Spatial Analysis Of A Bioterrorist Attack On Four Major United States Cities Using An Aerosolized Hemorrhagic Fever Virus

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ABSTRACT

Before the attack on September 11, 2001, the United States was very vulnerable to a biological attack. Since then, those responsible for the security of the United States Homeland Security have become more aware of the country’s vulnerability. Biological agents have the potential to give small groups of people unprecedented power to terrorize, as indicate by the “Amerithrax” attack in 2001, and of all of these agents, none have more potential for destruction than Ebola Hemorrhagic Fever (EHF). This research uses one of the deadliest viruses that have not been eradicated to identify the number of fatalities in an outbreak affecting the United States. EHF is one of the deadliest viruses known, and is classified as a category A bioweapon. This research uses current modeling technology with most recent data to model a worst-case scenario of an attack involving EHF-Zaire. Geographic Information Systems (GIS), Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT), and the Spatio-Temporal Epidemiological Modeler (STEM) was used to determine the number of index cases in hypothetical attacks on four United States cities, Los Angeles, Houston, New York City, and St. Louis, and each was processed in STEM to track the diffusion of the outbreak spatially and temporal. Fatality numbers were calculated from STEM, using recorded Comma Separated Variable (CSV) files. The fatalities for each scenario were over 136 million over the six month study period. An understanding of a worst-case EHF-Zaire scenario will be a valuable asset for emergency response and epidemiological personnel with regard to the crafting of response strategies and training scenarios.
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INTRODUCTION

Since the terror attacks of September 11, 2001, the topic of biowarfare has once again come to the attention of the disaster response community. Once thought to be consigned to the annals of history by the Bioweapons Convention of 1972, the threat of terrorist use of these weapons, coupled with recent revelations of Soviet treaty noncompliance, has once again placed this topic front and center as a matter of concern to those charged with responding to infectious disease (Darling and Woods, 2004). Rumors of terrorist interest in these most destructive and indiscriminate of weapons have only heightened this concern. There are three different groups of terrorist that might use biological agents to inflict terror. The first group and the most dangerous are the large, well-organized groups that are well-funded by a nation-state. The second groups are the smaller, less sophisticated organizations that may not conduct mass-casualty attacks but will use terror to further their cause. The last groups are smaller groups or individuals that limit their target to murder plots or to threaten (Kortepeter and Parker, 1999). For any or all these groups, bioweapons could offer a destructive modality of unprecedented power.

The purpose of this research is to identify how many casualties may be produced in a worst case scenario generated by a single source deployment of weaponized aerosolized EHF-Zaire virus in four major United States cities. This study will help emergency responders to develop strategies that will facilitate a rapid and effective response to an incident involving hemorrhagic fevers, or indeed any lesser disease. This research will enable emergency responders to implement mitigation strategies to slow
down or halt entirely, a regional epidemic, or a global pandemic, of such a disease. This research will be useful to anyone in the emergency response or Homeland Security communities who is confronted with the threat of a bio-attack.

EHF is extremely dangerous to the human population due to the fact that there is no available vaccine and the mortality rate can reach up to 90% (CFSPH, 2009). There are five types of EHF (Zaire, Sudan, Bundibugyo, Ivory Coast, and Reston), and the deadliest is the Zaire strain. The Zaire strain has the highest mortality rate and is the virus that causes most outbreaks. The last outbreak of EHF-Zaire was in 2007 in the Democratic Republic of Congo (Zaire) and killed 187 people out of 264 infected (CDC, 2010). This represents a 70% mortality rate, and previous outbreaks have featured mortality rates of up to 90% (CDC, 2010). The high mortality rate, potential for aerosolization, and lack of effective treatment make Ebola a very dangerous potential weapon of mass destruction.

Terrorists do not fight traditional battles, where both sides are standing on the opposite sides of the battlefield shooting. Terrorists by definition tend to favor weapons which feature indiscriminate effects and high potential noncombatant casualties. With the advancement of technology and the advent of inexpensive global travel, a terrorist can fly to The Democratic Republic of Congo, extract tissue samples from a human infected with EHF-Zaire, and bring it back to be aerosolized. After the collapse of the Soviet Union and termination of the former USSR biological weapons program, some scientists cannot be accounted for, and this might mean a terrorist group could be employing them. Given
this level of uncertainty, the United States needs to be prepared for the worst, because one never knows when an outbreak might come about.

This research consists of creating hypothetical plumes of aerosolized EHF-Zaire over four major cities in the United States. With the assistance of Geographic Information Systems (GIS) and the Spatio-Temporal Epidemiological Modeler (STEM), spatial and statistical models have been created that simulated a worst case scenario of an attack utilizing EHF.

LITERATURE REVIEW

General Biowarfare

Not all biological agents are suitable for use as weapons of mass destruction. The ideal bioweapon possesses the following qualities, according to Medical Aspects of Chemical and Biological Warfare: 1) availability or ease of production in sufficient quantity; 2) the ability to cause lethal or incapacitating effects in humans at doses that are achievable and deliverable; 3) appropriate particle size in aerosol; 4) ease of dissemination; 5) stability after production in storage, weapons, and the environment; and 6) susceptibility of intended victims with non-susceptibility of friendly forces (Darling and Woods, 2004). The ideal method of delivery would be in a dry powder composed of very small particles in the range of one to five μm in diameter (Kortepeter and Parker, 1999). The particle in this size range can readily penetrate the lungs, and attach to the sacs of the lungs, without being expelled (Kortepeter and Parker, 1999).
There are two different types of aerosol source machinery that can be used in deploying a biological weapon. The first type is a line source sprayer. An industrial insecticide sprayer designed to be mounted on an aircraft is an example. Line source sprayers will spray perpendicular to the direction of the wind, upwind of the intended target area. The other type is a point source sprayer. A point source is a stationary device for aerosolization of the agent, an example of one would be bomblets dispersed in a pattern on the ground by a missile or artillery shell designed to release such bomblets (Darling and Woods, 2004). This research will assume the use of an aerosol point source sprayer.

