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A Comprehensive Approach to Characterizing the Hazards of Explosive Countermeasures with Respect to Dismounted Troops

by Patricia S. Frounfelker, Stephen P. Swann, and Gregory K. Dietrich

ARL-TR-5608 **July 2011**

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14. ABSTRACT
Active countermeasures (ACM) are designed to increase protection to military vehicles and their occupants. Current military operations in urban environments have increased the need to understand the danger from these countermeasure technologies to dismounted troops and other personnel. The area of hazard around the interaction of the ACM and threat needs to be understood and quantified using a combination of testing and modeling and simulation (M&S). The U.S. Army Research Laboratory (ARL) has developed testing procedures and M&S tools utilizing the Operational Requirement-based Casualty Assessment (ORCA) and MUVES-S2 models to evaluate these vulnerabilities. Hazard characterization can be used to influence countermeasure development as well as the Tactics, Techniques, and Procedures (TTPs) for countermeasure-equipped platforms and personnel operating in their proximity. This paper will present the testing and data collection methodology, the modeling and simulation (M&S) tools, and the visualization tools developed by ARL to assess the associated risks and hazard areas.

15. SUBJECT TERMS
Collateral hazards, ORCA, injury, MUVES, APS, reactive armor

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1. Introduction

Active countermeasures (ACM), such as explosive reactive armor (ERA), have been installed on military vehicles for more than 20 years and continue to be developed for current and future platforms. New and innovative types of ACM, such as active protection systems (APS), are currently being developed and planned for military vehicles as well. The major distinction between the two types of countermeasures is method of threat detection. ERA only acknowledges and reacts to a threat at the time of impact. APS systems on the other hand require sensor input to both track and intercept incoming threats. These ACM have the potential to produce collateral hazards to dismounted troops and other personnel. Current military operations in urban environments have increased the need to understand the danger from these countermeasure technologies. The area of risk around the interaction of the countermeasure and threat needs to be understood and quantified using a combination of testing and modeling and simulation (M&S). Experimental testing allows for the characterization of a known threat interacting with a vehicular countermeasure system and provides the necessary data for executing the M&S portion of this type of analysis. Additionally, testing identifies unique defeat mechanisms of each ACM that require a better understanding. M&S provides a greater understanding of these elements by characterizing them both stochastically and discretely, which provides predictive insight that augments the information gained through testing.

The U.S. Army Research Laboratory (ARL) has developed additional testing procedures and M&S tools utilizing the Operational Requirement-based Casualty Assessment (ORCA) and MUVES-S2 models to evaluate these risks in the form of identifying potential hazard zones and areas of risk. Hazard characterization and M&S can be used to influence countermeasure development as well as the Tactics, Techniques, and Procedures (TTPs) for personnel operating in proximity to countermeasure equipped platforms. Collateral hazard characterization also enables troop commanders to make informed decisions about when and where to deploy the countermeasures and the risks involved. This report will present the ACM testing and data collection methodology, the M&S tools, the visualization tools, and the associated metrics developed by ARL to assess the associated risks and hazard areas.

2. Injury Mechanisms

Several different types of personnel injury mechanisms may occur due to a functioning explosive countermeasure and its interaction with a threat, regardless of whether the countermeasure is reactive armor or APS. These injuries may be due to the result of blast overpressure, penetrating fragments, or thermal energy. Injuries due to blast overpressure may include eardrum damage and lung damage. Injuries due to penetrating fragments may range from superficial skin penetration to deep tissue wounds depending on the size, density, velocity, and shape of the penetrating fragments. Thermal energy injuries like skin burn may occur as well. Additionally, there is a potential for blunt trauma injuries depending on the velocity, mass, and orientation of the debris.

While the potential exists for any of these injury mechanisms to occur when a threat engages an explosive countermeasure, the primary threats from current ACM are penetrating fragments and blast overpressure to dismounted Soldiers and non-combatants. Even though thermal burns and blunt trauma are hazardous, in order for those injury mechanisms to take effect, personnel would be subject to high levels of blast overpressure, as well as a large number of highly-energetic penetrating fragments, which are greater concern. Therefore, the testing and the scope of ARL's analyses focus on penetrating fragment and blast overpressure injuries.

