The Current State of the Vulnerability Assessment and Protection Option (VAPO) Software Program and its Applicability to the Explosives Safety Community

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Abstract:

The Defense Threat Reduction Agency (DTRA) started the development of the Vulnerability Assessment and Protection Option (VAPO) in 2003 to address the need for an integrated, GIS-based, 3D modeling and simulation tool for Department of Defense vulnerability assessors. The key methodologies that have been assembled include airblast, fragmentation, structural damage, glass damage, structural collapse, and human injury. As the VAPO user base has expanded over the years, the current VAPO 6.0 software tool has been pushed to its technical limits in the size of allowed calculations.

This paper describes how the VAPO 7.0 codebase has been developed over the past couple of years into a plug-and-play architecture with plug-ins created for the vulnerability assessment community. A Software Development Kit (SDK) is being developed for the government community that allows other agencies to create their own plug-ins to address their specific use cases that involve high explosive modeling. DTRA hopes that having a systematic way of sharing engineering methodologies using a shared architectural foundation will allow more agencies to collaborate and re-use engineering models, while saving the costs of re-developing similar codes and allowing funds to be directed towards truly unique problems that have not been solved in the past.

Background

The Vulnerability Assessment and Protection Option (VAPO) program was started in 2003 as a seed effort to collect requirements and survey the current state of software for vulnerability assessments. Operational groups within the Defense Threat Reduction Agency (DTRA), including the Joint Mission Assurance Assessment[1] (JMAA) and the Balanced Survivability Assessment (BSA) teams, were in need of a more comprehensive GIS-based assessment tool to better convey their findings and recommendations to decision makers at the assessed sites. VAPO was initiated to both create an end-to-end tool for vulnerability assessors as well as to create modeling and simulation visualizations that could be understood by non-engineers who needed to prioritize budgets for facility upgrades and retrofits.

In 2004, VAPO 1.0 was released to the DoD community. Since 2004, DTRA has consistently released new versions every 12-18 months. VAPO is fundamentally an integration of many engineering methodologies, with a long history of weapons effects testing and modeling. The software capitalizes on over 60 years of research investments by the DTRA and its partners. In addition to a substantial pool of antiterrorism research, VAPO uses research conducted for weapon development or offensive attack planning to develop protection-conservative models to better protect US and allied facilities from terrorist or military attacks. The program combines a diverse set of fast-running threat environment and vulnerable asset response models into a single integrated workflow.

Today, DTRA distributes VAPO throughout the DoD and US Federal Government as well as to state and local law enforcement through an agreement with DHS S&T and to allies through international R&D project agreements. VAPO has found a variety of uses with different communities with the primary use cases being vulnerability assessments for force protection, mission survivability, or major event planning.

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[1] Previously known as the Joint Staff Integrated Vulnerability Assessment (JSIVA) teams

<u>Primary Capabilities</u>

The first step in most vulnerability assessments is the characterization of the site of interest. VAPO tries to balance the need for quick modeling of a site and the assessors desire to accurately model the specifics of a particular location. A primary capability of VAPO is to model the above ground buildings of a site. Over the years, the approach to modeling buildings has been enhanced to include different levels of modeling based on the available data to the assessor and the need to model larger facilities. Before modeling particular buildings on the site, however, a user typically first ingests data to provide context to the building modeling. VAPO can import various formats of georeferenced and non-georeferenced imagery. In addition, VAPO can ingest various formats of elevation data to model the surrounding terrain. Figure 1 shows a scene with varying elevation and imagery draped over the site.

Figure 1. Terrain and Imagery in VAPO

Once imagery and terrain have been imported, the user typically models the buildings of interest on the site. VAPO can model the exteriors and interiors of buildings. The main caveat for buildings with interiors is that the wall layouts have to be orthogonal to each other. Figure 2 is an example of a typical multi-story office building created in VAPO. A two-dimensional editor exists in the tool that allows the user to customize the layout and individual components of the building. VAPO explicitly models walls, slabs, windows, columns, and beams in the building. Figure 3 is an example of s specification sheet in VAPO that allows the user to characterize a wall component. One of the major components of VAPO is the Automated Structural Designer (ASD). Once the user has defined inputs such as the type of building, number of stories, types of structural components, etc., the ASD module encapsulates building design codes such as ASCE 7-10 to size the structural members of the building. The goal of the ASD is to design a building that is realistic, without the user needing to be a structural engineer to ensure the building is a reasonable model that considers standard live, dead, and wind loads.
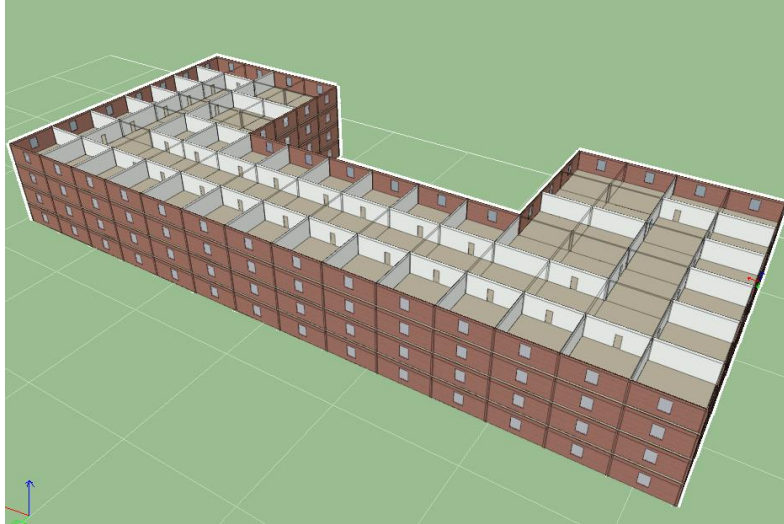
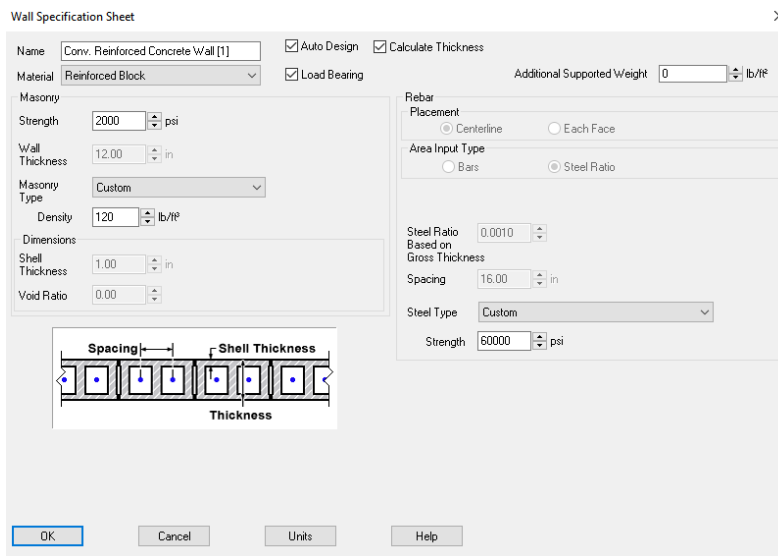*Figure 2. Building with Interior in VAPO*

