Faster and More Accurate CBR Emergency Assessment for Airborne Contaminants in Urban Environments

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ABSTRACT

An urban-oriented emergency assessment system for airborne Chemical, Biological, and Radiological (CBR) threats, called CT-Analyst^{TM} and based on new principles, gives greater accuracy ***and*** *much greater speed than possible with current alternatives. This paper explains how this has been done. The increased accuracy derives from detailed, three-dimensional CFD computations including, solar heating, buoyancy, complete building geometry specification, trees, wind fluctuations, and particle and droplet distributions (as appropriate). This paper shows how a very finite number of such computations for a given area can be extended to all wind directions and speeds, and all likely sources and source locations using a new data structure called Dispersion Nomographs^{TM}. Finally, we demonstrate a portable, entirely graphical software tool called CT-Analyst that embodies this entirely new, high-resolution technology and runs effectively on small personal computers. Real-time users don't have to wait for results because accurate answers are available with near zero-latency (that is 10 – 20 scenarios per second). Entire sequences of cases (e.g. a continuously changing source location or wind direction) can be computed and displayed as continuous-action movies. Since the underlying database has been precomputed, the door is wide open for important new real-time, zero-latency functions such as sensor data fusion, backtracking to an unknown source location, and even evacuation route planning. Extensions of the technology to sensor location optimization, buildings, tunnels, and integration with other advanced technologies, e.g. micrometeorology or detailed wind field measurements, will be discussed briefly here.*

1.0 INTRODUCTION

It has been clear for a number of years that effective defense of cities, large bases, and military forces against chemical, biological, or radiological (CBR) incidents requires faster **and** more accurate prediction/assessment technology to be successful. The existing plume prediction technology in use throughout the nation is based on Gaussian similarity solutions ("puffs"), an extended Lagrangian approximation that only really applies for large regions and flat terrain where large-scale vortex shedding from buildings, cliffs, or mountains is absent. These current plume methods are also not designed for terrorist situations where the input data about the source (or sources) is very scant and the spatial scales are so small that problem set-up **and** analysis must take place in seconds to be maximally effective. Both greater speed and greater accuracy are required. Advanced simulation technology for instantaneous situation awareness must be coupled to accurate analysis of the consequences of possible responses.

Greater accuracy and much greater speed **are** possible at the same time in an urban-oriented emergency assessment system for airborne CBR threats. Detailed, high-resolution, time-dependent fluid

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simulations of contaminant transport, accurately resolving urban geometries with buildings and trees down to a few meters and with realistic fluctuating winds, are captured and compressed by a new technology called Dispersion Nomographs^{TM}. The nomograph database for contaminant agent configurations for all near ground sources requires only a few megabytes for each wind direction. This compact representation can be constructed wherever the time-dependent, three-dimensional CBR agent behavior can be accurately known, i.e. from full fidelity simulations, from other approximations, or even from ground truth data. Real time users don't have to wait for results because the relevant database can be queried with near zero-latency (that is 10 – 20 scenarios per second). Entire series of different cases (e.g. continuously changing a source location or the wind direction) can be computed and displayed like a continuous action movie. In other words, you can have your cake and eat it with this new technology.

The accompanying presentation demonstrates a portable, easy-to-use, entirely graphical software tool called CT-Analyst^{TM} that embodies the new dispersion nomograph technology and runs on Macintosh, Windows, and Unix systems. Validation studies of this new technology and field trials on "beta test" have been successfully conducted. The plume "predictions" from CT-Analyst, based on a quantitative Figure of Merit, agree, within 80 to 90%, with the full FAST3D-CT CFD simulations on which they are based and yet are prepared and presented much faster than corresponding Gaussian plume estimates. A number of new features are also available as a result of using nomographs – features actually required to give first responders a chance to blunt the WMD attack rather than just cope with the evolving catastrophe. Multiple sensor fusion for instantaneous situation assessment is an automatic consequence of the nomograph tabular form. Using three or four appropriate observations or sensor readings, CT-Analyst can backtrack to an unknown source location with zero computational delay. The fielded implementation has fast forward and fast reverse for the plume envelope and contaminant density displays, direct sensor fusion, and the ability to vary wind strengths and directions in mid scenario. CT-Analyst also plots effective evacuation routes automatically. The CT-Analyst capability appears to the user as an infinite library of scenario movies with a graphical controller to select, morph, and manipulate the CBR scenarios graphically rather than through pull-down menus.

2.0 REQUIREMENTS

Techniques for accurate, fast prediction of smoke, obscurant, particulate, and CBR agents have been DOD and civilian requirements for a long time and have been expressed in a number of forms. The events of September 11 have highlighted the need for significant technological advances in battle management, personnel protection, crisis response, and consequence management for facilities, bases and populated areas that are potentially subject to accidental releases and purposeful attack. Nevertheless, specific requirements, cast in terms related to modern technologies, have been slow to emerge. Whatever the manner in which these requirements are eventually expressed, however, they must respond to the realistic features and time scales of a terrorist or covert CBR release. Efforts to satisfy these emerging requirements should maintain continuity with and leverage existing modeling and simulation (M&S) capabilities to provide a context for exploiting breakthrough technologies such as dispersion nomographs, CT-Analyst, and cheap, easy-to-use High Performance Computing (HPC).

The CBR defense of a fixed site or region has a number of important features that make it different from the predictive simulation of a contaminant plume from a known set of initial conditions. The biggest difference is that very little may be known about the source, perhaps not even its location. Therefore analysis methods intended for real-time response should not require this information. The best we may have is reports of people becoming incapacitated, the existence of a traffic pile-up at nearby locations, or an isolated sensor detecting some contaminant at the sensor's location. It is a crucial requirement to instantly build a situation assessment suitable for immediate action using anecdotal information, qualitative data, and any quantitative sensor data we may be lucky enough to have.

A software emergency assessment tool should be effectively zero-latency and easy to use because we require immediate assessment of new data, instantaneous computation of exposed and soon-to-be exposed regions, and the zero-delay evaluations of options for future actions. The software should also be capable of projecting optimal evacuation paths based on the current evolving situation assessment. These requirements should include the ability to estimate the infiltration of contaminant into buildings and structures, and the consequences on personnel safety and mission continuity of various possible strategies under these circumstances. These assessments must also be done with zero latency (zero delay) to allow rational selection of evacuation over sheltering in place when the latter option will not be effective.

Furthermore, computational delays of even a minute (not to mention delays of 5, 10 or 15 minutes for computation with existing transport and dispersion software) mean that the data on which the currently available assessments are based are **always** out of date by the computational delay. In weather forecasting this reality is dealt with by an expensive procedure called assimilation. In time-constrained defense against airborne contaminants, the only practical approach is to reduce the computational delay by a factor of one hundred to one thousand from what exists with current software systems.

Along with the ability for quick, accurate situation assessment, certain emergency management capabilities are also required. Since each jurisdiction may wish to retain its own GIS environment, it should be easy to import CBR assessments into the existing systems and to broadcast the results in a graphical format that is easy to interpret and use. Finally, some additional advanced features are important. The software must accept weather information electronically where those services are provided, must accept and display remote sensor reports, and perhaps even integrate these various observations automatically. This paper will demonstrate that these capabilities are possible and practical. Therefore current discussions of which of these real requirements may be ignored, delayed, or worked around and under what conditions can be abandoned.

To visually suggest that something more accurate than the existing transport and dispersion models is needed, Figure 1 compares a snapshot of an urban plume computed by FAST3D-CT (upper right panel) with three possible Gaussian similarity solutions. FAST3D-CT is NRL's high-resolution complex geometry CFD model as described below. In each of the four cases the point source (surrounded by a yellow circle) was located on the ground one half a kilometer upwind of a "target" building with the wind from the northeast at 3 meters per second. The Gaussian puff-like solutions for these comparisons were computed with the building and tree geometry turned off and with the diffusive transport coefficients set to constants as in most of the common-use models. Diffusion is used in plume/puff models to mimic the effects of convective dispersion caused by the complex geometry and the resulting building-scale turbulence. Each of the similarity solutions used a stratified boundary layer velocity profile with different urban roughness scales. The roughness scale for run "P1" was 10 meters, characteristic of the atmospheric boundary layer over an open area – as input to many open terrain models. "P2" used 30 meters, a deeper boundary layer, and "P3" used the 60-meter urban boundary layer determined self-consistently by earlier FAST3D-CT simulations. The diffusion coefficients where chosen to give representative plume widths and heights.

