

INTEGRATION OF TOXIC MODELS WITH GEOGRAPHICAL INFORMATION SYSTEMS FOR RISK MANAGEMENT

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Abstract

The goal of this research project is to determine the population at risk and the expected casualties as a result of toxic gas dispersions when faced with disaster within 120 seconds of a NASA Space Shuttle liftoff. The system resulting from this research can help emergency and engineer managers to estimate the population at risk in order to plan for areas to evacuate, shelter, and/or to determine the resources required to provide aid and comfort and mitigate damages in case of a disaster. In addition, this paper will discuss briefly extensions of the developed system for use in homeland security.

Introduction

In the face of a disaster such as a terrorist act emergency managers need to determine the population at risk. Decision-support systems based on simulation can enable emergency managers to determine mitigation projects, and better understand the different risks associated with a disaster. For example, if toxic gases are released, there is a need to predict where the gas plume will go, how far it will extend, and what the expected concentration of toxins and health consequences will be.

The Virtual Range Toxicity Model (VRTM) is a prototype of a virtual engineering environment to study the safety criteria of current and next generation space vehicles in the launch and range operations with emphasis on toxic releases. This has involved the development of a unique collaborative computing environment where range safety simulation models, geographic information systems (GIS), and weather information are hosted and integrated in a seamless fashion with parametric features of space vehicles and their flight trajectories. The prototype uses Kennedy Space Center (KSC), a parametric model of the NASA Shuttle, a model of the toxics dispersion tailored for the NASA Shuttle at low altitudes and a probabilistic calculator/simulator to compute the E_c (Expectation of Casualties).

The range is an essential element of space operations. The range has different definitions

depending on the NASA Center. In this report the range will follow the NASA KSC definition. The range is the volume through which the vehicle must pass on its way to and from Space and its projection to earth. The range encompasses many different operations. One of them, range safety, has a high level of complexity. The responsibilities of the safety offices include the study, modeling, and analysis of the hazards from potential launch accidents and the corresponding calculations of E_c .

Toxic effects, debris, and blast overpressures and their effects in the population are the primary hazards to be studied. The fuel of the vehicles as well as exhaust emissions may cause toxic effects. Vehicle explosions caused by system failures can produce debris. In addition, these explosions may also create blast overpressure. Modeling of these effects is required for launch safety. Currently, this is done by using models that are stand-alone and the sequential process to certify a new vehicle can take a considerable time. Therefore, the seamless integration of these models with flight trajectories, available weather information, and GIS systems can provide many benefits. Hosting the range models and vehicle models in a virtual engineering environment will support the development of risk management and reduce risk avoidance approaches. A Virtual Range can be used to design and evaluate flight termination systems (FTS), and to evaluate and implement a risk assessment scheme of legacy and new vehicles.

VRTM's goal is to determine the population at risk and E_c as a result of toxic gas dispersion when faced with disaster within 120 seconds of the NASA Shuttle Orbiter's liftoff. The system will help local authorities to estimate the population at risk in order to plan for areas to evacuate and/or for the resources required to provide aid and comfort and mitigate damages.

Toxic gas-related risk is a factor of exposure duration and toxic propellant concentration or dosage that would result in casualties (death or incapacitating injury) of normal and sensitive people in a given population area. Exhibit 1 displays the most commonly used Shuttle propellants. Public exposure to values

above the ceiling concentration may cause casualties. Values in the last column reflect time weighted average (TWA) concentrations that may cause casualties.

Exhibit 1. Commonly used Shuttle propellants.

Toxicant	Toxic Concentration	
	Ceiling [ppm]	60-min TWA [ppm]
Ammonium Perchlorate/ Aluminum (solid propellant)	10	2
Hydrazine	-	2
Nitric Acid (HNO ₃)	4	2
Mixed Nitrogen Oxides (NO, NO ₂ , N ₂ O ₄)	4	-

For the effects of this paper, the VRTM focuses on the health impact of the release of large amounts of hydrochloric acid (HCl), a major toxicant in the event of a loss of vehicle. The effect of exposure to HCl may range from mild irritation and headache to incapacitation due to constriction of the airway and lack of oxygen delivery to the brain. The analysis for other toxicants resulting from a Shuttle disaster will be similar.