Figure 3. Specification Sheet in VAPO

After the first version of VAPO was released, it became clear that users needed a way to model much larger buildings and not be limited to the orthogonal constraints of the building types in VAPO 1.0. In version 2.0 of VAPO, shell buildings were introduced eliminating the orthogonal constraints of regular buildings. Shell buildings can also be much larger than regular buildings because of the lack of explicit interior modeling. Figure 4 shows a typical example of a shell building in VAPO. One lacking feature of shell buildings is that the Automated Structural Designer does not apply to these types of buildings, thus the user has to manually input reasonable structural properties to make a realistic building.

The last significant addition to characterization of structures in VAPO occurred with the release of version 6.0. For the past five years there has been a tremendous increase of feely available 3D models on websites such as Trimble's 3D Warehouse. Various users requested the ability to perform assessments on large, unique venues such as stadiums or skyscrapers. In order to partially address this need, VAPO includes the ability to import COLLADA models. The main problem with these types of models is that they are typically intended for use in visualization only. They may look realistic, but from a structural or physical standpoint they are lacking in any meaningful detail. In order to allow for these models to be included in any type of VAPO calculations, these models have to be pre-processed in order to

ensure they are water-tight and suitable for the airblast calculations. Figure 5 shows an example of a COLLADA model imported and calculated against a VBIED.
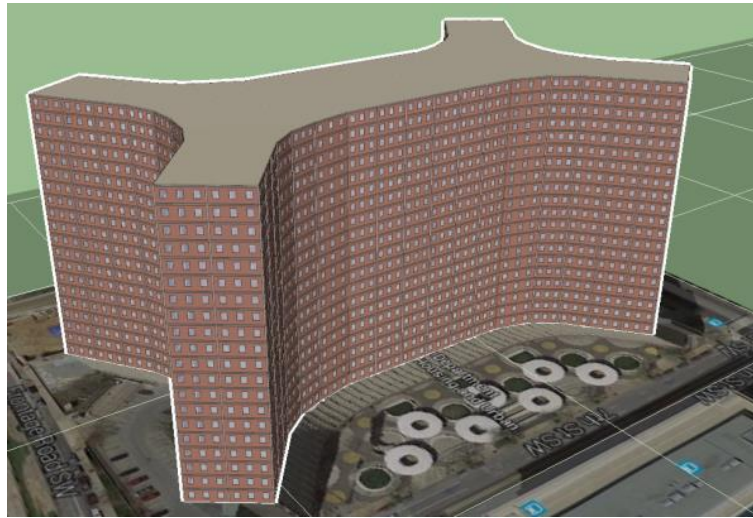

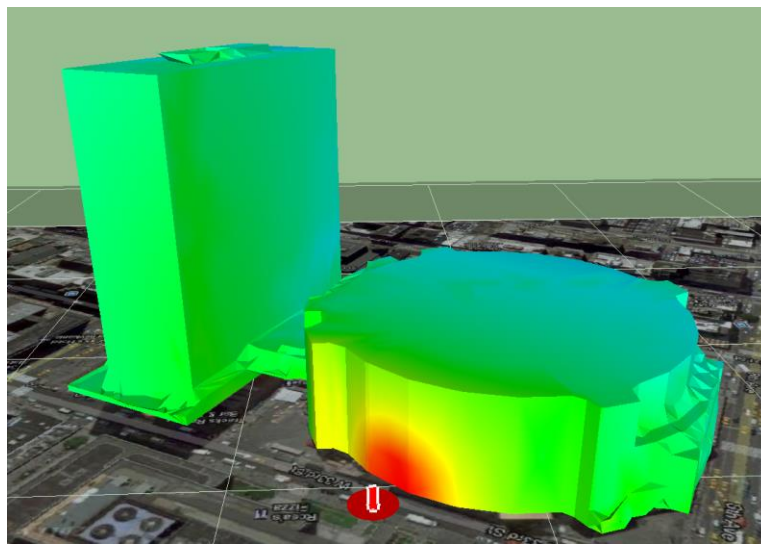*Figure 4. Shell Building in VAPO*

Figure 5. Imported COLLADA Model in VAPO

Once a user has characterized their site sufficiently, the logical next step in VAPO is to start various types of analyses to provide the assessor and decision makers answers to their "what-if" questions regarding potential threats on the site. One of the most used features in VAPO are the contour calculations. Various categories of contours exist in VAPO including worst structural, per structural, Unified Facilities Criteria (UFC) based, and user-defined. The structural contours in VAPO utilize a simple airblast routine and the structural component properties of the first floor of the buildings on the site to compute stand-off distances for the various levels of damage prescribed by the US Army Corps of Engineers Protective Design Center (PDC) [PDC-TR 06-08]. Within the structural damage category of contours, VAPO can calculate standoffs based off the walls, columns, roof slab, or windows of a building. The user can also select the desired charge weight to calculate the contours against. Figure 6 shows a small site with structural contours shown for Moderate, Heavy, Hazardous, and Blowout failure of walls. Since VAPO models individual building components explicitly, contour distances can vary based on the varying types of

