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Preparing a Small Town for a Hazardous Materials Incident: An Examination of Evacuation Routing Algorithms and Plume Models

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Abstract

Evacuation and shelter in place are two common protective action measures during hazardous events that involve the release of hazardous materials. These responses are complex and require advanced planning to determine their appropriateness to reduce human exposure to hazardous materials and minimize related health risks. Evacuation and shelter in place responses were assessed for people in the town of Erwin, Tennessee, USA, a small, rural town in the mountains of Northeast Tennessee, using a release of uranium hexafluoride (UF_6). The population at risk was identified using historical meteorological data and the Radiological Assessment System for Consequence Analysis tool to create plume models for a hypothetical release of UF6 from a nuclear fuel facility that downblends highly enriched uranium. Two hypothetical evacuation scenarios were modeled. One uses the total road network in Erwin and the other involves a train impeding access to an arterial evacuation route. Two routing algorithms available within the custom network analyst routing tool (ArcCASPER) were used for each scenario: 1) a basic shortest path algorithm and 2) a capacity-aware shortest path evacuation routing algorithm. Post-hoc analyses of each scenario and algorithm indicated that the capacity-aware algorithm predicted the quickest evacuation times for both scenarios. Roads with the longest evacuation times and all critical facilities that would benefit from sheltering in place were identified. The study concluded that the capacity-aware algorithm available within ArcCASPER is the most realistic for the town of Erwin.

Keywords

Radiological Assessment System for Consequence Analysis, Evacuation Modeling, ArcCASPER, Emergency Preparedness

1. INTRODUCTION

Industrial facilities that process hazardous materials have the potential to endanger the health and safety of the nearby population (Bertazzi et al. 1998; Bowonder 1985; Dhara and Dhara 2002; Vernart 2004). Consequently, communities must remain vigilant and develop emergency protocols that provide protection in the event of a release of hazardous materials. Such planning is a key component of emergency preparedness, which is one of the four major phases of the emergency management cycle (FEMA 1990). Community and individual response to releases of hazardous materials often involves evacuation and sheltering in place as a means to limit exposure and reduce risk to the hazard agent.

1.1 BACKGROUND INFORMATION

The town of Erwin is located in the southern Appalachian Mountains of Northeast Tennessee. It is situated near the Cherokee National Forest approximately 15 miles south of Johnson City, Tennessee and 45 miles north of Asheville, North Carolina. Nuclear Fuel Service (NFS) is a specialty fuel facility that has operated continuously within the city limits of Erwin since 1959. NFS down-blends Cold War-era nuclear fuel material into useable low-enriched uranium (LEU) for the Tennessee Valley Authority's (TVA) commercial reactors. NFS also processes highly-enriched uranium (HEU) into useable nuclear fuel for the US Navy's nuclear fleet of submarines and aircraft carriers. One of the major chemical compounds used at fabrication facilities to create fuel for nuclear reactors is uranium hexafluoride (UF_6). When released into the atmosphere, UF_6 will react with water vapor present in the environment to form hydrogen fluoride (HF) and uranyl fluoride (UO_2F_2) (McGuire 1991). Human exposure to HF gas can cause chronic and acute health effects ranging from skin burns to lung damage (Thiessen 1988). The health effects associated with HF gas are dependent upon the amount and length of exposure to the chemical (Salama 2004; Thiessen 1988). Emergency Response Planning Guides (ERPG) estimate that a dose greater than 50 ppm over a one hour period have the potential to induce life threatening health effects (AIHA 2014). Limiting a population's exposure time to the chemical is therefore critical to mitigate injuries and loss of life (Hans and Sell 1974). This can be accomplished through protective measures such as evacuation or sheltering in place (Hans and Sell 1974).

Evacuation is the removal of the populace from the threat, or actual occurrence of, a hazardous exposure zone (Georgiado et al. 2007). Sheltering in place action is finding shelter indoors, securing all openings to the dwelling, turning off all ventilation, and taking shelter in the innermost room of the dwelling (Chan et al. 2007). These actions can be used independently or in combination to mitigate injuries and loss of life to the populace in the hazard zone. An effective emergency plan considers the appropriateness of each of these protective measures by using current modeling software available to researchers and emergency managers.

1.2 Modeling and Software Applications in Emergency Preparedness

A geographic information system (GIS) integrates both hardware and software to aid in analyzing, capturing, managing and displaying geographic data (ESRI 2014). In the context of emergency preparedness, a GIS is a valuable tool because it has the capability to analyze a network dataset to determine if road networks are capable of handling evacuation traffic loads, identifying effective evacuation routes, and identifying safe zones away from hazard zones (Cole et al. 2005). A GIS is not limited to just network analysis. It has the ability to model complex scenarios when the hazard is viewed in both a spatial and temporal context (Cole et al. 2005).

Capacity-Aware Shortest Path Evacuation Routing (ArcCASPER) is a network analyst tool used in conjunction with a GIS (in this study, ArcMap 10.0) to produce evacuation routes to the nearest safe area by incorporating typical road capacity and travel times in an effort to reduce evacuation times and congestion (Shahabi 2012). ArcCASPER uses three separate algorithms and the results of each algorithm can be compared within the same environment allowing for the identification of the most effective method. These algorithms are referred to as: 1) shortest path, 2) Capacity Constrained Route Planning (CCRP), and 3) Capacity-Aware Shortest Path Evacuation Routing (CASPER). The shortest path method is the quickest method to calculate of the three methods, but ignores road capacity and has very low accuracy (Shahabi 2012). The CCRP algorithm prioritizes evacuees based on their distance from the safe zone, by giving those with longer travel times the ability to divert to alternate routes until that roadway reaches its full capacity (Shahabi 2012). The CASPER algorithm takes evacuees with the longest travel times and assigns them to a shortest path. Edge costs (i.e., amount of time it takes to travel a segment of road) are constantly updated to ensure global evacuation times are at a minimum (Shahabi and Wilson 2014).

Radiological Assessment System for Consequence Analysis (RASCAL) version 4.3 is an emergency response consequence assessment tool developed by Oak Ridge National Laboratory. The United States Nuclear Regulatory Commission makes dose and consequence projections in the event of a radiological emergency and these are incorporated into the RASCAL model (Ramsdell et al. 2012). RASCAL evaluates meteorological and atmospheric conditions around nuclear facilities to provide an assessment of the incident (e.g., plume models, plume height, plume temperatures) (Ramsedell et al. 2012). ArcCASPER and RASCAL alone are valuable to users interested in modeling evacuation and, but when combined they provide a powerful set of tools that aid in preparing actionable protocols for communities that may be at risk for a hazard and want to mitigate exposure via evacuation and sheltering.

1.3 Research Objectives

The objectives of this study are to 1) demonstrate the utility of evacuation modeling for industrial hazards that produce offsite airborne hazards, 2) determine if mandatory evacuations are preferable over sheltering in place, and 3) evaluate whether or not the current road network is sufficient to accommodate a mandatory evacuation. Depending on the intensity (rate of release), volume, and dose of UF_6 released, it may be better for citizens within the area to opt for a shelter in place action over a mandatory evacuation action, but no information is currently available to assist in making this crucial decision. Examination of the infrastructure will assist in determining the time necessary to evacuate an area, possible congestion points that may hinder evacuation, and location of timely evacuation routes.