A successful biological attack requires the right meteorological conditions. Even if an individual or a group has successfully created an aerosolized agent and a mechanism to deploy the agent; without ideal weather conditions, the agent will not reach its full potential. There are different types of meteorological conditions for different types of biological agents. Temperature, relative humidity, wind speed, and direction all need to be taken into consideration when deploying an agent. The wind speed needs to be strong enough to carry the agent downwind towards the target area. Also the individual that is deploying the agent obviously needs to stand up wind from the agent (Patrick, 2001).

Piercy et al. (2010) indicated that aerosolized EHF-Zaire will survive in 50-55 % relative humidity and 22 ± 3 degrees Celsius for 90 minutes. Also the Jaax et al. (1995) study of control monkeys that became infected with EHF-Zaire via the aerosol route was conducted under conditions of 40-70% relative humidity. This indicates that for
aerosolized EHF-Zaire, the relative humidity needs to be in the range of 40% to 70%, ideally 50%-55%, with the temperature in the range of 16 to 27 degrees Celsius.

Atmospheric Plume Modeling

Atmospheric plume modeling is used for a wide range of pollutants from car emissions to biological agents. An atmospheric plume model, also known as an atmospheric dispersion model, is defined as a mathematical description of how wind and other weather conditions determine the spread of a substance (Wagner et al., 2006). The mathematical core of an atmospheric plume model is a series of algorithms that predict the downwind concentration of a substance that result when a quantity of the substance is released (Wagner et al., 2006).

There are many different types of atmospheric plume models that will model chemical, nuclear, radioactive, and biological material. Areal Locations of Hazardous Atmospheres (ALOHA) and Hot Spot are some of the other different type of plume models. ALOHA is the plume modeling software that Computer-Aided Management of Emergency Operations (CAMEO) uses and this models chemical releases. Chemicals behavior different than biological agents and this is why ALOHA was not used in this research (U.S. Environmental Protection Agency and National Oceanic and Atmospheric Administration, 2007).

Hot Spot, which models nuclear explosions and radioactive particle plumes, is another atmospheric plume model. Hot Spot was produced for emergency response personnel and emergency planners to map releases of nuclear and radioactive material
(Homann, 2010). Hot Spot was not used in this research due to the fact that Hot Spot was specifically created for incidents involving radionuclides, which often behave differently in the ambient environment than aerosolized biological agents (Homann, 2010).

There are many different types of atmospheric plume models, but for modeling a biological agent, smoke plume models are ideal. Smoke plume modeling is not only used in determining the direction smoke particles will travel but also other types of particles of a similar size. Smoke particle diameter is less than five \( \mu \text{m} \), which is also the optimal diameter of aerosolized Class A bio-weapon agents, the ideal size for penetrating deep into the lungs of a mammal (Darling and Woods, 2004). VSmoke and HYSPLIT are some of the smoke plume models that can also model biological agents.

VSmoke was created by the United States Department of Agriculture Forest Service to establish the impact of smoke on visibility, and health of humans. Vsmoke uses Gaussian algorithms to model the dispersion of smoke particles. Vsmoke is also compatible with Geographic Information Systems (GIS) (Jackson et al., 2009). Vsmoke was not used in this study because it uses only Gaussian algorithms, and it was determined in a side-by-side comparison that the plumes created by Hybrid Single Particle Lagrangian Integrated Trajectory Model (HYSPLIT) were more realistic than those created by VSmoke, especially regard to turbulence and downwind effects.

The smoke model that will be used in this research is HYSPLIT. HYSPLIT is provided by National Oceanic and Atmospheric Administration (NOAA) - Air Resources Laboratory and Australia’s Bureau of Meteorology. This model is designed to respond to
atmospheric emergencies, diagnostic case studies, or climatologically analyses using previously gridded meteorological data (Draxler and Hess, 1998). HYSPLIT uses both Lagrangian and Eulerian algorithms. The results can be imported into GIS and can also model chemical transformation (Draxler and Hess, 1998). HYSPLIT has been around since the 1980s and has evolved over several stages. HYSPLIT_4, which is used in this research, is a complete system for computing anything from simple trajectories to complex dispersion and deposition simulations using either puff or particle approaches (Draxler and Hess, 2004).

Garner et al. (2006) used HYSPLIT for the wind transport and dispersal model to identify and rank farms that are at risk of wind-borne infection of Foot-and-mouth disease. Draxler and Hess (1998) describe the different type of scenarios HYSPLIT can be used to model. Escudero et al. (2006) utilized HYSPLIT to quantify the proportions of mineral dust originated from specific geographical areas in northern Africa. HYSPLIT was used in the Harvard Forest fire in July 2000, which modeled a 36 hour backward trajectory during and after the event (Sigler et al., 2003).