construction in a single building (e.g., retrofitted sides of a building versus un-retrofitted sides of a building). Figure 7 shows an example of a building with walls that are weaker on the west side of the building versus the east side of the building. Note how the stand-offs increase on the side with the weaker walls.
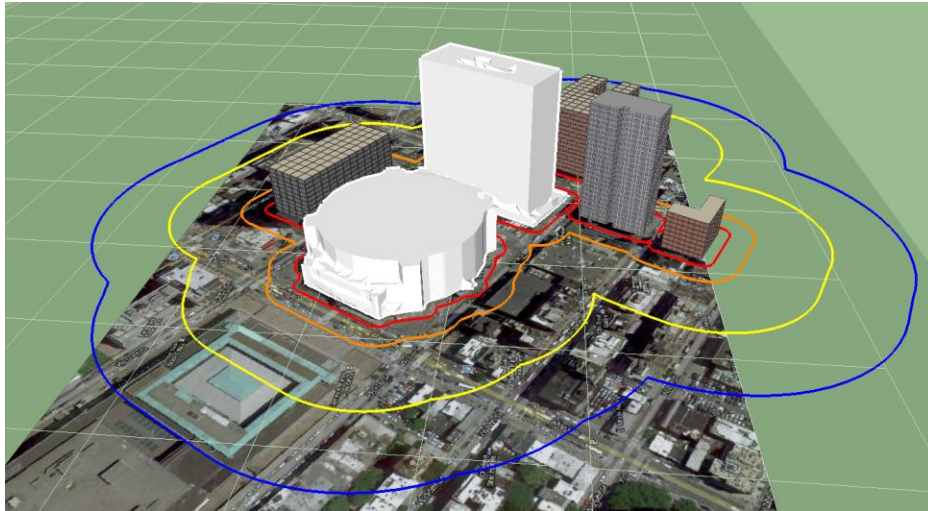

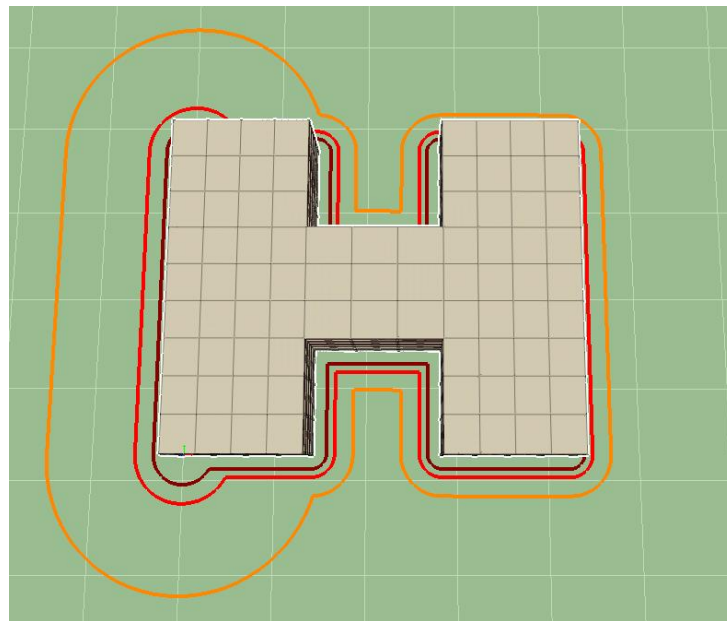*Figure 6. Structural Damage Contours in VAPO*

Figure 7. Per Structural Contours for a Single Building

Contours are a convenient and quick calculation that provides an easy to understand visualization for users and decision makers. Contours do not, however, consider any of the urban setting in the physics of the calculation. When an assessor wants to better understand the influence of other buildings on the building of interest, users need to create scenarios in VAPO. Scenarios can include buildings, equipment, free field gages (i.e., responding regions), and a threat. When a user includes multiple buildings in a scenario, VAPO calculates reflections from surrounding buildings that may enhance the airblast environment. Frank [2011] goes into detail on how an urban environment is

calculated using various fast-running methodologies. *Figure 8* depicts a scene with multiple buildings and an array of free field gages (i.e., responding region). The color map shown is a visualization of impulse values across the site. Note the distinct regions of higher impulse due to the complex geometry of the scene. You can see the areas where blast wave reflections are combined and result in higher accumulated values of impulse.
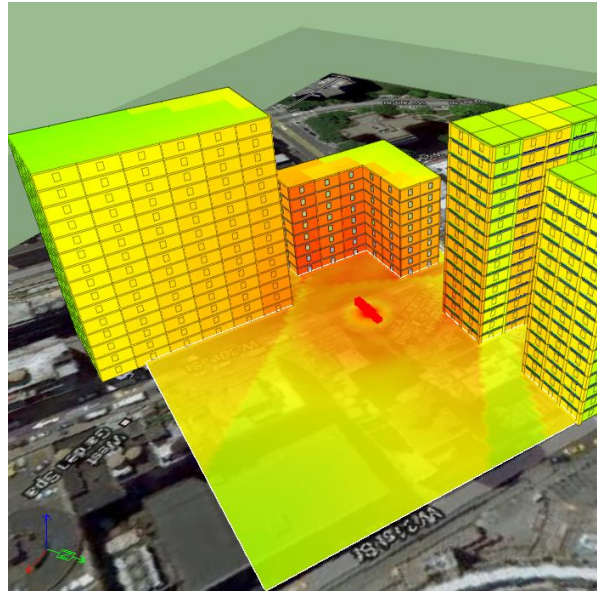