2. EXPERIMENTAL DESIGN

2.1 DATA AND METHODS

When evaluating emergency preparedness solutions involving a UF_6 release, it is important to take into account the current meteorological conditions since this will determine if evacuation and/or a shelter in place strategy is necessary for the community surrounding the industrial site. For example, a strong northerly wind indicates that a UF_6 plume will be carried in a southern direction affecting those who are located south of the site while, conversely, a southerly wind will carry a UF_6 plume in a northern direction affecting the community north of the site. RASCAL version 4.3 was used because the software allows for the input of meteorological data from the National Oceanic and Atmospheric Administration (NOAA) weather station located at the Tri City Regional Airport (KTRI) in Blountville, Tennessee–the closest reliable weather station in the area. The variables used in this process were wind speed, wind direction, estimated atmospheric stability, precipitation type, ambient air temperature, air pressure, and relative humidity. For the purpose of this study, the averages of historical meteorological data for the four calendar seasons (spring, summer, autumn, and winter) along with the yearly average for 2012 were calculated to assess seasonal differences in dispersion. A 30-year period of averages for wind speed and direction were calculated and compared with the averages for the year 2012 to determine if the 2012 averages were above or below the normal averages for the area. Spring was defined as March, April and May; Summer as June, July, and August; Autumn as September, October, and November; and Winter as December, January, and February. These data were then combined with the UF_6 cylinder inventory volume (Table 1) and release rate for liquid UF_6. The transportation, dispersion, and deposition of material for a one hour period from the initial time of release was calculated using a release fraction of 0.65, a release rate of 32 kg/s, and a cylinder enrichment level of 5% (Ramsdell et al 2012). This process created twelve plume models for each season and one plume model for yearly averages for hydrogen fluoride (HF) concentration, HF deposition, uranium (U) concentration, and U deposition. Plume models were imported into ArcMap 10.0 to identify the affected area.

Table 1. UF6 cylinder type and volume (Ramsdell et al. 2012).

Cylinder Type	Volume of UF_6 (kg)
Model 30A and 30B (2.5 ton)	2,277
Model 48A and 48X (10 ton)	9,539
Model 48Y, 48G, 48F and 48H (14 ton)	12,338

ArcMap 10.0 is the feature program within a GIS created by the Environmental Systems Research Institute (ESRI) and is used for map creation, spatial and statistical analyses, data editing and creation, and GIS dataset management. A GIS was used to import plume data and identify areas that are affected by a UF_6 chemical release. A dataset of Unicoi County, Tennessee at the census block level that included total population and housing units was used to determine the average household size per census block. The location of NFS and all critical facilities within a two-mile radius, known as an emergency planning zone (EPZ), of NFS were mapped within the GIS. A buffer zone of two miles was created to determine areas that require mandatory evacuation and facilities that would benefit from a shelter in place action (Spellman and Stoudt 2011). Two miles is considered to be the immediate danger and evacuation area surrounding a nuclear facility during an emergency (Spellman and Stoudt 2011).

Table 2. Comparison of evacuation model methods.

Method	Advantages	Disadvantages
ArcCASPER	• Three different model algorithms available (Shortest Path, CASPER, and Capacity Constrained Route Planner). • Easy to validate and reproduce models. • Output allows for the visualization of edge statistics and route costs.	• Only compatible with the network analyst tool within ArcMap. • Requires a network with no accuracy, alignment, or topological errors to function properly.
Agent Based Modeling	• Models are close to reality. • Ability to control agent behavior to simulate "real life" situations.	• Difficult to validate and reproduce the model. • Amount of data needed to influence agent behavior can be overwhelming. • Models can be difficult to disseminate.
Least Cost Distance Modeling	• Evacuation routing is not constrained to a road network allowing for different transportation options. • Slope and land cover data can be used to calculate travel costs. • Compatible with a GIS.	• Travel cost is calculated for each raster cell which requires high resolution data to ensure accurate travel times. • Limited to shortest path approach.

ArcCASPER (Table 2) was chosen over agent based modeling and least cost distance modeling because of its lack of major disadvantages when compared to the other two techniques and for its novel capacity-aware algorithm that has received minimal testing. ArcCASPER requires a network dataset (e.g., interconnected roadways with intersection nodes) for subsequent analyses. Two road networks of Unicoi County were digitized using an ESRI road base map and two network datasets were created based on the area roads. One dataset included the entire road network for Unicoi County while the other dataset excluded a segment of Tennessee Highway 107 to simulate a train restricting movement of vehicles along this segment of road. A capacity field was added to the dataset to account for the number of lanes contained in each road segment. Locations of the populace to be evacuated within two miles of NFS and the population downwind and adjacent to the plume were created using population totals at the census block level. Locations of the safe zones were determined by the plume direction. Some safe zones were located within the EPZ, as the main purpose of evacuation is to route evacuees to the nearest road that would allow for a quick departure from the chemical plume or to the nearest US Interstate 26 access point where emergency management personnel would direct traffic out of harm's way more quickly than on state roads. This is achievable because of an increase in both road capacity and the posted speed limit for automobiles. The ArcCASPER process was compiled to identify the areas at risk in two hypothetical scenarios. Both scenarios were devised to determine the effectiveness of a mass evacuation.

2.2 Scenarios

Two hypothetical evacuation model scenarios were created for this study. Scenario one uses the entire road network for the evacuation model. In contrast, scenario two simulates a train restricting the movement of automobiles on a segment of Tennessee Highway 107, which is an arterial road providing ingress and egress to and from Erwin. Erwin is unique in that the rail system runs parallel to US Interstate Highway 26 and between the Highway and the town. This creates limited evacuation points if a train is stopped on the tracks in the downtown area. Two different algorithms (shortest path and CASPER) were used for each scenario to determine the effectiveness of the CASPER algorithm in evacuation modeling. Safe zone locations for each model were Tennessee Highway 81 (Jonesborough Road) to the northwest, Tennessee Highway 352 (Temple Hill Road) to the south, Tennessee Highway 107 (North Main Avenue) to the north, US Interstate Highway 26 access on 2nd Street, and US Interstate Highway 26 access on Jackson Love Highway (Figure 1). A total of 250 evacuee locations were created using population totals at the census block level creating an evacuation size of 6,069 people.

3. RESULTS

3.1 Meteorological and Plume Results

Average wind direction for the year 2012 were comparable to the average wind directions for the historical 30-year period, while average wind speeds were found to be significantly higher for the year 2012 (t-test results of 7.84; $p < 0.01$) (Table 3). Average wind speed, wind direction, air temperature, barometric pressure, relative humidity, and typical precipitation type were summarized for 2012 (Table 4).

