

AN APPLICATION OF VIRTUAL REALITY FOR HAZMAT ASSESSMENT AND FIRST RESPONSE

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ABSTRACT

This paper presents the initial development of an integrated software tool intended to simulate the internal building environment and atmospheric transport of hazardous materials resulting from an explosion occurring within a building. The goal of the software is to integrate existing off-the-shelf engineering modules developed primarily for military applications with virtual reality technology for improving the state-of-the-art in HAZMAT preparedness, mitigation, and response. The software uses inputs such as the number of stories, approximate number of bays, room dimensions, type of construction, and material properties to generate 3D models of conventional multi-story buildings. Integration of the software with airblast propagation and chemical dispersion models permits the blast environment and chemical expulsion to be simulated along with the resulting consequences (e.g. potential loss of life, structural collapse, damage to mechanical and electronic components, and the quantities of hazardous materials that may spill or aerosolize). Agents expelled from the facility through voids in damaged walls, windows, vents, and places of egress can be quantified to estimate the geographic extent of the release outside the facility. A salient feature of the software is its 3D walk through option, which provides a full perspective on the internal environment and the actual layout of a building's entrances, windows, walls, columns, and staircases that may require negotiation in the event respondents enter the facility as part of a mitigation effort. Recommended enhancements before the software's operational use are presented.

1.0 INTRODUCTION

Over the past several decades, breakthroughs in computer technology have led to the growing development of fast-running analytical, empirical, and hybrid models for predicting the results of explosive detonations and chemical/biological agent expulsions. The impetus for the development of these models has been the military's need to both assess the effectiveness of various munitions and establish appropriate design criteria for construction of hardened storage facilities used to house hazardous chemicals and sensitive energetic materials. More recently, the increasing threat of terrorism in the United States and throughout the world has led to the initiation of a National directive to strengthen the capabilities to prevent, respond to, and manage the consequences of terrorist use of chemical and biological agents. As a result, there has been a growing interest in tools that assist planners and first respondents in developing operational plans during catastrophic events.

The current paper presents the early development status of one such tool that integrates various numerical models, developed primarily for defense applications, and virtual reality technology. The goal of this integration is the development of an application that demonstrates functionality that may prove useful for both training and planning for responses to assaults on conventional facilities. To that end, the application must strike a balance between the accuracy of the predicted results and the speed at which those results can be produced. The potential risk to human life when entering a compromised facility emphasizes the importance of not misleading the user in a virtual reality setting about the confidence level or detail of the results predicted by low fidelity engineering models.

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A description of the software's architecture and the current models interfaced by the software are detailed in the section that follows. An example of a 1000-pound car bomb exploding within the underground parking area of a low-rise facility is used to demonstrate the current capabilities of the engineering models and illustrate how the results are depicted in the 3D window. Finally, limitations of the current version and proposed enhancements for future versions are discussed.

2.0 SOFTWARE DESCRIPTION

2.1 Overview

The product consists of a suite of applications, which include the Geographic Data Manager (GDM), Facility Editor (FE), and Response Planning Board (RPB). The GDM assists the user in the initial step of creating the topography of the region of interest. Not only does the topographical model act as a data feed to the external dispersion model, it also serves to provide realism and an area for staging vehicles, resources, neighboring facilities, infrastructure, and/or obstacles that might affect the response. The FE application gives the user the ability to create custom conventional or hardened building facilities that are to be placed on the terrain field created by the GDM. The FE assists the user in quickly developing an accurate geometric and illustrative representation of 3D buildings from user input data such as the number of stories, approximate bay and room dimensions, type of construction, and material properties. From this data the FE designs the interior/exterior walls, columns, floors, and beams in accordance to U.S. building code standards. The final step is to invoke the RPB, create the desired scenario, and run the simulation. Choices of models include an internal blast model to propagate gas and shock, air blast and fragment fragility models, and an internal dispersion model to predict temperature and agent dispersion within the facility. The results produced from these engineering models can be displayed in 2D or 3D. The software also provides the option to output plume data for analysis by an external agent transport model.