3. Terminology and Metrics

Survivability-type analyses, including collateral hazard assessments, have two considerations regarding personnel effects. Survivability is best characterized in terms of injury severity since this metric has a direct correlation to a Soldier's threat to life. We define injury using the Abbreviated Injury Scale (AIS) 2005 (*1*). AIS scores each single injury and assigns a severity score. AIS is an anatomically-based, consensus-derived, international severity scoring system that classifies each injury by body region, tissue types, and its relative severity on a 6-point ordinal scale. The Maximum Abbreviated Injury Score (MAIS) is used as an anatomical measure of injury and acts as a means to provide a single value metric in the event of multiple AIS scores for a given injury and/or event. The AIS scale, referenced in table 1, ranges between 0 and 6.

When conducting collateral hazard assessments, our threshold of unacceptable injury for crew and dismounted troops is an AIS 3, or serious injury. A serious injury is one that requires immediate medical attention, without which there is potential for loss of life. Using the same scale, our threshold of unacceptable injury for civilians is an AIS 1 or AIS 2, or a minor or

moderate injury respectively. Minor and moderate injuries range from superficial to those that are fully reversible given medical attention and pose little threat to loss of life. Personnel who exceed these thresholds of unacceptable injury would be considered a medical casualty.

Table 1. AIS scale.

MAIS	Injury Level	Head Injury Example	Type of Injury
0	None	No injury	None
1	Minor	Minor laceration of scalp	Superficial
2	Moderate	Major laceration of scalp	Reversible injuries, medical attention required
3	Serious	Fracture of skull	Reversible injuries, hospitalization required
4	Severe	Depressed skull fracture, penetration > 2 cm	Non-reversible injuries, not fully recoverable without medical care
5	Critical	Depressed skull fracture, laceration of spinal artery	Non-reversible injuries, not fully recoverable with medical care
6	Maximal	Massive brain stem crush	Virtually unsurvivable

Incapacitation is a secondary concern and is related solely to operationally-relevant personnel. Incapacitation is the inability to perform, at a level required for combat effectiveness, the physical or mental tasks required in a particular role at a specific time after wounding. Incapacitated personnel impaired to a level below minimum capabilities are considered an operational casualty. While incapacitation is dependent on injury, the level of incapacitation is not directly dependent on the injury severity. For example, an abdominal wound perforating the colon is a significant wound with an AIS of up to 4. However at 30 seconds post-wounding time, the individual may remain fairly capable, depending on the task defined, since the infection associated with the perforated intestines does not set in for hours or days. Conversely, an open fracture of the forearm is an AIS 2, yet if an individual's task is to fire an M4 carbine, at 30 seconds post wounding, they would be considered incapacitated due to their inability to fire the weapon.

4. Objectives for Testing and Analysis

As previously discussed, several current armored military vehicles contain some form of ERA. Further, program managers (PMs) for these same vehicles, as well as many vehicles under development are considering APS, in place of, or in addition to ERA. In light of current military dogma focusing on combined arms operations, and the need to conduct military operations in urban terrain (MOUT), Soldiers and non-combatants operate in proximity to these vehicles. The Army must quantify the hazards associated with penetrating fragments and blast overpressure resulting from the interaction of a threat and an explosive countermeasure.

Experimentally, collateral hazards are assessed at a given distance from the detonation point in terms of probability of injury given an event (P(Injury|Event)), shot, or hit due to blast overpressure and penetrating fragments for the explosive countermeasure alone, the threat alone, and the combined effects of the countermeasure and threat. Once P(Injury|Event) is characterized experimentally for a known distance from the detonation point, ARL determines the hazard as a function of increasing distance out to a point where the potential for injury becomes negligible. A hazardous area can then be calculated based on the operational characteristics, methods of employment, and mount locations on a vehicle. This area acts as a basis for the comparison of ACM solutions and ultimately developing TTPs by the user, should the system be fielded.

However, there are some additional considerations when discussing this characterization effort. The system level tests are typically expensive in terms of time, materials, and assets, especially when involving production or full up system level prototypes. The data collection and analysis process for these tests are time consuming and labor intensive. Due to these expenses and risks, there are often a limited number of tests representing limited test conditions and do not provide statistically strong test matrices. Finally, it is important to note that collateral hazard analysis does not represent a safety assessment, but is intended as a data point in the comparison of ACM alternatives and as information for the user.