Ebola Hemorrhagic Fever- General

Ebola Hemorrhagic Fever (EHF) is in the family of Filoviridae in the order of Mononegavirales along with Marburg Hemorrhagic Fever (MHF). Filoviruses are enveloped, non-segmented, negative stranded RNA viruses of varying morphology; Ebola virus particles are uniform in diameter (80 nm) but the length can reach up to 14,000 nm (Feldmann and Geisbert, 2010). There are five species of EHF: Zaire, Sudan,
Ivory Coast, Reston, and Bundibugyo. All of these species of EHF are named after the location of the index outbreaks.

The locations of most of the species of EHF are in several African countries south of the Sahara. EHF-Sudan is found in eastern Africa (Sudan and Uganda) and EHF-Zaire is found in west-central Africa (Gabon, Republic of Congo, and Democratic Republic of Congo). Antibodies for Ebola have been found in Cameroon, where outbreaks have never been reported (CFSPH, 2009). Peterson et al. (2004) identified EHF as being located in a humid rain forest environment in central and western Africa and MHF in drier more open areas of central and eastern Africa.

EHF is transmitted by physical contact with infected body tissue, fluids, secretions, and semen of a person (CFSPH, 2009). A study done by Chowell et al. (2004) identified that the number of secondary cases generated by an index case ranged from 1.34 to 1.83 people. However, Legrand et al. (2007) indicated that the number of secondary cases produced by an index case ranged between two and seven people. Both of these studies used the same data from the 1995 outbreak in Democratic Republic of Congo and the 2000 outbreak in Uganda. The different conclusions of these two studies result from the fact that Chowell et al. (2004) used standard deviation and Legrand et al. (2007) used confidence interval in calculating the multiplier of the disease.

The incubation period of EHF ranges from two to 21 days, with a mean of 4-10 days (Feldmann and Geisbert, 2010). The symptoms begin with fever, severe weakness, headache, and muscle pain. These symptoms resemble those of the common cold, and
many other less serious diseases, making accurate diagnosis difficult (CDC, 2010). After these symptoms set in, a rash begins to form along with mucous membrane hemorrhages, vomiting blood, bloody diarrhea, pinpoint and small lesions under the skin that often ooze blood at puncture sites. These symptoms can be noted after five to seven days of the illness (Feldmann and Geisbert, 2010). When the acute stage is reached, the central nervous system and internal organs begin shutting down and the patient goes into shock. Death ensues in short order for up to 90% of those infected (CDC, 2010).

Epidemiology of EHF

The first outbreak of EHF occurred in 1976 in Zaire, now Democratic Republic of Congo. Also, in the same year another outbreak of EHF surfaced in Sudan. The outbreak in Democratic Republic of Congo killed 88% of 318 infected people and the outbreak in Sudan killed 53% of 284 infected people (CDC, 2010). It was determined that the Zaire outbreak was caused by the re-use of contaminated needles (Baron et al., 1983). Baron et al. (1983) conducted a study on how the virus transmitted from person to person in the Sudan outbreak. This study determined that EHF may have been transmitted via the airborne route but also suggested that this might have not been the primary mode of transmission. From 1976 to 1980, there were five EHF outbreaks, mainly in Sudan and Zaire. But one of the outbreaks had reached all the way to England; it was feared that its next jump might carry the disease to the United States (CDC, 2010).

In 1989, EHF reached the United States. The outbreak occurred in Reston, Virginia at a laboratory facility that housed monkeys. The monkeys all died from an
unknown virus. Once the virus was extracted and examined, the scientists concluded that it was a strain of EHF but different from Sudan and Zaire. This strain was named after the town it was found in, Reston, and it only affects monkeys (Preston, 1996). EHF-Reston has also been found in the Philippines. From 1989 to 1996, the strain of EHF-Reston was identified in the United States in three different locations: Reston, VA, Philadelphia, PA, and San Antonio, TX (Feldmann and Geisbert, 2010).

After 1989 outbreak of EHF-Reston, outbreaks occurred every year. In 1994, another strain of EHF was identified in Ivory Coast, which proved to be non-fatal. This strain was identified as Ebola-Ivory Coast. In 1995, EHF-Zaire killed 250 people out of 315, 79% mortality rate, in the Democratic Republic of Congo (CDC, 2010).

After 1995, the outbreaks of EHF stayed consistent, with at least one outbreak each year. The last major outbreak of EHF was in Democratic Republic of Congo. EHF-Zaire was the virus and it killed 187 people out of 264 infected. The outbreak occurred in Kasai Occidental Province and was declared over November 20th, 2007 (CDC, 2010). Also in 2007, a new strain of EHF was discovered. This outbreak occurred in the Bundibugyo District of Uganda and lasted for seven months. The mortality rate of the Bundibugyo strain was 34% out of 116 infected people (Wamala et al., 2010). This strain proved to be less deadly than Zaire or Sudan, but this indicates that new strains of EHF are yet to be discovered.
Aerosolization of EHF

Even though spread via aerosol is not believed to have been a significant factor in EHF outbreaks in the human population, the aerosol route is the ideal way to deploy a biological agent for an attack. Leffel and Reed (2004) determined that MHF and EHF can be used as biological agents that could be deployed as bioweapons. In 1995, Jaax and colleagues reported that after injected EHF-Zaire infected rhesus monkeys died, the two control rhesus monkeys also contracted EHF, and died in turn. Since the control monkeys were isolated from all but atmospheric contact from the infected monkeys, this led to the conclusion that EHF can be spread through the air. Johnson and colleagues (1995) performed another study identifying all the factors that might have caused the uninfected control monkeys to become sick and die. They came to the conclusion that when cleaning the infected monkey’s cages with pressurized water, the spray might have caused the virons of EHF-Zaire to be sprayed in the air and might have infected the control monkeys.

