Case Study of the Application of Gurney Equations to Simplified Shrapnel Lethality Estimation in Comprehensive Military Utility Analysis Models

Paul Vogel
Northrop Grumman Information Technology, TSAC
Socorro, NM
pvogel@nmt.edu

Dr. Seokbin Lim
Dept. of Mechanical Engineering, New Mexico Tech
Socorro, NM
lim@nmt.edu

ABSTRACT

It has become common practice to employ comprehensive simulations in performing military utility analysis (MUA) to evaluate candidate military systems and architectures. But the accuracy and flexibility of these simulations rely on accurate individual models focused on detailed resolution of local events. This study evaluates the efficient and advanced employment of the Gurney equations within the context of a comprehensive MUA model. The resulting model evaluates a wide range of criteria including multiple mixed detonations, target armor, warhead placement and endgame maneuvering, buildings and terrain, and environmental criteria to estimate shrapnel lethality. The result is an efficient model that can be used either stand-alone or embedded within the larger framework. It has sufficient detail to analyze shrapnel effects in munitions ranging from the individual IEDs (Improvised Explosives Devices) employed in asymmetric warfare up through the employment of alternate artillery rounds in conventional warfare. This model evaluates individual warhead detonations by predicting shrapnel velocity and geometric distribution based upon the type and amount of the core charge, physical properties of the outer casing creating fragments, the incoming vector velocity of the warhead, etc. Burst density and a kinetic energy distribution are derived from these factors. These are compared to the presented vulnerable area of all targets within the region in lethality evaluation. When embedded in the JFORCES simulation environment the results of this model are directly used to measure to impact on localized operations and effectiveness. In addition to introducing the model this paper includes a sample analysis to demonstrate its within a larger framework.

ABOUT THE AUTHORS

Paul Vogel has 27 years of experience in the development and use of comprehensive military simulations involving detailed representations of individual platforms, perceived information, Intelligence, Surveillance and Reconnaissance (ISR) performance, and Battle Management, Command, Control, Communications, Computation and ISR systems. He has led the Joint Force Operational Readiness and Combat Effectiveness Simulation (JFORCES) simulation development since 1987. He has developed simulation applications using this technology combining live fly, virtual and constructive simulations used in range training support and training extensions by the Wisconsin National Guard and the Egyptian Wargaming System. He has also developed comprehensive closed loop military utility analyses focusing on ISR and communications architectures. Mr. Vogel currently works for Northrop Grumman and is a graduate student in Mineral Engineering and Explosives Technology at New Mexico Tech.

Dr. Seokbin (Bin) Lim is an Assistant Professor of Mechanical Engineering Department at New Mexico Tech, expertise in energetic materials. His research efforts have been concentrated on the application of energetic materials in various areas including shaped charges technology, blast mitigation, shockwave and detonation, steel structure demolition, active protection system (APS), etc. He is an active member of the International Society of Explosives Engineers (ISEE).

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BACKGROUND

Both military exercises and military utility evaluations employ comprehensive models to evaluate the contribution of specific changes to overall operational performance. These models address a wide range of combat and support operations to evaluate their composite effectiveness based on the interactions between individual warfighters and systems. In exercises these models are often required to run quickly either to "fast forward" past epochs of less interest or to guarantee real-time interoperability with operational hardware including sensors, planning tools and the like. Likewise, the simulations used in military utility analysis (MUA) typically emphasize performance in their effort to permit analysts to rapidly evaluate a range of candidate system configurations. Typically this requires a tradeoff between detail and simulation extent. This is recognized in the modeling representation pyramid, shown in Figure 1. At the apex high-level models address broad representation at a perfunctory fidelity level. At the base detailed models focus though a soda straw to bore down in remarkable detail on severely limited domains. This pyramid addresses the different representational levels consistent with the trade-off between runtime performance, representational extent, and fidelity. The tradeoff between representational extent and fidelity is compounded by the multiple facets of fidelity, including temporal resolution, unit aggregation, and the mathematical rigor employed in representing specific interactions. The balance of these factors results is a multi-dimensional definition of fidelity involving the component trade-offs to match fidelity needs with execution performance.

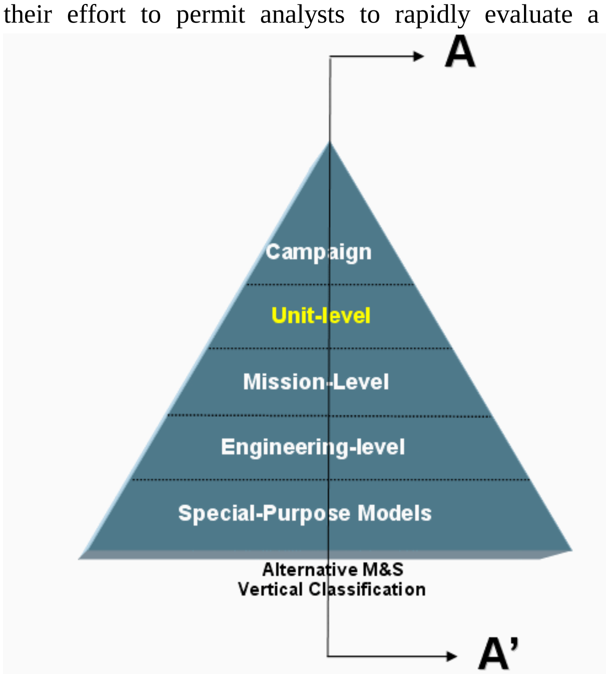


Figure 1- Modeling Representation Pyramid

This leads to the artistry of selecting a mix of models of appropriate fidelity that will interoperate within the domain of a simulation confederation. The selected models must interact with each other in a synchronized execution. They pass information using a common language that might be dictated by either a rigorous standard (e.g. DIS), or confederation-specific agreement (e.g. HLA). By their nature the broader-based simulations provide a canvas of operations within which the system level models evaluate component effectiveness. Results from relatively detailed component models are broadcast to the federation, which in turn folds these detailed results into the overall operational flow and ebb. Hence having a stable of selectable detailed models is required to dial-in the appropriate local fidelity for the current use and performance requirements. This paper describes the development of a shrapnel lethality model to augment the Joint Force Operational Readiness and Combat