2.2 Geographic Data Manager

The Geographic Data Manager merges information from a large number of Geographic Information System files, which can include image, vector, and elevation data. Currently, all geographic data must be in the WGS84-datum, geographic (lat./long.) projection, and geographic decimal degree units. The following imagery data files are supported: NIMA-CADRG, NIMA-CIB, ESRI ArcInfo GRID, JPEG, GIF and BMP. Vector data files can be either ESRI Shape Files or ESRI ArcInfo Coverage. Elevation data files can be in the following formats: DTED Level 1, DTED level 2, ESRI ArcInfo ASCII Grid, and xyz ASCII point list. The GDM produces a single index file that can be imported by the RPB to generate the terrain model used in the simulation.

2.3 Facility Editor

The FE is a WindowsTM-based support application to the RPB used to graphically and interactively build conventional aboveground buildings and hardened facilities. The 2D level editor allows the user to model the actual internal layout of a multistory facility by creating hallways, non-rectangular rooms, and arbitrarily located doorways and floor openings. The editor allows drag-and-drop placement of individual elements including: walls, beams, columns, floor slabs, and openings. A specification sheet for each element permits idealizing structural elements comprised of steel, reinforced concrete, masonry, and composite members. Users may describe the specific properties of each structural member and its dimensions, or alternatively invoke the automated structural designer to size members in accordance to building code standards. The constructed model can be viewed in 3D using an ACISTM solid model generated from the 2D Level Editor description. Users can interactively switch between the 2D Level Editor window and the 3D OpenGLTM model window to gain full perspective of the building model from arbitrary points of view as it is being constructed. Indexes to 3D functional models of secondary building systems or auxiliary features (e.g. mechanical/electrical equipment, HAZMAT containers, etc.) may be arbitrarily placed within the confines of the facility. The final building and functional models are stored in a database that can be interpreted by the RPB for performing engineering calculations and representing the model graphically in a virtual environment.

2.4 Response Planning Board

2.4.1 User Interface

The RPB is a Windows™-based application that hosts three paned windows called views within the main program window. The names of the paned windows are as follows: the Geographical View, Map Annotation Control View and Text View (Figure 2.1).