In 1995, Jaax et al. conducted another study by exposing rhesus monkeys to aerosolized EHF-Zaire virions, and concluded that aerosolized Ebola will infect primates as effectively as injection with EHF-Zaire. Leffel and Reed (2004) states that even with high mortality rate and no vaccine, this does not necessarily mean that aerosolized EHF-Zaire would cause large-scale infections and deaths if employed in a terrorist attack. However, an even low dose of aerosolized EHF-Zaire is lethal for guinea pigs and nonhuman primates (Leffel and Reed, 2004).
Piercy et al. (2010) tested the survival of filoviruses in liquids, on solid substrates, and in a dynamic aerosol. The study used EHF-Zaire, EHF-Reston, and MHF. In the aerosolization of EHF-Zaire, they used a Goldberg drum and attached aerosolized EHF-Zaire to *Bacillus atrophaeus* spores. They ran the drum for 90 minutes and collected samples every 15 minutes. This study concluded that, EHF-Zaire, EHF-Reston, and MHF, if liquefied and subsequently dried on a surface, can survive for extended periods. Aerosolized EHF-Zaire can survive and stay infectious up to 90 minutes as an aerosol.

**Treatment and Prophylaxis**

Treatment is supportive for an infected person since no effective treatment exists. Carefully monitoring fluid and electrolyte balance, and blood pressure is vital due to the fact that there has not been a vaccine approved by the Food and Drug Administration (Borio et al., 2002). There is no specific treatment for EHF for humans that has been approved, but along with monitoring fluids and blood pressure, mechanical ventilation or dialysis is sometimes used (CDC, 2010). EHF replicates at an unusually high rate that overwhelms the protein synthesis apparatus of infected cells and the host’s immune defense (CDC, 2010). Equine immunoglobulin has been identified to delay the disease onset in nonhuman primates, but more effective treatment of human patients may require antibodies with higher specific activities and more favorable pharmacokinetic properties. However, this treatment could be useful for emergency treatment of accidental infection (CDC, 2010).
In recent years, studies have been conducted with the goal of producing a vaccine for EHF. Bukreyev et al. (2007) used topical respiratory tract immunization as a method of vaccinating against aerosolized EHF-Zaire. This study recognized that this vaccine confers substantial protection against EHF, and was the first study in which topical immunization through the respiratory tract achieved immunization of an infected primate with viral hemorrhagic fever (Bukreyev et al., 2007). In 2008, Geisbert and colleagues used a vesicular stomatitis virus-based vaccine against aerosolized EHF and MHF. This study was a limited success, insofar as the vaccine did not confer complete immunity, but did reduce the mortality rate to zero. This promising work continues apace, but there remains no approved vaccine for any strain of EHF.

There is no real study on modeling the deployment of EHF against cities and producing a worst-case scenario. The above cited research indicates that EHF has been looked at as a bio-weapon and that there are atmospheric models that will model a biological particulate plume, but no one study incorporates all three of these concepts, with EHF being deployed against a city as a bio-weapon with spatial display and identifying the index cases and obtained worst case numbers from each attack. This research embraced all three of these aspects that need to be addressed when modeling a bio-weapon, whether EHF or a less deadly bio-agent.
METHODOLOGY

The methodology that was used in this study created a series of plumes using HYSPLIT, and importing the plumes into GIS, ArcGIS 9.3, running the plume over four major United States cities (New York City, Houston, Texas, Los Angeles, California, and St. Louis, Missouri), obtained the initial cases from each plume, created and ran a Spatio-Temporal Epidemiological Modeler (STEM) scenario for each separate hypothetical attack, and obtained the calculations of a worst case attack of EHF-Zaire on each city from STEM.

Process

An individual scenario was created for each city to be studied. A plume was generated for each city, which was then imported into ESRI ArcGIS, ArcMap. Once the plume was in ArcMap, the plume was overlaid on to census tract data that was obtained from the Census Bureau. The population data was the 2000 national census data. Overlay analysis was used to identify how many people were affected by the plume and for a worst-case scenario, 15% of the people underneath the plume were assumed to be infected. Fifteen percent was regarded as a very conservative infection percentage especially since the few aerosolization studies involving EHF have resulted in 100% infected (Jaax et al., 1995). This number represented the index cases and served as the initial infection number used in STEM. STEM was then be used to model the spread of the disease across the United States at the county level. Scenarios were run
simultaneously. Overall meteorological conditions remained relatively constant, but were obviously not identical.

**Software**

The software that was used is HYSPLIT, GIS, ArcGIS 9.3, and the Spatio-Temporal Epidemiological Modeler (STEM).

HYSPLIT was the atmospheric plume model that was used in the research. The meteorology used by HYSPLIT is linked to Air Resources Laboratory (ARL) and National Weather Service (NWS) meteorological data server and has access to forecasts and archives including National Center for Atmospheric for Atmospheric Research (NCAR)/ National Centers for Environmental Prediction (NCEP) reanalysis. The air concentrations are in 3D particle dispersion or splitting puffs (top-hat or Gaussian), and outputs a multiple resolution concentration grid, and mass can be transferred to an Eulerian module for global-scale simulations (Draxler and Hess, 1998). The plume produced in HYSPLIT was imported into Environmental Systems Research Institute (ESRI) ArcGIS 9.3.