5. Test Configuration

There are several challenges that must be addressed when testing ACM for collateral hazards. The first is designing cost-effective tests that provide the necessary data to fully characterize the primary injury mechanisms. The second is creating test plans where the data collection material and instrumentation will not interfere with the ACM system itself. Fragment collection media and blast overpressure sensors must not interfere with camera angles, flight paths of threats or countermeasures, nor disrupt APS sensors, such as optical sensors or radar.

The two main types of test configurations leveraged by ARL are full-scale arena events and modified arena events (figures 1 and 2). The full-scale arena events are performed according to the Joint Munitions Effectiveness Manual (JMEM) to characterize the behavior of the ACM and each threat of interest individually (*2*). Within this test configuration, one half of the recovery arena is comprised of celotex bundles, which capture all fragments to identify mass, shape factor and other characteristics of each fragment. The other half of the recovery arena is comprised of velocity screens and high-speed cameras, which capture fragment velocity. The data from these events are packaged into a z-data file format which creates statistically relevant mass/velocity bins based on spatial distributions. The second test configuration was developed by ARL to characterize the combined interaction of the ACM and the threat munition. The modified arena event uses marine-grade plywood to capture fragment characteristics and discrete fragment trajectory from either a dynamic or static test event. BOP gauges are incorporated into each test configuration as well, positioned both outside and inside the protected platform (when applicable).

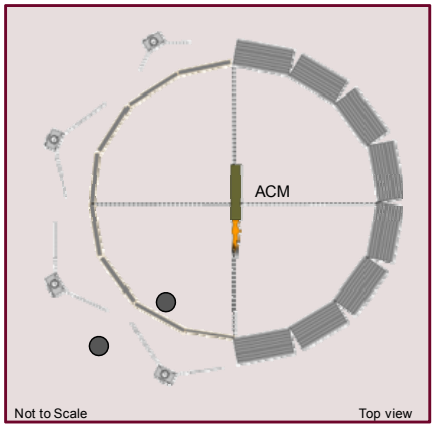


Figure 1. Full-scale arena.

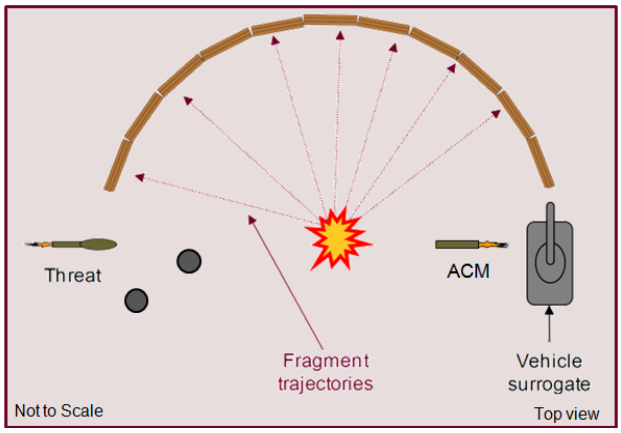


Figure 2. Modified arena.

6. Characterization of Blast Overpressure Effects

The BOP instrumentation (free-field pressure gauge or blast test device) collects the pressure-time history needed to model the personnel effects of the BOP, specifically eardrum rupture and percent lung damage. This information is processed through two submodels within ARL's ORCA Model (*3*). The first embedded model is INJURY 8.2 (*4*), which is used to predict lung tissue damage. The U.S. Department of Energy (DoE) (*5*) auditory injury criterion is used as the second embedded model to predict ear drum rupture. The pressure-time history traces collected are used as the input insult against personnel without hearing protection facing the direction of the blast. Injuries as a result of lung tissue damage range from a MAIS 2 to a MAIS 5. Injuries from ear drum rupture are considered a MAIS 1. Each distance where BOP data were recorded is evaluated to determine where BOP damage effects become negligible. Extrapolation may be needed to determine this maximum distance if the distances used in testing were not great enough.

7. Characterization of Fragment Effects

Penetrating fragment data collected from the modified arena witness panels include length, width, depth, and location of damage on the panels. This information is entered into a pre-processing tool used to calculate a limit striking velocity and a mass (if not recovered from the witness panel) for each impacting fragment based on the damage to the marine-grade plywood.