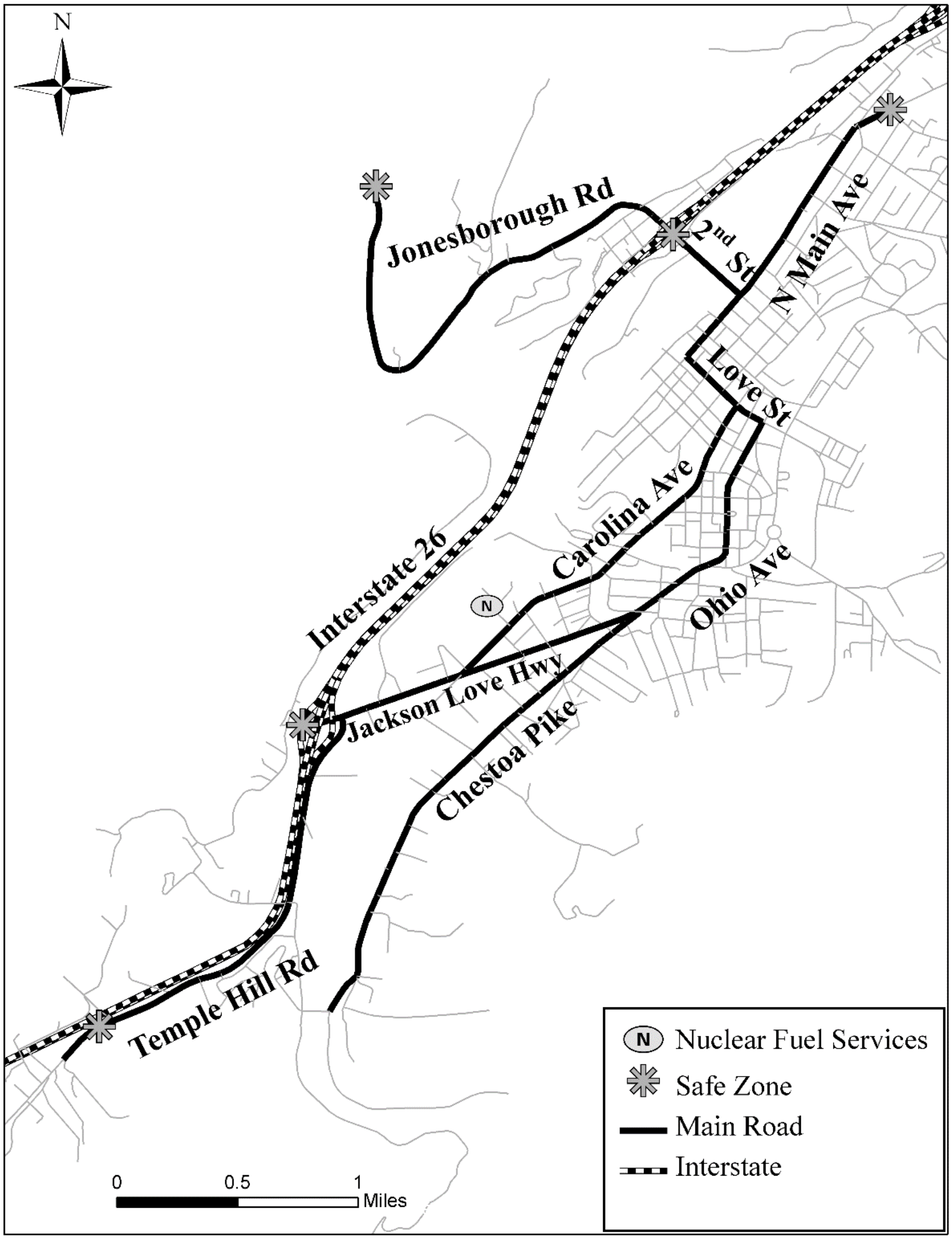

Figure 1. Major arterial roads and safe zones in Erwin, Tennessee.

Table 3. Average wind speed and direction over 30 years and for 2012 only.

30 Year Wind Averages			2012 Wind Averages		
Season	Wind Speed	Wind Direction	Season	Wind Speed	Wind Direction
Spring	6.5 mph	268°	Spring	7.5 mph	268°
Summer	4.3 mph	270°	Summer	6.2 mph	271°
Autumn	4.8 mph	275°	Autumn	6.6 mph	276°
Winter	6.7 mph	275°	Winter	8.4 mph	262°
Annual	5.5 mph	267°	Annual	7.2 mph	267°

Table 4. Meteorological averages by season for the year 2012.

Season	Wind Speed	Wind Direction	Air Temp	Pressure	Relative Humidity	Precipitation
Spring	7.5 mph	268°	60.5°F	1016 mb	70.6%	Rain
Summer	6.2 mph	271°	72.7°F	1015 mb	75.8%	Light Rain
Autumn	6.6 mph	276°	54.5°F	1018 mb	76.7%	Rain
Winter	8.4 mph	262°	41.7°F	1018 mb	76.9%	Light Snow
Yearly	7.2 mph	267°	57.4°F	1017 mb	74.9%	Rain

The spring UF_6 plume reached a peak maximum temperature of 168°F (76°C) at a distance of 31 meters from the release point (Figure 2). The plume temperature then decreased after the plume extended beyond 31 meters with the temperature falling to 136°F (58°C) at 65 meters from the release point. The plume height ascended rapidly between 30 and 65 meters from the release point from a height of 5 meters to a height of 52 meters at a distance of 65 meters (Figure 3). According to the model, all UF_6 reacted with moisture at a distance of 64.4 meters from the release point.

The summer UF_6 plume reached a peak maximum temperature of 165°F (74°C) at a distance of 27 meters from the release point (Figure 2). The plume temperature then decreased after the plume traveled beyond 54 meters with the temperature falling to 150°F (66°C) at 83 meters from the release point. The plume height ascended rapidly between 28 and 83 meters from the release point from a height of 5 meters to a height of 75 meters at a distance of 83 meters from the release point (Figure 3). According to the model, all UF_6 reacted with moisture at a distance of 82.9 meters from the release point.

The autumn UF_6 plume reached a peak maximum temperature of 167°F (75°C) at a distance of 28 meters from the release point (Figure 2). The plume temperature remained consistently high until the plume reached a distance of 60 meters when the temperature dropped from 159°F (71°C) to 77°F (25°C) at a distance of 88 meters. The plume height ascended rapidly from a height of 5 meters to 59 meters at a distance of 60 meters from the release point and then increased gradually to a height of 70 meters at a distance of 88 meters from the release point (Figure 3). Per the model, all UF_6 reacted with moisture at a distance of 88.1 meters from the release point.

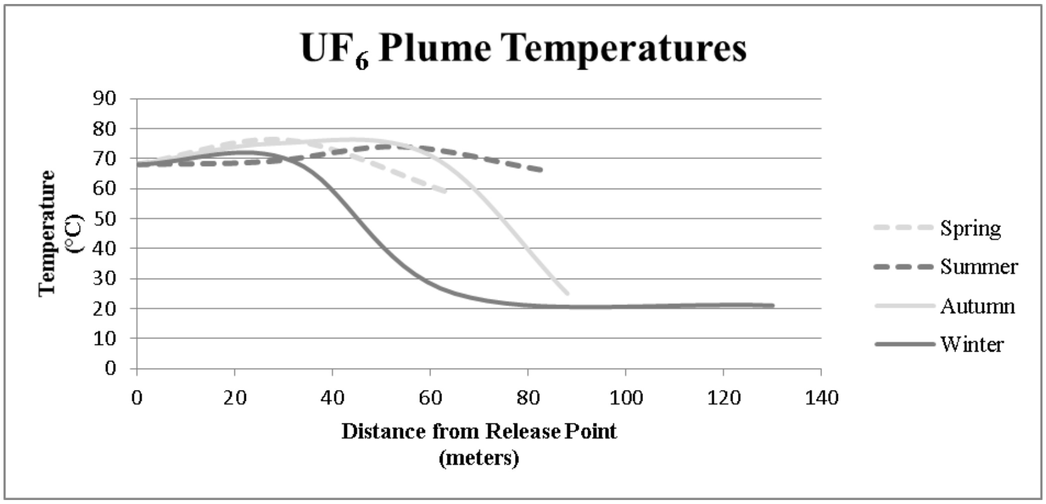

Figure 2. UF_6 plume temperatures for all seasons.