The GIS software package that was used is ESRI ArcGIS 9.3. ArcGIS is provided by ESRI and this software allows users to capture, manage, analyze, and display data from all forms of geographically referenced information (ESRI, 2010). The plumes were overlaid on to census population data and obtained the number of initial index case numbers. This initial case number served as the basis for the STEM temporal diffusion study.
For mapping the spatial diffusion of EHF-Zaire, STEM was used. There is another spatial epidemiology model, Epigrass, but Epigrass will only run on Unix-based software and was not compatible with the software that was being used in this study (Coelho et al., 2008). STEM is an open source spatiotemporal epidemiology model created by the Eclipse Foundation, in cooperation with the United States Air Force and the University of Haifa. STEM is designed to help scientists and public health officials to create and use spatial temporal models of emerging infectious disease and can utilize many different compartmental diseases models (Eclipse, 2010). STEM can assist in understanding and potentially preventing the spread of diseases (Eclipse, 2010).

Four Cities

Four cities were chosen due to the unique characteristics each city possesses. Each city covers the general range and urban type of most United States cities. New York City is one of the largest cities in the United States, and was hit on September 11, 2001. This city represents the dense-packed, old urban city. With its narrow streets and skyscrapers this city was an ideal location to spread a biological agent due to the density of the population.

The second city that was chosen was Los Angeles, California. This city represents the west coast, open style landscape, post WW II urban setting. This was an ideal city with which to model the spread of a disease over an open space urban city. The third city that was used is Houston, Texas. Houston represents the sun-belt and is a major hub for the oil industry. The last city that was used is St. Louis, Missouri. St. Louis represents the
Midwest states and the "old style" central city. The deployment of the agent was located in each city to obtain the greatest number of index cases.

The deployment of St. Louis, Houston, and Los Angeles weapons were carried out on a highway in the suburbs of the cities. These cities have urban sprawl and have the greatest concentration of people in the suburbs. The New York City weapon was deployed in the Bronx with a southwest wind to blow the agent into Manhattan. The location of the deployment of the weapon was in all cases along a highway in a residential area close to a major business district.

Parameters for HYSPLIT

The parameters of HYSPLIT are: the agent will be deployed at six in the morning and dissemination was taken place for an hour. The vehicle will be parked on the side of the road with a small size insecticide sprayer that will hold six gallons of EHF suspended in a fluid suitable for aerosolization. Six gallons is how much the insecticide sprayer will hold that was used in this study. The meteorological data will include a low wind speed and a low relative humidity. The temperature will be in between 16 to 26 degrees Celsius.

Meteorological Data for the Cities

The meteorological conditions and dates selected for the hypothetical attack were optimal or close to optimal for the deployment of aerosolized EHF-Zaire and all deployments occurred at 6 a.m. The New York City (40.87,-73.91) scenario occurred on May 27th, 2010. The temperature was 25.7°C with a relative humidity of 57% and the wind direction was northeast at 11 knots. The St. Louis (38.68, -90.22) scenario occurred
on April 30th, 2010. The temperature was 18°C with a relative humidity of 61% and the wind direction was blowing from the south at nine knots. The Houston (29.74, -95.35) scenario occurred on April 10th, 2010. The temperature was 16°C with a relative humidity of 73% and the wind direction was blowing from the southwest at nine knots. The Los Angeles (34.05, -118.23) scenario occurred on May 7th, 2010. The temperature was 17°C with a relative humidity of 48% and the wind direction was blowing southwest at eight knots. All data was obtained from HYSPLIT archived meteorological data.

Parameters for STEM

The parameters for STEM were: the population was tabulated down to the county level to insure adequate spatial resolution, air and road transportation were modeled down to the county level, and utilized a six month study period with a cycle period of one day. A deterministic Susceptible, Exposed, Infected, and Recovered (SEIR) model was used to model the disease with an incubation period of seven days and an R-zero, the average number of susceptible animals that are infected by each infected animal, is five. A deterministic model is more uniform and this will help analyze each scenario side by side.
RESULTS

Plumes

Figures 1 through 4 illustrate the modeling of the plumes over the cities. The length of each plume is: Los Angeles, 2.74 miles; St. Louis, 24 miles; New York, 14.62 miles; and Houston, 9.44 miles. The index case number for each city is: Los Angeles, 4,618 people; St. Louis, 1,398 people; New York, 14,898; and Houston, 100,788 people.
Figure 2- This plume represents the deployment of EHF-Zaire in St. Louis.

Figure 3- This plume represents the deployment of EHF-Zaire in New York City.
STEM Simulations

The total population of Americans that became infected is:

- Los Angeles, 136,737,184 people
- St. Louis, 136,734,753 people
- New York, 136,737,025 people
- Houston, 136,729,670 people

Figure 4 - This plume represents the deployment of EHF-Zaire in Houston.
people that became infected and died in each outbreak.

people that became infected and died in each outbreak.

represent the epidemic waves of each outbreak. Figure 9 illustrates the total number of

All of these totals are $44\%$ out of $306$ million Americans. The figures (5-8) below

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Graph 4 - This is an epidemic wave of the Houston outbreak.