Effectiveness (JFORCES) scenario model, originally built to evaluate and train Command, Control, Communication, Computing, Intel, Surveillance and Reconnaissance (C4ISR) concepts. In this application the described shrapnel model bolstered a shortcoming of the scenario model to accurately assess the impact of improved command and control in operations. On a larger scale the interface to this model was developed generically to support other simulation confederations as well. And it is hoped that the approach used confederating this lethality model into the selected scenario model will document a template for the incorporation of additional component-level models.

SHRAPNEL MODEL

Fundamentally the shrapnel model was developed from an initial estimate of fragment velocity based on Ronald Gurney's kinematic estimates developed during World War II. These equations provide the velocity of fragments flying from a detonation based on the initial fragment/explosive geometries, masses, and the explosive energy. The results can be combined with the detonation velocity to provide an initial fragment velocity vector relative to initial plate configuration for the fragment centroid. These specifications are adequate to evaluate the initial fragment spray pattern for the explosive. Table 1 describes the geometries addressed by this model and the core velocity equations used for each. In this table M is the total fragmentation mass, C is the charge mass, E is the specific explosive energy in $(km/sec)^2$, and v is the resulting velocity in km/sec. C_1 is the adjusted charge adjusted for side losses and tamping. Charge radius and height inputs also affect the effective detonation energy imparted to fragments.

Table 1 - Included Explosive Geometries

Geometry	Typical Application	Velocity Calculation
Spherical	Grenades, IEDs, Mortars	$v = \sqrt{\dfrac{2E}{.6 + M/C}}$
Cylindrical	Most Artillery	$v = \sqrt{\dfrac{2E}{.5 + M/C}}$
Flat Plate, Rigid back & Tamped	Claymore Mines	$v = \sqrt{\dfrac{2E}{.333 + M/C_1}}$

This initial velocity is reduced as the fragments propagate out from the detonation according to air drag based upon either 1) The fragment geometry specified by the user, or 2) A user-input drag profile. This permits calculation of the speed of the fragments based on the range from the detonation. Starting from this initial configuration the spray pattern propagates outward and drops from a linear projection as the trajectory is affected by gravity. Together these two factors morph from an unlimited range projectile flyout to a fountain shaped shrapnel coverage. These factors define the maximum fragment flyout range based on gravity as well as the ranges at which the fragment is "spent" as a result of drag.

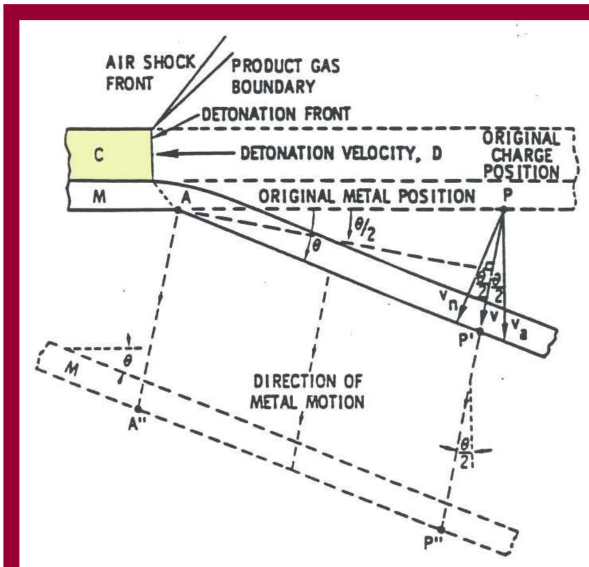


Figure 2 - Spray Pattern Variation Based on Detonation Configuration

The initial pattern is adjustable by factors that do not significantly impact the velocity estimate that are included as separate model parameters. These include the Taylor angle offset for the flyout direction. This angle is caused by the finite charge detonation velocity propagating from the detonation point relative to the initial fragment flyout velocity. The result is a deviation from the central gas expansion vector as shown in Figure 2 (Taylor).

In addition warhead designers often construct the back plane of the explosive to extend the spray angle, as is the case with the Claymore mine (Figure 3) Instead of modeling each of these aspects of warhead design discretely, this model permits the analyst to define the spray pattern appropriate to the specific geometry.