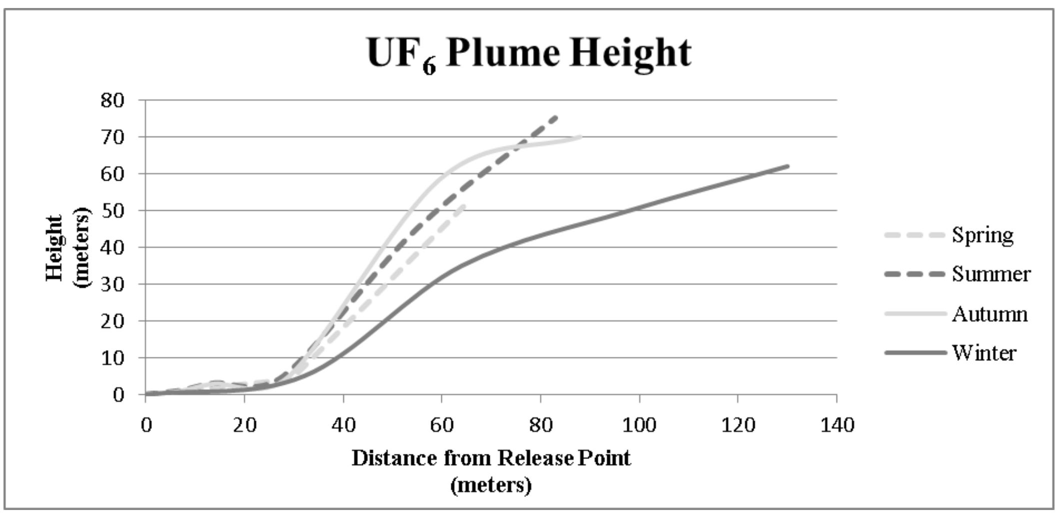

Figure 3. UF_6 Plume heights for all seasons.

The winter UF6 plume reached a peak maximum temperature of 156°F (69°C) at a distance of 32 meters from the release point (Figure 2). The plume temperature was consistent from the release point to 32 meters when the temperature dropped drastically to 77°F (25°C) at a distance of 65 meters from the release point. It then decreased gradually to a temperature of 69°F (21°C) at a distance of 130 meters from the release point. The plume height ascended drastically from a height of 5 meters at a distance of 32 meters from the release point to a height of 62 meters at a distance of 130 meters from the release point (Figure 3). Per the model, all UF_6 reacted with moisture at a distance of 128.7 meters from the release point.

HF concentration plume models for all seasons and tank sizes ranged from 0.001 ppm to 50 ppm with health effects ranging from no adverse health effects to life threatening health effects (Figure 4). HF deposition plume models for all seasons and tank sizes ranged from 0.001 g/m^2 to 1 g/m^2. U concentration plume models for all seasons and tank sizes fell below the Environmental Protection Agency's (EPA) Protection Action Guides (PAG) range in the 0.001 to 1 rem range. U deposition plume models for all seasons and tank sizes ranged from 0.01 g/m^2 to 100 g/m^2.

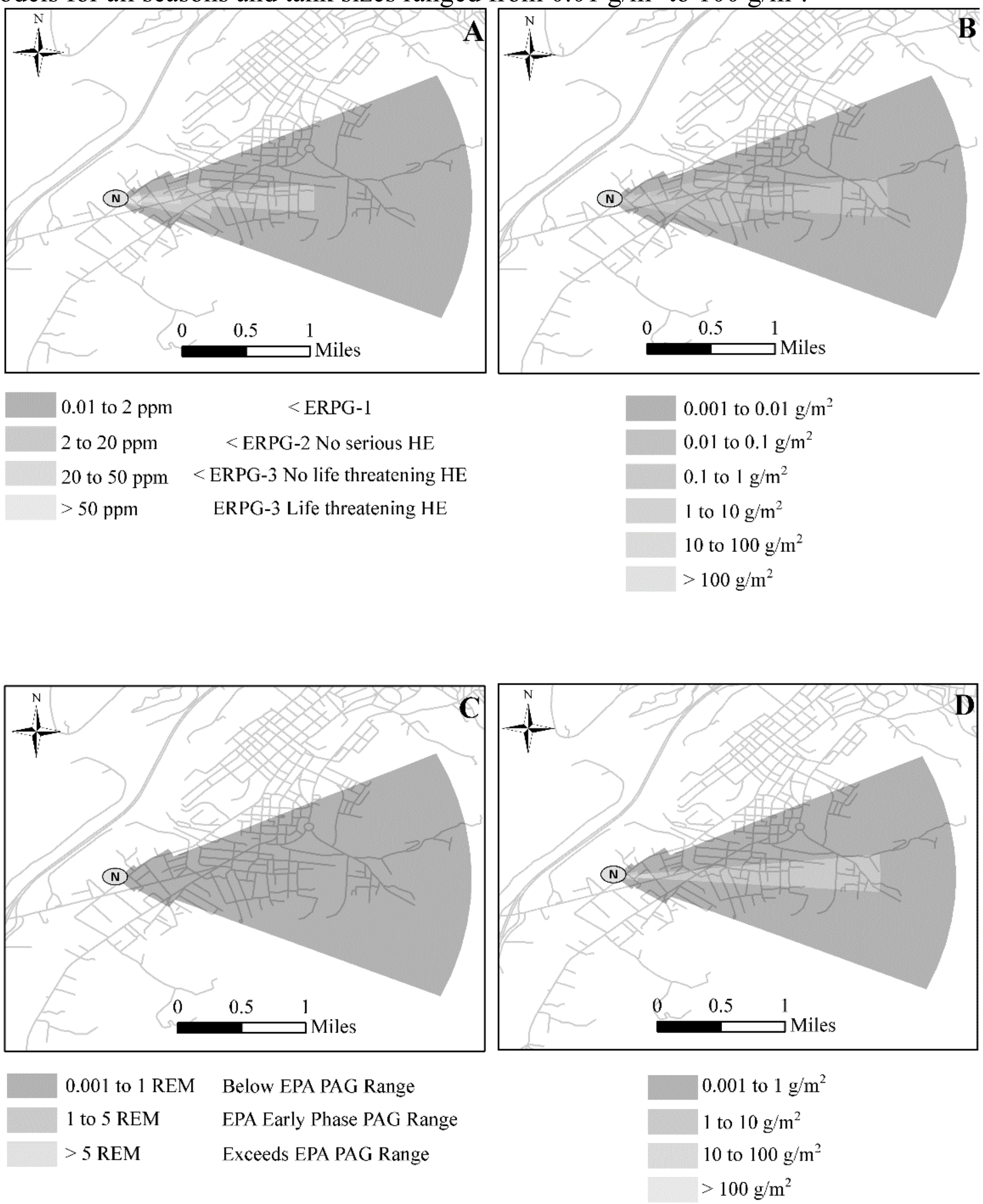

Figure 4. HF and uranium concentration and deposition plume models. Models are based on a 14-ton cylinder using meteorological averages for the year 2012.