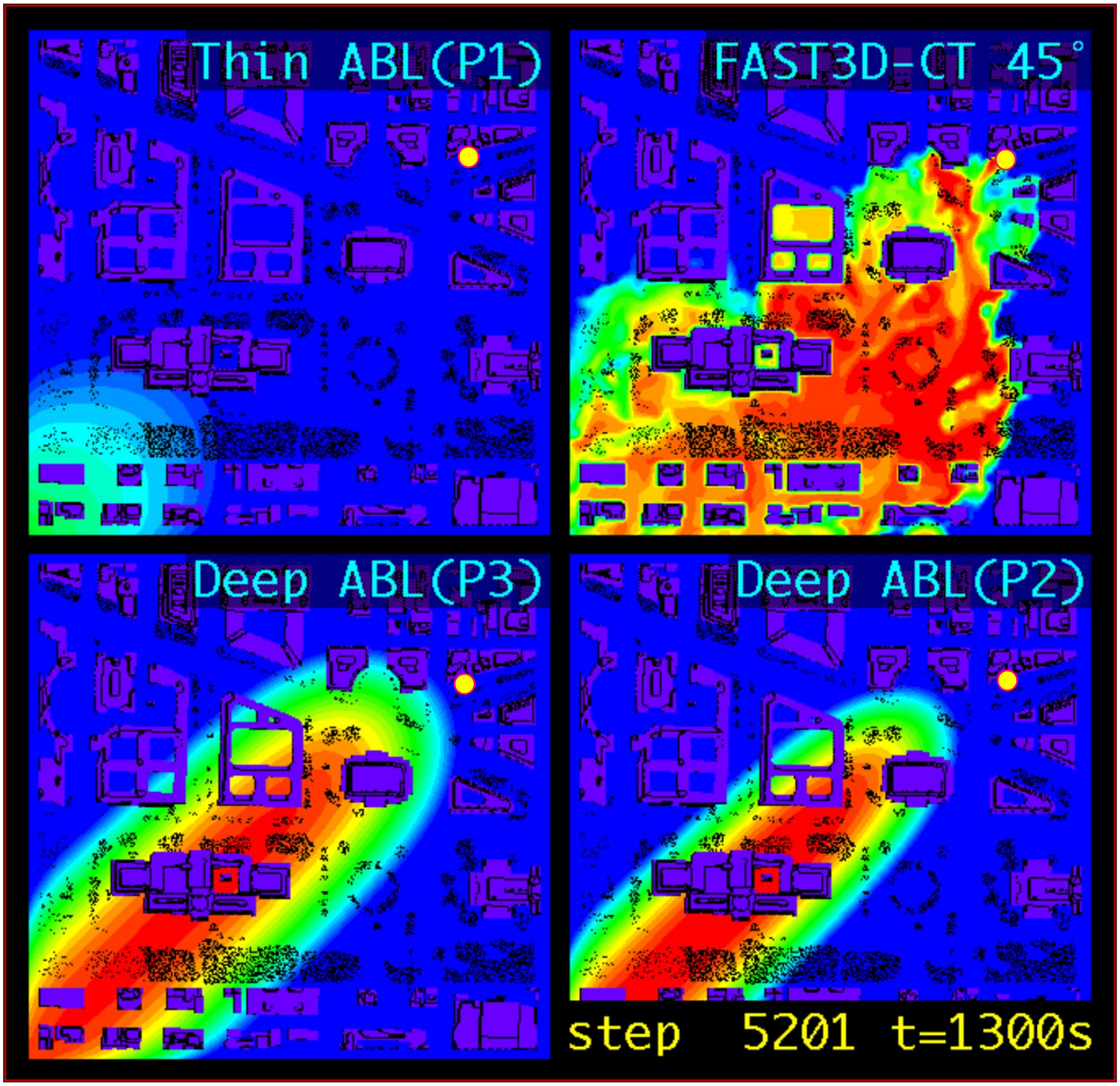


Figure 1: Comparison of a detailed 3D solution computed using the FAST3D-CT simulation model with three idealized Gaussian similarity solutions in an urban area.

The approximate Gaussian solutions are characterized by some initial direct spreading of the contaminant upwind by the diffusion, regardless of wind speed. The characteristic differences between the three Gaussian similarity solutions are similar to the differences between different plume/puff models. None of these solutions has an aerodynamically determined plume shape, contaminant trapping behavior, or plume width seen in the upper-right panel of the figure that shows a cross-section 10 meters off the ground from a 5-meter resolution FAST3D-CT simulation. In the real world contaminant gets trapped in the re-circulation zones behind buildings and continues to spread laterally long after simpler models say the cloud has moved on. Additional formulae and computations, added to some Gaussian plume models to approximate the omitted fluid dynamic effects, greatly increase the running time.

3.0 CONCEPTUAL MODEL

To meet the real requirements, this project has developed an integrated Chemical-Biological-Radiological emergency assessment tool that is much faster than current "common use" models with accuracy comparable to 3D, physics-based flow simulations for scenarios involving complex and urban landscapes. The focus is on situation assessment through sensor fusion of qualitative and incomplete data. A terrorist probably will not tell us the amount and location of an agent source or even what the agent is. Therefore we should not expect this information early enough for action in a crisis unless we somehow can generate what we need from the hints that will be available.

Any approach to sensor fusion and situation assessment of contaminant scenarios is based on an interpretive transport model, whether this is stated explicitly or not. **Maybe** the model is just a set of qualitative notions in the head of an operator or commander making crucial decisions that things will generally go downwind at some rate and spread a lot. **Usually** this interpretive model is computational at least in part. In the past, more accuracy has always meant more computing and more computing means more delay. Waiting even one or two-minutes for each approximate scenario computation can be far too long for timely situation assessment. State-of-the-art, engineering-quality 3D predictions that one might be more inclined to believe still take hours or days.

The answer to this major dilemma is to do the best computations possible well ahead of time and to capture their salient results in a way that can be recalled, manipulated, and displayed instantly. Thus the conceptual model underlying CT-Analyst assumes pre-computation of a highly compressed, general database through which an extremely broad class of scenarios can be constructed graphically with zero delay. The dispersion nomograph format satisfies this intermediary database function for airborne contaminants in complicated geometries. Satisfying the list of requirements stated above implicitly defines the remainder of the CT-Analyst conceptual model and the content and structure of this database. This conceptual model requires only limited information, the kind of data and isolated sensor readings that will come in sporadically for situation assessment during the first few minutes of a chemical, biological, or radiological release scenario.

4.0 PRACTICAL IMPLEMENTATION

The only existing software tool with these capabilities is called CT-Analyst (Contaminant Transport Analyst) and is both zero-latency (near zero-delay) **and** high fidelity. CT-Analyst is entirely visual, i.e., "point-and-click," in application. Beta-test versions, treating all of the buildings and structures in a two-square-mile area of downtown, has been delivered to the city of Chicago, to the Missile Defense Agency, and to other officials in the Department of Defense. A corresponding capability has been delivered to civil emergency-management authorities in the District of Columbia. This fully functional prototype, implemented in modest laptop and workstation versions, can be imported to any location in minutes. It can accept remote (networked) sensor data and qualitative anecdotal reports. The connectivity of the current system also includes wireless connection with hand-held systems such as ruggedized PDAs.