Figure 8. Per Structural Contours for a Single Building

In addition to airblast phenomenology, VAPO models other early time blast effects including fragmentation and cratering. Fragmentation is primarily a line-of-sight calculation that accounts for drag and gravity of the individual fragments. Fragment properties can be used as an input to other damage methodologies including equipment damage and human injury. *Figure 9* shows an example of a Person-Borne Improvised Explosive Device (PBIED) with the associated fragmentation energy. Cratering is computed in VAPO leveraging the curves from UFC 3-340-01, "Design and Analysis of Hardened Structures to Conventional Weapons Effects." *Figure 10* shows a cross-section of crater for a VBIED.
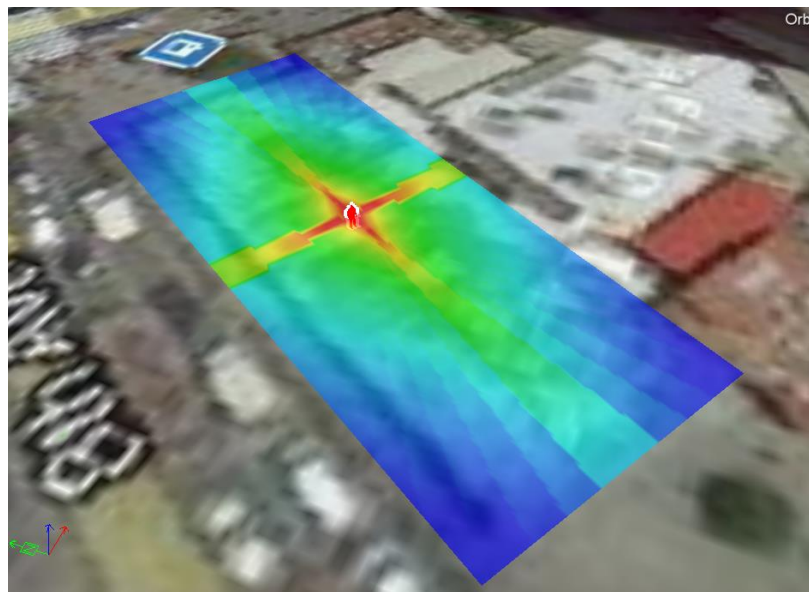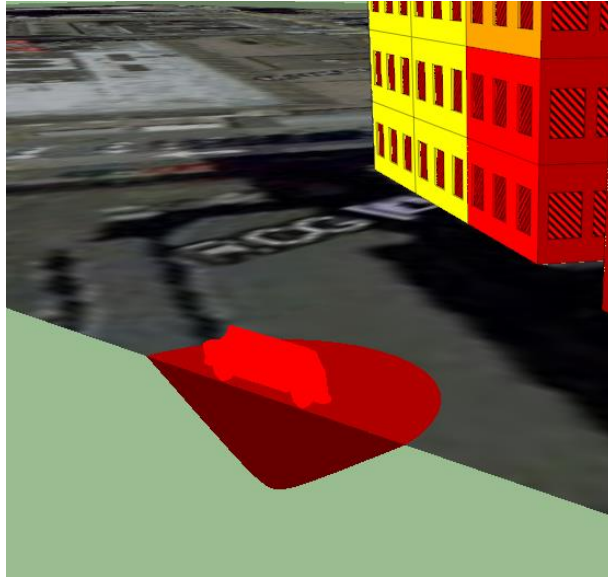

Figure 9. Fragmentation Energy for a PBIED

Figure 10. Cratering in VAPO

Another key output of VAPO is the damage to individual components of a facility (*Figure 11*). VAPO contains various damage models to components like walls, slabs, columns, beams, and windows. Most of the calculations for damage are some variation of a single-degree-of-freedom model, with damage criteria set by the US Army Corps of Engineers Protective Design Center [PDC-TR 06-08]. The primary damage methodology for both structural components and windows comes from the Single-degree-of-freedom Blast Effects Design Spreadsheet (SBEDS and SBEDS-W) [PDC-TR 06-01]. For very large sites, the user can manually choose to run a pressure-impulse damage methodology derived from the Component Explosive Damage Assessment Workbook (CEDAW) [PDC-TR 08-07]. Both the SBEDS and CEDAW methodologies assume a uniform loading on the building component, which isn't always applicable to close-in detonations such as satchel charges against a column. In those circumstances, the user can choose a breach or multi-degree-of-freedom model called the Column Blast Analysis and Retrofit Design (CBARD). *Figure 12* shows plots from the various building component damage methodologies. One of the last methodologies to run on the building determines the level of collapse. VAPO has two different models for collapse. One model is a simple load path collapse model that does not consider catenary forces and connection failure. A more sophisticated model was added to VAPO in version 5.0, namely the Progressive Collapse Analysis Tool (ProCAT). This model accounts for connection strength and can model catenary forces more accurately. *Figure 13* shows a screenshot of a collapse scenario in VAPO.
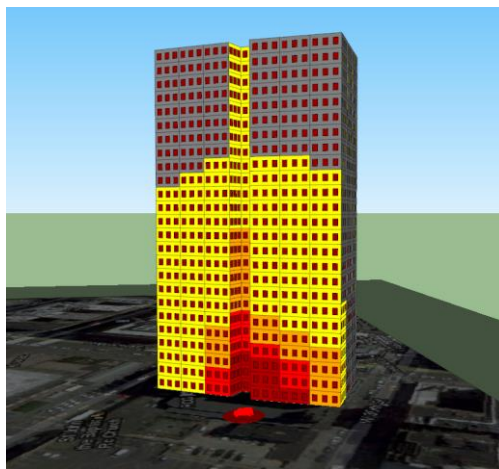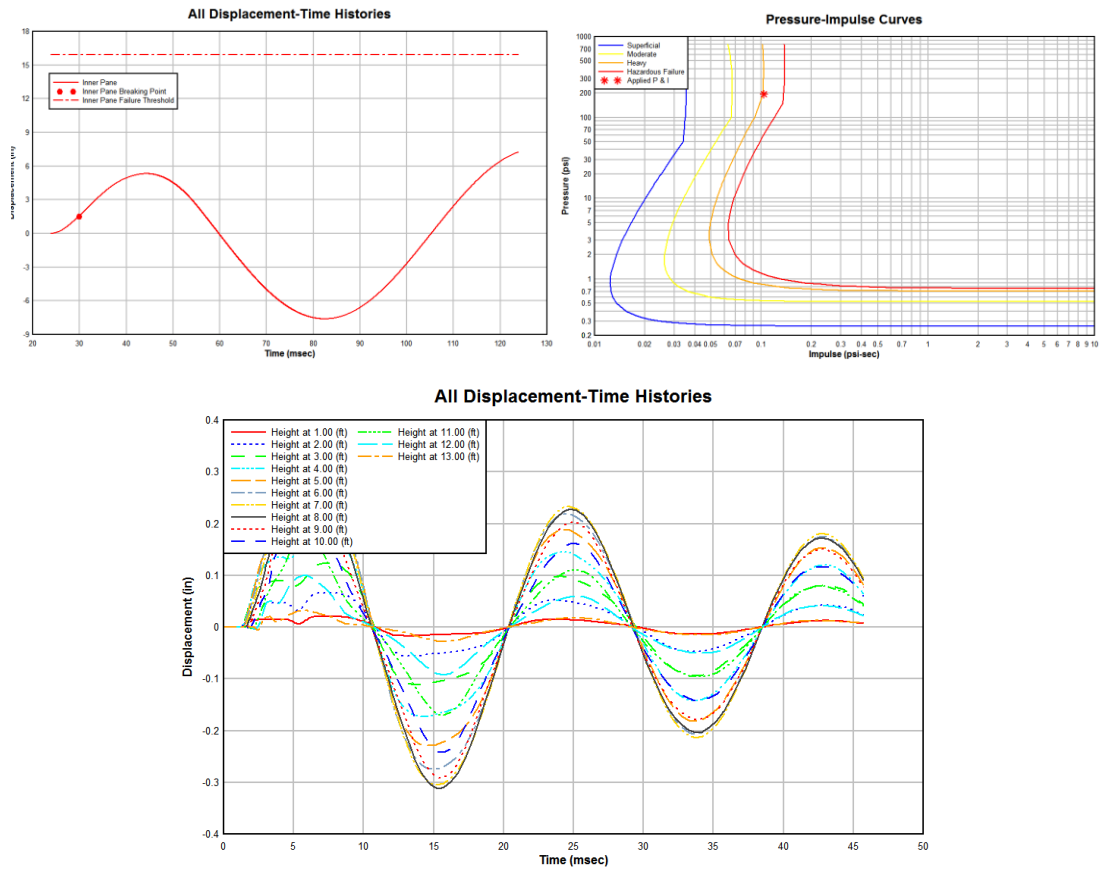