3.2 Scenario One Results

Scenario one used the entire road network (i.e., state maintained roads) for evacuation purposes. The shortest path algorithm resulted in the evacuation of the EPZ in 66 minutes (Figure 5). Routes are defined as each possible evacuation pathway inclusive of a starting point and ending point (i.e, safe zone). The majority of the evacuation routes were in the high range of 55 to 66 minutes (i.e., it “cost” an evacuee 55-66 minutes of time to evacuate to the nearest safe zone) with less than a quarter of all evacuation routes in the <11-minute range. The 55 to 66 minute evacuation routes centered in the downtown area of Erwin (Figure 6). The major road arteries affected by congestion were Ohio Avenue, Carolina Avenue, North Main Avenue and Love Street (Figures 1 and 6).

The CASPER algorithm resulted in the evacuation of the EPZ in 33 minutes (Figure 7). The majority of the evacuation routes ranged between 20 to 25 minutes, which accounted for approximately 20% of the total evacuated population. Congestion points were located in the 25 to 33 minute range. Arterial roads affected by congestion were located in the southern portion of the EPZ (Figure 8) and included Chestoa Pike, Jackson Love Highway, and Carolina Avenue (Figures 1 and 8).

3.3 Scenario Two Results

Scenario two simulated a train restricting the movement of cars on a segment of Tennessee Highway 107 making a portion of the road unavailable within the evacuation model. The shortest path algorithm for scenario two resulted in the evacuation of the EPZ in 72 minutes (Figure 9). The majority of the evacuation routes were in the 24 to 36 minute range followed by the 60 to 72 minute range. Only two routes were found in the 36 to 48 minute range, mostly explained by all routes above 36 minutes having the same safe zone end point and, consequently, increased congestion along a single road. Congestion was centered in the southeast section of Erwin affecting the major roadways of Ohio Avenue and Jackson Love Highway (Figures 1 and 10).

The CASPER algorithm for scenario two resulted in the evacuation of the entire EPZ in 42 minutes (Figure 11). The majority of the evacuation routes ranged between 21 to 28 minutes. Congestion points for the CASPER algorithm for scenario 2 were located in the downtown area and in south Erwin (Figure 12). The congested roads in the downtown area were secondary roads. Primary roads in the southern section that were affected by congestion were Carolina Avenue, portions of Jackson Love Highway, and portions of Ohio Avenue (Figures 1 and 12).

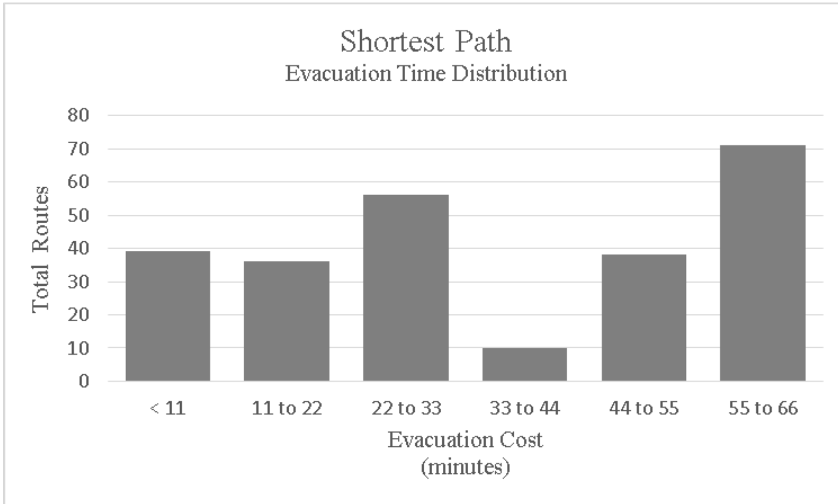

Figure 5. Scenario one shortest path algorithm evacuation time distribution.

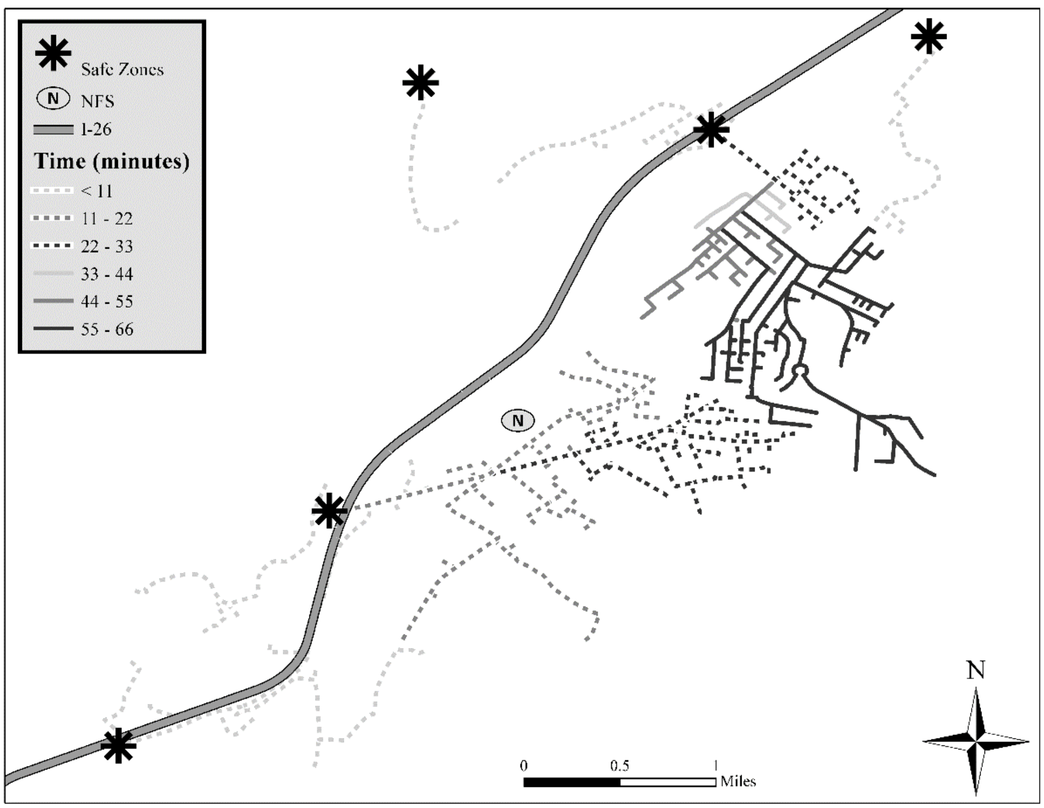

Figure 6. Scenario one evacuation model using the shortest path algorithm.