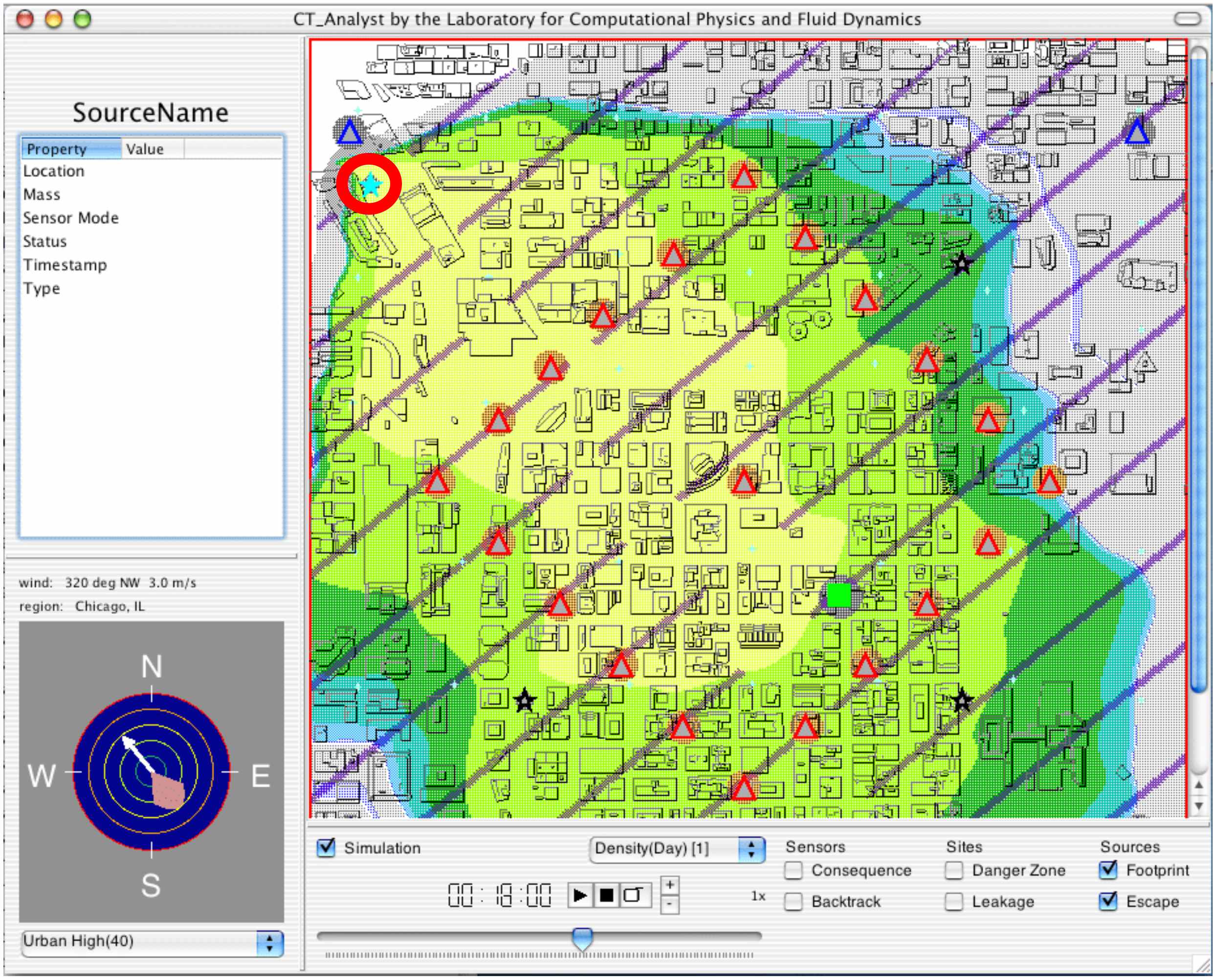
Each location in a domain of interest, if considered a source point, has a downwind region called the footprint that can be contaminated by any agent reaching that source point. Any selected location (considered as a site of interest) also has an upwind region (the danger zone) within which contaminant would have to be released to reach that site. These two classes of regions are completely complementary, being effectively each other's inverse. The interlocked source footprints and site danger zones have boundaries that change continuously as the source or target location is moved continuously. Computations and field experiments show there is excellent vertical mixing to above the height of typical buildings in an urban area. This has simplified model construction considerably – though it is not a necessary assumption – because this result allows two-dimensional displays within the urban canopy.

All assessments in CT-Analyst are "computed" by manipulating these two distinct regions for sensor report locations, for selected site locations, and for source locations. The dispersion nomograph representation is designed to make these manipulations very fast and to require only a minimum amount of data for each wind direction tabulated. The CT-Analyst implementation integrates these capabilities in a graphically oriented framework to treat airborne scenarios requiring higher spatial and temporal resolution than current operational tools. The focus in this new urban capability is on the first few minutes to an hour after a CBR release and the first few miles from the source beyond these limits, the user has much more time to respond and spatially varying weather data plays a progressively greater role.

As indicated above, the dispersion nomograph representation and processing algorithms also allow some new features. Multiple sensor fusion for instantaneous situation assessment is an automatic consequence of the nomograph tabular form. The methodology can accept qualitative and anecdotal input and does not require knowledge of a source location or a source amount. In fact, backtrack to an unknown source is also accomplished graphically with zero latency using overlap operations on the danger zones of a number of "hot" and "cold" sensor reports.

Figure 2 below shows a typical CT-Analyst display for an urban area, in this case Chicago's downtown. The contaminant concentration plot (yellow-green-blue contours) fills exactly the same area as the corresponding plume envelope and is embedded in the contamination footprint (gray region). Star-shaped nodes are sources, triangular and circular nodes are sensor reports, and square nodes indicate specific sites. When a source node is active it is colored light blue, as shown inside the red circle. Footprints, plume envelopes, contaminant concentration plots, and escape routes can be displayed for sources by activating buttons on the lower portion of the CT-Analyst screen. Triangular sensor report nodes inside an active plume envelope are "hot" (red) while those still uncontaminated are "cold" (blue). Downwind consequence regions (for active "hot" reports) and upwind backtrack estimates (for all active "hot" and "cold" reports) can be displayed for the active sensor nodes, indicated by filled triangles. Contamination zones from down wind leakage and upwind danger zones can be plotted for all square site nodes (bright green when they are active). The diagonal purple lines are the recommended evacuation (escape) routes.

To compute displays such as danger zones, plume envelopes, and backtracks to unknown source locations, knowing the actual concentration of the airborne agent is not necessary. Indeed, until the total amount of the contaminant is known, plotting the actual concentration distribution isn't even possible. Therefore, CT-Analyst provides a relative concentration until the mass of the agent from a specific source can be determined. Fortunately, this relative concentration and its time history are all that is needed to minimize the inhaled dose of contaminant. The normalization used for Figure 2 was chosen to correspond to the integrated mass of the source used in the FAST3D-CT simulation shown in Figure 3 below. This normalization also accounts for the contaminant that leaves the grid through an analytic extension of the nomograph tables. The contour levels in Figure 2 are similar but not identical to those in Figure 3 throughout the range of concentrations since the CT-Analyst representation must be generic.



wind: 320 deg NW 3.0 m/s
region: Chicago, IL
Urban High(40)
☑ Simulation
Density(Day) [1]
☐ Consequence
☐ Backtrack
☐ Danger Zone
☐ Leakage
☑ Footprint
☑ Escape

Figure 2: CT-Analyst full screen display showing contaminant concentration contours (yellow, green, and blue), contamination footprint (grey), and evacuation routes (magenta/purple) overlaid on a city map.

Visually comparing the CT-Analyst concentration plots with the particular realization from FAST3D-CT plotted below shows how well the compression process used to generate the Dispersion Nomographs captures the urban geometry-induced deviations from a smooth plume shape. For example, indentations in the concentration contours shown in the upper right and in the lower left of the figure above correspond generally with those in Figure 3 below. In the section entitled “Basis of Confidence” below, a quantitative Figure of Merit measuring the congruence of the CT-Analyst rendering with the underlying database is described and plotted. For the case above the Cumulative Figure of Merit is about 80%. While this is good, representing a significant step up over other available models, much additional data are being collected from the detailed simulations that are not yet being used in nomograph construction. Therefore, further improvements can be expected. For, example extensive data are being collected from FAST3D-CT runs relating to temporal variability and multi-realization variability. Space has been already been planned for displays to relate this information to the user, should it be useful. What exactly to plot, however, remains a question.