Architecture of the Virtual Range

The prototype involves the integration of different models, (Exhibit 2) as follows:

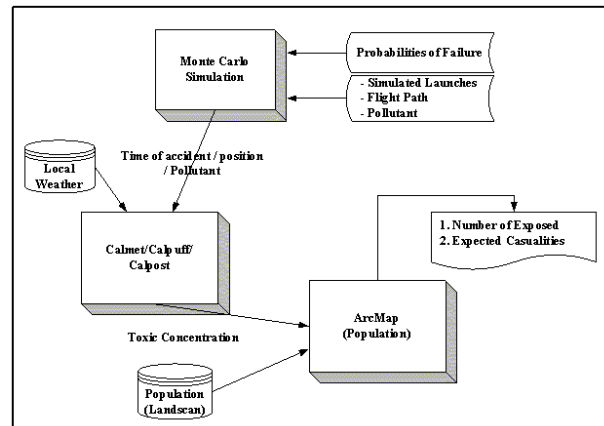
- ArcGIS, Spatial Analyst: A sophisticated Geospatial Information System
- LandSCAN: Database of World-Wide Population (provided by Oak Ridge Labs)
- CALPUFF: An advanced non-steady-state meteorological and air quality modeling system developed and distributed by Earth Tech, Inc. (Earth Tech, 1997, 2002)
- Shuttle Failure Description Table: Description of the Failure Models
- Monte Carlo Simulation and Calculation Agents: C Program

The development of a computing architecture for a Virtual Range is a very complicated task. There is a need to model the geographical and population characteristics, obtain the weather information (real-time!), and on top of that to add the different models of range safety (blast, debris, toxic, and E_c calculations), flight trajectory models, and of course add a relevant user interface, then the user can use this with the

objective of evaluations in his/her mind. This task is reduced by the utilization of leading edge solutions already developed (e.g., GIS systems). ArcView is for MS Windows environments and uses the Visual Basic for Applications (VBA) framework for integration. In addition, ArcView has been integrated seamlessly with LandScan. LandScan is a dynamic population of the world provided by Oak Ridge National Laboratories.

We use Monte Carlo simulation to account for the effect on risk of factors such as vehicle position and consumption of propellants, wind uncertainties, and vehicle guidance and performance deviations. For example, the risk is affected by variability in the meteorological and launch vehicle parameters, wind uncertainties, and other weather related characteristics. We use Monte Carlo simulation to perform sensitivity analyses. For any planned flight path, sensitivity analyses are needed to determine how E_c varies with changes in input parameters, such as type of vehicle and wind velocity. These sensitivity analyses will identify parameters with the largest impact on the value of E_c and, therefore, show where modeling accuracy is most important.

Exhibit 2. VRTM Architecture.

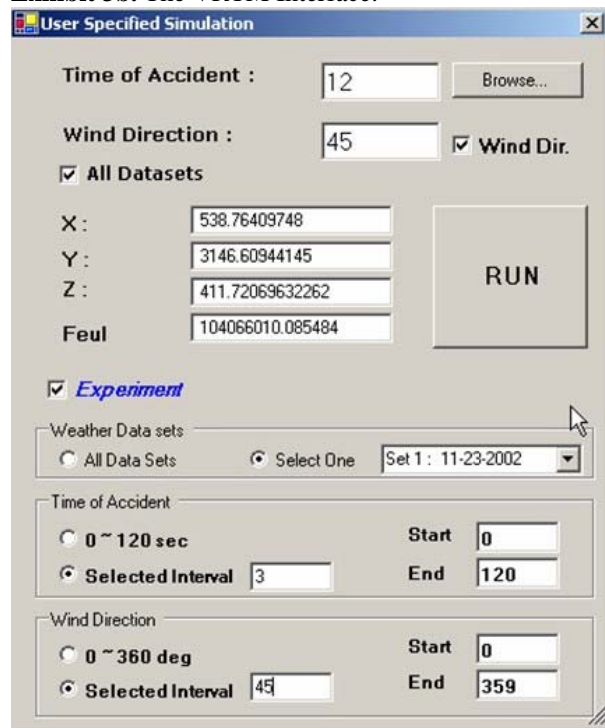


The VR incorporates flight trajectories and weather information in and around KSC, a model of the toxics dispersion tailored for the NASA Shuttle at low altitudes, a GIS to visualize the area over land affected by the disaster, a population model to determine the number of people exposed in that area, and a probabilistic calculator/simulator to compute E_c .