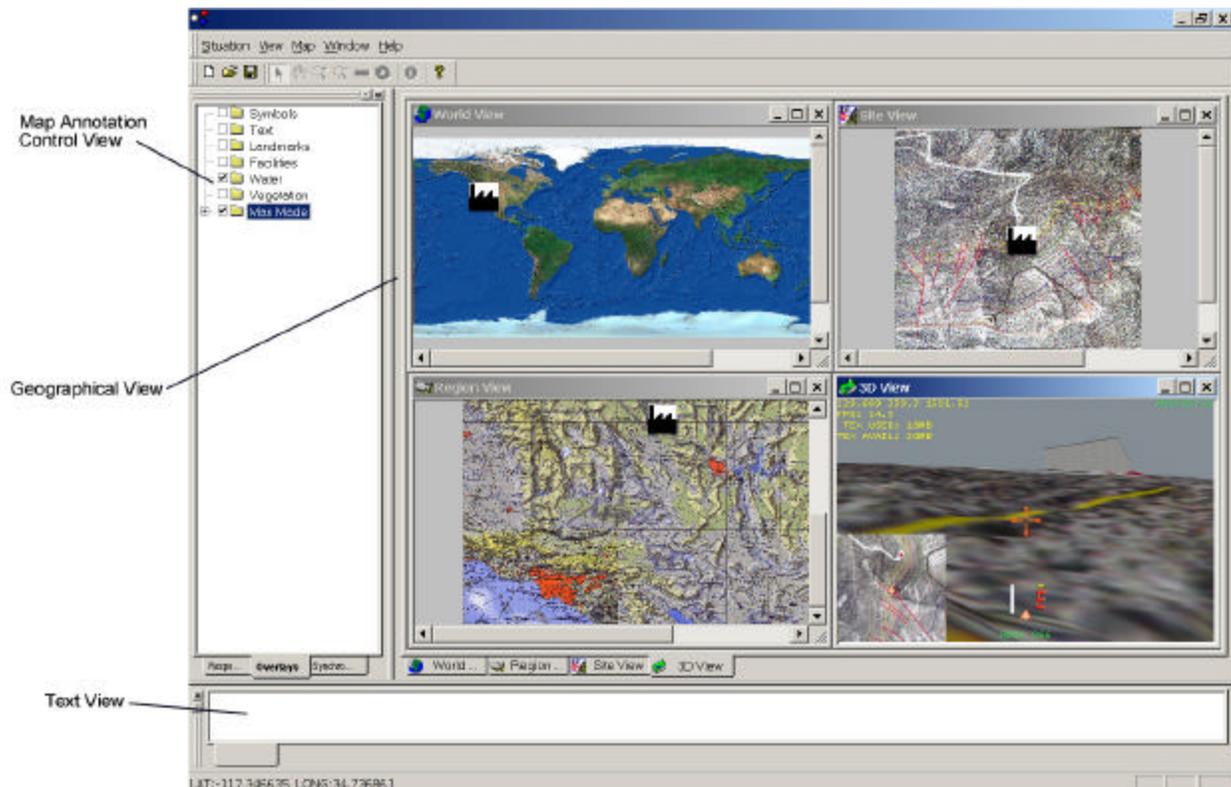


Figure 2.1: Response Planning Board user interface.

The Geographical View contains as many as four different tabbed windows. The first tabbed window displays the entire world so that the user can get a global perspective on the location of the site of interest. The second tabbed window displays a closer view of the region of the world in which the site of interest is located. The third tabbed window contains only the geography immediately surrounding the site of interest. The size of this area is dependent on the highest resolution data available and on the potential area of impact should an incident occur at the site of interest. Finally, the user can create a fourth tabbed window in order to view facilities, additional map annotations and the surrounding terrain in 3D. In addition to representing the data in 3D, the user can walk in and around buildings, place and detonate explosive charges, and inspect the resulting damage all within the virtual environment.

The Map Annotation Control View contains three tabbed windows, which allows the user to select between the Response, Overlay and Synchronization Matrix Windows. The Response Window allows the user to create multiple scenarios while maintaining the same maps within the Geographical View. Each scenario contains its own set of map annotations. The Overlay Window allows the user to create groups of map annotations and/or facilities that the user may view in both 2D and 3D. Each grouping can be selected to be on or off so that the user can view as many or as few map annotations at one time as desired. Map annotations can include facilities, symbols and features. Facilities include any buildings that the user can create within the facility editor along with any functional areas that have been placed within the building. Symbols include items such as points, lines and arrows, while features include items such as bridges, trees, and towers. The Synchronization Matrix Window allows the user to specify which map annotations exist in an overlay group at a given time. Thus, the user can create a time history for a given scenario.

The Text View allows the user to detail a response to the scenario that he/she has created in the Map Annotation Control View. In addition to formatted text, the user can insert graphics and images. For example, the user has the option to insert a snapshot of the currently selected view of the geography. After completing a description of what response to take given the defined scenario, the user has the option to save all the information to a Microsoft PowerPoint™ presentation.

2.4.2 Architecture

The various components that comprise the RPB communicate with one another via Microsoft's Component Object Model (COM). COM permits a programmer of one component to access the functionality of another component solely through sets of functions called interfaces. As long as the interfaces to a given component remain the same, a developer can make an enhancement or modification to the component's internal structure without affecting any other component's design. As a result, a specific modification can usually be restricted to a single component, which makes code maintenance more manageable. In addition, it is possible to reuse a given component in a different application with little or no change to the component's internal structure.

Internally, each component uses an object-oriented design using the C++ programming language. However, the engineering component also makes calls into some non-object oriented structured code written in the FORTRAN programming language that is contained in dynamic linking libraries.

2.4.3 Virtual Environment

The virtual reality component of the RPB utilizes a gaming engine created by Numerical Design Limited (NDL) named NetImmerse™ to create 3D representations of facilities, other map annotations, functional areas, explosives and the surrounding terrain. NetImmerse™ provides a hierarchical data structure called a scene graph into which all the geometry, 3D transformations, textures, material properties, and lighting are organized.

In order to construct the geometry for the terrain, the component retrieves the data from the geographical data component of the RPB. Afterwards, the component uses ACIS™ solid modeling functions to cut holes into the terrain where the facilities are to be located. To create the 3D representations of the facilities that will fill the holes, the component reads information about the buildings out of a database created by the Facility Editor. Information about functional areas contained within the buildings is obtained from files that store the information about the functional areas associated geometry, textures and material properties.