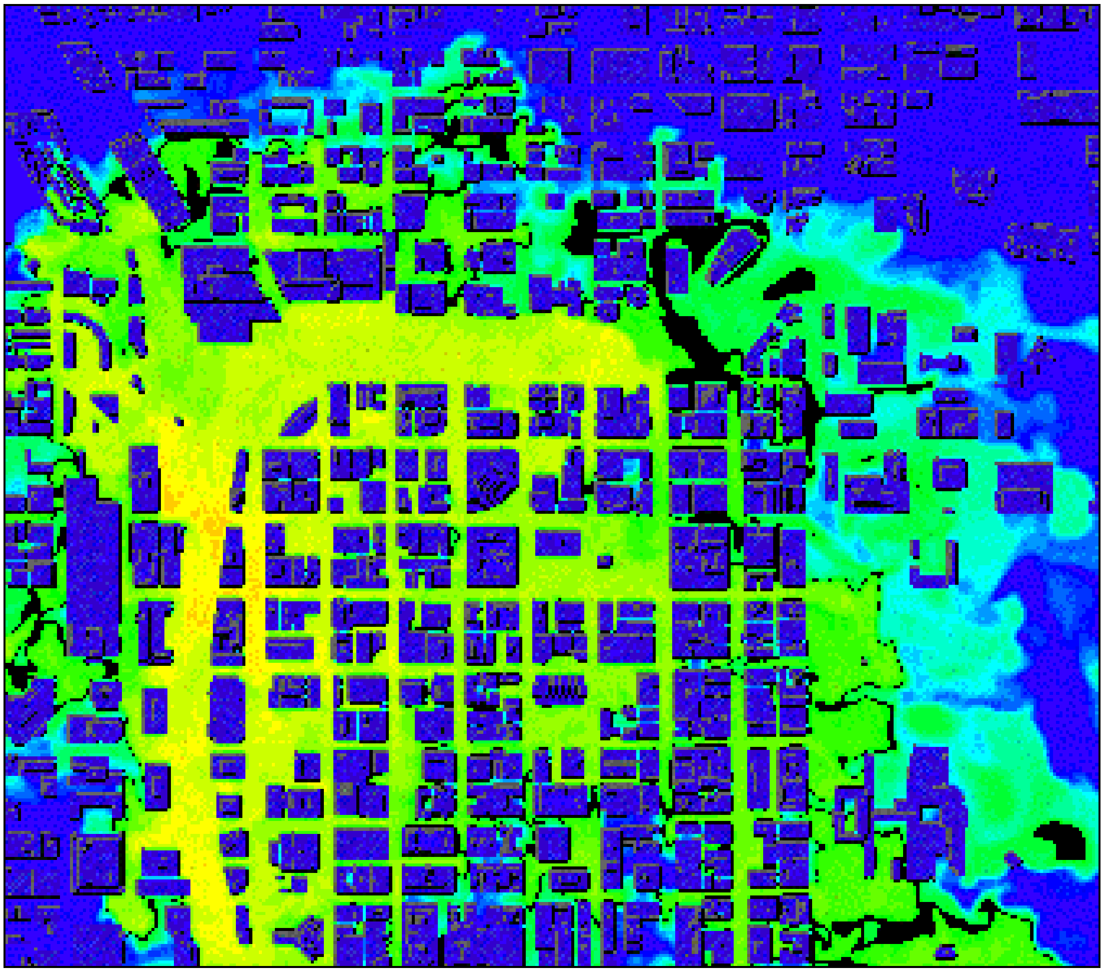


Figure 3: FAST3D-CT simulation of a contaminant cloud in an urban area with the average wind from 320 degrees at 3 m/s. The time after release, source location, and conditions correspond exactly to the CT-Analyst scenario shown in Figure 2 above.

The contamination footprints plotted by CT-Analyst are chosen to provide plausible worst cases, that is, they are designed to “safe-side” the resulting situation assessments. The plume envelopes, which expand in time to fill the footprint, share this conservatism in the “predictions.” This means that the edges of the plume envelope and the footprint are smoothed to maintain continuity in such a way that the predicted contamination areas should always be slightly larger than observed in the field. This is an interpretation designed for first responders. In practice this means that any particular realization, e.g., Figure 3, may only fill a part of the plume envelope depending on the structure of the wind gusts for that particular run. CT-Analyst attempts to indicate all regions that may be dangerously contaminated with a minimal degree of uncertainty. This is different from an ensemble average because the edges of the plume envelope are quite sharp and this is reflected in the concentration plots provided. This also is a feature of the individual high-resolution realizations during the first few minutes of any scenario.

Data analysis of a number of scenarios and realizations used to provide the Cumulative Figure of Merit plots in Figure 6 below support the following easy-to-remember interpretation. If you are outside the plume envelope (at or before the time indicated for that particular envelope), you can be 95% certain to be in an uncontaminated region. If you are outside the contamination footprint, you are 98% certain to be in an uncontaminated region. These seem to be reasonable design goals and a simple way to express the uncertainty to a user or manager. These numbers arise from maximizing the Cumulative Figure of Merit. They could be changed somewhat by changing the relative penalty in the Figure of Merit function for deviating inside the plume envelope and deviating outside of it. By making the penalty of finding contaminant outside of the plume envelope relatively larger and then re-computing the plume envelop to maximize the figure of merit, the certainty of being safe can be increased but the utility of the results would be reduced. The current ratio used for the outside penalty to the inside penalty is 4 to 1. Of course, if you have entered a big error in the wind or the wind speed, for example, some or all of the added fidelity could be lost. Even in this circumstance, however, CT-Analyst seems advantageous because it so quickly allows evaluation of these real-world possibilities.

One can view a dispersion nomograph as providing a coordinate transformation between the shape the contamination footprint would have with flat-earth geometry and the shape existing in the real world as captured in the underlying detailed database. The plume envelopes and the concentration contours within these envelope shapes are implemented as simple, polynomial interpolations into the transformed footprint shapes. These representations are chosen for their simplicity, ease of computation, and fidelity to the trends seen in the detail simulations and required of any believable answer. The plumes move generally downwind and generally arrive on the ground from above because the wind speed is usually higher above the building tops. The mathematical concentration representation fully conserves mass and is guaranteed positive, There is no magic in these simple mathematical models; they derive their accuracy from the fact that they are interpolations where the time integration has already been done – extremely carefully. By way of contrast, even very complex, carefully contrived forward-integration schemes, with many effects and correction factors included as in current plume models, are still just extrapolations in time in which small errors can accumulate unacceptably. Interpolation is always better.

As the meteorological fidelity of the underlying 3D fluid dynamic simulations is improved and/or validated, we can also improve the compressed CT-Analyst results by reducing the degree of conservatism and thus can provide analyses and displays that are more sensitive to meteorological factors. For future operations planning, CT-Analyst predictions are limited in accuracy by the wind forecasts that must be provided for the operational area. The near zero-latency feature of CT-Analyst can be used to reduce this uncertainty in the planning process, however, by allowing easy analysis of a wide range of probable conditions about those predicted hours or days in advance by the meteorological models.

5.0 THE UNDERLYING FAST3D-CT SIMULATION MODEL

An article, entitled “The Threat of Biological and Chemical Terrorism: Preparing a Response”, appeared in the March/April 2002 issue of **Computers in Science and Engineering**. This article [Reference 1] presents the time-dependent three-dimensional simulation model FAST3D-CT as it had been published prior to 9-11 in much greater detail than can be treated here. FAST3D-CT is our time-accurate, high-resolution CFD model and underpins the initial implementation of the Dispersion Nomograph representation described here. References [2], [3], and [4] explain the key fluid dynamic algorithms in FAST3D-CT and reference [5] describes many of the auxiliary algorithms and coupling procedures in detail. The references in [1] describe a number of the development, application, and validation projects that give a basis for confidence in the FAST3D-CT model (e.g., see [6] through [11]).

