Battlefield Smoke - A New Dimension in Networked Simulation

Rick D. Bess
Brian T. Soderberg
BBN Systems and Technologies Division
Bellevue, Washington

ABSTRACT

The use of atmospheric obscurants such as battlefield smoke to modern day tactics is critical. Recent military activity in the Middle East Gulf Conflict has highlighted the impact of reduced visibility on manned vehicle and smart weapon system effectiveness. Battlefield smoke is used for tactical cover and concealment, to silhouette targets, and to cause enemy disorientation and confusion. The simulation of this feature will ensure faithful and comprehensive tactical team training for armor, and airborne vehicles.

The technical challenges presented by the simulation of volumetric atmospheric obscurants have hindered prior implementation of battlefield smoke in tactical trainers. This paper considers technical limitations associated with simulation of visual effects of smoke using real-time computer image generation, as well as less obvious problems such as the effects of smoke on various sensors (e.g. thermal sensors). Further, emphasis is given to challenges associated with creating a consistent and realistic simulation of smoke for trainers that are networked together in a distributed simulation environment. Recent advances in real-time computer image generation and simulation system technology can now be applied to solutions for simulating battlefield smoke.

This paper provides an overview of the issues associated with the visual simulation of atmospheric obscurants (e.g., battlefield smoke) in tactical team training. First, it reviews the training requirements for atmospheric obscurants in training systems by providing background on the tactical significance. Secondly, the problems associated with simulating obscurants such as smoke in tactical trainers are discussed. Finally, solutions to these problems are proposed. Photographs and video tapes will be used to illustrate the benefits of proposed solutions.

Introduction

The ability to simulate armor combat via networked simulators has sparked the desire for further battlefield realism. In response to these evolving needs, innovative technologies are being developed such as visual simulation of 3-D volumetric atmospheric obscurants. Smoke, dust, and poor weather have been and continue to be utilized as part of military tactics. These degraded atmospheric conditions alter the view of the battlefield for soldiers, and weapon systems.

Computer based, networked training systems such as SIMNET [1] have demonstrated that team tactics can be effectively taught using simulators. SIMNET has also prompted insightful feedback for areas of improvement. The realistic portrayal of battlefield obscurants was noted as a deficiency of the system for tactical training. [2]
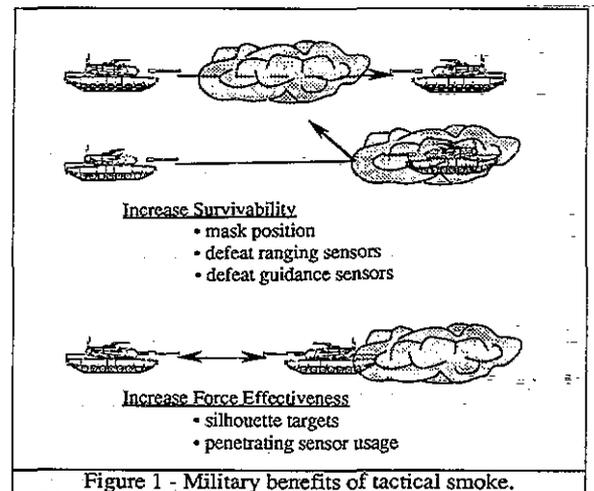
In this paper, the background of atmospheric obscurants associated with team tactics is covered to better understand the technical implementation of the visual simulation. The military weapon system details and tactical descriptions included in this paper are based on documented feedback from U.S. and German Army experts, military smoke munition manufacturers, and simulation system research and development projects. In the second part of the paper, a comprehensive examination of the technical challenges of visual simulation of volumetric atmospheric conditions is provided. This paper concludes with innovations in computer image generation technology that address these visual simulation needs.
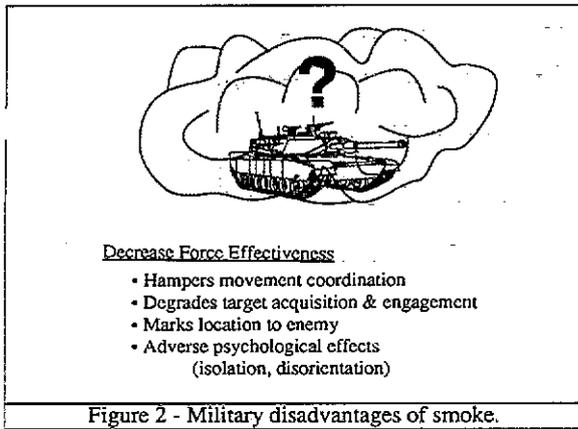
Training Requirements for Smoke