After building the scene graph, the component allows the RPB user to walk in and around the buildings that are on the terrain. The component employs a simple collision detection methodology based on ray intersection testing so that the user cannot walk through objects such as facility walls. In addition, the program maintains the user's height a specified distance off of the surface of the terrain in order to maintain the sense that the user is actually walking in a real environment.

Within this virtual environment, the user has the option to place explosive charges, detonate them and inspect the resulting damage. Items that the engineering models determine are damaged or destroyed are rendered in red. The user can also inspect gauge points that are placed at specific locations within a facility to determine temperature and hazardous material density.

2.4.4 Engineering Models

2.4.4.1 Internal Blast Models

The current version has three models available for calculating the internal blast environment and response of the building. The blast models are 1) BlastX Code, Version 4.2 developed by the Science Applications International Corporation (SAIC) for the Corps of Engineers¹; 2) the Multi-Chamber Blowdown Model (MBLM) developed by Maxwell Technologies, Inc. (currently owned by SAIC)²; and 3) the internal blast code used and developed by Applied Research Associates, Inc. (ARA) in version 4.0 of the Munitions Effects Assessment Module for Buildings and Bunkers³. The choice of which model to use depends on the particular objectives of the analysis.

Both the BlastX code and the ARA developed blast code are based on the use of semi-empirical free-air source models that apply ray-tracing algorithms for parallelepiped as well as non-parallelepiped room shapes. The pressure waveforms from the free-air source models for image bursts are nonlinearly superimposed to develop the complete pressure wave, particle density, and velocity time histories at prescribed locations within the facility. Quasi-static gas pressures that may build up within a facility and disperse spilled or aerosolized agents are modeled using the venting algorithm of MBLM introduced later.

2.4.4.2 Damage Models

With the exception of the model used to predict fragment damage to chemical containers, the software models damage to structural elements, equipment, and personnel using fragility functions that describe damage thresholds due to exposure to blast and fragments. These simple models are straightforward alternatives to higher fidelity computational schemes and require minimal computation time.

For shock and pressure induced damage to structural elements, the ARA developed blast code internally computes pressure-impulse functions for each structural element of the facility exposed to the blast. The list of elements includes the building block elements (beams, columns, wall, floor slabs) used to design the building in the FE. For pressure and impulse values that exceed the maximum threshold value given by the fragility functions, the code assigns a damage flag to the element and removes it from future computations. Loads supported by the element are redistributed to neighboring elements. As a result of the redistribution, the coding verifies capacities of other connecting elements are below their ultimate limit states. If a connecting element attains its capacity, it is identified as damaged and the process is repeated until no further redistribution of the loads is required. Those elements damaged directly from blast, or indirectly from load redistribution, are rendered with a red shading in the 3D window.

Lethality estimates are based on a linear fragility function that predicts the probability of survival from blast effects. With regard to equipment, damage from blast is limited to shear mode failure of the equipment's supports. The model computes the shear force imposed by the detonation products from velocity and density time history output. The resistances of the connections are used as limit state criteria for determining if the equipment is destroyed and stored as attributes of the functional model (the option to predict equipment failure induced by blast is currently unavailable).

The personnel fragility model used to determine casualties from exposure to fragments is based on the work of Feinstein, which defines the threshold of lethality for fragment weights in terms of kinetic energy³. The software computes the fragment weight that satisfies the kinetic energy criterion and determines the probability that the fragment density projected on an assumed human profile is above the lethal threshold. Equipment damage (mechanical, electrical, etc.) is determined using a generic equipment fragility model based on the expedient method outlined by Hacker, Pires, and Mitlehner³. The method reduces the equipment that may be subjected to fragments to an idealized steel plate of equivalent volume for which vulnerability to fragment damage is documented. The probability that a piece of equipment is destroyed is assumed equal to the probability fragments penetrate the fictitious plate within a vulnerable region.

Fragment damage to liquid chemical/biological containers is computed using the Agent Release Model (ARM) developed by ITT (formerly Kaman Sciences Corp.). The model is a fragment fly-out and hydrodynamic ram model that predicts container damage and agent spillage due to beam spray fragments interacting with a cylindrical steel storage tank. The liquid is assumed to either remain in the container, pool on the floor, or spray into the air as an aerosol. The aerosolized portion is assumed to be entrained in the blast environment and is available for expulsion as the facility vents, as computed by MBLM.