Figure 3 above shows contaminant density contours (plotted 10 feet off the ground in a top view) from the fully three-dimensional FAST3D-CT simulation of the urban area corresponding to Figure 2. This figure illustrates the complexity of the typical geometry (see also Figure 4 below for New York) and the complexity and resolution of the flow. The FAST3D-CT model has important droplet and aerosol physics including evaporation and conservative relofting when the particular problem being solved warrants including these effects. The model runs as one phase (vapor), two phase (vapor and particles OR vapor and droplets), or three phase (vapor, particles, AND droplets) depending on the problem being solved. It is a “multi-group, multiphase” model in these latter uses, the only one of this sophistication we know of. Each threat can be many separate chemicals and they can react chemically – since FAST3D-CT started as a reactive flow code. Each species can contribute to the density with buoyancy effects taken into account. The equations solved therefore include pyroclastic flow such as occurs in volcanic releases and when the World Trade Towers fell.

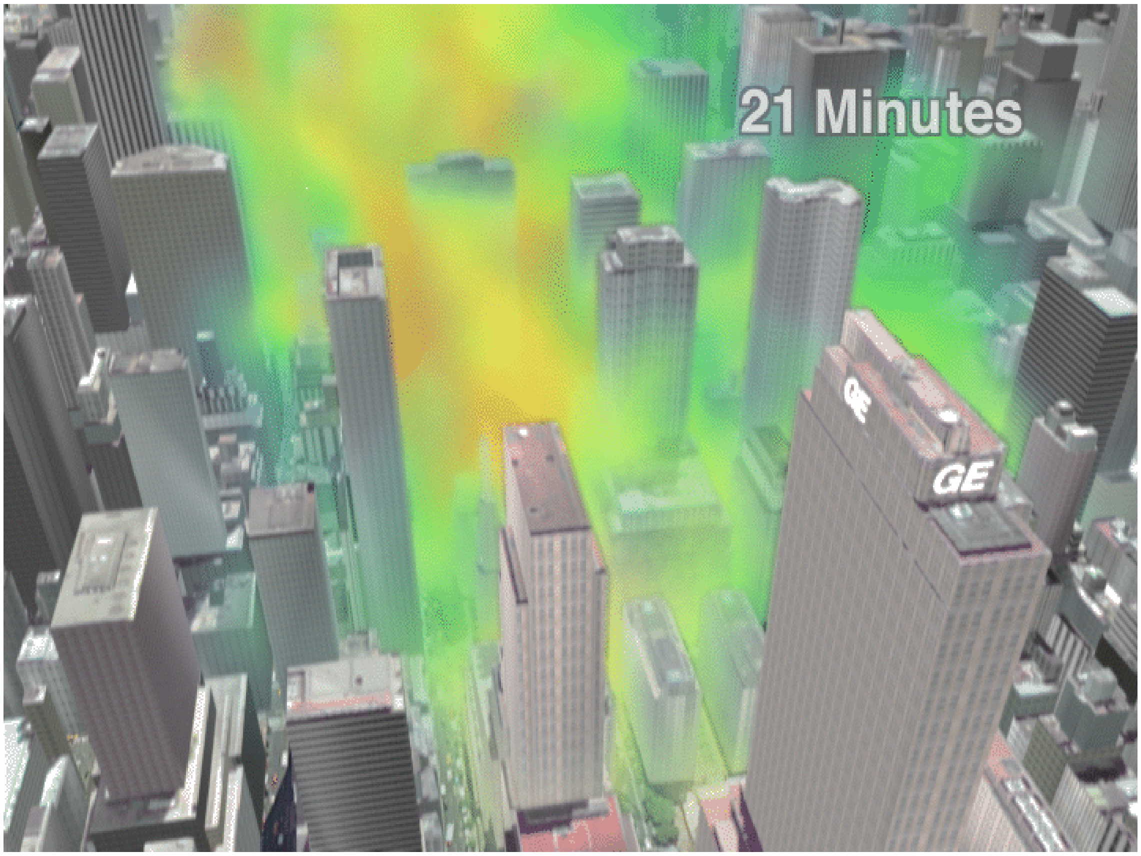


Figure 4: Three-dimensional rendering of a FAST3D-CT simulation showing geometric complexity of the urban geometry database and the good vertical mixing caused by the building vortex and recirculation patterns in midtown Manhattan.

The largest problem left is what numbers to input for all this physics. Though the physics itself has been included rather simply, much of the input is tenuous for many of these processes, particularly in the case of unknown WMD materials. FAST3D-CT simulations based on plausible worst case threats are used provide the compressed databases that drive the CT-Analyst software. These simulations can also be applied directly to sensor system optimization, to computations supporting the defense of specific sites, to physics and environmental sensitivity studies, to forensics, and as a source of virtual field trials for micro- and nano-scale atmospheric fluid dynamics and aerosol physics relevant to WMD defense.

The pacing technical item for reducing uncertainty in the results of these detailed simulations is an improved model of the dynamic fluctuations in the wind on the thirty-meter to one-kilometer scale. On the computational side this requires development of a micro-scale weather model, an extensive R&D activity outside the scope of this project. For real-time operational use, however, CT-Analyst requires current observational information about the locally prevailing wind speed and direction – and the relative strength of wind fluctuations. By design, the dispersion nomograph databases capture information that is relatively insensitive to instantaneous detailed meteorological predictions. The databases can bracket a range of possible conditions. One optimizes prediction accuracy at execution time by choosing the operational data set to match the currently observed conditions or be interpolating appropriately between bounding data sets.

6.0 CT-ANALYST USERS AND APPLICATIONS

CT-Analyst requires very little user training (one or two hours plus a simple manual). It is designed to look and feel like a computer game. The user interface is generally point and click (could be converted to touch the screen for hand-held computers) and is based on dragging icons across a map, modifying them, and selecting displays from hot buttons on the screen. Expertise in fluid dynamics, the properties of possible CBR agents and sources, or comprehensive weather prediction is not required. Possible customers for a widely distributed version (if applicable security measures permit) would be the fire department (also applicable for smoke and ash spread), the police department, emergency management officials, and building managers. CT-Analyst requires the current wind direction and performance improves with specification of atmospheric stability, e.g. time of day, whether it’s cloudy or sunny, etc. This information could be input by the user or fed to the unit remotely (e.g. airport weather). Other potential users of dispersion nomograph technology are commanders and emergency response officials faced with making quick situational assessments about CBR attacks, accidents, and natural disasters on urban battlegrounds and for defense of fixed facilities, large building complexes, and urban regions. These same officials might well be the primary users for operations planning and virtual reality training in well-equipped command centers. The potential users are also field operators charged with building and maintaining a comprehensive contamination situation assessment using combinations of fixed and mobile sensors, and civilian and military personnel faced with planning/ coordinating escape routes and controlling crowds in the vicinity of an accidental release or suspected CBR attack.

CT-Analyst provides these different classes of users with entirely new capabilities to backtrack to a source using “hot” and “cold” sensor measurements and to conduct high-resolution, zero-delay sensor fusion for real-time CBR situation assessment. The technology is crucial because it is specifically designed for realistically complex situations such as urban locales with building complexes, trees, and rugged terrain. In these regions existing fast modeling approaches, that still take minutes for each computation, degrade or fail. The new capabilities here are useful enhancements to existing Gaussian models that are best applied to open terrain engagements, for distances more than a few kilometers, and for times more than an hour. For these latter uses, this new technology would probably best be interfaced through existing interfaces and used to extend the validity and utility of those models. Personnel in the field, as well as headquarters staff, will have a fully graphical interface and display so that operator information can be entered by point-and-click or stylus contact with the screen on a map of the local area. “Hot” sensors, on site observations, and wind direction observations can be entered this way or communicated to the system from a central networked source. The operator will have a choice of displays. Commands can be communicated to a number of remote systems to coordinate actions.

One display button in Figure 2 calls up the source backtrack capability, illustrated in Figure 5 below. The CT-Analyst backtrack can find an unknown source location based on sensor and observational data when the locally prevailing wind is known. The compound probability of the source location is computed by overlapping the upwind backtrack regions of all the active sensors. In typical use the backtrack probability is represented by a 0 – 1 threshold region, as shown in the figure, but the use of continuous probability distributions can account for false alarms and environmental uncertainties more quantitatively.