Graph 3 - This is an epidemic wave of the St. Louis outbreak.
SPATIAL RESULTS

Los Angeles, California Scenario

On May 7, 2010 aerosolized EHF-Zaire was deployed over the city of Los Angeles, and infected 4,618 initial cases. By the fifth day of the outbreak, the infection had spread to Nevada and Arizona as well as, northern California, Wyoming, Dallas, Kansas City, and some counties in the east, as well as Alaska (Figure 5). On the tenth day of the outbreak, the infection had jumped to a majority of the major cities in the United States (Figure 6). Each major city had at least one infected person. Three weeks after the outbreak, major cities were serving as secondary infection foci, and the disease was spreading outward from these new sources (Figure 7). All counties in California, Nevada, and Arizona had been exposed; also Alaska and Hawaii featured 100% exposed. After a
month, all of the West and Northwest regions of the United States had been infected (Figure 8). The only areas that had not been infected were the remote areas of the Midwest, South, and Eastern regions of the United States. Two months after the initial outbreak, the disease had spread to the entire United States (Figure 9). The infection continued to be transmitted until the end of the six month study period (Figure 10).

Figure 5- Fifth day after the outbreak in Los Angeles.
Figure 6- Tenth day after the outbreak in Los Angeles.

Figure 7- Three weeks after the outbreak in Los Angeles.
Figure 8- One month after the outbreak in Los Angeles.

Figure 9- Second month after the outbreak in Los Angeles.
St. Louis, Missouri Scenario

On April 30, 2010, aerosolized EHF-Zaire was deployed over St. Louis, Missouri, infecting 1,398 initial cases (Figure 11). Six days later the infection has spread to counties in Illinois and to Kansas City (Figure 12). In the next four days, the infection spreads to surrounding counties in Missouri and spreads to Orlando, Las Vegas, and to Wyoming and to the East via air transport (Figure 13). After a month from the initial outbreak the infection has spread to the major cities of the United States but the majority of the infected areas are still in Illinois and Missouri (Figure 14). Over the second month, the infection spreads throughout the United States and after three months the infection has spread all across the United States. Furthermore, the whole United States has been infected and has at least one person infected in each county (Figure 15). But by the last
But by the last couple of weeks of the study period, the infection starts to die out near the initial area of infection (Figure 16).
Figure 13-Ten days after the outbreak in St. Louis.

Figure 14-One month after the outbreak in St. Louis.
Figure 15-
Three months after the outbreak in St. Louis.

Figure 16-
Six months after the outbreak in St. Louis.
New York City Scenario

On May 27, 2010 aerosolized EHF-Zaire was deployed over New York City, New York, resulting infected 14, 898 initial cases (Figure 17). Ten days after the outbreak, the disease had spread to upstate New York and on the twelfth day of the outbreak, the disease had reached counties in Nevada, Wyoming, Kansas, Florida, Arizona, Texas, Alaska, Hawaii, and the Eastern region of the United States (Figure 18). On day 20, the infection had reached all the major cities in the United States and had started to spread to the counties surrounding major urban areas (Figure 19). Half way through the test period, the whole United States has been exposed (Figure 20). This remained constant until a couple of days before the test period ended. The disease then begins to die out near the origin area of infection (Figure 21).
Figure 18- Ten days after the outbreak in New York City.

Figure 19- Twenty days after the outbreak in New York City.
Figure 20- Three months after the outbreak in New York City.

Figure 21- Six months after the outbreak in New York City.
Houston, Texas Scenario

On April 10, 2010, aerosolized EHF-Zaire was deployed over Houston, Texas, resulting in 100,788 initial cases (Figure 22). Two days after the outbreak, the infection had spread to all the major cities in Texas (Figure 23). Four days after the initial attack, April 14, the infection had spread to counties in California, Washington, Nevada, Arizona, Wyoming, Colorado, Florida, Kansas, and Virginia (Figure 24). Ten days after the initial outbreak, the infection had spread to all the major cities in the United States and also to Alaska and Hawaii (Figure 25). During the first month of the outbreak, the whole Western and Eastern regions were exposed and the only areas that were not exposed were the remote areas of the South and the Midwest (Figure 26). Two months from the start of the outbreak, the whole United States had been exposed to the disease (Figure 27). By the fifth month of the outbreak, the infection had started to die out in the areas that were hit first (Figure 28). At the end of the study period, the infection had diminished in the regions that were first infected and also in the East (Figure 29).
Figure 22- The first day of the outbreak in Houston.

Figure 23- Two days after the outbreak in Houston.
Figure 24- Four days after the outbreak in Houston.

Figure 25- Ten days after outbreak in Houston.
Figure 26- First month after the outbreak in Houston.

Figure 27- Second month after the outbreak in Houston.
Figure 28- Fifth month after the outbreak in Houston.

Figure 29- Six months after the outbreak in Houston.
ANALYSIS/DISCUSSION

Deployment of the Agent

There were significant differences in the plumes despite the similar initial meteorological conditions. This may have been caused by the terrain. Los Angeles is in a valley and temperature inversions are common in the LA area, and this might have led to the plume not traveling as far as the other plumes. The Houston plume was affected by the winds coming off of the Gulf of Mexico. The St. Louis plume traveled the furthest because the terrain is generally flat; with steady winds the particles were able to travel a long distance.

Each plume is obviously very different and even though the wind speeds only varied by a couple of knots, the other elements that are part of the plume are very different and this is represented in the movement pattern of each plume. The St. Louis plume is the longest and the narrowest of the plumes and the index case number was the smallest out of the four. This may be caused by the relative humidity and consequent variations in atmospheric stability.