2.4.4.3 Agent Dispersion Models

The RPB directly interfaces MBLM to calculate the time-varying interior flow within the structure subsequent to the introduction of one or more energetic sources. MBLM is a physics-based code that has evolved since 1978 from special-application programs that were developed under sponsorship of the Defense Threat Reduction Agency (DTRA), the Corps of Engineers Waterways Experiment Station (WES), and the Air Force Research Laboratory (AFRL)². The model estimates the quasi-steady environment within a multiply-compartmented sealed or vented facility, and the associated transport and venting of airborne gases, particulates, and liquid droplets. Flows are

treated with compressible or incompressible fluid dynamics as appropriate, and gravity effects are included. Chemical equilibrium material properties are used throughout. MBLM incorporates detailed, finite-rate lethality models for both chemical and biological agents, in which the effects of vaporization, decomposition, and combustion are included for chemical agents, while both thermal and biocidal kill are included for biological agents. Although the model is faster than multi-dimensional hydrocodes, typical run times range from one minute to one hour depending on the complexity of the structure and the scenario run. Consequently, the model may not be suitable in some cases for time-constrained decision-making that requires faster turnaround times.

MBLM models agent releases to the atmosphere through modeled air ducts, windows, doors, elevator shafts, and voids created in the facade of the facility during the explosion in the form of plume data stored in a descriptive Cloudtrans file format. Outside of the RPB, the Second-order Closure Integrated Puff model (SCIPUFF) can be launched to input and interpret the plume information to perform transport computations over the region⁴. SCIPUFF is an atmospheric dispersion model that is capable of modeling transport, steady and non-steady emissions of gas or particle pollutants, and buoyant or neutral sources using time-dependent meteorological data. Meteorological data may be as simple as a constant velocity wind field from a fixed direction, or may include surface and upper-air observations/forecasts, or 3D grid data. The SCIPUFF model has a graphical user interface that runs on a PC for defining the problem scenario and displaying color contour plots of the resulting pollutant concentrations over the region at user prescribed time intervals.

3.0 SIMULATION: VEHICLE BOMB IN LOW-RISE FACILITY

The following example is used to illustrate the current capabilities of the software and the steps required to simulate an explosion and chemical release within a building. The incident involves a 1000 pound vehicle bomb exploding within the below ground storage/access area of a five-story reinforced concrete building composed of masonry exterior and interior walls. Liquid chlorine is delivered and stored within containment vessels below the building, which serves as a laboratory for a water treatment facility of a large metropolitan area. The building is located within a geographic region characterized by both rolling hills and moderately steep terrain.

The steps involved in creating the scenario are: 1) create a terrain model of the site topography and; 2) construct and place within the terrain model a facility model with attributes that approximately match the structural and dimensional aspects of the building. The facility model should include functional models of equipment, personnel, and HAZMAT containers relevant to the incident, which are spatially located as they occur in the real facility. The final step, 3) is simulating the incident and viewing the results.

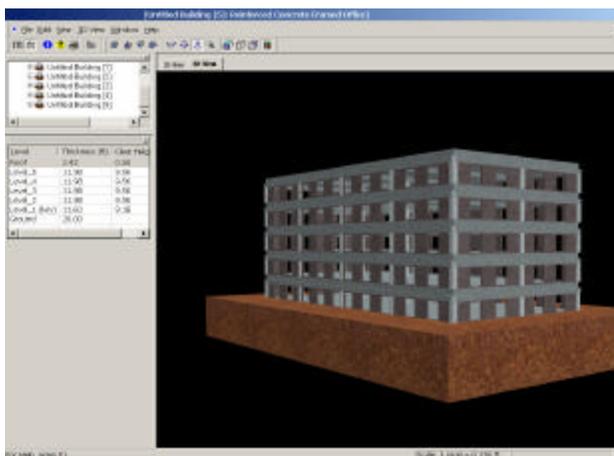


Figure 3.1: Five-story office building used in simulation.

For the first step, we launch the GDM application and create a single terrain index file for the geographic region from multiple map coverages. Next, a model of the five-story building under consideration is created using the FE. In Figure 3.1, the image shows the ACIS™ solid model view of the designed facility. For this particular example, each of the interior and exterior walls were defined similarly by a single default specification sheet for non-load bearing masonry partition walls and placed according to the layout plan of the actual facility. Since specifications sheets for beams, columns, and floor slabs are generally unknown without construction drawings of the facility, the internal automated design function was used as an alternative to size members to meet typical service load requirements. Accordingly, functional models of the chemical storage containers, personnel, and equipment are placed within the facility.

