

5. Summary and Commentary

A step-by-step description of the process that was used to generate the initial database by hand is in the appendix of this paper. The process was performed with a copy of PcCOMBIC. The process has been automated to run on a UNIX-based computer and is able to generate a more extensive data table. Several limitations of the process need to be identified.

First, a limited number of sources have been assumed. These sources may consist of a cloud caused by several rounds all starting at the same place and time. However, this is still not an extensive number of sources. As described above, the Army deploys smoke in single quantities only for a relatively few number of missions. Since the sources considered are close by and directly in line with the target, these sources will have the strongest influence on the transmission to the target. However, the presence of other sources can have a significant impact on the results, thus the results here should be considered a first approximation.

When a second source is considered, interactive effects on the computation are possible. For example, suppose a second source is placed 25 m from the first source and in a direction perpendicular to the wind direction. Then the plume from this second source can expand to cover the target. However, the direct effect of this cloud is minimal since only the edge covers the target. The major effect will be on the level of smoke measurement, since the entire line of sight now has a concentration of smoke present. This was not the situation for a single source.

Another limitation of this database is caused by the geometry of the cloud with respect to the aircraft's line of sight. In developing the database, an assumption was made that the centerline of the cloud had passed over the target; that is, the target was in the very center of the cloud. Another assumption was that the plane passed directly over the target while flying with the wind direction. If the plane passes at an offset to the target, observations of the target could be made that look underneath the cloud.

Other phenomena that are not taken into account are the effects of terrain variations in the distribution of smoke and a nonuniform wind field. A basic assumption in the model is that the smoke evolves over a flat terrain with a constant wind speed and direction. The interaction with the ground by the smoke will cause depletion of the cloud. Also, it is possible with a varying terrain for vehicles to travel above the upper level of the obscurant.

Another topic that needs to be examined is the characterization of dust produced by the explosion of artillery rounds. Since this is a random event on the battlefield, the assumption of symmetrically placed rounds is not valid. However, to portray this properly would require data that are not readily at hand. Because of the smaller radius of the high-explosive dust clouds, the results are more sensitive to the correct placement of the source. Thus, the information required would have to be the actual placement of the rounds, both in time and space. This information varies from scenario to scenario and will vary extensively between simulations.

The final complete database was calculated under the control of a Tool Command Language (TCL) script developed by Bruce Van Aartsen of TASC, Inc. The script is based on the steps that were executed by hand using PcCOMBIC and they are described in the appendix. The scripts were executed on a Silicon Graphics, Inc. (SGI) computer using the UNIX version of the COMBIC model. This model is the same one used within the ONTAR PcCOMBIC model. Only the creation of control files and tools for interpreting the outputs are different.

References

1. D. W. Hoock, R. A. Sutherland, and D. Clayton, *EOSAEL 87, Vol. II: Combined Obscuration Model for Battlefield-Induced Contaminants (COMBIC)*, U.S. Army Atmospheric Sciences Laboratory, TR-0221-11 (October 1987).

2. J. Andrews and F. Hansen, *The Pasquill Stability Categories: A Decision Tree Solution*, U.S. Army Atmospheric Sciences Laboratory, OSD-1366 (April 1989).

3. Patti S. Gillespie, *TARGAC Technical Description and User's Guide*, U.S. Army Research Laboratory, ARL-TR-273-3 (April 1995).

4. *Smoke Operations*, Field Manual 3-50, U.S. Army Chemical School (4 December 1990).

5. Alan Wetmore and Scarlett D. Ayres, *COMBIC Technical Document Users Guide*, U.S. Army Research Laboratory, ARL-TR-1831 (March 2000).

APPENDIX. PROCEDURES FOR COMBIC SIMULATIONS WITH PcCOMBIC

A-1. Introduction

This appendix describes the procedures used in the initial simulations that were performed for modeling a database that contains the values of transmission through smokes. The model used to determine the transmission value was the PcCOMBIC model available from ONTAR Corporation. The procedure that was developed depends on the manner in which the user interface is structured by the software.

A-2. Definitions

Because a number of different simulations were used with different starting parameters, a naming convention was set up to separate the different versions. This convention follows the following format:

> [Multiple or Single Observer] [Strength of Munition] [Two letter name for munition] [Wind speed in meters per second] [Pasquill Stability] [Temperature] [Range of source to origin].