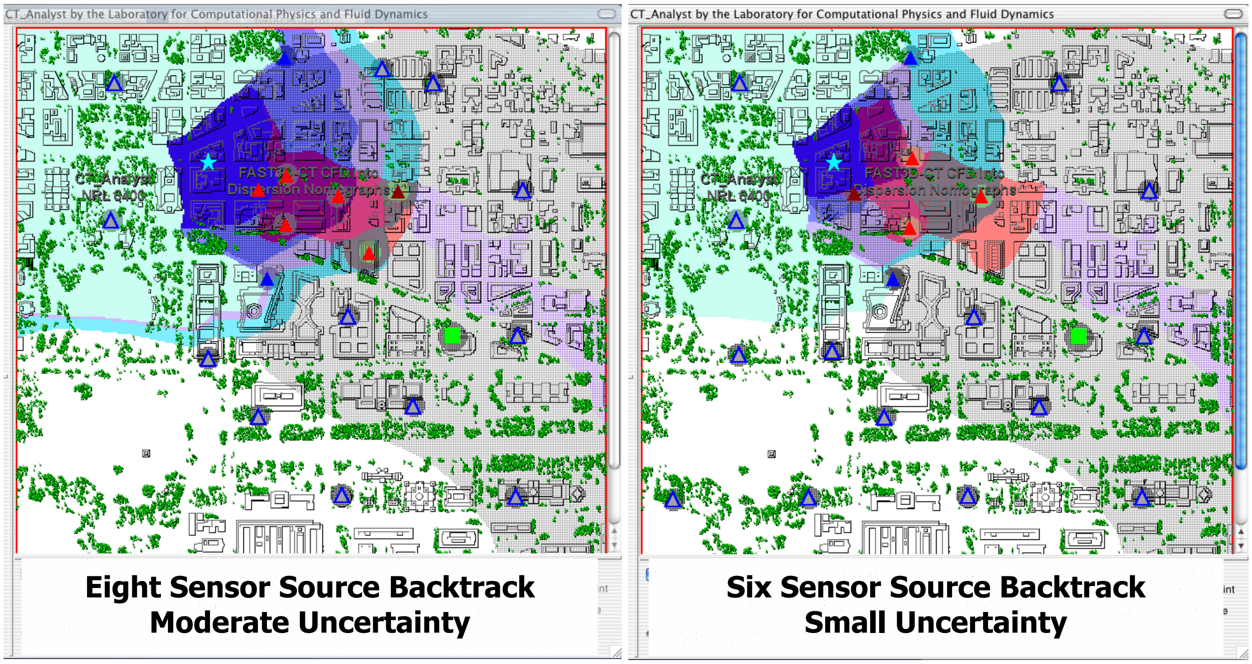


Figure 5: The unknown source backtrack region (dark blue) is shown for two similar configurations of hot (red) and cold (blue) simulated sensors. On the left, eight sensors are combined by CT-Analyst to locate the source with a moderate degree of uncertainty. On the right, six slight-adjusted sensor positions give a much less uncertain backtrack at lower cost.

As a planning tool, the CT-Analyst backtrack capability can be used to optimize sensor placement and thus reduce the cost of WMD defenses while increasing their effectiveness. The figure compares two sensor configurations for identical source and wind conditions. The configuration on the left was taken from one of the standard demonstrations used over the last two years for CT-Analyst. In this case eight sensors, six hot (marking contaminant) and two cold (sensing clear air), were used to estimate the source location. The dark blue area shows the region of uncertainty for the source location. The configuration and spacing of the sensors, the configuration and spacing of the buildings and the character of the wind fluctuations all enter the determination of this probable backtrack region. On the right all conditions have been kept the same except two of the sensors have been removed and the four remaining hot sensors have been moved slightly. The result is an estimated backtrack region with half the area (half the uncertainty) and requiring 25% fewer sensors. For example, if several million dollars were being spent on the equipment for each installation or base (e.g. the DoD PM Guardian Program), these computational analyses would pay for themselves ten times over. Each region would also have the resulting Dispersion Nomographs, adapted specifically for the region and geometry, for real-time emergency use in CT-Analyst.

7.0 PAYOFFS

The dispersion nomograph technology in CT-Analyst can address current urban and personnel protection requirements, battle management, and other homeland security issues such as decontamination with a technological leap-ahead that can provide a *significant increase* in operational capability. We now have a capability to respond quickly to qualitative warnings of chemical and radiological as well as biological attack in complex landscapes – fast enough to save unprotected lives and close down buildings and facilities before their air-handling systems become contaminated [11]. The accuracy of the proposed system, coupled with the capability to perform thousands of scenarios in an hour, also makes the system a "must" for site defense, personnel protection, battle management, and operations planning as well as detailed forensics. The speed and accuracy make the system well suited to virtual reality training.

Figure 5 above in the previous section showed how CT-Analyst could be used in the planning phases of a system to save money while increasing system effectiveness. This is certainly a payoff. Figure 6 shows how many human lives can be saved using CT-Analyst to issue a timely evacuation warning. This warning must identify the plume centerline and urges evacuation away from the centerline across the wind. In the example of this particular figure, 10,000 people would receive a lethal dose if no warning were ever issued. The figure shows that perhaps 25% of these people can avoid lethal exposure if the appropriate warning is issued in 15 minutes. 50% can escape if the warning delay is only 9 minutes. Approaching 85% can walk away if the warning is issued within 3 minutes. In other words people are dying at rates in excess of ten people per second for each second delayed in issuing the warning. In cases where 100,000 people would die if no action were taken, each second delay translates to about a hundred deaths. The people should be instructed to walk away from the plume centerline perpendicular to the wind. For people walking away upwind or downwind in this example, more people than 10,000 could actually be overexposed than if they went nowhere because the very act or walking forces them to inhale more air. Put in plain terms, four out of five people who would otherwise die, can be potentially saved by timely use of CT-Analyst.

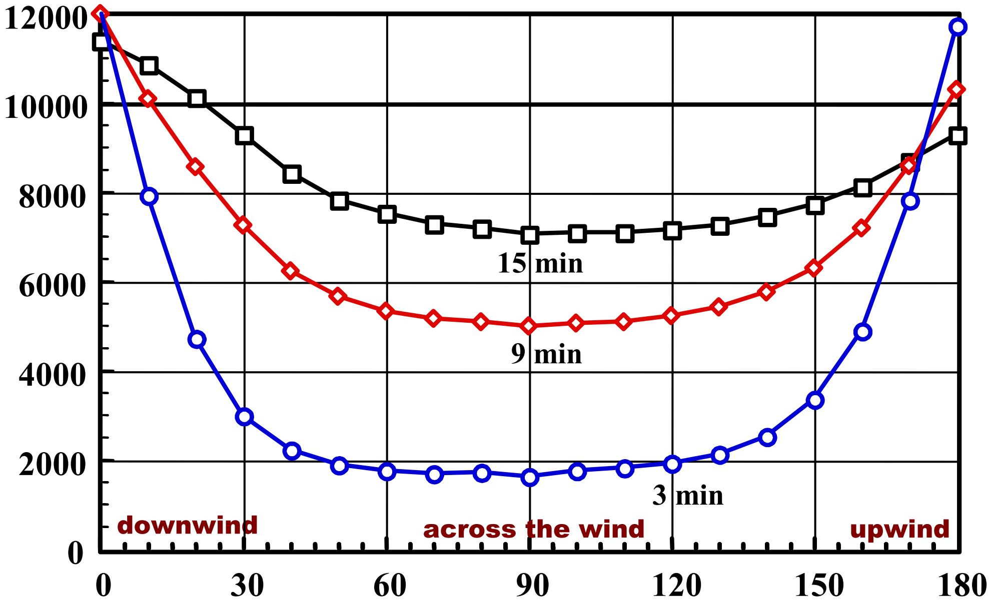


Figure 6: Walking perpendicular to the wind allows most of the people to escape lethal exposures – if the warning is issued quickly enough and accompanied by the correct direction to walk.