For the purpose of discussion in this paper, the use of tactical smoke will be used as the primary example of volumetric atmospheric obscurants. Training requirements for team tactics that include smoke are uncovered by examining the military significance of smoke, the deployment methods, and the tactical maneuvers employed in combination with smoke. Effective training will prepare the soldier in the proper use of smoke, and solicit the predicted responses when affected by the obscured visual conditions.

Military Significance of Tactical Smoke

The military benefits of tactical smoke [3, 4] are summarized in Figure 1. These benefits represent why smoke is deliberately used to improve the soldiers effectiveness on the battlefield. In other situations, smoke may have potential disadvantages [3, 4] as listed in Figure 2. For example, if the soldier has superior fire control over the enemy, smoke deployment would not be preferred.

Increase Survivability
- mask position
- defeat ranging sensors
- defeat guidance sensors

Increase Force Effectiveness
- silhouette targets
- penetrating sensor usage

Figure 1 - Military benefits of tactical smoke.

Figure 2 - Military disadvantages of smoke.

Decrease Force Effectiveness
- Hampers movement coordination
- Degrades target acquisition & engagement
- Marks location to enemy
- Adverse psychological effects
  (isolation, disorientation)
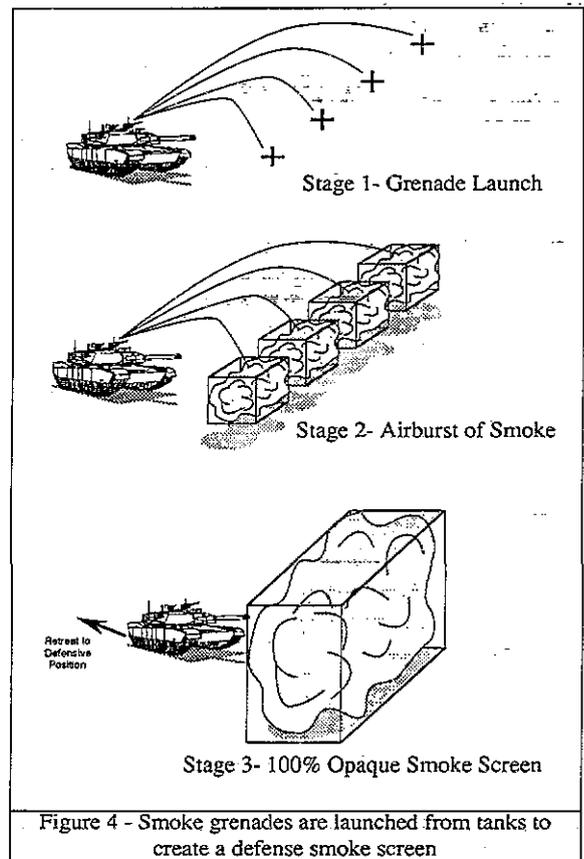
Effect on Weapons Systems

The majority of Army weapon systems have at least one common trait: reliance on electromagnetic energy propagation through the atmosphere. Virtually all viewing systems, sensors, and laser systems are degraded in some manner by obscurants, as shown in Figure 3. [5]

Sensor Wavelengths (Microns)	←UV→ .3	Visible .4	Infrared Near .7	Mid 5	Far 8	12	←Microwaves→ 220-35 GHZ
Oil Smoke Generators, Exhaust							
WP Projectiles, Grenades							
Weather Fog, Rain Clouds							
(M76) Brass Flakes							

Figure 3. Various obscurants affect different sensor portions of the electromagnetic spectrum.