Figure 11. Structural Damage in VAPO

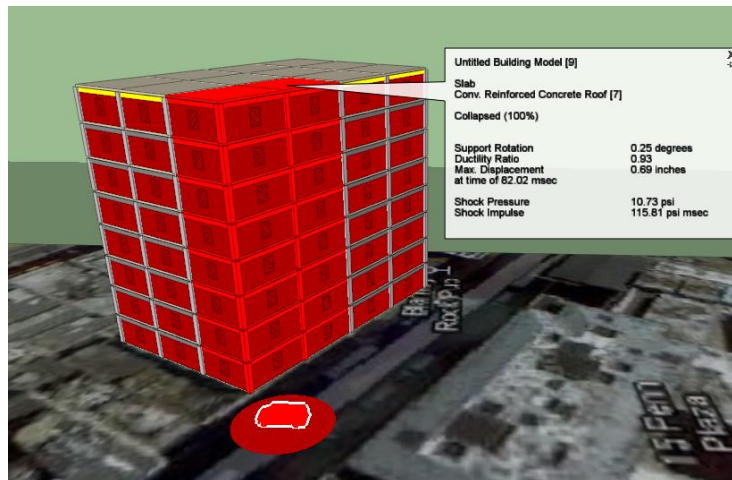Figure 12. SDOF, P-I Curves, and MDOF Plots from VAPO

Figure 13. Collapse in VAPO

One of the more critical metrics of an assessment is the number of injuries estimated for an explosive event. For injuries inside a building, VAPO relies on the Building Injury Calculator and DatabaseS (BICADS) methodology [Oswald 2005]. This methodology determines the injury of occupants near the exterior of a building (i.e., glass and

wall debris injuries) and the interior of a building (i.e., airblast and ceiling debris). *Figure 14* shows an example of injury predictions for both and external room and internal room of a building. For injuries outside of buildings, DTRA collaborated with the UK Defence Science and Technology Laboratory (DSTL) on integrating the Human Injury Predictor (HIP) model. This model looks at both the airblast environment and fragmentation environment to probabilistically compute injury levels. *Figure 15* depicts how HIP categorizes injuries in a responding region.
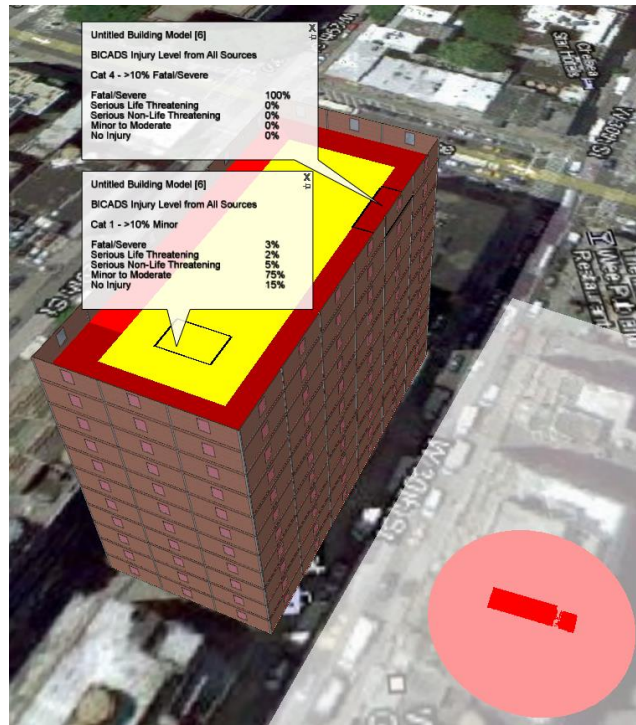

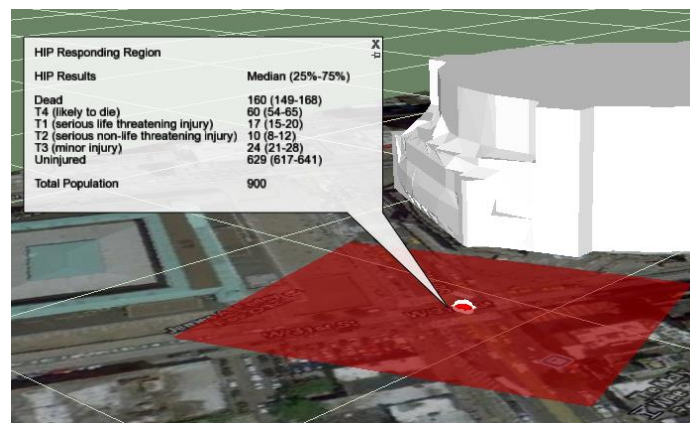*Figure 14. Building Injuries in VAPO*

Figure 15. Exterior Injuries in VAPO

<u>Current Work</u>

The first version of VAPO (2004) was developed off of a codebase that already had an extensive history (> 10 years). After six versions of the product, many of the limitations that are foundational to the codebase started to prohibit the development of new features users were requesting. In addition, the open source modeling community was developing numerous data format standards that VAPO could not ingest (e.g., OpenStreetMap data, Terrain Tiles on Amazon Web Services, etc.).