The landscape of the cities is very different too. Even though the wind speed only ranged from 007 to 011 knots, the length of the plumes varied significantly. New York City had the strongest winds but the length of the plume was only 14 miles. This might be caused by the topography of the built environment. The tall sky scrapers may have blocked some of the particles from reaching the maximum distance due to surface roughness turbulence. In the St. Louis scenario, wind speed was 009 knots and produced
the longest plume. The St. Louis plume probably traveled further than the New York City plume because the particles were released in a residential area, and did not have tall objects creating turbulence and slowing the spread. This allows the particles to travel the maximum distance.

The concentration of the particles varies in each plume even though the same amount of aerosolized EHF-Zaire was released into the atmosphere. This might have been caused by meteorological factors. The terrain would have to be a major factor in why there were significant variations in concentration. Houston had the greatest concentration. The weather conditions may be an important factor in this concentration. The relative humidity of Houston was 72%, but Los Angeles had the second greatest zone of concentration with a relative humidity is 48%. There is obviously another factor that is causing this zone of concentration to be different for each city that is neither terrain nor relative humidity, but this factor cannot be determined without future research.

There is also a wide range in the number of initial infections. Houston had the largest number of people infected but had the lowest wind speed. The difference in the initial infections may have been caused by the location of the deployment of the weapon, since this study identified where the greatest effect of deployment would be in each city. The Houston weapon affected a more residential area than in other cities, due to the wind direction. St. Louis was also deployed over a residential area but the plume crossed a river which would not have anyone living on it. Wind direction proved to be more important than wind speed.
It was assumed that the bigger the plume area, the greater the number of people infected, and this proved to be the case. The Houston plume is the largest in area and produced the greatest number of infected people. This was because of the direction of the plume. As noted above, the meteorological conditions are of great importance in the deployment of a bio-attack.

Spatial Diffusion of the Disease

Once the initial cases were created by the biological plume, in three of the four test cities, the spread of the disease was relatively uniform over the first six days of the outbreak. The disease spread only to the surrounding counties in those first six days. The exception was Houston, where the disease diffused rapidly due to air travel and the high number of index cases, and took only one day to spread to the surrounding counties. After the sixth day, the spread of the disease was variable in each scenario. It took the Houston outbreak less time to spread across the United States than all the other outbreaks due to the large number of index cases. The St. Louis scenario took the longest to spread through the United States due to the small number of index cases.

The Houston scenario spread throughout the whole United States in the shortest period. It took only a month to expose the whole United States. It took both the St. Louis and the New York City scenarios two and a half months to spread to the whole United States, the longest of the four scenarios. This difference cannot be attributed solely to the number of index cases, however, St. Louis had the least number of index case, 1,398, but the New York City scenario had 14,898 index cases, the second highest of the four
scenarios, and the spread of the disease was roughly the same for each. This difference might have been caused by the length of time it took the infection to reach the major cities in the United States.

Why the New York scenario took the longest to spread across the United States is unknown at this point. New York City is one of the biggest cities in the world and thousands of people come in and out of New York City each day. There is obviously another unknown factor that caused the New York outbreak to spread so relatively slowly; what this factor might be could serve as a profitable avenue for future research.

The Los Angeles scenario was second only to the Houston scenario in rapidity of spread. It took 13 days for the infection to reach Alaska and Hawaii and this is probably due to the popularity of these states as tourist destinations. It only took four days for the infection to reach Alaska and Hawaii in the Houston scenario. It took the New York City scenario longer for the outbreak to reach popular tourist destinations in the United States. However it spread to Buffalo, NY within five days.

The greatest spread of the disease was near the initial point of attack. The outbreak spread to the surrounding counties first and had the greatest impact due to transportation by road and these areas also developed the largest caseload. In the Houston scenario it took only one day for the disease to reach the surrounding counties and the major cities in Texas.

The disease did not jump with great rapidity to the major cities in the United States even factoring in air travel. It took the Houston scenario the shortest amount of
time taking eight days for the disease to reach all the major cities of the United States. It took 17 days for the Los Angeles outbreak, 26 days for the St. Louis, and 34 days for the New York City to reach the major cities in the United States. Once the disease entered the major cities, these cities became secondary foci of the outbreak. Air travel helps the disease to reach the major cities, which helped further the spread of the disease.

Rural areas were the last to be hit with the disease. The rural areas of the Midwest and the South were the last to be infected, due to the low population density and lack of major cities to serve as secondary infection foci. However, the Midwestern region has a significant amount of land that is designated as farmland and there is a lot of travel through these areas, especially the time of year this study was conducted. All the test studies were run from late spring to early fall. This time is extremely busy time for these regions since it is harvest season. The population movement modeler of STEM may not take into this into consideration.

The location of the initial outbreak did not play a significant part in the spread of the disease. The St. Louis scenario took the same amount of time to saturate the United States with infection as the New York scenario. Centrality of the initial attack did not play a factor in the spread of the disease.

The Houston scenario “burned” through the United States the most rapidly, and the Houston scenario also died out the most rapidly. This might be caused by the number of index cases. The greater the number of index cases, the quicker it will spread but the
disease will die out more quickly. This might not be good for a bioweapon since it dies out too fast to reach the entire population.

The disease spread to Alaska and Hawaii rapidly. The disease spread to these states more rapidly than to the major cities in the United States. This might be caused by the amount of travel to these states. Also the disease would spread to popular tourist destinations before spreading to the major cities. The disease would spread to Alaska, Hawaii, Las Vegas, Yellowstone, and Orlando with great rapidity. These are heavy tourist destinations, especially in the summer.