Methods to Deploy Smoke

The methods used to deploy smoke to the battlefield include grenades, artillery, rockets, fires, and vehicle exhaust. Smoke grenades and artillery have both ground and air burst capability. Armored vehicles such as the U.S. M1-A1 and German Leopard II tanks have smoke grenades that can be launched to obscure their positions, as shown in Figure 4. In this example, a pattern of four smoke grenades will airburst in front of the tank providing complete visual obscurance in less than 0.3 seconds. [6] The resulting smoke screen will persist for several minutes depending on wind conditions.

Stage 1- Grenade Launch

Stage 2- Airburst of Smoke

Retreat to Defensive Position

Stage 3- 100% Opaque Smoke Screen

Figure 4 - Smoke grenades are launched from tanks to create a defense smoke screen

Smoke from fires and smoke pots are used to obscure areas of the battlefield. This technique was frequently used in the Gulf Conflict "Desert Storm". [7] During the middle of February 1991, frequent reports by the Associated Press stated that use of smoke from fires hampered military operations.

Smoke artillery is used to visually obscure large areas. The individual artillery shells are aimed in a staggered pattern to fill an entire area with smoke. Additional smoke artillery rounds are used to prolong the effect, or to intensify the reduced visibility to defeat enemy operations.

Tactical Maneuvers Used With Smoke

The principal tactic employed with battlefield smoke is one of short-term self-defense of friendly forces. These tactics have one thing in common: the decision to commit smoke to the battlefield is made rapidly and under pressure.

The self-defense tactics include:
- cover and concealment when unexpectedly threatened by the enemy
- retreat from a fire-fight against a superior enemy
- concealment of a position change from enemy observation
- recovery of failed vehicles

Tactical smoke can also be used as an offensive tool. These tactics are more calculated and are used in coordination with other forces in the area.

The offensive tactics include:
- smoke laid directly on enemy positions to confuse and disorient
- smoke laid behind enemy forces to silhouette for better detection
- decoy smoke launched to confuse or mislead enemy forces
- smoke is used to visual degradation of the battlefield to take advantage of superior sensors.

Visual Simulation
Technical Challenges

This section of the paper will discuss the technical challenges of implementing battlefield smoke within a networked simulation environment. In particular, we will focus on the visual simulation and effects of volumetric smoke.

The physical characteristics of smoke which influenced our determination of an implementation of a smoke rendering technique include the spatial volumetric nature, the variability of visual transmittance, and the dynamic temporal effects. These characteristics of battlefield smoke which impact the visual simulation are well documented by empirical data collected in battlefield smoke studies [4, 8].

Challenge #1
Spatial Volumetric Nature of Smoke

Tactical smoke clouds cover only a portion of the battlefield. Soldiers can be outside the smoke looking in, inside the smoke looking out, inside smoke looking within, or visually unaffected. This characteristic must be preserved from the vantage point of armor troops on the ground and aviation troops in the air, as shown in Figure 5.


Figure 5 - Smoke is a 3-D volume that must be presented correctly from all vantage points.
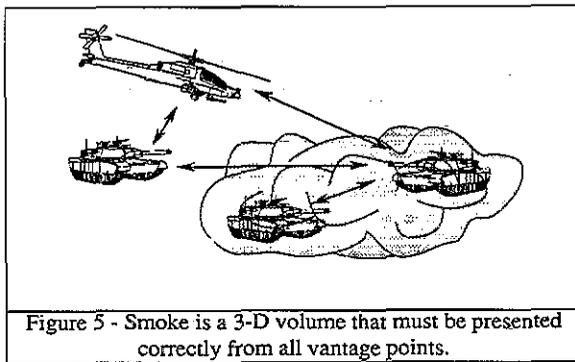
Smoke can consist of a single large cloud with a totally homogeneous density, or many individual, localized smoke clouds each with it's own silhouette or geometric shape. The separation of multiple smoke clouds becomes an issue spatially and with respect to viewing depth from a viewpoint. The example in Figure 4 showed multiple smoke clouds from grenades. The visual transmittance associated with a tank sitting between two separated smoke clouds will differ from a tank sitting within two overlapping smoke clouds.