Table 1 just below summarizes the advantages realized from using this new CT-Analyst paradigm where the substantial computing time required is performed before the application of the tool. The computer time to obtain useful results is much less, the training time is much less, and the data storage is less. Having a high fidelity result **no longer** equates to waiting for an answer. Computational Fluid Dynamics is still not a "common use" technology except through some intermediary such as Dispersion Nomographs. It still takes the equivalent of several years of advanced training (e.g., a Ph.D.) to become proficient. Runs can take a day or more to give engineering quality, believable predictions. The current common-use models are about a thousand times faster than CFD but still can take a minute of so to run – once all the data have been entered for the scenario via pull-down menus and dialogue boxes. CT-Analyst computes and displays each scenario another factor of one thousand faster. This speed does not come at the expense of accuracy and CT-Analyst now fast enough that multivariable sensor optimizations can be run using the nomograph library functions to drive a genetics algorithm directly in hours where the corresponding use of common-use models would take months or years [12].

Table 1: Comparing Airborne Contaminant Plume Solution Methods

	Approximate Time to Run (seconds)	Approximate Time to learn to Use (days)	Approximate Data requirements (MB)
Computational Fluid Dynamics models	**50,000**	**1,000 (~Ph.D.)**	**180,000**
Puff/Plume Models	**50**	**10 (1-2 weeks)**	**180**
CT-Analyst Using Nomographs	**0.05**	**0.1 (~2 hours)**	**18**

8.0 BASIS OF CONFIDENCE

While the data compression technology embodied in dispersion nomographs and the slick user interface that results are new, there is a long and careful history behind the evolution and testing of FAST3D-CT. Therefore the results being presented originate in a seasoned, carefully tested fluid dynamics capability. Nevertheless, an overarching task encompassing the further testing and validation of the CT-Analyst and FAST3D-CT components using field data, previous test cases, and in situ validation "targets of opportunity", continues on into the future. The zero-latency models and detailed analysis inserts, based on a general Application Programmer's Interface, will be developed with potential user and system-designer suggestions and then beta-tested by these users.

Comparing the CT-Analyst plume envelope predictions with FAST3D-CT computations for a number of specific agent release scenarios validates the dispersion nomograph representation of the underlying data and also verifies the CT-Analyst software. As an example of these validation studies, two wind directions were selected, from 320 degrees (labeled N320 in Figure 7 below) and from 220 degrees (labeled S220). For each wind direction three source locations were selected and four realizations of each source were computed in special runs of FAST3D-CT.

The Cumulative Figure of Merit (CFoM), computed quantitatively as a function of time, is defined and summarized in Figure 7 for each of these six scenarios. For the three N320 scenarios, the sources were released in areas of closely spaced "dense" buildings. The CFoM curves reach a maximum of 80 to 90% at or shortly after 10 minutes and then decay slowly as the plume envelopes continue to expand slightly at late time due to continued creep of the contaminant in the wakes of adjacent buildings. The three locations for the S220 scenarios were chosen in large open areas, i.e. "sparse buildings". The fluctuations and dips in the CFoM curves in the first 10 to 15 minutes is related to the relatively large influence of major wind fluctuations in areas away from concentrations of buildings. In these more open cases, the FAST3D-CT plume realizations do not tend to expand beyond the plume envelope before the contaminant can blow away down wind, so the CFoM can actually reach its maximum late in time. Using more than four realizations for each scenario would increase the Figure of Merit further towards unity by a few percent. Additional improvement in the CfoM can be expected when the initial safety radius for the source increases realistically from zero, as in the FAST3D-CT simulations, and when the degree of conservatism in CT-Analyst is reduced through differentiating wind fluctuation conditions through more extensive dispersion nomograph tables.

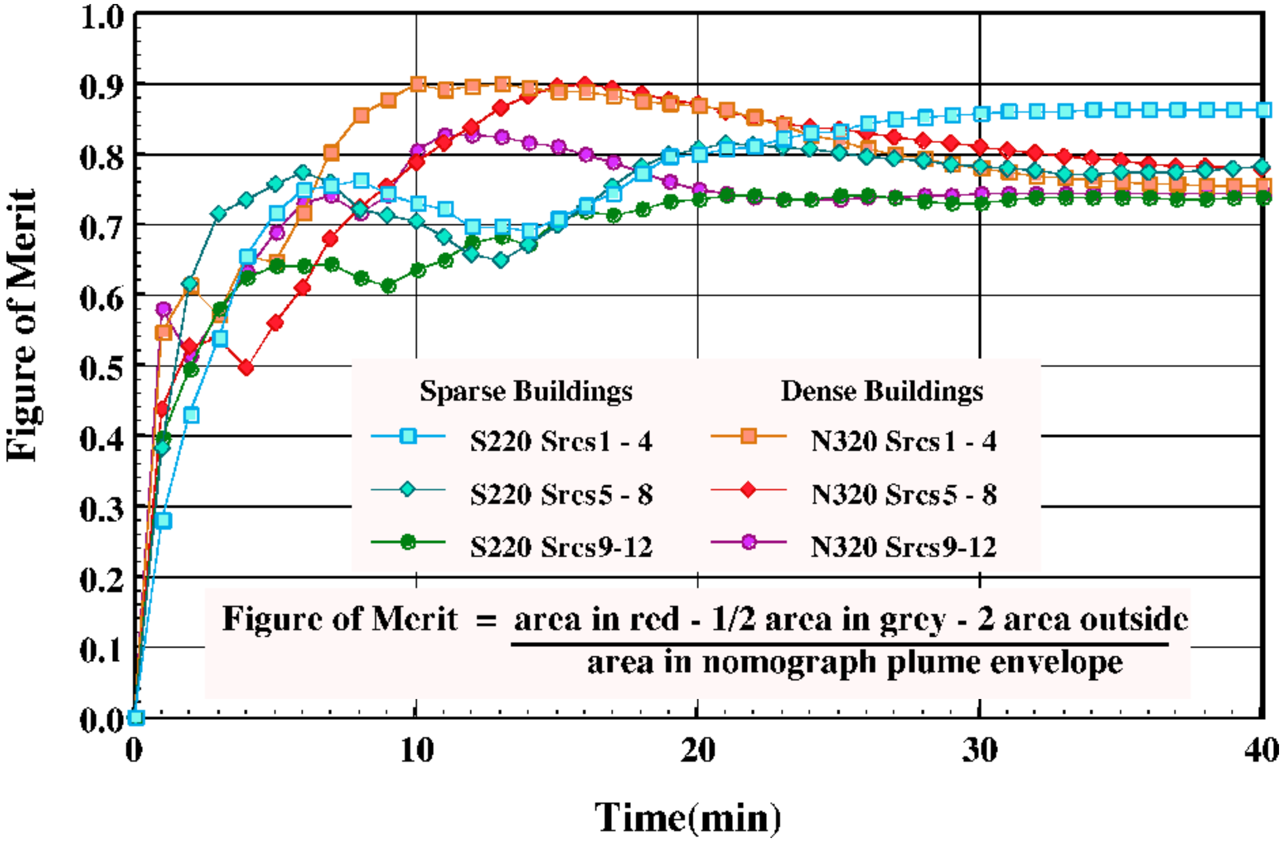


Figure 7: Cumulative Figure of Merit for six urban release scenarios plotted as a function of time. The CF0M starts at zero because the plume envelope begins with a minimum radius of 100 meters, a safety factor. The CFoM rises to 80 or 90% as each specific realization expands into the contaminated regions as defined by the CT-Analyst plume envelope.

This validation procedure only indicates how closely the nomograph representation tracks a data set computed using a particular simulation tool. Although developed using FAST3D-CT, the technology can be extended to other simulation methods provided the correct multi-source simulations are run and the correct data sets are collected during the runs. The figure of merit metric shown below cannot answer the question of how accurate any underlying simulation methodology is. Nevertheless, in principle, with "perfect data" for an ensemble of real scenarios, a set of dispersion nomographs could be developed to capture this "perfect" data set with an accuracy of 80 to 90%.