The mass and velocity of each fragment along with other known or measured fragment properties (such as material density and shape factor) are then used as the insult against personnel with and without personnel protective equipment (PPE) within the ORCA model. The ORCA model is used to calculate the personnel vulnerability metrics, specifically injury severity characterizations for each fragment. To assess the average likelihood of injury over the body, two assumptions are used within this portion of the characterization. The first assumption is that each fragment collected could have hit anywhere on the personnel simulated. The second assumption is that the probability of hit equals one (the probability of hit is assessed in a different portion). In order to accommodate both assumptions, each fragment is processed in a grid analysis within ORCA. A grid analysis uses the same fragment threat conditions with a uniform grid of shot lines against the entire ORCAman at various aspect angles and/or elevations around his body. Grid runs reveal the vulnerability of a Soldier to the witnessed insults at various impacts to the body and provide a probability of MAIS > X injury given a hit (figure 3) depending on which level of unacceptable injury is being illustrated.

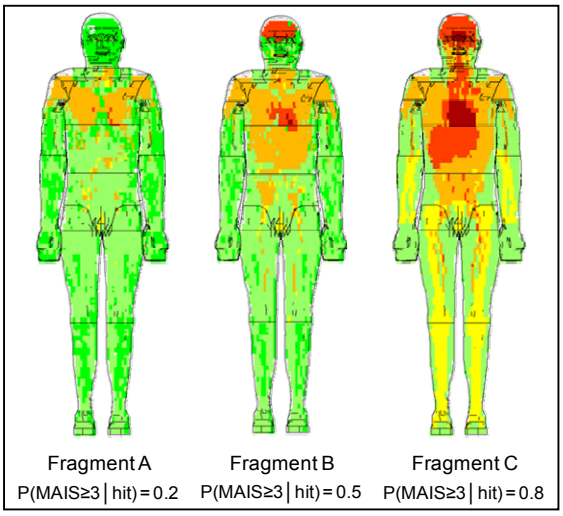


Figure 3. Example plots of personnel grid run analysis from 0 degrees.

The assessment of fragment data collected will reveal the level of injury and/or incapacitation for each tested distance away from the intercept point. Also a general pattern can be analyzed for all impacting fragments from each discrete modified arena event. Each hit location, color coded by the probability of injury, can be illustrated as in figure 4. This will provide characteristics of the fragment spray, such as spray bounds, symmetry, focused groups, and shifting. Further characterization can then be completed to highlight areas of most concern about the intercept point.

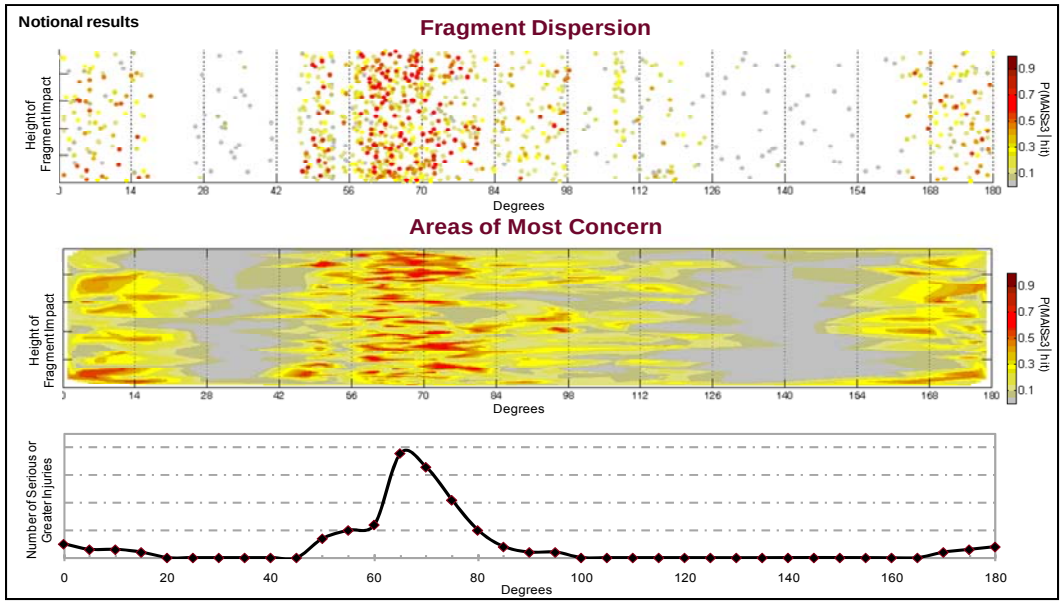


Figure 4. Example plots of fragment dispersion and areas of most concern.