If an accident occurs, the model determines the position, volume, and initial dispersion velocity of the released pollutants. These values are the input to CALPUFF – a multi-layer, multi-species, non-steady state Lagrangian puff dispersion model – which in turn predicts the toxic concentrations for the toxicant at a specified time after the onset of the accident. These

The path of the shuttle for equatorial launches is calculated from data of past launches given in Earth-fixed geocentric (EFG) coordinates. This information was converted into latitude, longitude, and altitude assuming a spherical model of the Earth. Because of this assumption the conversion gave us an error of less than 0.5% as compared to the real position of Pad39a (Pad39a is the infrastructure/location utilized to launch the NASA Shuttle) in KSC. The altitude was obtained using as reference the distance from the center of the Earth to the position of the NASA Shuttle before launch.

Exhibit 3b. The VRTM Interface.



Failure Model for the NASA Shuttle. The VRTM interface provides the emergency manager the ability to select a random occurrence for the accident (e.g., to use Monte-Carlo Simulation) or to “fix” the time of the accident. There is also a third time-related option, which is to specify a series of observations at fixed time intervals (for example, at 0, 10, 20, 30, etc. seconds after launch).

Monte Carlo simulation works by generating random numbers based on probabilities of occurrence of certain events. In order to obtain the probability of losing the vehicle at the different stages, the first 120 seconds were divided into representative events associated to the main components such as external tank, space shuttle main engine, integrated solid rocket booster, and orbiter. Reports developed for failures of

the NASA Shuttle were analyzed in order to create this failure model (Fragola and Maggio, 1995).

The Toxicity Model. Mixed oxides of nitrogen are used as oxidants for the hydrazine fuels, which are used in relatively small amounts during the Orbiter Maneuvering Stage to guide the orbiter in space. Nitric acid is the major combustion product. In order to launch the NASA Shuttle into space, the Shuttle relies upon two solid rocket boosters. These contain aluminum powder as fuel and ammonium perchlorate as its oxidizer. Hydrochloric acid (HCl) is a major combustion product.

Due to its relative quantity, the expected dispersion of HCl gas is the major determinant of shuttle GO-NOGO decisions. The gas is initially exhausted as an aerosol, which dissipates within a few minutes of flight and remains as gas. With normal operation of the Shuttle, total exhaust of HCl is 163.3 tons during the first 15 kilometers of flight. About 72.5 more tons are exhausted by two minutes after launch (AIAA, 1991). In the event of a disaster, the Solid Rocket Boosters (SRBs) separate from the NASA Shuttle, burning as they fall.

The health impact of the release of large amounts of hydrochloric acid, a major toxicant in the event of a loss of vehicle, may be catastrophic. The effect of exposure to HCl may range from mild irritation and headache to incapacitation due to constriction of the airway and lack of oxygen delivery to the brain.

If a “loss of vehicle” event occurs close enough to lift-off, it is possible under some meteorological conditions that the ground concentration would exceed 7 ppm, the limit short-term exposure limit (STEL) for HCl for normal people (Hill Brothers Chemical Co., 2001). For HCl, mild symptoms include irritation and headache, which are reversible within 48 hours and do not interfere with normal activity or require medical attention (Philipson, 1999). Moderate symptoms include cough and shortness of breath, and medical attention might be sought. Severe symptoms include disorientation due to constriction of the airway and consequent shortfall in delivery of oxygen to the brain; changes to lung tissue are irreversible in this category. Of course, the STEL values for sensitive people (children, the elderly, and people with asthma or other respiratory disease) are even smaller.