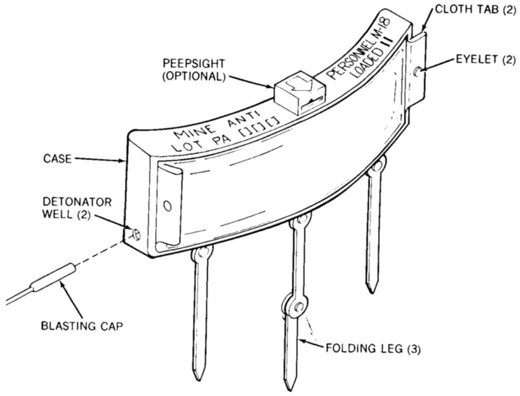


Figure 3 - Design Implemented Spray Pattern

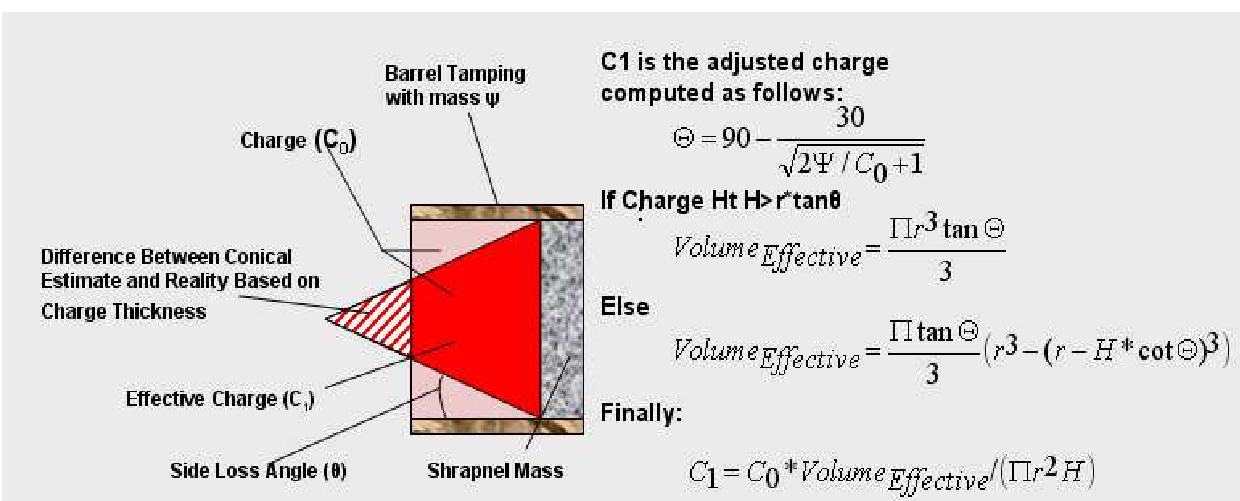
The total charge mass is adjusted according to the side losses from the explosive. The default side losses are based on a 30° setback angle, but are adjusted according to the tamping material surrounding the charge as described by Baum's analysis, summarized in Figure 4.

The core fragment velocity estimate provided by this model is further adjustable according to additional factors that reflect the developers' interest in using this model in determining the effectiveness of improvised explosive devices that might be used in asymmetric warfare or homeland security applications. First among these additional factors is the packing density of the fragmentation material. This factor is important in improvised explosives designed to wound civilians, for example the proverbial suitcase bomb packed with a charge and nails. An adjustment to the Gurney equations is required to model the gaseous losses around the relatively loose packed nails. The Gurney equations were originally designed to model simpler configurations, like a homogeneous layer fragmentation material over an explosive core as found in simple artillery warheads. Work by Kennedy and Chou has indicated that the reduction in velocity can be represented by estimating the decoupling effect of air volume in successive layers in the assembly of nails.

TARGET VULNERABILITY MODELING

The target vulnerability model consists of two distinct components, a target vulnerable region profile and a line-of-sight obstruction model. Given the size and type of fragments that this model addresses, an uninterrupted flight path is required between the detonation and the target. So the modeling includes only substantial line-of-sight obstructions that would impede the fragment. These include the terrain and curtain walls. The organic line-of-sight model built into this application is a straightforward employment of a user-provided matrix of elevation data representing the composite terrain elevation overlaid with any substantial man-made obstacles including buildings and walls. But the programming interface to this model includes the ability to override this representation with any routine runtime-linkable to the application. Given this, the more mature JFORCES line-of-sight model was employed. This model uses digital terrain elevation data (DTED) data directly and overlays this data with the community building specifications for building footprints and heights. This relieves the user from explicitly defining the local terrain and also

Figure 4 – Explosive Energy Side Losses



permits the rapid evaluation of mixed target vulnerability over an entire region or route. Figure 5 provides a visual representation of possible impact zones for a focused detonation.

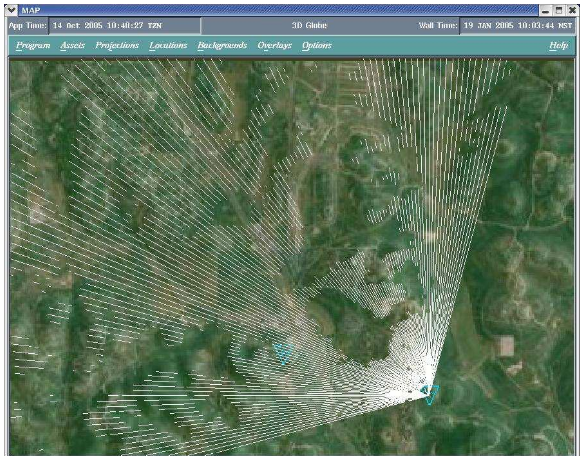


Figure 5 - JFORCES Terrain Obstruction Analysis Incorporated into Vulnerability Model