8. Predictive Analysis of Characterized Events

ORCA, in conjunction with another ARL model MUVES-S2 (*6*), are used to fully characterize and predict the potential for damaging effects of fragmentation from each event. MUVES-S2 creates the virtual environment, which is used to lay out target arrays, provide fragment characteristics and fly-out trajectories for threats, controls metric reporting, and acts as a "physics engine" for all events during a simulation run that do not involve personnel. The personnel injury portion of a simulation uses ORCA, which characterizes, evaluates, and quantifies insults to personnel. These two models, working in conjunction, provide metrics for injuries to personnel using the aforementioned AIS scale, with emphasis on the associated MAIS score for both stochastic and discrete modeling scenarios.

The initial conditions that MUVES-S2 uses for each fragment (mass, velocity, shape factor, density, and trajectory) are created using data gathered during testing. When modeling a discrete event, individual fragment characteristics are modeled using information garnered from impact locations on plywood panels during modified arena tests. These fragments are considered to be traveling in straight line paths, with velocity degradation taking place due to air drag. A stochastic event on the other hand, is modeled using statistically derived data gathered during a full-scale arena test. This test assumes a symmetrical fly-out based upon a judicious choice of test setup and creates mass velocity pairings and bins them by the angle of fly-out. This data is

then used to generate a z-data file, which in turn creates the initial conditions for MUVES-S2 to perform modeling runs with variable fragment fly-outs.

The second portion of this type of modeling effort is creating the associated target geometry for both discrete and stochastic simulations. Discrete simulations use an array format with ORCAmen placed in concentric half-rings at specified distances from the initiation of fragment fly-out. Each set of initial fly-out conditions is run once, as there is no variability. This provides a snapshot of a single event. A stochastic run, on the other hand, aligns the ORCAmen in grid fashion around the point of initiation, with each ORCAman being placed one at a time on the grid, in order to prevent any shielding of the ORCAmen at further ranges due to those ORCAmen who are closer to the detonation point. These runs are performed 25 times for each individual ORCAman with their position on the grid changing by 25, 50, and 100 cm depending on the size of the grid being run (30 m, 50 m, and 100 m respectively). The ORCAmen for both discrete and stochastic modeling can be positioned in varying elevations to simulate terrain differences, in varying postures, with varying levels of PPE, and at variable ranges.

The analysis associated with characterizing collateral hazards due to explosive countermeasures is directly linked to the type of inputs that are used in the modeling as mentioned previously. That said, for a discrete modeling run the following metrics/products are generated (for each specified range) and color coded by the MAIS value generated:

- Count of impacts to the ORCAmen that result in a MAIS = X
- Visualization of fragment fly-outs that impacted ORCAmen (figure 5).

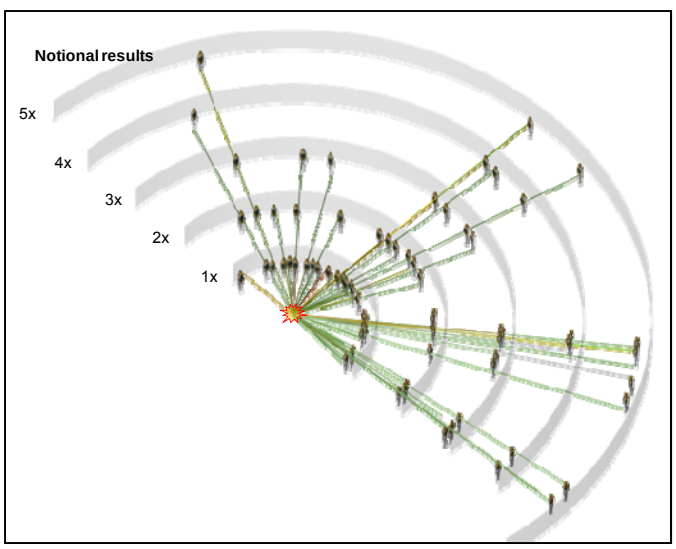


Figure 5. Example visualization characterizing each trajectory.