For the evaluation of the gas dispersion and toxic effect we use CALPUFF, developed and distributed by Earth Tech, Inc (CALPUFF Modeling System, 2004). CALPUFF simulates the effects of time and space varying meteorological conditions on pollutant transport, transformation, and removal under inhomogeneous and non-stationary conditions with a one-hour time step. CALPUFF has modules to assess

toxic effects of specific chemical agents and factors such as variability of meteorological conditions, dry deposition and dispersion over a variety of spatially varying land surfaces, low wind speed dispersion, or pollutant wet removal.

CALMET, CALPUFF's preprocessor of weather related information requires four types of input files: surface meteorological data, upper air data, overwater observations and geophysical data. (Earth Tech 1997, 2002) The weather information that we gathered corresponds to days in 2002 in which a launch took place, specifically March 1, April 8, June 5, October 7, and November 23. In simulating future launches, for a given launch window (projected day and time for launch), we will gather similar weather information that occurred for the same time frame within the same week in the previous three years and use the average and extreme values observed for the simulation.

Meteorological Observations. The surface meteorological observations were obtained from the National Oceanic and Atmospheric Administration (NOAA) website (National Oceanic and Atmospheric Administration, 2004). CALMET's meteorological data files require hourly observations of wind speed, wind direction, temperature (part of surface data file), cloud cover, ceiling height, surface pressure, relative humidity, and precipitation type code. We used the data from four different stations in Florida: Orlando (2), Daytona Beach, and Melbourne.

The upper air observations were also obtained from the NOAA website. This set of observations contains twice-daily observed vertical profiles of wind speed, wind direction, temperature, pressure, and elevation. The data was obtained from station XMR in Cape Canaveral, Florida.

For overwater data, CALMET requires the overwater transport and dispersion. For this purpose it is necessary to have the following information: Air-sea temperature difference, air temperature, relative humidity, overwater mixing high, and wind speed and direction. The information collected was taken from the closest buoy, in this case Station 41009 - CANAVERAL 20 NM East of Cape Canaveral. This information has been obtained from the National Data Buoy Center a division of the NOAA (National Data Buoy Center, 2004).

Geophysical data inputs required by the CALMET model include gridded fields of terrain elevations and land use categories. Optional fields include surface roughness length, albedo, Bowen ratio, soil heat flux constant, anthropogenic heat flux, and vegetative leaf area index.

Geographic and Population Models. The VRTM uses ArcGIS – a powerful commercial geographical information system (GIS) application that provides data visualization, query, analysis, and integration capabilities along with the ability to create and edit geographic data – to identify the region covered by the dispersed gas.

The area covered in our simulation is basically the area near and around the Cape Canaveral region in Florida, which includes mainly Brevard and Orange Counties and a large part of the sea around Cape Canaveral. The simulation covers about 150 km in each direction from the source (Cape Canaveral). Since this area is a flat, noncomplex terrain and surrounded by sea, it has a good flow of winds, pressure and temperature variations through it. So, the weather data plugged into the model plays an important role in the simulation. The area covered by the simulation is divided into a number of grids with equal spacing to facilitate the study of concentrations of the explosions in the area considered. Each grid can be a square block, whose side can range from 10s of meters to 100s of kilometers.

Using the LandScan Global Population Database – a public domain database of the world's population developed by Oak Ridge National Laboratory (ORNL) – to present population data associated with the covered region, the VRTM determines the population at risk (LandScan, 2004).

LandScan includes the best available census counts for each country and allocates these figures into rural and urban population distributions on a 30" X 30" lat/long grid cell system. To assign values to a specific grid cell, LandScan calculates a probability coefficient for each cell and applies the coefficients to the census counts. The probability coefficient is based on slope, proximity to roads, land cover, nighttime lights, and an urban density factor.

Exposure Response Functions. Exhibit 4 shows Exposure Response Functions (ERFs) for HCl for sensitive and normal people subject to a 10-minute exposure. The sensitive population was defined as children through age 14 and adults aged 75 and over, as well as all others with respiratory illnesses. In Brevard County, recent census data shows that 42% of the population is made up of those 18 and younger and those 65 and older and this number is expected to increase to over 55% by the year 2010 (United Way of Brevard County, 2002).