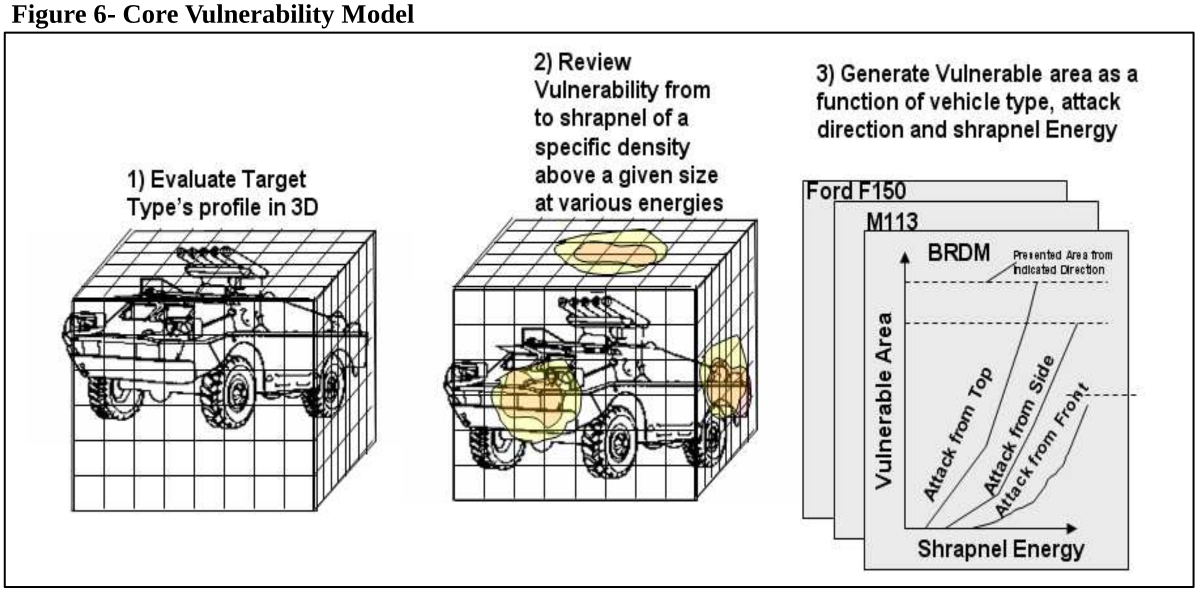
This model supports a traditional armor vulnerability model profiling the vulnerable area of any vehicle (or human) configuration using the vulnerable area presented from the six cardinal sides (top, bottom, right, left, front and back) for fragments with a range of different energies. As shown in Figure 6, these are defined by target class and inherited by any instance of a target type.

While these models are adequate when the data is available, this data is not always available for new or emerging designs. To compensate for this a dynamic hybrid Eulerian / Lagrangian modeling approach was used to evaluate the vulnerability of soldiers in the field to fragments from the M107 155 mm artillery warhead. Typical fragments from this warhead are about 20 grams and have an initial velocity of less than 1 km/sec (as computed using the velocity equations presented in Table 1). The actual energy of the fragment at the target is modified by the effect of drag on the fragment for the specific target/warhead geometry dictated by the scenario model. This provides the typical fragment density and energy at impact which is then cross-indexed in the vulnerability table to determine the presented vulnerable area at the scenario-defined angle of incidence. The likelihood that a fragment hits the target is based on the number of critical fragments and the presented area of the expanding front defined by the warhead's spray pattern and this vulnerable area. The decision of whether an impact occurred is then made based on a Monte-Carlo draw from a uniform distribution and comparing the result to the computed likelihood of impact.

A simple vulnerability analysis addresses armor effectiveness evaluation utilizing a commercial hydrocode AUTODYN® which is capable to model shockwave propagation in a material of interest. This software is designed for modeling the non-linear dynamics of solids, fluids, gases and their interactions especially for explosives related matter such as blast and impact (Cowler 2005). The calculation process in this hydrocode requires the complex problems to be broken into a finite number of smaller and simpler problems, and this required process called 'Discretisation'.

The hydrocode includes several solver options including a Lagrangian grid-based method modeling discrete material sections moving with the material, an

Figure 6- Core Vulnerability Model



Eulerian grid-based method modeling discrete spatial sections fixed in space, and SPH, a particle-based Lagrangian method. Each Autodyn simulation part can have multiple parts, and the different parts within each model interact with other solver options. Examples include Lagrange-Lagrange interactions, and Euler-Lagrange interactions.

In this analysis, the penetrator and target material was constructed with Lagrangian elements, representing shrapnel impact on a surface of vehicle. In order to increase the numerical accuracy in a large deformation of elements during/after penetration of the wall and to enhance detailed visual identification of the penetration process, SPH elements were used to create the steel wall structure. The wall thickness was varied 1/16", 1/8", ¼" and ½" thick representing four different vehicle armor thicknesses, and multiple virtual gauges were attached in the penetrator, steel wall and target to analyze numerical values and behaviors prior and after penetration (Figure 7).

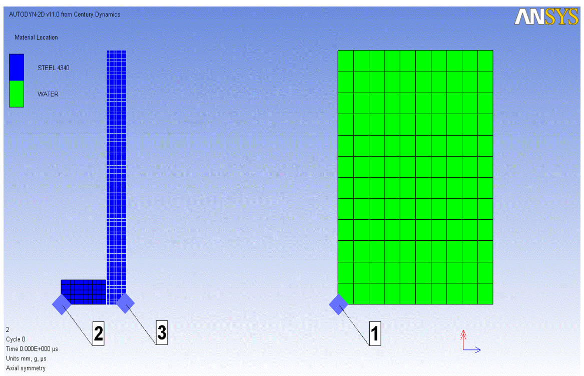


Figure 7 - Modeling Setup with Three Gauges

In addition, the velocity of the penetrator was varied 1, 0.8, 0.6, 0.4, and 0.2 km/sec to evaluate the steel wall and target behaviors. The wall height was 6in., the distance between the steel wall and target was 3in., and the height of the target was 6in. The size of the cylindrical shaped penetrator was determined based on the density of Steel 4340 and an expected individual shrapnel weight of a 155mm artillery shell, 19gram. The 2-dimensional problem statement shown in Figure 7 was rotated to a radically symmetric solution space and the pressures and velocities for both the penetrator and any additional fragments generated by the target were measured within this 3-D space. See Figure 8.