In order to address some of the more fundamental limitations of scale and heterogeneous data formats, DTRA started a new codebase (i.e., VAPO 7.0) to re-architect some of the core components of VAPO and to address fundamental technical limitations such no interiors on non-orthogonal building outlines. Technical limitations were not the only motivation for starting from the ground up for VAPO 7.0. Over the years, international interest in VAPO has steadily been increasing. Every time a version for a specific international partner was created, parts of the code had to be manually removed in order to comply with export control regulations. This process was tedious and expensive to produce one-off versions for each international partner. In order to quickly configure and release VAPO versions with our international partners, the new codebase had to address these configuration issues.
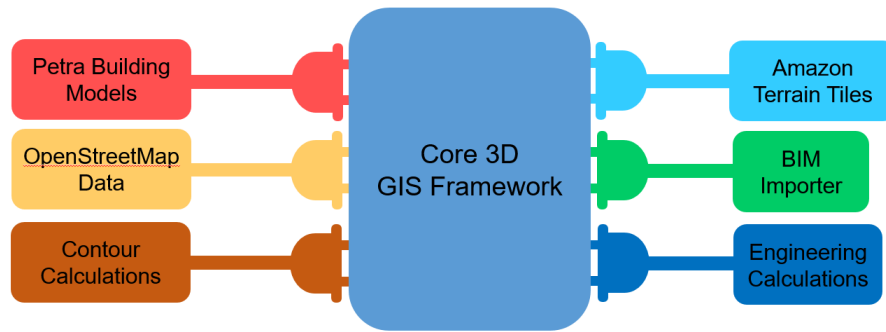

Figure 16. VAPO 7.0 Plug-in Architecture

When starting the development VAPO 7.0, the development team decided that there would be a core framework agnostic to any particular modeling and simulation domain. *Figure 16* depicts how a domain-specific application like VAPO is assembled through the configuration of plug-ins. The 3D, GIS core framework depicted in the figure is agnostic of any modeling and simulation domain and provides functionality common to any 3D modeling and simulation application. Software developers must develop domain-specific plug-ins in order to create an application like VAPO. There are a few major advantages to enforcing this plug-in design system. First, configuring an application to meet the needs of international agreements becomes much easier; the development team can easily add or remove plug-ins that are approved to be shipped to international partners. Secondly, the modeling and simulation domains that the software can accommodate are extremely configurable. Over the past 15 years of VAPO usage, requirements have been submitted to cover entirely new domains such as subway systems, underground tunnels, and bridges. Having the core framework be agnostic of any particular domain allows software developers to add in the particular models of interest, while getting the benefit of a common, high performance 3D view with geo-located elements backed up by a high performance database.

Figure 17 shows a screenshot of VAPO 7.0. One of the more recently developed features is the Geolocation plug-in that allows the user to easily locate their site using the Google Maps API. The 3D window in VAPO is synchronized with the 2D map window. Other plug-ins have been developed that also allow the user to easily download imagery through Mapbox and terrain through Amazon AWS. In *Figure 18*, a large city is characterized using Mapbox imagery, AWS terrain, OpenStreetMap building outlines, and the surface modeling plug-ins. OpenStreetMap allows the user to download building outlines across the globe, and the surface modeling plug-in allows the user to quickly extrude those outlines into simple building models.
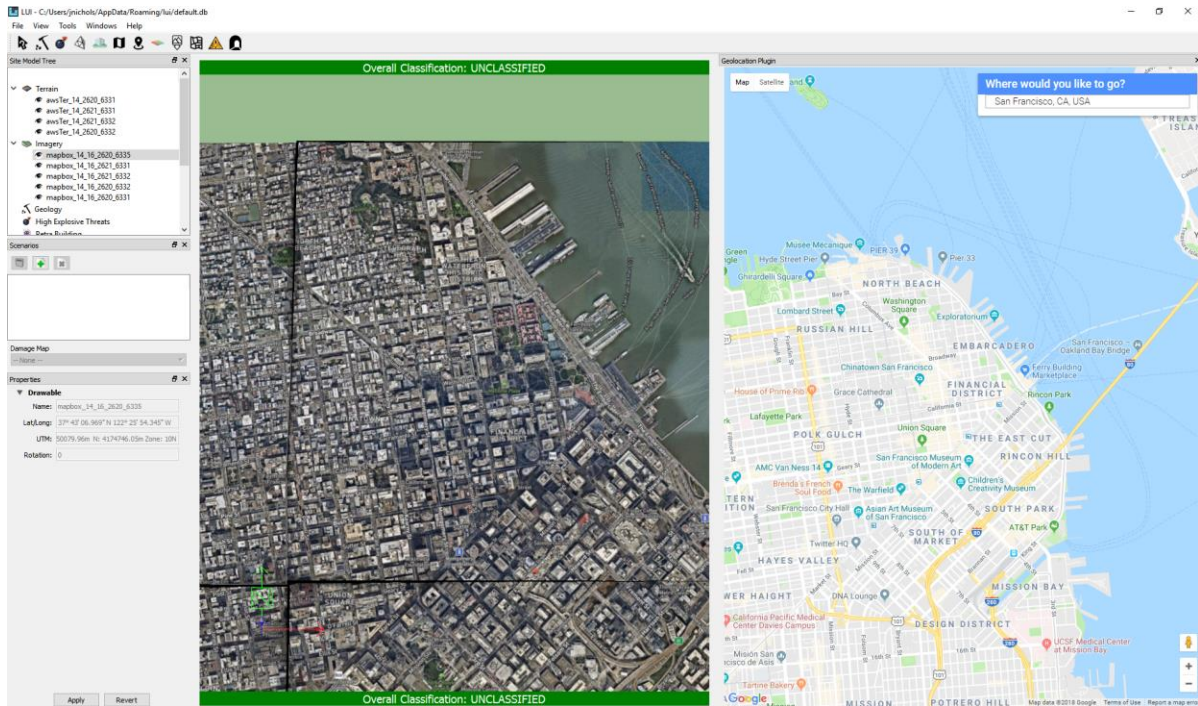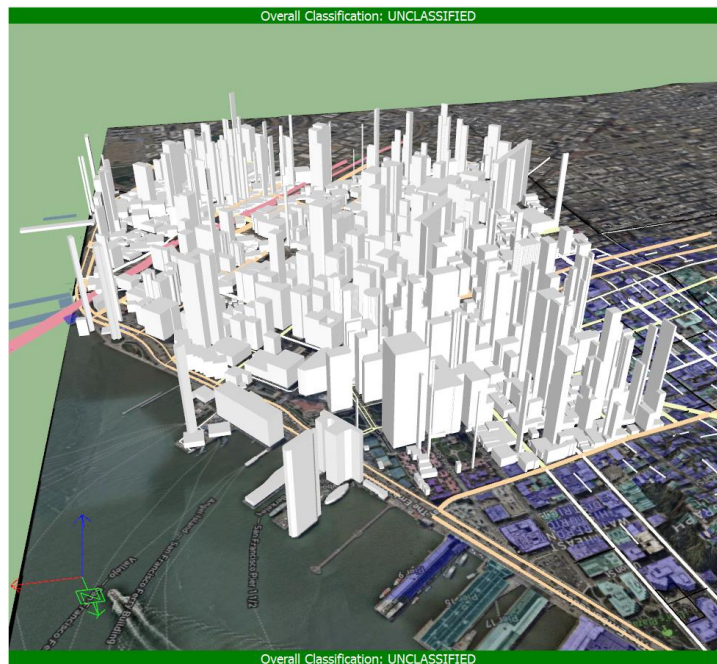
Figure 17. Geolocation Plug-in in VAPO 7.0