Of particular value in the realm of validation activities is the in situ validation of the entire procedure. Greatest confidence would be gained by pre-computing the nomographs before a series of tests in an urban area and then using the nomographs themselves to interpret the tests as they are happening. Data such as reportedly obtained in Urban 2000 would provide good a posteriori validation but real time, in situ application of the system would provide a lot more feedback about the actual use of the system as well as the accuracy of specific results. In this sense, data sets of contaminant releases such as fires or spills in any covered urban area provide excellent opportunities to validate the whole system.

9.0 FUTURE DIRECTIONS

Future tasks will build on the existing capabilities (FAST3D-CT and CT-Analyst) to broaden the base of users by expanding the range of applicability and increasing confidence in the methodology. The first such task is to work with users and technical collaborators to couple the current CT-Analyst stand-alone capabilities into existing command and control and urban GIS systems through appropriate input and output Application Programming Interfaces. Eventually the underlying nomograph utility library would be accessed and called directly. Currently, we are extending the capability to larger areas. The largest high-resolution computations performed to date (that have been converted to Dispersion Nomographs) cover an area of 10 by 8 kilometers (Baghdad). A reasonable target for the next year is to compute 18 wind directions for 10 square miles simultaneously on a 64-node SGI Altix computer and to prepare the high-resolution nomographs in less than a week. Eventually others could collect and prepare the data for producing the dispersion nomographs, perhaps using a range of high-fidelity models. Test cases would probably be selected for their complex topography and their intrinsic military and/or civilian value. We are also providing interfaces enabling connection to (and from) other representations of near-ground threats computed by open-area battlefield models such as PEGEM, HPAC, and NARAC for the CT-Analyst prediction space and features. The PEGEM interface has been demonstrated for a ground release (e.g. an accident, a ground burst of a munition, or a terrorist attack. The continuous contaminant cloud propagates off the urban domain and is automatically rendered into puffs that are picked up by PEGEM and propagated over much greater distances using SCIPUFF through HPAC. This approach would enable all the sensor fusion (backtrack) and personnel-decision capabilities of CT-Analyst vis-à-vis evacuation and building protection for the existing Gaussian puff/plume models. This would also enables contaminant trapping, delayed dispersion, and staged infiltration of the contaminant into buildings for higher fidelity computations where force protection and civil defense are concerned.

Another task is to develop an improved capability to produce dispersion nomographs for areas about 50 km by 50 km. A finite-volume, three-dimensional model for transport and dispersion using 4D meteorological wind data as a driver is envisioned with resolution of 40 to 50 meters in the horizontal. This would produce nomographs well matched to the kind of information that could be obtained from high altitude and satellite photos and detailed land use maps. The goal here is to produce a complete set of low-resolution nomographs for the entire region in four hours using a relatively low cost parallel system. This capability is designed to produce immediately useable wide area nomograph tables with more geometry effects included than current models. In time-critical situations unacceptable delays of days or weeks for high-resolution computations would be unnecessary. High-resolution (5-10 meters) would be reserved for specific facilities and the downtown area of cities and merged with regional-scale dispersion nomographs in CT-Analyst.

The nomograph representation allows embedding the local, high-resolution dispersion nomographs into regional coverage as they become available without re-computing the entire domain. This regional scale is also the appropriate scale to interface with and to leverage many of the existing plume modeling capabilities via an API as discussed just above.

We are also building a capability into CT-Analyst to compute contaminant infiltration at the building scale for the analysis of health facilities, other building complexes, and cities. Urban areas, ports, and bases are characterized by a number of large buildings so the question naturally arises: is it better to stay inside and wait out an attack? This is a complex question and the answer is NOT generally yes. As in wholly external scenarios, it is possible to minimize the inhaled dose by knowing key timing data and relative density time histories without the need to know what the agent is or how much of it there is. However, the time history of the relative concentration, provided by the new agent concentration maps such as illustrated in Figure 2, is required. Personnel protection in battle management applications and in general homeland security is only comprehensive when coupled interior-exterior capabilities are provided. Zero-latency analysis is as important here as it is for external threats. Therefore an independent server, coupled through the API to CT-Analyst, will be used to provide near zero-latency predictions for hundreds or even thousands of individual buildings while CT-Analyst is engaged assessing the evolving emergency through the sensor data and observations.

A primarily military application requires extending the zero-latency capabilities to support missions involving mobile sensors such as fleets of robots, ground vehicles, or UAVs. This task also requires remote network input of sensor and threat data to the composite analysis system for immediate operational use. Though of less direct interest in civilian quarters, this task will lead to more completely automatic emergency assessment tools from which everyone will benefit.

The pacing issues for introducing CT-Analyst to a number of different locales are to reduce the cost of preparing the nomograph data tables and the availability of the geometry data for each area. The Army has run an ACTD employing an aircraft fly-over with a laser scanner with hoped for turn-around of a few days. The properties of the resulting data are quite adequate, as determined by test for a section of the Norfolk Naval Base, to construct the dispersion nomographs. NGA and several contractors can also construct adequate geometry data files from archived data or satellite fly-overs but the time frame is several weeks to months and the costs are currently high. The implementation of the high-resolution dispersion-nomograph technology is computer intensive. Techniques for reducing the required computer time are being investigated but there is a trade-off between accuracy of the zero-latency product and the time necessary to produce the compressed files.

Even with more efficient production implementations, days to weeks of time on a High Performance Computing system will be required to produce a year-round CT-Analyst capability for the downtown area of a city or a substantial building complex, military base, or port. The cost, however, is relatively small. Relative to current “rapid response” capabilities, this investment can potentially save tens of thousands of lives in major emergencies. Reducing the response time from 15 minutes to 3 to 5 minutes, for example, allows four out of five people who would otherwise be critically dosed (die) to survive the incident. Implementing CT-Analyst will also cost far less than the physical security and sensor systems that will need to be installed and can pay for itself many times over by increasing the effectiveness and reducing the costs of such systems.

10.0 CONCLUSIONS

CT-Analyst has undergone several years of stringent testing and meets the necessary real-world and real-time requirements for an urban airborne contaminant emergency assessment tool. The conceptual model coincides with the software tool as actually implemented. Furthermore, the underlying CFD technology is uniformly convergent so answers automatically get better with increasing computer power because higher resolution CFD simulations can be used to build the Dispersion Nomograph data sets. In addition, the resulting capability includes necessary, crucial features not found elsewhere. The effectiveness of the near zero-latency nomograph technology built into CT-Analyst will be measured in a several ways depending on the application. The real-time laptop and handheld units will be effective if the area covered by the nomographs is chosen properly (i.e. site defense or urban implementation) and if the contaminated zone predictions correspond closely with reality. In planning mode, the system's performance will be measured by the usefulness of the various types of information that can be conveyed to the user with zero delay and the ease of use. In the absence of data from actual CBR attacks, operational effectiveness can be assessed in simulated exercises.

Dispersion-nomograph technology has revolutionary ("transformational") aspects. It has uses in a number of sectors and represents a revolutionary enhancement of common-use models. The applicable standards, regulations, and requirements are still being formulated and revised, in part as a result of the existence of CT-Analyst. Security concerns also arise with respect to how widely distributed and licensed the technology should be (e.g., beyond civilian first responders?) and whether suitable wind/weather will be generally available or encrypted. Changes that may be required for field use and for planning will evolve as the various classes of users are exposed to the full range of emergency assessment tools and ask for more and varied capabilities.

This is an unusual modeling and simulation effort in that the risks are unusually low and the rewards particularly high because of the unique features of the nomograph technology and the open architecture of CT-Analyst. In typical contaminant transport prediction systems a complex set of phenomenological models are layered one on top of another beginning at the lowest level with a flat earth approximation with uniform transport coefficients and no vortex shedding. Since these fundamental approximations are questionable in complex geometries, errors are introduced right at the onset and compound exponentially as more and more approximations are built one on another. By way of contrast, the CFD computations captured by CT-Analyst are rather complete detailed solutions and provide defensible input. They also place reasonable physical limitations on any additional simpler models. The geometry is correctly treated through the nomographs. Furthermore, unique new capabilities including evacuation routes, accurate contamination footprints, and unknown source backtracks make the payoffs very large. The unique combination of speed and accuracy make the composite capability as useful for emergency response and personnel protection as for planning.

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