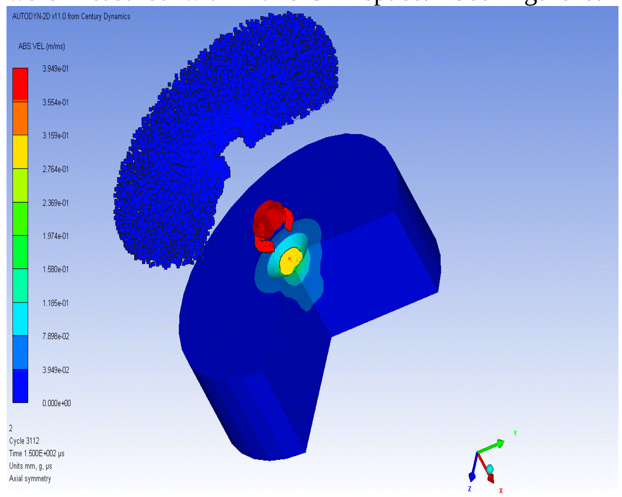


Figure 8- 3D Fragment Penetration Analysis

The simulation runs until a specific impact velocity was determined where no complete penetration was observed. A typical fragment velocity for an oblique impact is shown in Figure 9 and the testing results for the final fragment velocity after penetrating armor of each thickness are tabulated in Table 2. In the scenario used for this sample study it was decided to ignore the effects of secondary fragments generated from glancing armor impacts. This decision was made because the vehicles in the target column all had similar armor providing sufficient protection to eliminate any reasonable chance of casualty resulting from the secondary fragments. But this analysis did provide secondary fragment data that could be used a scenario considering the effects on a more heterogeneous target set, possibly including unprotected civilians.

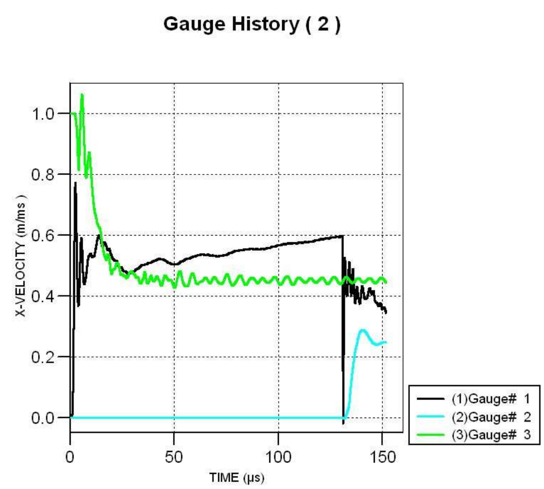


Figure 9 - 3D Fragment Penetration Pressure Model

		Initial Fragment Velocity (Km/Sec) (19 Gram Cylindrical Fragment of 4340 Steel)				
Armor Thickness		1	.8	.6	.4	.2
	½”	NA	NA	NA	NA	NA
	¼”	.44	.15	NA	NA	NA
	1/8”	.79	.61	.39	.26	NA
	1/16 ”	.9 (est)	.71	.52	.32	.09