The two-letter names for the obscurants are

- White phosphorous WP,
- Hexachloroethane HC,
- High explosive HE, and
- Fire smoke from a burning vehicle (a mixture of diesel fuel, oil, and rubber) FO.

An example of one file name would be

> Mult2WP5D10.

This name is interpreted as a run that involves multiple observers of a white phosphorous smoke round that has a source strength of 2. The external environment conditions are a wind speed of 5 m/s, a neutral Pasquill category of D, and a 10 °C ambient temperature. Because there is no mention of range, the default range from source to target is 100 m.

Several model parameters are the same for all runs. The first six observers are at an altitude of 1000 m and they are in the *x-z* plane; that is, $y = 0$ for all six observers. These observers represent the observations that would be made from an aircraft flying on a straight line at an altitude of 1000 m over the target. The values chosen for x determine the look angle for the observer when tracking a target at the origin. Look angles are 0°, 45°, 55°, 65°, 75°, and 80°. Corresponding x-values are 0, 1000, 1428, 2144, 3732, and 5671. The seventh observer and the target that the seventh observer views are both in the *y-z* plane through the origin. That is, $x = 0$ for both of these objects. There is a 100-m separation between the observer and the corresponding target. Both are symmetrically placed with respect to the origin: $y = +50$ m and

$y = -50$ m, correspondingly. The height chosen for this seventh set of observers was initially set at 2 m (an average eyesight level of a man) for the runs involving white phosphorous. However, when hexachloroethane was used as the obscurant, the cloud would rise above this level and there would be 100 percent transmission along that path length. To place this observation path within the cloud, an arbitrary choice of 5 m was made. An argument can be made for placing this height at the height of the center of mass of the cloud when it passes through the line of sight (see the discussion below). For hexachloroethane, this would correspond to a choice of $z = 6.33$ m. Resolution of this choice involves a discussion of the meaning of the terms light, medium, and heavy when describing the appearance of an obscurant.

The terms light, medium, and heavy have been equated to values for the optical depth of the obscurant and are based on definitions contained in the TARGAC computer model [3]. These definitions are given for transmission in the visible wavelength band. Table A-1 lists the corresponding values of these terms

Table A-1: Category terms and corresponding values.

Category term	Optical depth	Transmission (%)
Light	0.5	60.6
Medium	1.5	22.3
Heavy	3.0	4.98

These definitions do not specify the procedure for measuring the optical depth. For normal use, with an observer at ground level looking for a target that is also at ground level, a height of 2 m would be satisfactory. Inherent in this concept is the assumption that the concentration of the obscurant is uniform in all directions and covers both the observer and the target. This description does not exist in real life nor does it exist in the COMBIC model representation of an obscurant that I used. If a single source cloud is considered, a measurement that is symmetrical with respect to the centerline of the cloud is reasonable. Except for the height of the cloud, the coordinates would be fixed for all situations. However, the height would vary with the temperature and wind speed. Since most smokes tend to rise, it is possible for the cloud to float above the eye height level; the result is 100 percent transmission. Also, if more than one round is generating this cloud and any additional rounds are not placed at the same spot and are not initiated at the same time, a problem occurs in working with the center of mass. It is possible for the center of mass of multiple rounds to be at a point where there is no concentration of the obscurant. Rather than complicate the analysis, I decided to select a value for a single round that would correspond to a height near the center of mass of the obscurant. This observation could be made by either a ground observer or an observer on a small platform.

Table A-2: Summary of x, y, z coordinates for targets and observers.

	Coordinate (m)		
	x	y	z
Target 1	0	0	0
Observer 1	0	0	1000
Observer 2	1000	0	1000
Observer 3	1428	0	1000
Observer 4	2144	0	1000
Observer 5	3732	0	1000
Observer 6	5671	0	1000
Target 2	0	–50	2, 5
Observer 7	0	+50	2, 5

One further point concerns the timing of the data extraction. That is, before a cloud passes across the line of sight for observer 7, the observer will initially have a clear view to the target with a high value for the transmission. As the cloud passes, the transmission will drop and then begin to increase. After the cloud passes, the transmission is again high. This means that there are at least two times that a transmission value will correspond to the high, medium, or low transmission values. If the earlier time is selected, then the transmission for an observer who is positioned at the higher look angles (that is, 80°) will probably have a very high value–the observer is looking underneath the cloud. On the other hand, if a later time is selected, the observer at the higher look angle is looking through the majority of the obscurant. The transmission value will be lower. For this analysis, the later time has been selected for the extraction of other look angle data.