The key factors are the shape of the smoke cloud and the transmittance function through the cloud. Smoke requires more than just an exterior geometric definition. It must be thought of as a volume with its interior being as important as its geometry. This information is necessary for determining the visible effect of the smoke volume(s) on objects on the battlefield. This interior characteristic of the smoke cloud is discussed in the next section on transmittance.

Challenge #2
Variable Transmittance of Smoke

Transmittance is a quantitative measure of the ability to see an object within a smoke cloud. A value of 1 means clear viewing and no effect from smoke; a value of 0 means total smoke opaqueness. The attenuation, or visible change to an object's color due to the smoke cloud, is a function of the smoke density and the depth of the object into the smoke along the ray from the viewpoint, as shown in Figure 6.

Figure 6 - Transmittance is based on the objects depth into the smoke and the smoke density.
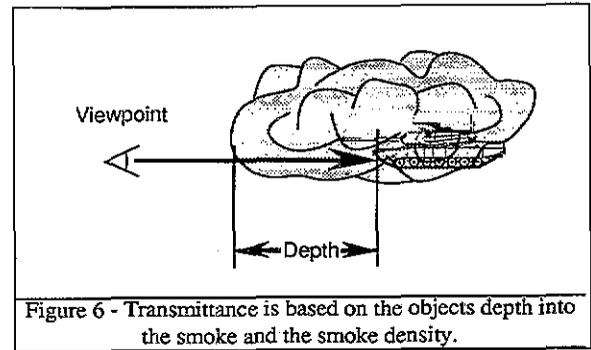
The following equations describe attenuation through the atmosphere.

Equation 1:   Attenuation = $(1 - W)$

where: W is the transmittance weight

If the cloud density is assumed homogeneous for a sampled ray through the volume, then radiant energy transport theory suggests a Poisson attenuation function for points within the cloud.
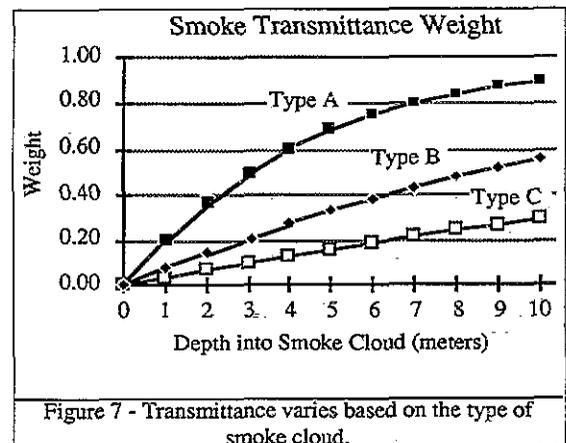
Equation 1.1: $W = \exp(-\beta z)$

where:
z is the depth into the smoke cloud
β is a factor for types of smoke

The attenuation weight values for different types of smoke can be estimated using various values of β in Equation 1.1, as shown in Figure 7.

Figure 7 - Transmittance varies based on the type of smoke cloud.

Sensor systems acquire various spectral bands as discussed in the first part of this paper. Different smoke types have different spectral characteristics, providing varying transmittance as viewed through a sensor. For example, red phosphorous smoke works well to defeat visual and near-IR spectrum sensors and M76 brass flakes defeat far-IR and millimeter wave regions of the spectrum. [4]

The overall variability of transmittance profiles for various sensors and visual modes must be modeled for a visual smoke capability in networked simulation.

Challenge #3
Temporal and Dynamic Smoke Features

The physical characteristics of smoke shape, size and density are dynamic. Physical changes are largely due to changing atmospheric conditions such as windspeed and temperature. For example, a smoke grenade after launch, emission, and dissipation, can move *two kilometers down wind, and grow to 600 meters in width within* 7 minutes. [4]

The density of various smoke types can change extensively over time. For example, the density of brass flakes (M76) will vary from 5 to 0 grams/m3 in less than 20 seconds. Under the same atmospheric conditions, red phosphorous smoke will vary from 2.5 to 0.3 grams/m^3 in 5 minutes. [4]

CIG Technology Limitations

Current Computer Image Generation (CIG) technology has several fundamental limitations with respect to rendering localized volumetric battlefield smoke effects. These limitations include areas such as planar geometric modeling versus volumetric, restrictive occulting methods, homogeneous transmittance models, and graphics performance limitations.