This portion of the analysis, in addition to the visualization of the discrete event and a count of injuries resulting in a given MAIS score, provides a means to quantify what the potential hazard is to dismounted troops for any single event.

The second portion of this characterization relies on the stochastic method of modeling and provides the following products that will directly feed into the final summary graphics and metrics:

- Survivability map of the probability of receiving a MAIS > X given an event due to penetrating fragments for the threat only
- Survivability map of the probability of receiving a MAIS > X given an event due to penetrating fragments for the countermeasure only
- Survivability map of the probability of receiving a MAIS > X given an event due to penetrating fragments for the combination of the threat and the countermeasure (figure 6)

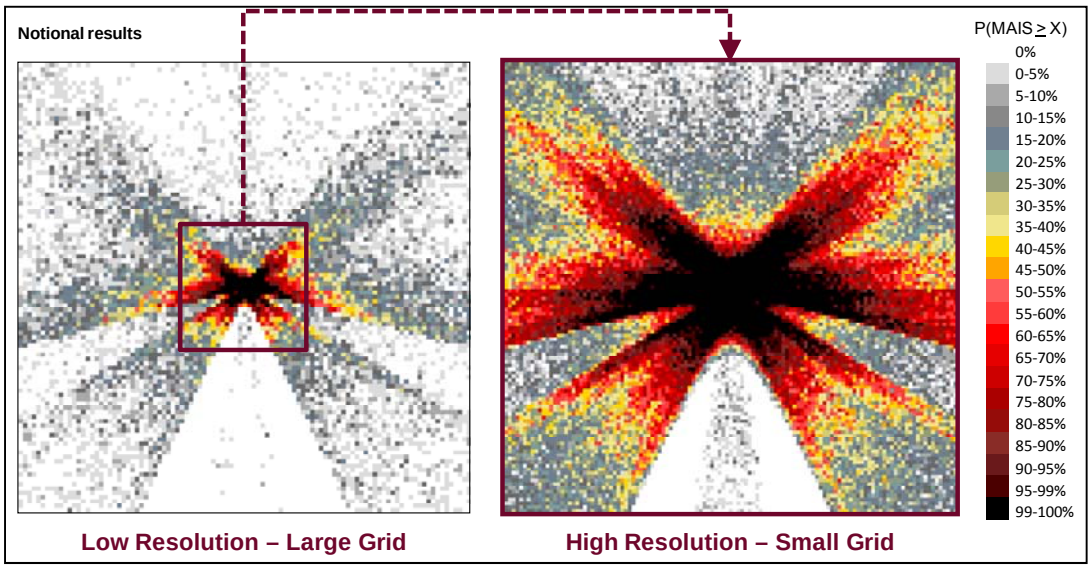


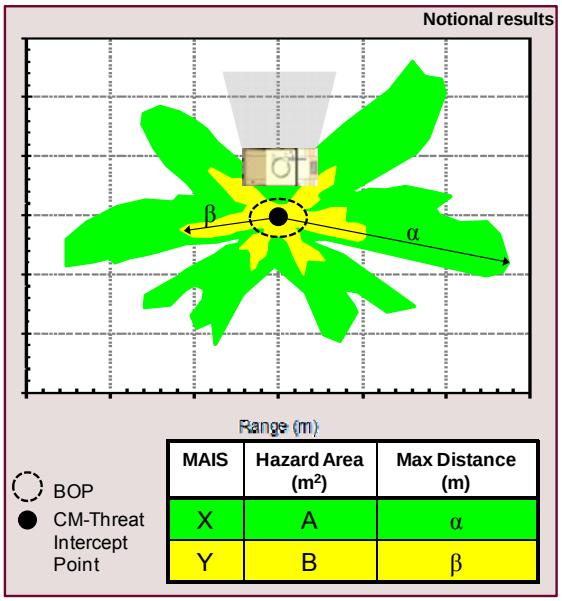
Figure 6. Example visualization characterizing the interaction between threat and ACM.

9. Final Summary Graphics and Metrics

Once P(Injury|Event) is characterized experimentally for a known distance from the detonation point, ARL determines the hazard as a function of increasing distance out to a point where the potential for injury becomes negligible, as previously discussed. A hazardous area, given an ideal intercept, can then be calculated based on the operational characteristics, methods of employment, and mount locations on a vehicle.