A-3. Procedures

Operating PcCOMBIC at its initial settings and starting with the Combic Input menu choice, the PHAS screen is selected. On this first screen, the title of the run is entered using the format described above. The Next button is then selected.

On the Combic Environment screen, the windspeed values, the Pasquill Stability Factor, and the Air Temperature are set. The Pasquill Stability Factor is set using the choices from this category's selection menu. This menu does not have a scroll bar and the keyboard arrows may have to be used to make a selection. The Next button is then selected.

The first choice on the Combic Munition Screen is for the number of the source being used. This is a numeric convenience for labeling the source and does not denote any quantitative measures regarding the source. The only other choice made from this screen is to select the source from the list that is generated by the Select Source from option. The Next button is then selected.

For this Extinction screen there are no values to be set since the default values were set by our selection of the obscurant on the previous screen. The Next button is selected.

At this point, we are past the data entry point for a phase 1 simulation and the model could be run. However, this information is not of immediate interest and the data entry for the specification of the scenario and line of sight will be the next screen entries to be performed.

The screen that is now visible is the Scenario Screen. The wind direction is specified on this screen to be 270° with respect to north. The three Printout times (also on this screen) are useful in controlling the volume of output data that can be produced. For the basic simulation using default time values, a 28-page paper printout was obtained. When smaller time durations are used, the time increment can be changed to 0.1 s. The Next button is now selected to proceed to the next screen.

The screen that is now available defines the location and timing of the various sources that are used. For this simulation, there is only one stationary source and it is present from $t = 0$ to the end of the simulation. The y and z position of the source are always zero. Depending on the value of transmission that observer 7 needs to achieve, two different choices will be made. If a higher transmission value is needed, then a larger x value will be selected. The starting value that is used in this simulation is $x = -100$ m. When this value is used, there is no designation in the file name. However, if $x = -200$ m, the file name will include a designation of Rng2. Similarly, for $x = -300$ m, the file name will include a designation of Rng3, and for $x = -400$ m the file name will include a designation of Rng4. If a lower transmission value is desired, the Scale factor parameter is used. This parameter adjusts the strength of the smoke source. Initially it is set to 1. If the transmission does not decrease to a low enough value, the scale factor value is increased to 2, 4, or 6 until the desired low transmission is achieved. The Next button is now selected to proceed to the next screen.

This is the final input screen used in this simulation. The locations of all the observers and the corresponding targets are entered. Once the initial settings are entered, the only numbers that are changed are the height of observer 7 and the corresponding target, target 2. As mentioned above, the height was changed from 2 m to 5 m corresponding to a change from white phosphorous smoke to hexachloroethane smoke. After the settings are properly set, the OK button is pressed.

Since all data entries are now complete, the file is saved. This is accomplished using one of the File menu options; the Save As option. Choices on this screen include the location of the file to be saved and the name of the file to be saved. The naming convention described above is used for assigning a name. Note that the file extension cmb is automatically assigned to this file. The next function is to run COMBIC using the Run Combic menu option.

After the run is completed, the View menu is selected and the option to view the COMBIC output file is selected. There is an extensive amount of information in this file, including all the input parameters that were used for both a phase 1 calculation as well as a phase 2 calculation. Starting from the end of the file and scanning towards the beginning, the transmission value is sought for observer 7 that matches the optical depth value of immediate interest. If the value is found in the column labeled 0.4 μm–0.7 μm spectral band, all the data that occur at the same time are collected and pasted into a new file. The other data values correspond to transmission values at other wavelength bands and are computed internal to the COMBIC model. The name of the new file follows the same format as described above. If the transmission value falls between two values, a finer time increment is used and the model is rerun. If all the transmission values in the data file are higher than the desired value, then the source-strength value is increased and the model is rerun. Finally, if the targeted transmission values indicate that the time of occurrence is either very close to the beginning or end of the run, the source range is increased and the model is rerun. All three runs are combined in the same saved file.

A Microsoft Excel spreadsheet is used to record all the data for future sorting and manipulation. The simulations that I ran produced about 5400 table entries. These data can be easily selected and output in the format of a flat test file, and this is the format my sponsor has requested.