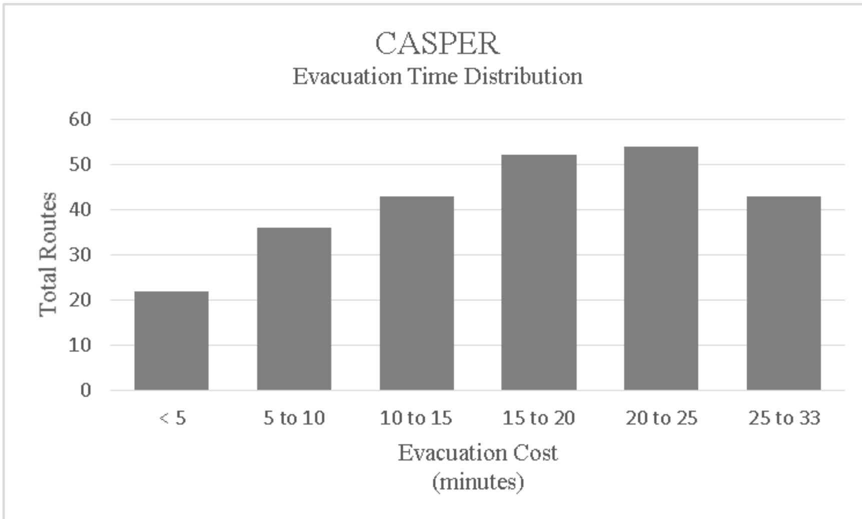

Figure 7. Scenario one CASPER algorithm evacuation time distribution.

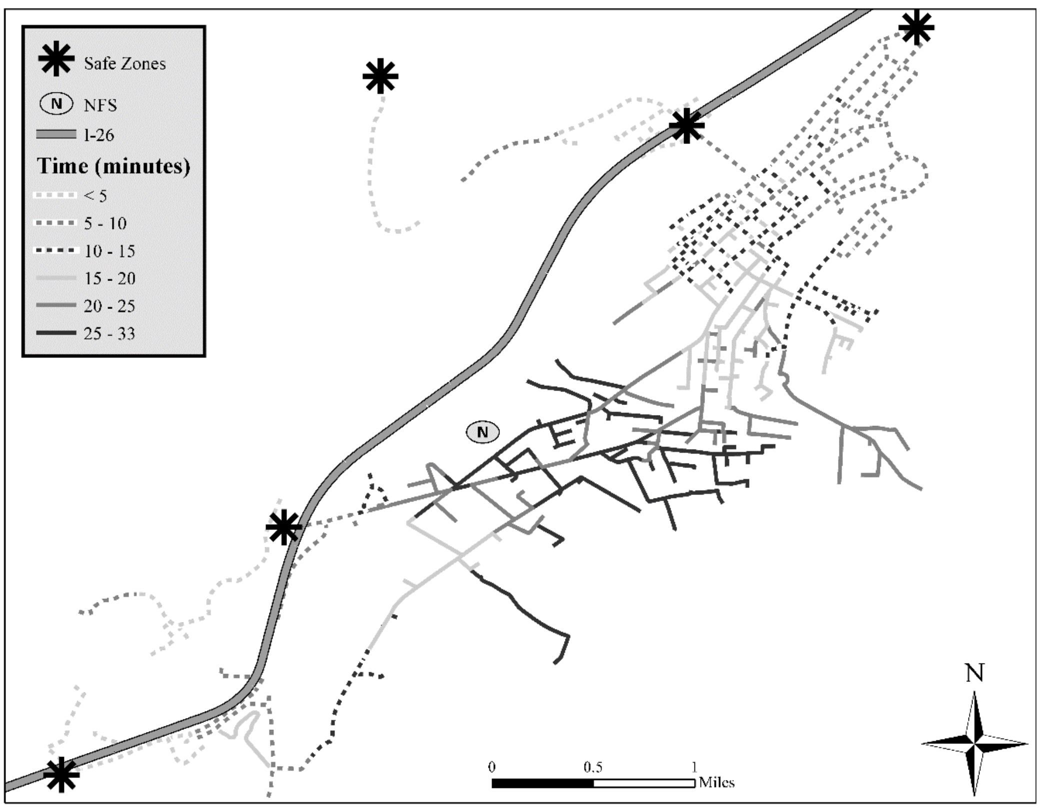

Figure 8. Scenario one evacuation model using the CASPER algorithm.

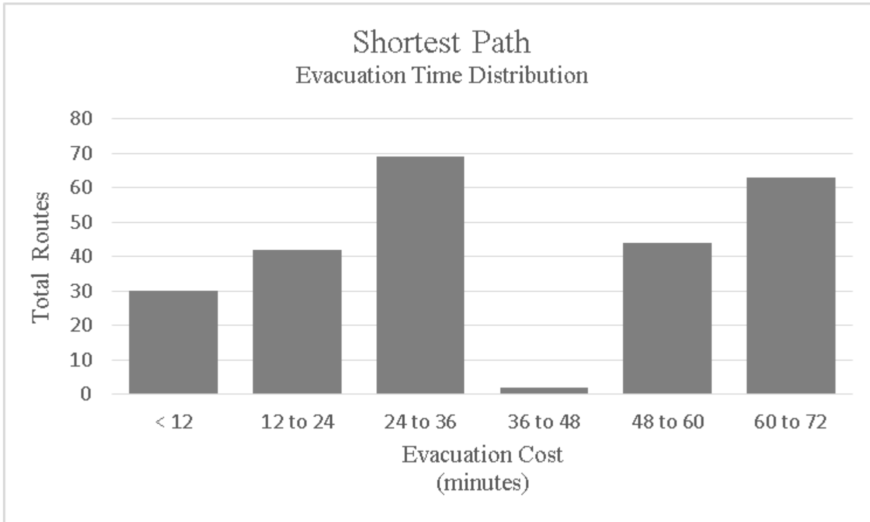

Figure 9. Scenario two shortest path algorithm evacuation time distribution.