The final step is to run the simulation in the RPB after importing the terrain file and placing the facility on the terrain map. Figure 3.2 shows an image from the first-person window that was used to negotiate the facility and position the explosives within the facility's basement. Once in place, the simulation is run and pertinent information about the environment for each room of the facility can be viewed in a text window, or illustrated within the 3D environment. In this case, respondents can inspect the extent of chlorine dispersed throughout the facility. As indicated by the red shading in Figure 3.3, the 3D window shows that shock destroyed the interior partitions and fragments penetrated the chemical storage containers.



Figure 3.2: First-person view before detonation.



Figure 3.3: First-person view after detonation.

4.0 FUTURE DEVELOPMENT

The following outlines proposed enhancements to future versions of the software.

- The current software does not model the progressive collapse phenomenon, nor does it account for structural integrity losses from thermal effects. A matrix representation of the facility is proposed to improve the automated structural designer routine and permit a framework for a new collapse algorithm.
- The current FE is limited to rectangular building plans. Future versions of the FE could include: arbitrary building plans and shapes, courtyards designs, multiple tower facilities, and rooms with arched ceilings and unrestricted heights.
- The current software is restricted to internal blast calculations. Future versions could include provisions for modeling explosions external to the facility and means to handle shock wave and chemical agent re-entry.
- In the future, it is proposed to incorporate detailed damage models that better predict fragmentation and partial damage of compromised structural elements and equipment. This would lead to better prediction of the overall structural integrity of the facility as well as provide a means for depicting more realistically the damage caused by the event.
- Future versions will aim to increase the realism of the scene with multi-textures. Multi-textures would provide a means of showing damage to walls, floors, beams, and columns although the elements themselves might still be intact, but at reduced capacities and stiffnesses.
- The current version requires the user to launch SCIPUFF outside of the RPB application. Future versions could interface directly with SCIPUFF and include capabilities to overlay transport results in the regional terrain map window.
- The current software is restricted to single or multiple simultaneous detonations. A more realistic prediction of the environment would include collateral effects from sympathetic detonation or burning of affected storage containers.
- The software must be subjected to and pass comprehensive and rigorous testing programs before operational use is recommended.

5.0 CONCLUSIONS

The software discussed in this paper integrates state-of-the-art time-constrained engineering modules on blast, fragments, structural damage, and chemical dispersion with virtual reality technology. The goal of this integration is to produce a tool that may prove useful to emergency personnel for both training and planning for responses to assaults on buildings. In support of this objective, the software uses a COM based architecture, which makes it extensible, scaleable, and customizable. As a proof of concept, the predicted consequences resulting from a terrorist incident involving a vehicle bomb detonating within the underground chemical storage area of a five-story building is demonstrated. The simulation illustrates the steps required to create a realistic incident and obtain information on anticipated casualties, agent dispersion, and structural damage from fragments and blast pressure-impulse. The software's first-person walk through option depicts for each room the predicted temperature, agent release, and damage to both equipment and the building's structural members. Although the software currently remains early in its development cycle, the proposed enhancements would make an operational version of the software feasible.

6.0 ACKNOWLEDGEMENTS

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7.0 REFERENCES

1. Britt, J. R., Ranta, D. E., Joachim, C. E., *BLASTX Code, Version 4.2, User's Manual*, ERDC/GSL TR0102, Science Applications International Corporation, St. Joseph, LA, March 2001.
2. Pierce, T., *MBLM Version 42c User's Reference Manual*, DTR-96-15508, Maxwell Technologies, Inc., La Jolla, CA, September 1996.
3. Frank, R.A., Lorence, J. L., Shope, R. L., Lavelle, F. M., *Munitions Effects Assessment Module for Building and Bunkers Version 4.0 Methodology Report*, Applied Research Associates, Raleigh, NC, June 2001.
4. Sykes, R. I., Parker, S. F., Henn, D. S., Cerasoli, C. P., and Santos, L. P., *PC-SCIPUFF Version 1.2PD Technical Documentation*, ARAP Report No. 718, Titan Corporation, Princeton, NJ, September 1998.