Figure 18. Large Scale Modeling in VAPO 7.0

Another significant feature of the new architecture is the handling of large amounts of data. With VAPO versions prior to 7.0, the vulnerability assessor was limited to the number and size of buildings they could characterize in a single database. The new architecture is designed with large scale sites in mind, such as the one shown in *Figure 18*. Key architectural concepts for both the visualization system and the database system are levels-of-detail (LOD) and

dynamic data paging. Every 3D object in the scene can be represented by multiple LOD models, so that when the user zooms in or zooms out, a higher or lower fidelity model can be loaded into the scene to optimize performance. A similar concept for the database is used to automatically load only the data in the site that the user is currently viewing or editing. Your database may contain thousands of models, but the database will only load data into memory for the 100 or so buildings you are currently viewing or calculating. *Figure 19* shows the concept of dynamic data paging in the new architecture.
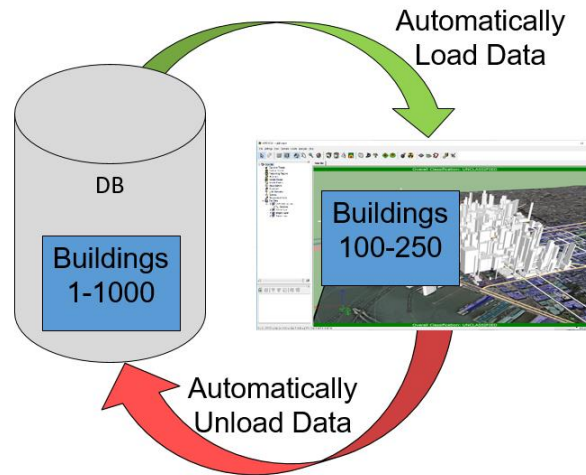

Figure 19. Dynamic Data Paging in VAPO 7.0

Calculations in VAPO 7.0 are handled by a plug-in with its own significant architecture. Similar to the core GIS framework described previously, the calculation plug-in is itself a plug-in system. Technically, the calculation plug-in utilizes a microservices design pattern that allows modular services to be connected through a routing system to ultimately compute the results that the user is interested in visualizing. The microservice based architecture allows calculation models to be easily added and removed, addressing the need to be able to quickly configure which models are deployed to various user groups. The scale of calculations has also been greatly increased as depicted by the example shown in *Figure 20*.
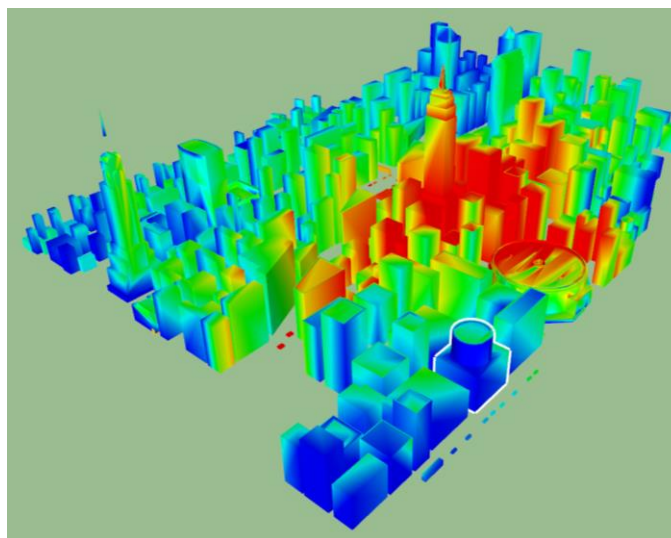