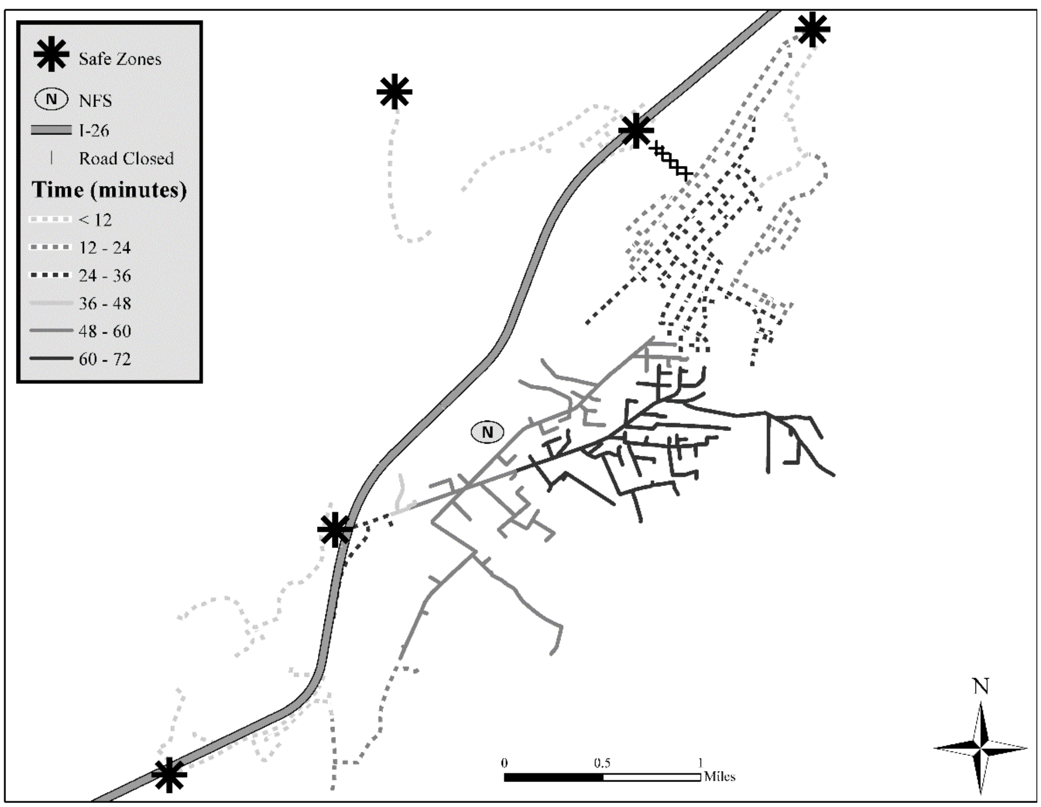

Figure 10. Scenario two evacuation model using the shortest path algorithm. The crosses in the top center of the figure indicate road closure due to trains blocking the roadway. An overpass bridge is located approximately two miles north and an underpass bridge is located approximately three miles south of this point.

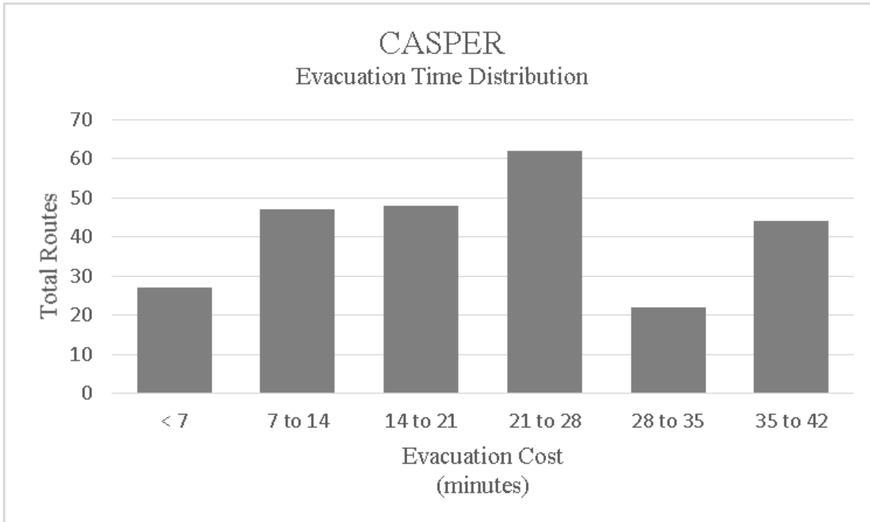

Figure 11. Scenario two CASPER algorithm evacuation time distribution.

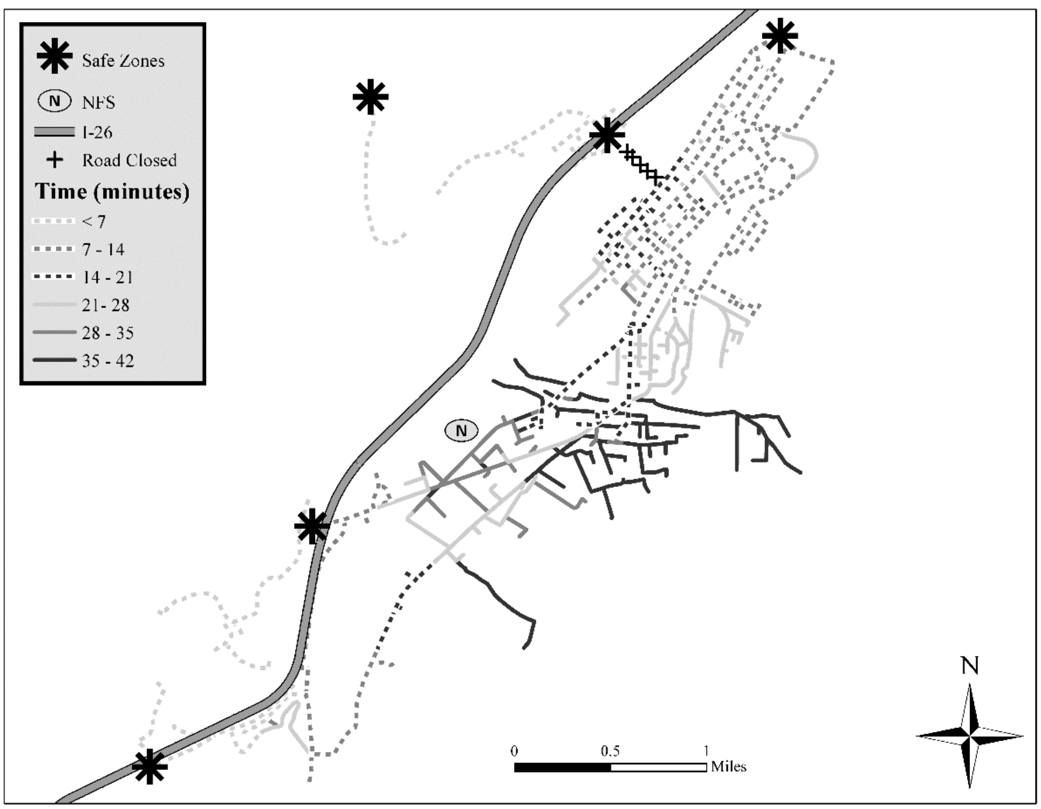

Figure 12. Scenario two evacuation model using the CASPER algorithm.

4. DISCUSSION

The CASPER evacuation algorithm was determined to be the most effective method of modeling evacuation routes for two reasons: 1) it employed an organic technique that allowed traffic to follow routes that were the quickest (i.e., time-dependent) and not just the shortest (i.e., length-dependent), and 2) contrary to the results of the shortest path algorithm, it did not arbitrarily cut streets in half after distance was calculated, but instead allowed cars to travel across a continuous street network, thus reducing travel times. The CASPER algorithm's prediction of traffic flow patterns based on time AND length resulted in more realistic evacuation scenarios that were quicker than those predicted by the shortest path algorithm. Yazici and Ozbay (2010) indicated that roadway capacity and the seeming randomness of evacuation demand were the most common sources of uncertainty in evacuation modeling. The CASPER algorithm primarily addresses the issue of roadway capacity, but also secondarily addresses the randomness of evacuation by continually rerouting if congestion is high. Pel et al. (2012) advocated for a "hybrid route choice model" that incorporates en-route switches, thus validating a possible behavioral reaction to congestion—a reaction that is incorporated by the updating of edge costs within the CASPER algorithm.