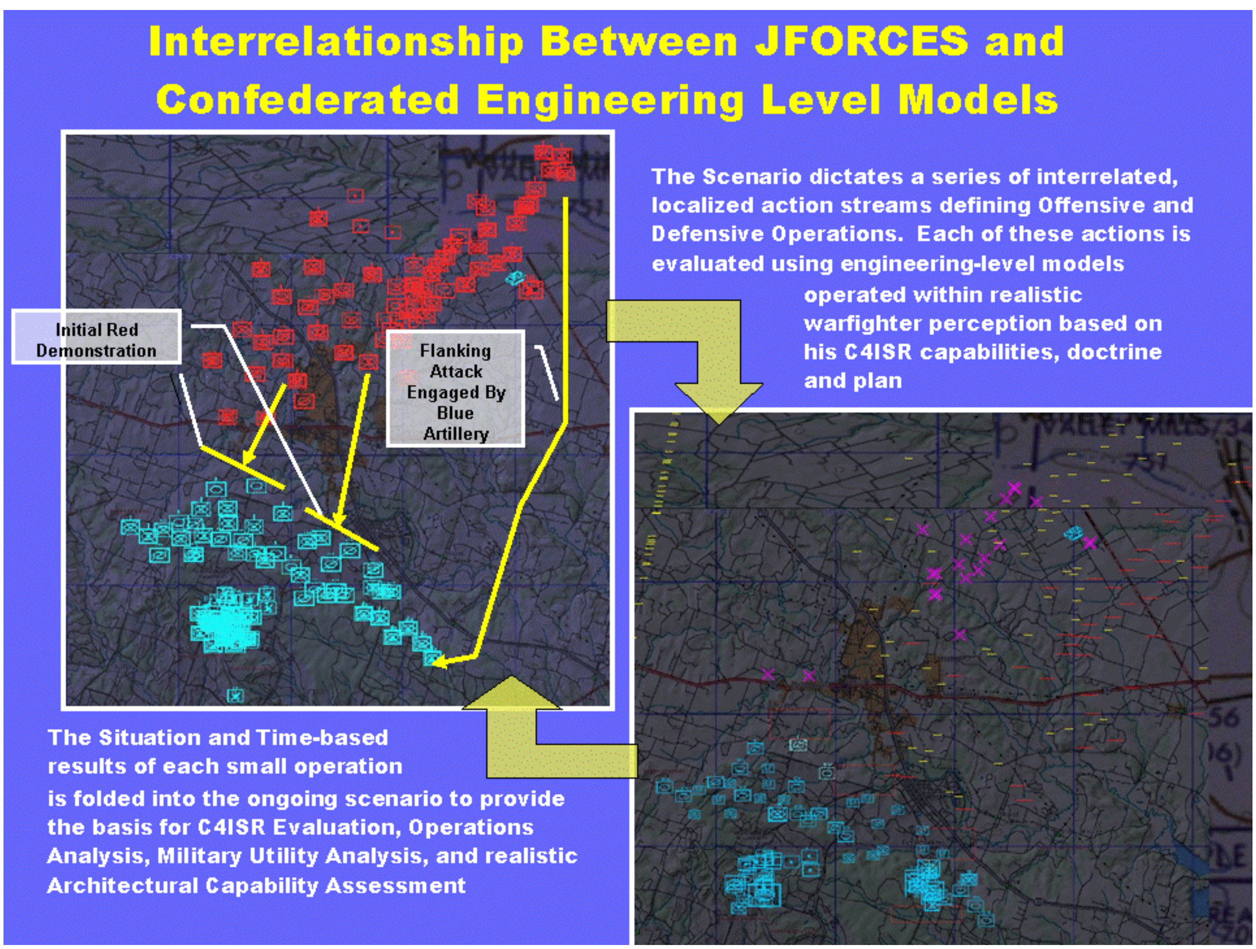
Table 2 – Final Fragment Velocity after Armor Penetration
(Oblique Impact, 4340 Steel, Results Are Primary Fragment Velocity in Km/Sec.)

SCENARIO MODEL

The JFORCES model was selected as the joint theater-level scenario model in this application. JFORCES is a government-owned simulation environment supporting a broad range of military functions such as training and readiness, acquisition support, doctrine development, requirements definition and contingency planning. This model was originally developed in 1987 to explore alternative command and control concepts using a combination of live and simulated systems and operators working in a realistically perturbed, limited perception synthetic environment. It has been used since that time in a variety of applications ranging from training and exercise support for the Air National Guard as well as being employed in military utility analyses (MUA) focusing on ISR and communications analysis. It is used for MUA studies by Air Force Research labs, the National Security Space Office, and the Transitional Satellite programs.

Critical to the core application, JFORCES is constructed around a message-passing executive supporting inter-process communication for real-time, distributed, parallel processing. This environment also provides a robust set of analyst-oriented or operator-oriented interfaces for pre-simulation configuration, scenario generation, runtime controls and post-process analysis. These provide realistic information on the quality, timeliness and completeness of information available to decision makers during military operations.

Figure 10- Component / Aggregate Interaction within JFORCES Scenarios



This information includes both real and false (fog-of-war) information using messages consistent in content, detail and rate-of-presentation with live systems. It is capable of executing either real-time or faster scenarios, involving high-fidelity, platform-level representation of tens of thousands of entities. The JFORCES architecture accommodates simulation activities spanning the conflict spectrum, from entity-level of detail to full theater-level and campaign-level functionality of weapons, sensors and communication systems.

While JFORCES provides an accurate depiction of the information available to commanders throughout operations and on the ability of the commander to maintain control of the combat and ISR assets, its organic combat models are relatively simple. While adequate to support a range of training missions, a better lethality model was desired to evaluate the combat effectiveness of the actions taken. The shrapnel model described in this paper is a step towards enhancing this capability.

The left side of Figure 10 shows the JFORCES scenario used in this study. Red is making a demonstration against a strong Blue position. At the same time a Red flanking force is circling around the Blue force on the North and will be able to encircle Blue if not detected and stopped. The left side of Figure 10 demonstrates that JFORCES accurately addresses whether the ISR plan and subsequent information distribution is adequate to task the ISR assets, communicate the raw data, process the collections and fuse them across multiple platforms, exploit the data, and disseminate the information to the warfighter. But this incorporation of the more detailed lethality (and associated morale models) extends JFORCES ability to evaluate the effectiveness of the commander's responses using the range of available scenario options. The approach to integrating the shrapnel model into JFORCES execution is consistent with the real-time, model-in-the-loop approach used in the C4ISR component integration. This approach maintains a common scenario picture at all federates within their scope of interest and generates requests for the resolution of specific events (detonations in this case). as they occur within the scenario. The results are then injected into the scenario as requests to change specific asset states (or information in the case of C4ISR) and, if deemed valid, are folded into the scenario execution stream. These changes in turn can change the situation either according to the ability to affect a mission or alter command perception (either human or modeled) and thereby indirectly affect the downstream command decisions. The implementation is described in the next section.