Limitation #1 - Geometric Modeling

The current generation of real-time CIG systems model all geometry with planar or polygonal primitives. This is appropriate for solid objects and thin translucent surfaces such as windscreens, but *does not appropriately define a volume with internal attributes such* as density.

Early experiments with smoke visual simulation used simple 3-D geometric shells. This approach provided the outer surface definition of a smoke cloud, although no internal density profile was maintained.

Limitation #2 - Occulting Methods

The occulting requirements for smoke include the need to handle large numbers of dynamic objects in the scene, and to handle partial occulting of semi-transparent objects.

The current generation of real-time visual systems is based on one of two hidden surface elimination methods or a hybrid of the two. These methods are depth buffer, and binary space partition (BSP) techniques.

Both techniques work well for performing basic occulting or sorting of planar polygonal surfaces. The depth buffer is better suited for handling multiple dynamic objects, as it sorts objects implicitly at the pixel level. BSP systems are efficient with only relatively few dynamic objects. (i.e. less than a dozen)

These two methods are not naturally amenable to handle localized volumetric densities of smoke. This means that simple front-back relationships are not good enough to determine partial occulting for semi-transparent objects in the scene. Therefore new supplemental or modified methods are required to handle hybrid primitive collections of planar and volumetric methods.

Limitation #3 - General Transmittance

Current CIG technology typically incorporates a homogeneous atmospheric effect technique that globally affects all things in the scene. This method relies on a predefined function based on the distance from the viewer into the scene (depth) to determine the appropriate level of haze attenuation to apply to objects. This method will not handle multiple localized smoke volumes that cover different spatial sections of the screen.

Limitation #4 - Graphics Performance

CIG system performance is measured by both polygon throughput and pixel throughput or depth complexity. [9] Polygon performance requirements are a function of database complexity including parameters such as: terrain complexity, density and complexity of static cultural features, and vegetation models. In our networked simulation applications, we have experienced substantial additional polygonal loading because of moving objects and special effects such as bomb bursts, dust, and smoke.

Pixel processing requirements in networked simulation are largely driven by three parameters; database roughness, object density, and dynamic object and special effect occurrences. The first two can be well planned in the database engineering of an environment, but special effects are typically uncontrolled. For example, a tank commander may launch a dozen smoke grenades resulting in very high pixel requirements.

Visual Simulation
Technical Innovations

This section discusses the innovations for the visual simulation of smoke. A volumetric rendering method is presented which has been implemented in real-time CIG hardware for networked simulation and training systems. [10]

Innovation #1 - Volumetric Definition

To properly manage multiple localized overlapping volumetric smoke processing within a hybrid depth buffer architecture, we developed a technique which manages multiple smoke volume buffers in addition to the standard color and depth frame buffer elements, as shown in the Figure 8. [11]

Figure 8 - Multiple smoke volumes simulated.
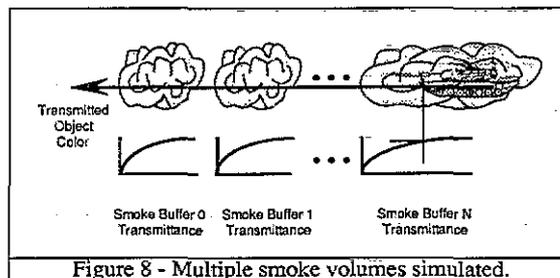
The smoke volume buffers must be separately managed to allow proper attenuation of non-smoke volume objects such as targets that fall within or beyond smoke volumes.