These curves show that concentrations of 15 ppm and 41.5 ppm of HCl result in an expectation of casualties of about 30 in a million ($E_c = 30 \times 10^{-6}$) for sensitive and normal people, respectively.

ERF curves have been computed for nitric acid aerosol, nitrogen dioxide, and hydrochloric acid. They were constructed by a panel of about 20 expert toxicologists who provided best estimates of the 1- and 99-percentiles of expected casualties. Below the first percentile, “essentially no one in a population of a given sensitivity category would be affected to a given level of severity.” Above the 99th percentile, “essentially all in the population would be so affected.” Twelve estimates (with ranges of uncertainty) for each substance and duration of exposure (10, 30, 60, and 120 minutes) were provided by members of the panel of experts: one for each percentile, casualty type (mild, moderate, and severe), and victim type (sensitive, normal). Some of the panelists computed duration estimates from 1-hour estimates according to Haber’s Law, which states that “an effect level is directly proportional to exposure concentration multiplied by time” (Philipson, 1999). Once these estimates were decided upon by the panel, ERF curves were then calculated as cumulative distributions.

Geographic Data Model. ArcGIS is used along with LandScan Global Population Database. In this GIS environment, the model of population distribution is integrated with the gas dispersion model to calculate Ec for that risk component given a loss of vehicle.

Spatial Analyst, an extension toolset in ArcGIS, is used to generate the query on the HCl data from the Gas Dispersion Model to select the region where the concentration of the HCl exceeds a critical value. Zonal Statistics calculates the statistics for each zone of

a zone dataset based on values from another dataset. A zone is a region in which all the cells in a raster have the same value, regardless of whether or not they are contiguous. The sum of the output gives the total number of people affected in that critical HCl concentration zone.

For the VR, the sensitive and normal HCl severe ERFs were combined according to the sensitive and normal population mix in Brevard County, Florida. A critical value of 15 ppm was used as a baseline. This value represents a value where most sensitive people will be affected but most normal people will not. In the sensitivity analysis we will vary this factor by increasing the critical HCl concentration by increments of 10 until we reach 45 ppm, a value where almost the whole population will be affected. Exhibit 5 shows an example of the ArcMap display of a layer of contaminants over the sea.

Information Flow and Example

In summary, the VR works as follows: An Arena model simulates the time of accident, which is determined by the cumulative probability of accident in ten different stages during a launch. Each of these stages has a different duration and probability of an accident. Once the stage is determined, the time of accident is fixed by equal chance within the stage. Based upon the time of accident, the model references coordinates of path of orbiter and determines the volume of remaining pollutants from the existing model data file.

Exhibit 4. ERF for HCl.