CONFEDERATION APPROACH

All model confederation is handled through the dynamic discovery of model presence on the system. This permits JFORCES to run regardless of whether the shrapnel model is present or not. In this case JFORCES uses its own warhead models to represent any detonations. But when a running shrapnel model is discovered JFORCES announces its scenario and sends the initial scenario profile. The shrapnel model responds by broadcasting a list of warheads that it is capable of modeling. After having received this information JFORCES will send detonation requests for any detonations of warheads of these types to the external shrapnel model instead of running these calculations locally. This approach has several advantages, including the fact that JFORCES maintains a list of models associated with each warhead type, so multiple shrapnel models can be running simultaneously and JFORCES can deconflict which model to send detonation notifications to. Also the JFORCES internal warhead lethality model can be used when higher fidelity models are unavailable. The actual implementation of inter-simulation communications is through TCP/IP connections managed through the federate services library. Figure 11 illustrates the messages passed between the scenario model(s) and the shrapnel model. The concept was to provide a complete true-information picture of all assets within the shrapnel model's area of regard. In this case the scenario employed this area of regard included all players on the ground, but in a larger scenario could be limited by region. A message for each asset currently known by the scenario model is passed at simulation handshake (which can occur at any point of the scenario). Similar initialization messages are passed for new assets as they are discovered either from live-element fly-ins or check-ins by other simulations. The shrapnel model reciprocates with a list of warhead types it models. This information is maintained at the local JFORCES model; currently there is no effort to forward this information throughout the system. JFORCES will only pass detonation information for warheads controlled by JFORCES to the shrapnel model. Lethality for detonations from warheads or assets controlled by other simulations is presumed to be addressed in the owner's environment.

The shrapnel model receives scenario laydown-information from the scenario model, but it uses its own target vulnerability and warhead fragment definitions. The definitional requirements for the shrapnel model

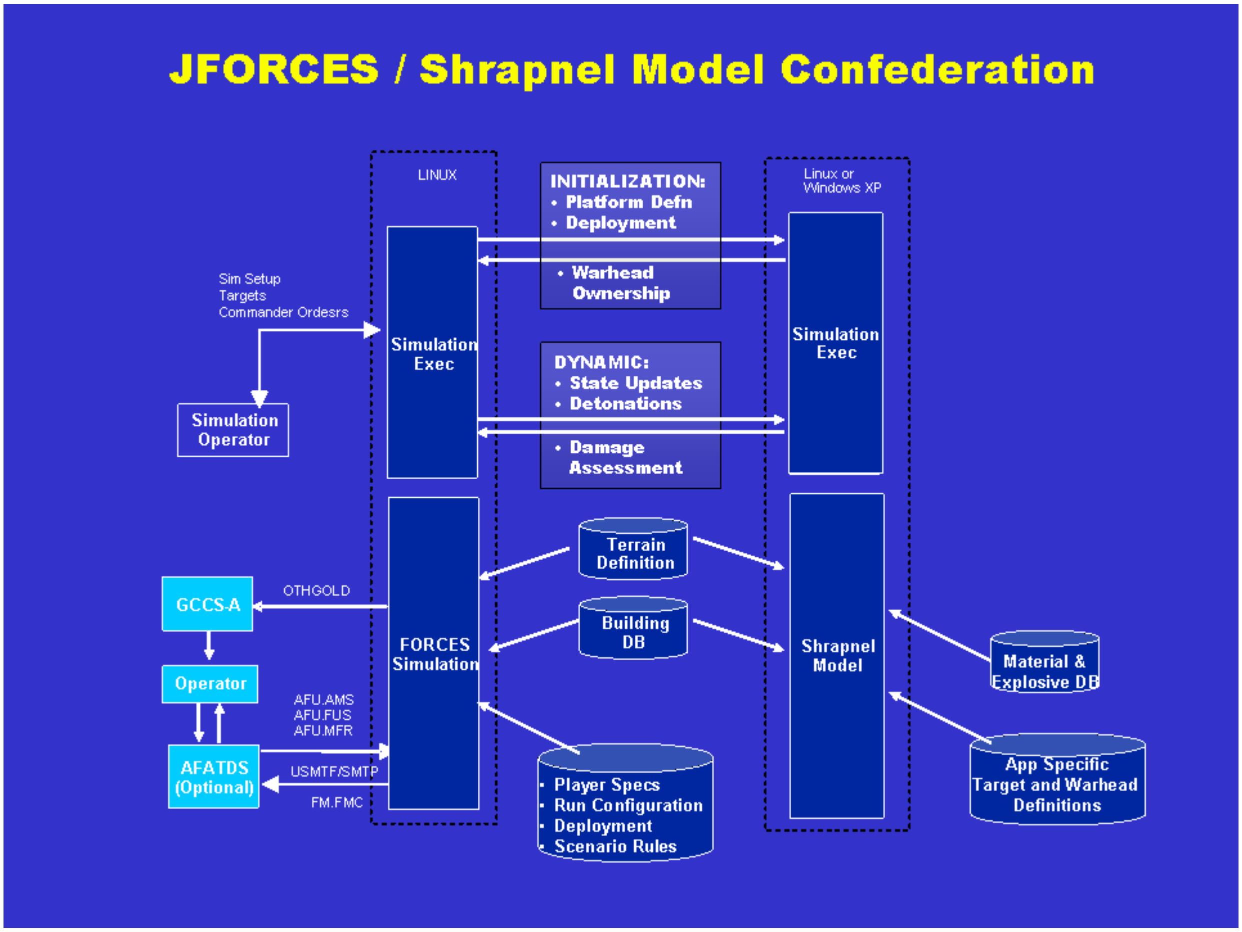


Figure 11- Shrapnel / Scenario Model Confederation

are necessarily different from the scenario model in that they only need to model the kinematic and vulnerability aspects of these players, but these attributes need to be modeled in greater fidelity than is required by the scenario model. The different resolutions of the various models is respected and maintained in this approach. An exception is made to the separation of definitions in the case of the terrain model. The shrapnel model was built to permit the use of alternate terrain and building models, so it was decided to employ a shared object load of the JFORCES terrain model since it was more robust than the one organic to the shrapnel model.