In this way a formula for managing multiple smoke volumetric attenuation levels is adopted:

Equation 2: $W_i = w_i [\pi(1-w_k)] (1-w_h)$
$k=1{:}n, k{\neq}i,$
for all k in front of i, $(Z_i-Z_k) > 0$

where:
W_i is the attenuated transmittance for cloud i.
w_i is the transmittance level of ith cloud as f(z)
$(1-w_k)$ is the attenuation of the kth cloud
$(1-w_h)$ is the haze attenuation at the ith cloud
Z_i is the depth to front of cloud i
Z_k is the depth to front of cloud k

The non-smoke transmittance weight contribution (W_O) is as follows:

Equation 3: $W_O = [\pi(1-w_i)] (1-w_h)$
$\quad i=1{:}n$, for all i in front of p,
$\quad (Z_i-Z_o) > 0$

where:
W_O is the object transmittance weight
Z_o is the depth to front of object surface

Equation 4: $W_h = 1 - \Sigma(W_i \times W_o)$

where:
Wh is the attenuated transmittance for haze

These formulas can then be used to sum each element of transmitted color times it's weight (W_i) level:

Equation 5: $C_p = [\,\Sigma(W_i * C_i)\,] + (W_o * C_o)$
$\qquad\qquad + (W_h * C_h)$
$\quad i=1{:}n$, for all i

where:
C_p is the transmitted color
C_i is the color of cloud i
C_o is the color of object in the scene
C_h is the color of haze

The result represents the appropriate color occurrence at a given pixel location. Additional opaque and transparent pixels can subsequently have smoke applied and potentially be combined into the same pixel location.

Innovation #2 - Hybrid Occulting Method

Since we are focused on networked training systems with hundreds of moving vehicles, we investigated a modified hybrid depth buffer approach for integrating volumetric and planar hidden surface removal and rendering.

The volumetric smoke rendering method presented here is integrated into a hybrid depth buffer CIG rendering system. This requires that depth and density elements of multiple smoke buffers per frame buffer pixel be retained to allow proper smoke application. Smoke buffer pixels cannot be processed and thrown away since the depth and density values are necessary to properly calculate the attenuation and transmittance of each smoke cloud.

The smoke buffer attenuation is then applied with a "depth buffer" method modifying Equations 2.0 thru 5.0. The depth buffer tests, $(Z_i - Z_k) > 0$ and $(Z_i - Z_o) > 0$ are used to determine whether a smoke buffer element is nearer than the non-smoke entity and if attenuation should be applied. In the same way w_i is modified through a depth difference $(Z_i - Z_o)$ to determine if a non-smoke entity (o) is within the smoke cloud i. This will allow smoke weight w_i to smoothly transition to zero opacity as an object moves through the smoke cloud.

Innovation #3 - Variable Transmittance

The transmittance model for smoke must be variable for different types of smoke as well as variations in spectral sensing. [12] The w_i in Equations 2 and 3 above must follow a modeled transmittance profile such as that shown in Figure 7. The depth at which an object falls within the smoke volume must then use the proper transmittance along the curve to attenuate the object transmittance level. Various transmittance profiles are stored to allow for varying density levels associated with wind, temperature, and other environmental conditions. A parametric transmittance table can allow selection of the proper transmittance profile based on meteorological conditions. Additionally the table allows for variations based on the sensed spectral band or visual spectrum.

Innovation #4 - Efficient Processing

We determined it was too costly to model complex smoke shapes with the traditional method of many front and back facing planar facets to define a volumetric region. We came up with an efficient method of using a single gimbaled polygon, which has a complex depth offset representation defined within the applied texture map as shown in Figure 9. The transmittance attributes are also stored within the texture map. This turns out to be very useful in reducing the polygonal load while still allowing complex geometric smoke shapes.
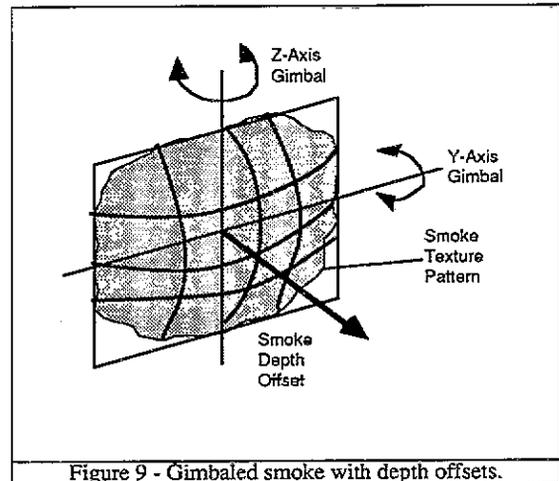

Figure 9 - Gimbaled smoke with depth offsets.