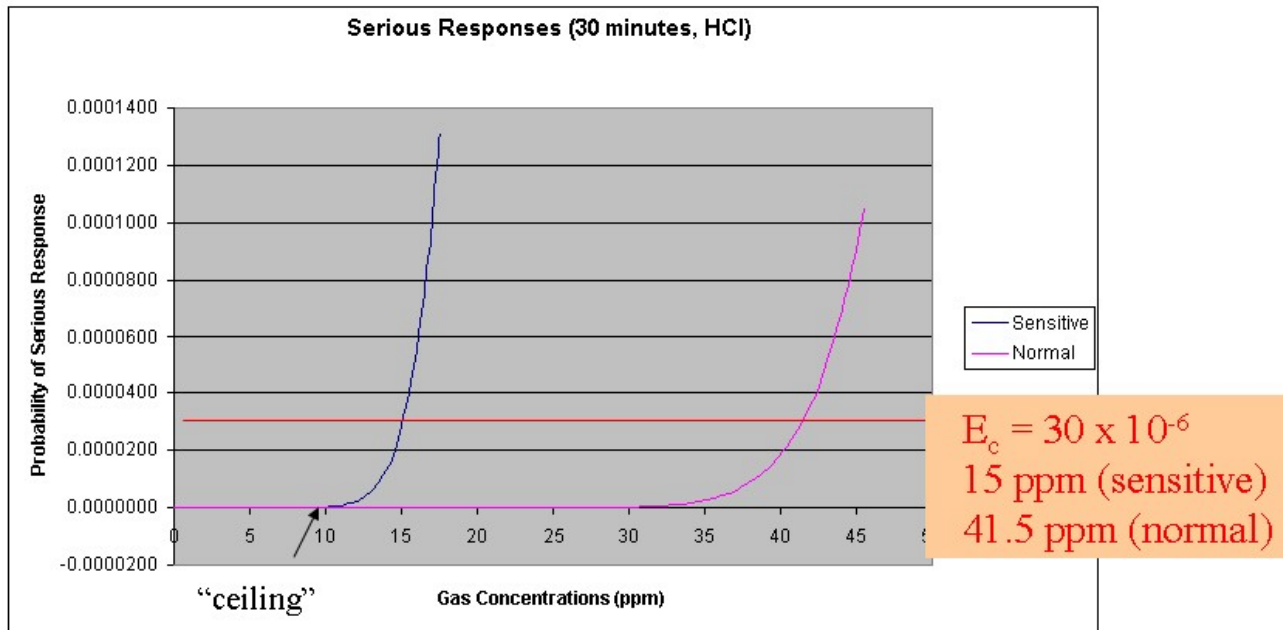
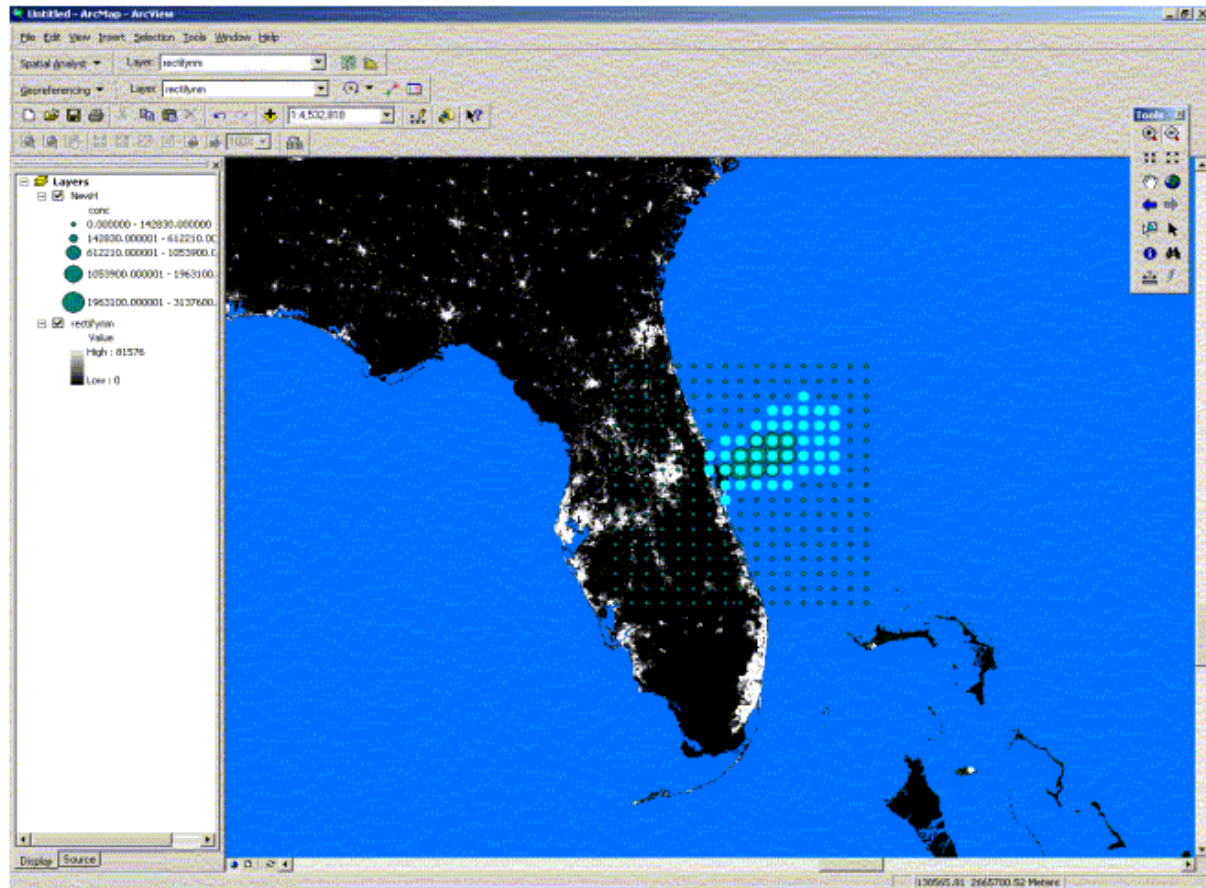