Figure 20. Large Scene Calculation in VAPO 7.0

Building characterization is a core capability of VAPO. For VAPO 7.0, a new building model design was started from the ground up. One of the main limitations of previous VAPO versions was the inability to model interior

layouts for buildings with arbitrary exterior wall layouts. This limitation, combined with the desire from other government programs to have a fully detailed building model description for other types of analyses, led to the creation of the Petra building model libraries. Petra is a stand-alone set of software components that can be leveraged outside of VAPO for other types of modeling and simulation tools. Petra is a flexible model description of a structure that can be extended to contain and store any properties a user needs for calculation or visualization. Petra contains an import and export library that allows different model formats to be imported. Currently, Petra supports the importing of Industry Foundation Classes (IFC), which is a file format that can be exported from most Architectural, Engineering, and Construction (AEC) and Building Information Modeling (BIM) tools. Currently, Petra allows the user to create non-orthogonal layouts and realistic interiors such as the one depicted in *Figure 21*. Work is ongoing to structurally layout components in these non-orthogonal layouts so that an Automated Structural Designer can properly size the components based on location and country-specific building codes.
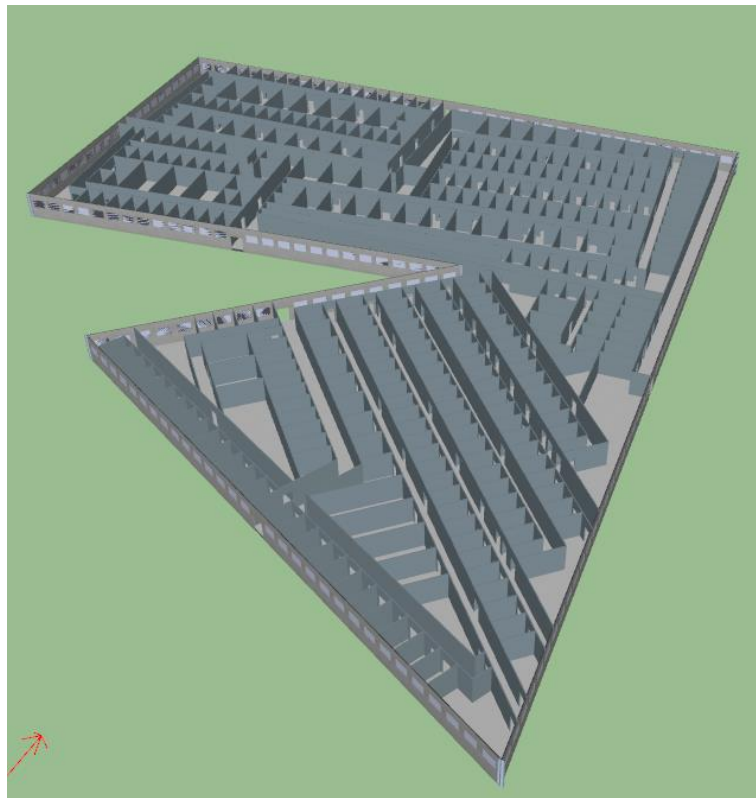

Figure 21. Petra Building Model in VAPO 7.0

More recently, DTRA has been leveraging the new architecture for domains that haven't traditionally been modeled in VAPO. Underground modeling is a domain of interest for various types of simulations. In the upcoming year, new plug-ins will be developed that allow a user to characterize the geology of a site as well as model underground structures such as tunnels. These capabilities will serve as a good test of the extensibility of the new architecture since the domain is drastically different than characterizing above ground structures. *Figure 22* and *Figure 23* show screenshots of some of the progress already made modeling geology and tunnel systems.
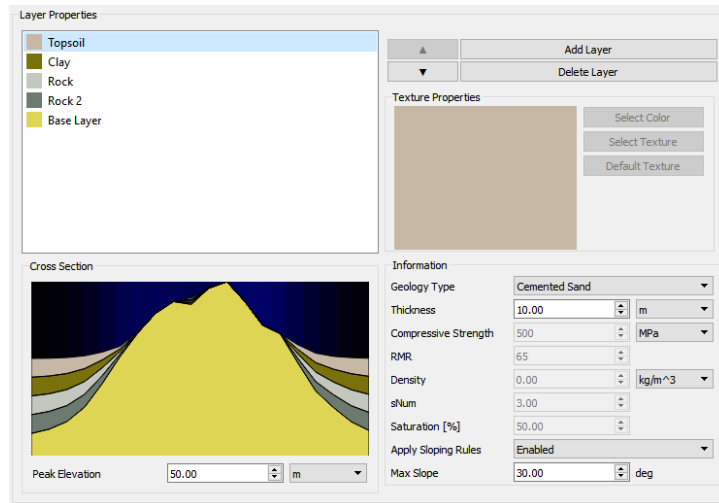
Figure 22. Geology Modeling in VAPO 7.0

Figure 23. Tunnel Modeling in VAPO 7.0

Summary

VAPO encapsulates a long history of weapons effects modeling into an easy to use interface for assessors. As the blast effects problems users have become more complex because of urban settings, underground locations, or unique threats, the VAPO program has shifted its focus to creating a new architecture that can address the scale and complexity of the questions being asked. DTRA has created a vision of the architecture that spans domains beyond just vulnerability assessments and is reaching out to other agencies and international partners to create re-usable capabilities (i.e., plug-ins) that can be shared between funders. Sharing of capabilities is a win-win from both a financial perspective and a technological perspective. In any fiscally constrained setting, providing base capabilities across multiple software products prevents agencies and governments from re-inventing the wheel and wasting funds on common capabilities that most modeling and simulation packages need. Having a core framework with shared plug-ins allow the government to focus less on infrastructure and maintenance of software and more on the ever-evolving problems in their particular domain. Regarding the explosives safety community, in particular, DTRA believes there is significant overlap of interest in characterization of structures, blast modeling, fragment modeling,

ejecta modeling, and human injury. When looking at potential explosion sites and trying to compute major separation distances (e.g., inhabited building distances, public traffic route distances, etc.), VAPO's detailed contouring capability could be of interest to the community. The new structure characterization efforts (i.e., Petra) should allow the modeling of structures specific to explosive storage. DTRA hopes that this high level overview of VAPO and its capabilities can initiate ongoing discussions on how the explosives safety communities modeling and simulations interests can be coordinated and shared with the DTRA's mission to combat and protect against improvised threats.

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