The Western region of the United States became infected more rapidly any other region during each scenario, with the exception of the New York scenario. During the New York scenario, New England became infected prior to the far west. This might be an artifact caused by the large county sizes in the Western states. This is somewhat odd, since the population density is greater in the East compared to the West. Once at least one person is infected in a county, STEM identifies the county as infected. This might prove to be a profitable area for the future research.

Fatalities

After six months, the initial fatalities did not differ that significantly between scenarios. The Houston outbreak led to 136,729,670 deaths, the New York City outbreak caused 136,737,025 deaths, the Los Angeles outbreak caused 136,737,184 deaths, and the St. Louis outbreak caused 136,734,753 deaths. This is 44% of the United States population of 306 million. Even though Houston had more index cases, this did not lead
to a greater number of deaths. There was only a 7,000 fatality difference between Houston, with the lowest number of deaths, and Los Angeles, with the greatest number of deaths.

As noted, the disease in the Houston scenario died out faster than all the other scenarios because of the rapidity of spread across the United States. In month four of the Houston outbreak, the disease started to die out in the area that was first infected. This might have led to a slightly lower death toll for the Houston outbreak because everyone was infected in the first month and it died out before it generated a second wave. The disease almost kills too rapidly to reach its maximum potential.

The greater the index cases the faster the epidemic peak is reached. The Houston scenario epidemic peaked in the first month, while the other scenarios peaked in the third month. This also indicated that the more index cases the less time to respond. But the Houston disease died out the most rapidly as well.

One might suspect that the states surrounding the state where the initial outbreak occurred from would be hit the hardest but this was not the case. In all the scenarios, California was hit the hardest. California’s fatality numbers ranged from 15 to 16 million deaths. This is almost certainly because California is the most populated state in the United States. The state that had the second highest number of deaths was Texas. Even in the Houston scenario, California had the most deaths. In all scenarios, Texas had 10 million deaths and California had over 15 million deaths. It did not matter where the outbreak occurred, the more populated state were hit the hardest with the disease.
CONCLUSION

This research used state of the art modeling technology with up-to-date data to model a worst-case scenario of an attack involving EHF-Zaire as the agent. By using EHF-Zaire as the agent, this research can be applied to other category A biological agents and also other categories of biological agents. EHF-Zaire is one of the deathliest diseases in the world, and if one knows how to react to an EHF outbreak then the United States will be prepared to face anything less deadly. This research will not only aid in understanding the diffusion of a biological agent but will also assist in the creation of new methodologies and techniques which will aid other researchers in modeling or creating response strategies to biological terrorist attacks or natural outbreaks.

If an outbreak of aerosolized EHF-Zaire ever occurred in the United States, it would be a tragedy. At least 44% or about 136 million people would die out of a total population of 306 million people. This is almost half of the population of the United States. This would destroy the United States as a functioning society, and the effects of such an outbreak would not be confined to the United States.

Air transportation is a key in spreading the disease and will enable the disease to spread rapidly. The rapid spread to other major cities will create secondary infection foci and this will enable the disease to spread to those surrounding counties. When responding to an outbreak, air travel needs to be the first thing that needs to be shut down due to the rapidity of spread to other major cities.
The number of index cases is important because different numbers of index cases create differently structured epidemics. The Houston scenario spread the fastest because of the high number of index cases but also there were other factors that aided the disease to spread more rapidly than in the rest of the scenarios. The New York scenario had the second largest index case number, but spread just as fast as the St. Louis scenario, which had the lowest index case numbers. The number of index cases is important but there are other factors that play a role like the location of the city and the dispersal characteristics of the plume.

The city that the disease is released in plays a major factor in the spread. The Houston scenario spread the most rapidly because of air travel, but the size of the city is not of primary importance in spread. New York City is the largest cities in the United States, but the New York outbreak did not spread as quickly as Houston. The type of air travel has a major part because Houston is a major hub for the oil companies and Houston is a major departure point for cruise ships.

The location of the deployment of the weapon and the wind direction are another factors that are important in determining the number of initial cases, and hence the structure of the ensuing epidemic. The Houston plume was deployed over a residential area and this reached the highest number of index cases out of the four scenarios. The St. Louis plume was deployed over a residential area as well but since St. Louis is flatter than Houston the wind carried the agent further but in a narrow band, and hence affected a smaller segment of the population.
The meteorological conditions need to be suitable for deployment of the agent, especially EHF-Zaire. Since there has never been any test on aerosolized EHF-Zaire in the environment, only in the laboratory, one can only estimate. Since EHF-Zaire is a tropical disease, the best environment would be medium to high humidity and temperatures. The conditions chosen to provide optimal contagiousness of the agent necessarily affects the structure and shape of the aerosol plume. Also the wind direction plays a significant role in the spread of the disease via the aerosol plume. The location of the deployment is a factor in obtaining the highest number of index cases. The agent was deployed at the location that would obtain the greatest index cases in each city.

An understanding of a worst-case EHF scenario will be a valuable asset to emergency response and epidemiological personnel with regard to the crafting of response strategies and training scenarios. Prior to September 11, 2001, the United States population was very vulnerable to a terrorist attack using a biological agent. But since then, those responsible for the security of the U.S. population have become more aware of how vulnerable the population is. This research will help those charged with homeland security and disaster response to better understand the nature of a bio-terror attack or a natural disease outbreak, and to create responses that will better ensure the safety and security of the American populace.
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