Exhibit 5. CALPUFF data displayed in ArcGIS.



These values are the input to CALPUFF, which in turn predicts the toxic concentrations for each toxicant after one hour. We enter these values as a layer into ArcMap, to determine the envelope over land where the pollutant concentration exceeds the ceilings imposed by the corresponding ERF. ArcMap's Spatial Analyst has the ability to determine the number of people covered by the displayed layer. We use the number of exposed people and the parameters resulting from the pollutant's ERF (we use as critical values the concentrations defined for $E_c = 30 \times 10^{-6}$) to estimate the number of casualties for that simulated disaster resulting from exposure to toxic levels of the released toxic pro-pellant. Repeating the procedure for enough simulation runs, we can get enough information to generate an "average" boundary and its associated confidence interval.

Extensions to Homeland Security

The September 2001 terrorist attacks on the American homeland raised the issue of Homeland Security (HLS) and the emergence of new threats to a completely new level. A fundamental responsibility of government

(federal, state, local) is protection of its citizens. In January 2001, the U.S. Commission on National Security in the 21st Century, more commonly known as the Hart-Rudman Commission, released findings regarding future threats to U.S. national security. The commission concluded the "primary national security challenge that the United States will face in the next 20 or 30 years will be an attack by an adversary on the American homeland which could produce thousands of casualties." (Balogh et al., 2004). In light of September 2001, it is clear America is witnessing the emergence of these threats. To effectively meet the challenges ahead, U.S. civilian authorities, senior military leaders, and emergency managers are re-thinking how to coordinate federal, state, and local resources to detect, prepare for, prevent, protect against, respond to, and recover from asymmetrical threats. Simulation modeling will play a major role in these assessments. This section discusses areas where we are investigating contributions from VRTM.

Generation of GIS-based maps depicting inundations and other problems related to hurricanes in Florida. We are trying to modify this environment to assist emergency managers,

transportation planners in assessing the risks associated with hurricanes. Real-time tracking, forecasting, and modeling are required processes to be added to our environment. Currently, we are working with the NASA Ames Research Center (ARC) to add capabilities of real-time weather to VRTM. This resource can provide valuable to emergency managers for mobilizing personnel and planning evacuation routes.

Chemical and Biological Agent Release. The current Virtual Range can be modified and a library of different “chemical” species and dispersion models can be added. This environment can be used to study asymmetric threats and be used for training. This is important for emergency managers in the different institutions related to HLS.

Conclusions

In conclusion, the VRTM develops a prototype of a virtual engineering environment for the NASA Shuttle that focuses on the first two minutes after lift-off from KSC. The scope for E_c calculation is restricted to toxic gas dispersion, and we focus on displaying boundaries for $E_c = 30 \times 10^{-6}$. Toxic gas-related risk is a factor of exposure duration and toxic propellant concentration or dosage that would result in casualties (death or incapacitating injury) of normal and sensitive people in a given population area. The VRTM’s easy-to-use, “intuitive” interface provides numerical and graphical summaries of potential outcomes, with user-defined preferences for the display of units of measure, geographic locations, and time values. We are studying extensions for HLS risk management.

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