Results allude to accessibility, network configuration, and network design issues inherent to evacuation planning (Aksu and Ozdamar 2014; Abdelgawad and Abdulhai 2009; Wei et al. 2008; Sohn 2006). Networks are often configured in a somewhat haphazard manor where roads are built to mirror migration and urban expansion—sometimes well planned, but often poorly planned (Abdelgawad and Abdulhai 2009). Network configuration creates varying levels of accessibility for residents at various locations throughout the network. To quantify accessibility, however, one must define what needs to actually be accessible. In this study accessibility is defined as how quickly and efficiently residents can evacuate to designated safe zones at or near the interstate. If designated safe zones are changed, then accessibility within the evacuation models will also change.

In scenario number two, a train blocking Tennessee Highway 107 increased the total time necessary to evacuate the EPZ in the CASPER model by 9 minutes and by 6 minutes in the shortest path. In both scenarios, the major roadways of Carolina Avenue, Jackson Love Highway, and Ohio Avenue experienced the most congestion. These areas are very close to the release point, but evacuation times are short enough to reduce the exposure to UF_6 so an evacuation over a shelter in place action is still suggested for those residents if the evacuation order is given immediately after the release occurs.

Wind speed has a direct influence on a chemical plume's dispersion across an area. Wind speed for the year 2012 was higher than the 30 year average, which resulted in the chemical plume traveling further from the chemical release point. This shearing of the plume reduced the plume's width. In contrast, lower wind speeds decreased the dispersal distance of the plume from the release point and increased the plume width. Plume model results demonstrate that the dispersion of the chemical is under the EPA PAG ranges for the majority of the area even during years when wind speeds may exceed the norm. Wind speed does not have a direct impact on the evacuation models so evacuation times will remain the same. It does, however, have an impact on the plume models since higher wind speeds will extend the distance of each hazard zone away from the release point.

U deposition is dependent upon meteorological conditions and mass released, with stronger winds and larger tank sizes (filled to capacity) creating a higher level of U deposition across a greater area than when lighter winds and smaller tanks are considered. Seasonally, stronger winds appear to occur in spring and winter months, which may result in longer but narrower ranges for dispersion. Despite this, the models demonstrate that the levels of U concentration remain below the EPA PAG range and are not an immediate health hazard. Similar results were found for HF deposition, but HF concentration could be significant enough to cause life threatening health effects as mass increases. A 2.5-ton cylinder filled to capacity in any season has the potential to cause severe health effects, but an increase to a 10-ton cylinder filled to capacity introduces the possibility of life threatening health effects. The 14-ton cylinder life-threatening zone stays consistent with the 10-ton cylinder results, but the severe health effects zone extends farther from the release site. The yearly averages along with the 14-ton cylinder specifications allowed for the evaluation of evacuation and shelter in place actions that can be implemented in the early stages of a UF_6 release for any season.

Sheltering in place is suggested in both scenarios for all critical facilities in the direct path of the UF_6 plume. Evacuation of large populations from critical facilities such as schools, hospitals and nursing homes takes considerable time, which potentially increases an individual's exposure to a hazardous cloud. This increase in potential exposure time increases the likelihood that an individual will experience life-threatening health effects. Additionally, this strategy is recommended for citizens who lack the means to evacuate due to a lack of transportation, poor health or age, and for those outside of the two-mile buffer zone.

This study demonstrated that the potential for a cylinder rupture is low, and that the impact of a cylinder rupture is minor due to the dissipation of the UF6 chemical before it reaches a large populace. However, it is imperative that the populace remain vigilant for industrial hazards as history has demonstrated that complacency can lead to a false sense of security. A hazard can unexpectedly manifest into a disaster, so it is important to develop emergency protocols during the emergency preparedness phase to mitigate injuries and loss of life.

4.1 Study Limitations

Due to the sensitivity of the subject matter, knowledge of currently stored chemicals and other variables were unknown. Because of this, several assumptions were made involving key components of the study:

1) UF_6 cylinders have been present on the NFS site in the past, but it could not be confirmed if they are currently being used and stored on site.
2) The cylinder inventory list included within the RASCAL 4.3 software program was used to determine tank size and volume because the size of tanks in use at the NFS facility is unknown.
3) It was assumed that UF_6 was in a liquid state when modeling chemical release plumes using RASCAL 4.3. The release rate, release fraction, and uranium

enrichment level variables for liquid UF_6 were obtained from the default values within the RASCAL 4.3 software program.

4) A direct release to the atmosphere with no reductions (e.g. through a building, through filters) was used for each chemical plume model because it is not known where on site UF_6 cylinders have been stored.
5) As with any evacuation model, how an individual or group of individuals responds to evacuation orders and to the actual act of evacuating will likely result in different evacuation time intervals (Kuligowski and Gwynne 2010; Schadschneider et al. 2009), but models provide a reasonable congestion and evacuation time prediction.

4.2 CONCLUSIONS

Evacuation and shelter in place responses were examined for two hypothetical scenarios involving a chemical release within the city limits of Erwin, Tennessee. Of the many software programs available to model evacuation, we chose to use the custom network analysis routing tool ArcCASPER for evacuation modeling and RASCAL 4.3 for modeling chemical release plumes. Results demonstrated that RASCAL 4.3 and ArcCASPER in conjunction with a GIS are useful geospatial modeling software programs in creating an emergency evacuation and sheltering in place plan for a chemical release. We conclude that:

1) Mandatory evacuation and sheltering in place used in combination with each other were determined to be effective strategies in the event of a chemical release. Both responses reduce exposure time and protect the populace from life-threatening health effects associated with chemical exposure.
2) The infrastructure in Erwin is sufficient to accommodate an efficient and timely evacuation (less than 42 minutes in "worst case" scenario using the CASPER algorithm) of the populace within two miles of the chemical release and downwind of the projected chemical plume.
3) The CASPER algorithm within ArcCASPER is the most realistic for the town of Erwin. The CASPER algorithm reduced evacuation times in both hypothetical scenarios and routing resembled realistic evacuation patterns.

This study has laid the groundwork for future work on improving emergency preparedness methods for the town of Erwin. This is important since the town faces transportation problems as it relates to road infrastructure and the rail system. Currently, there are three major access points that allow for vehicles to cross the rail system that runs directly through the center of the town. Two of these points are either underpass or overpass bridges that permit the flow of vehicular traffic even if a train is present on the tracks, but the access point in the downtown area cannot be crossed if a train is present. A proposal to build a bridge in this area is currently in the developmental phase and it would benefit the community if research on evacuation modeling were conducted in the future to determine the effectiveness of this bridge in facilitating evacuation. Additionally, the CASPER model exhibits potential for expansion beyond small town applications. Original CASPER models were created for the city of San Francisco (Shahabi and Wilson 2014), thus moderate to large cities could develop suitable evacuation models based on the CASPER algorithm.

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