Summary and Future Work

This presented approach is a unique visual simulation of volumetric atmospheric obscurance. The resulting visual representations of tactical smoke are very realistic as shown in Figures 10 & 11. BBN is continuing refinement of the algorithms and applications for tactical team training.

Future work has been identified to investigate the smoke impacts to networked simulation such as wind effect simulation, Semi-Automated-Forces (SAF), and intervisibility determination.

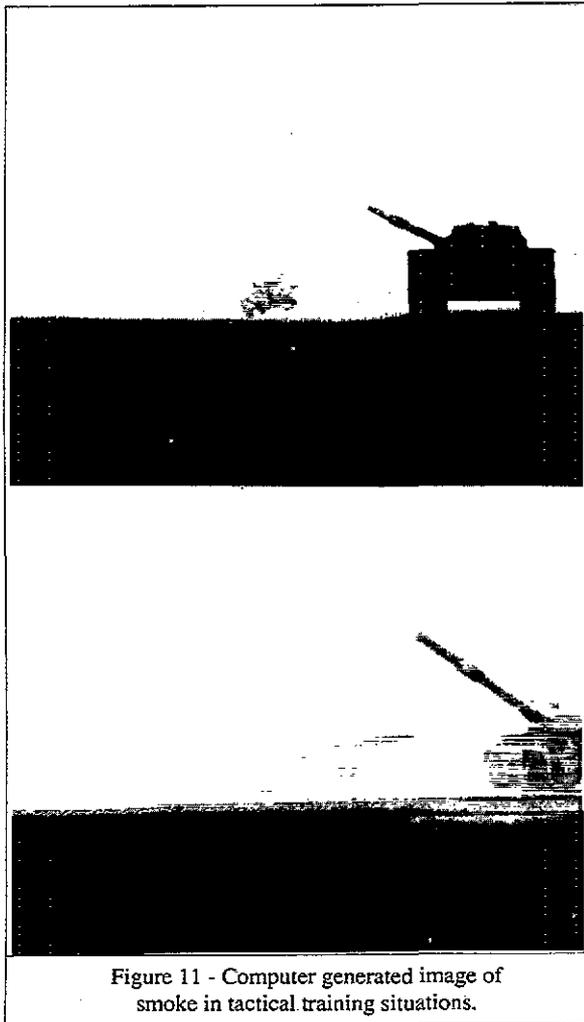Figure 10 - Computer generated image of tactical smoke clouds in a village.

Figure 11 - Computer generated image of smoke in tactical training situations.

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ABOUT THE AUTHORS

Rick Bess is currently the Product Manager for Visual System Products in the Systems and Technologies Division of Bolt Beranek and Newman. Mr. Bess has a long history with networked visual systems, having worked at the Boeing Advanced Computer Graphics Technology Lab in 1982, and having been a 1984 core team member of the SIMNET distributed simulation and training program. His related technical background include being a senior software engineer developing CIG database creation systems, and graphics algorithm design. He has a Bachelor of Science degree in Aerospace Engineering from the University of Kansas.

Brian Soderberg is currently the Project Engineer for BBN's New Visual System Product Development Programs. Mr. Soderberg has been active in numerous research teams to study the simulation of Battlefield Smoke. Previously, Brian held the position of senior software engineer involved in graphics algorithm development. Since 1982, Brian has been involved in computer graphics research and development with techniques involving depth buffers, lighting models, texture mapping, surface rendering, motion design, and ray tracing. In addition, Brian has lectured on computer graphics at various companies and at the University of Washington. Brian has a Bachelor of Science degree in Mechanical Engineering from the University of Washington.