SAMPLE APPLICATION

A simple question will be addressed to illustrate the utility of this model suite. The sample application will examine alternate warhead configurations in a traditional military engagement, but it should be mentioned that the purpose in developing the new shrapnel model was to span the range from tradition military applications through response training and route vulnerability analysis in asymmetric warfare where limited numbers of improvised explosive devices might be employed.

In this sample it was conjectured by Dr. Kennedy that there might be benefit to altering standard artillery shells by adding small charges to either the front or rear that could be blown as the warhead approached the target to tilt the warhead. The effect of this would be to alter the fragmentation spray pattern relative to targets on the ground and spread these fragments more efficiently.

It appeared that it would be reasonable to use either a horizon sensor or a proximity fuse to detonate these small charges just prior to impact to orient the warhead relative to the ground fuse. Given this addition it seemed a reasonable extension would be the ability to tailor the detonation altitude. This could result in minimizing fragments wasted on terrain features. A variable detonation altitude parameter could be used either in training artillery teams by providing accurate lethality analysis of their operations or employed in a cost-analysis trade for evaluating alternate warhead configurations in future buys.

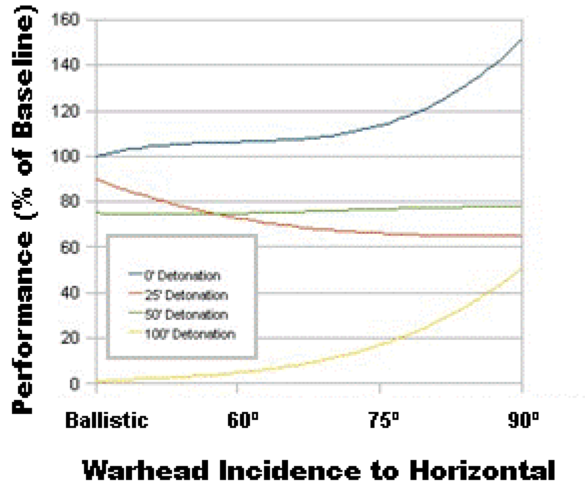
It was decided to use the scenario illustrated in Figure 10 to provide an initial insight into impact of altering the fusing altitude and the warhead orientation at detonation. The scenario component chosen for detailed rendering was the artillery defense against the red flanking formation on the east. To isolate this component it was decided to always employ a 15 minute artillery barrage by the entire artillery battalion of three batteries starting at the time the lead red unit crossed the highway heading east from the town. The artillery was to be directed by a forward observer. The artillery rounds would either land as determined by the ballistics at that range (about 30 degrees relative to Earth) or would be tilted at detonation to 60, 75 or 90 degrees from horizontal. In addition, the effect of detonating the warhead at impact with the ground would be compared to the effect of detonating the warhead at 25, 50 or 100 feet about the ground.

The results of each of these approaches are tabulated in Table 3. The results are normalized to a M107 warhead detonating at impact.

Table 3 - Fragment Lethality Efficiency as a Function of Detonation Angle and Altitude

		Warhead Angle At Detonation (Relative to Horizontal)			
		Ballistic	60	75	90
Detonation Altitude (ft A.G.L.)	**0**	100	116	88	152
	25	90	66	65	65
	50	75	73	78	79
	100	1	5	20	51

The relative lethality as a function of warhead angle of incidence with respect to horizontal is graphed in Figure 12. The results demonstrate that there was a significant benefit to tilting the warhead to the vertical at detonation; this put many more targets in the spray pattern and increased the number of collateral kills. The loss of fragments to the ground was not overwhelming based on the high outward velocity imparted to each fragment relative to the warhead's downward velocity at impact. In addition this warhead was modeled as having a fairly wide spray pattern around the belt, so about a third of the fragments received a substantial upward velocity at detonation that put them in the vehicle kill zone instead of buried in the ground.



There was a consistent fall-off of lethality as detonation occurred at higher altitudes. This reflects the reduced fragment densities (in terms of fragments/burst front area) that accompany a higher altitude detonation. Simply put, the further from the detonation that a vehicle is the less likely it is to be hit because of the expanding spray angle. But part of the reason that this is observed it the terrain in this scenario is not rugged and there are no buildings in the area of the attack. In a scenario either fought in an urban environment or more rugged terrain the benefits of plunging fragments to increase the likelihood of direct line-of-sight from the detonation to the target might overwhelm the decreased performance for greater target-to-detonation range. Evaluating the benefits of tailoring detonation altitudes for scenario-specific conditions await further study.

FUTURE WORK

There are many candidate efforts that could extend the utility of both the shrapnel model in stand-alone use and in conjunction with scenario models, but current work focuses on adapting the current model to more accurately address the fragment fly pattern and lethality zone of improvised explosives. This would be useful in both evaluating and teaching route planning to limit unit vulnerability.

This model was developed in two configurations to support both standalone quick analysis and support scenarios models in a confederation. The standalone configuration would be useful in a number of applications including the evaluating the risk of sending convoys over alternate routes and evaluating the highest risk location for IEDs. The code was written as to support open academic exercises and should be available for a more open distribution than the scenario model. While no code release has occurred to date, the authors are working with the Wisconsin Air National Guard (WIANG) to determine whether this might be possible. In the meantime, an unclassified version of the code is available for US Government supported uses through the WIANG.

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