All outputs created are designed to provide answers to questions that are posed by two unique communities: requirements writers and evaluators, and TTP writers and operators. The survivability maps and metrics associated solely with the threat, ACM, and the combination of the two give PMs, requirements writers, and evaluators the necessary information to baseline the performance of various systems, as well as make side-by-side comparisons of their potential for injury. The visualizations of fragment fly-outs also provide this community with a snapshot of a single event and the ability to quantify, discretely, the maximum range at which penetrating fragments have the potential for various levels of injury. This can be used as both a benchmark and/or a means of comparison. The survivability maps and metrics this analysis provides with respect to the vehicle platform are of particular value to TTP writers and operators as it highlights a distinct area of hazard. This hazard area can be used to minimize the risk to dismounted troops when positioned in the vicinity of vehicle platforms equipped with explosive countermeasures.

ARL recommends both communities use the following summary graphics and metrics for both BOP and penetrating fragments (figures 7 and 8) where the green and yellow area represents a greater than or equal to 50% chance of receiving a minor injury (MAIS 1) and a serious injury (MAIS 3), respectively.



MAIS	Hazard Area (m^2)	Max Distance (m)
X	A	α
Y	B	β

Figure 7. Threshold map for intercept point.

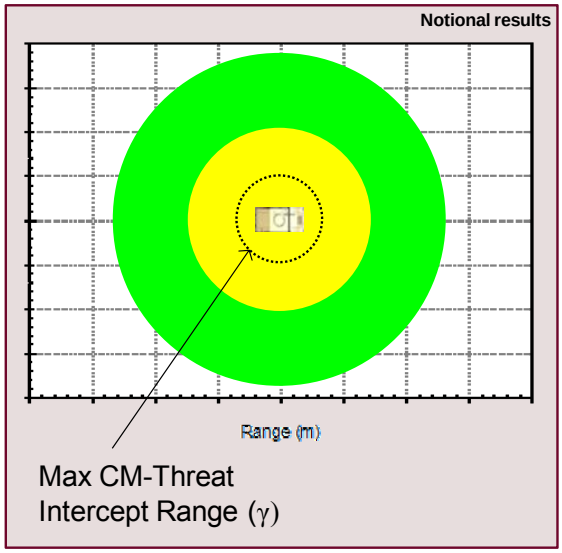


Figure 8. Threshold map for vehicle platform.

Specifically, these summary graphics and metrics contain:

- Focus for requirement writers and evaluators (figure 7)
  - Threshold map identifying the area that penetrating fragments have a P(MAIS>X) > 50% given an event with respect to the intercept point
  - Maximum range from the intercept point that a Soldier would receive a P(MAIS>X) > 50% given an event
  - Total area, with respect to the intercept point, producing a P(MAIS>X) > 50% given an event
- Focus for TTP writers and operators (figure 8)
  - Threshold map identifying the worst-case area that penetrating fragments have a P(MAIS>X) > 50% given an event with respect to the vehicle platform
  - Worst-case range from the vehicle that a Soldier would receive a P(MAIS>X) > 50% given an event
  - Worst-case area, with respect to the vehicle, producing a P(MAIS>X) > 50% given an event

10. Conclusion

ACM present hazards to dismounted troops and non-combatants in the vicinity of ACM-equipped platforms. In addition to standard singular fragment and combined area of effect characterization garnered through testing, ARL has developed methodology using ORCA and MUVES-S2 to better characterize and predict the risk/effects of collateral hazards to the dismounted Soldier. Collateral hazards results may be used to compare hazardous areas between ACM solutions to assist with acquisition decisions; develop TTPs for combined arms operations requiring dismounted Soldiers to work near ACM-equipped platforms; and assist commanders deploying ACM-equipped platforms in MOUT operations near civilian populations.

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List of Symbols, Abbreviations, and Acronyms

ACM	Active countermeasures
APS	active protection systems
ARL	U.S. Army Research Laboratory
DOE	Department of Energy
ERA	explosive reactive armor
JMEM	Joint Munitions Effectiveness Manual
M&S	modeling and simulation
MAIS	Maximum Abbreviated Injury Score
MOUT	military operations in urban terrain
ORCA	Operational Requirement-based Casualty Assessment
PM	program manager
PPE	personnel protective equipment
TTPs	Tactics, Techniques, and Procedures

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