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HIGH-RESOLUTION VULNERABILITY METHODS AND APPLICATIONS

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U.S. ARMY LABORATORY COMMAND

BALLISTIC RESEARCH LABORATORY
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Over the past five years, considerable attention has been focussed in the Army on the requirements of vulnerability modeling. Both the applicability of extant models to an expanding number of uses and their accuracy have received scrutiny. In response to needs for improved capability, the Ballistic Research Laboratory (BRL) has developed a high-resolution stochastic vulnerability model. In this paper, the core logic structure used to represent target functioning is presented. In addition, the means for introducing stochastic damage mechanisms are described.

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HIGH-RESOLUTION VULNERABILITY METHODS AND APPLICATIONS

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ABSTRACT

Over the past five years, considerable attention has been focussed in the Army on the requirements of vulnerability modeling. Both the applicability of extant models to an expanding number of uses and their accuracy have received scrutiny. In response to needs for improved capability, the Ballistic Research Laboratory *(*BRL*) has developed a high-resolution stochastic vulnerability model. In this paper, the core logic structure used to represent target functioning is presented. In addition, the means for introducing stochastic damage mechanisms are described.*

INTRODUCTION

The ***vulnerability*** of a combat system [1] is an assessment of its susceptibility to damage, given a specific encounter with a particular threat. Therefore the term vulnerability is associated with the ability of military systems to continue fighting subsequent to an interaction with a lethal mechanism delivered by an opposing force. By contrast, ***lethality*** is the effectiveness with which an attacking weapon can inflict damage on a particular target. ***Survivability*** subsumes vulnerability as a key factor, but includes such other elements as detection probability and munition delivery errors.

The assessment of vulnerability, the subset of survivability which assumes a very specific munition/target interaction to assess damage, plays a key role in many Army programs. Table I gives a list of some roles supported by Vulnerability/Lethality (V/L) studies [2].

Table I. Uses of Vulnerability Data [2]

• **Major Milestone Decisions**	• **Concept Tradeoffs**
• **Data for Decision Makers**	• **Inputs to War Games**
• **Vulnerability Reduction**	• **Lethality Optimization**
• **Estimates of Spare Parts & Repair Times**	• **Planning and Analysis of Live-Fire Testing**
• **Generation of New Measures-of-Effectiveness**	• **Use of Reference V/L Models for Calibration**

A number of models are used in support of V/L objectives [1]. Included are codes based on terminal ballistics considerations which perform estimates of penetration depth into armor along with (possible) residual overmatch. At the next level of sophistication, there are lumped-parameter codes. These codes use the penetration equations to examine possible residual warhead entry into the interior of a tank or armored personnel carrier. The residual is tracked only to interior elements (fuel, ammunition) which may cause catastrophic fire or detonation. However the destruction caused by fragments emanating from the rear surface of the armor, normally referred to as Behind-Armor Debris (**BAD**), is assessed through experimentally derived curves which reflect the *average* effect of this phenomenon on the system.

The most detailed V/L models are called point-burst. They are supported by submodels for BAD which describe both the lethality of the fragment cloud as well as the susceptibility of interior components struck by fragments to be killed. This susceptibility of components to fragment damage is normally couched in the Component Conditional **P**robability of **K**ill, Given a **H**it, or $\mathbf{P_{K/H}}$. The most advanced of such models is called SQuASH [1] and was developed as an extended point-burst code into which key elements of stochasticism were introduced.

For military ground vehicles the conventional direct-fire threats normally include **K**inetic **E**nergy (**KE**) and **C**hemical **E**nergy (**CE**) rounds, **E**xplosively **F**ormed **P**enetrators (**EFPs**) and mines.

Typically these threats cause damage to a target *via* mechanisms which perforate an interior portion of a vehicle. During this process fragments interact with critical interior components. As these components are killed, there is possible loss of battlefield capability. Important ancillary damage can also occur when certain exterior portions of a combat vehicle are damaged, particularly suspension components. This can lead to significant loss of mobility.

Representatives of the three services have been invited to the 1991 **P**robabilistic **S**afety **A**ssessment and **M**anagement (**PSAM**) Symposium in the recognition that some profit may be gained by comparing V/L methods with those used in the risk discipline, particularly those involved in nuclear safety issues. Possible similarities involve the logic structures used to assess faults; differences will hopefully include the nature of the specific threats themselves and how they interact with constituent parts to cause dysfunction.

ORGANIZATION OF ITEM-LEVEL LOGIC

The manner in which a target is logically organized for high-resolution analysis will now be described. This description will follow the most recent methodology developed by the USA **B**allistic **R**esearch **L**aboratory (**BRL**) and the US **A**rmy **M**ateriel **S**ystems **A**nalysis **A**ctivity (**AMSAA**). Called **D**egraded **S**tates (**DS**) [3-6], this is a methodology which relates *loss of specific combat vehicle components* finally to *loss of vehicle (or item) utility*.

A logical hierarchy can be written giving the top-down structure in five levels where:

- **Level 1- Item:** This is the highest level of the hierarchy and represents the sum of the **M**easures-**o**f-**U**tility (**MoUs**) supported by the lower levels. This level describes a whole combat vehicle or other integral structure.
- **Level 2- Functional Categories:** The functions of, say, a tank are divided into six categories: MOBILITY, FIREPOWER, ACQUISITION, CREW, AMMUNITION and COMMUNICATIONS. These Functional Categories support the principal battlefield roles and establish the utility of the item.
- **Level 3- Functional Subcategories:** The six Functional Categories of Level 2 are described in terms of performance characteristics. Table II gives these Subcategories for a heavy battle tank [4].
- **Level 4- Fault-Tree Support for Functional Subcategories:** At this level the Functional Subcategories of Level 3 are committed to fault-tree analyses. The fault-trees reflect the series/parallel design of the engineering systems which support the performance characteristics as *defined* in Level 3. Some examples of fault trees are shown in Fig. 1. Each of the four examples shows how individual critical components, shown as single-pole, single-throw electrical switches are assembled to represent particular Subcategory support.
- **Level 5- Critical Components:** The lowest level of the hierarchy is formed by the *critical components* which are the elements of the fault trees. A critical component *is defined* as a component, which if killed, *might* lead to a loss of capability as defined in one of the six Functional Categories defined in Level 2.

Consider a combat vehicle component characterized by a **L**oss-**o**f-**F**unction (**LoF**) where:

$$0.0 \leq \text{LoF} \leq 1.0$$

Zero (0.0) LoF means a component is operating at normal design (pre-shot) specifications. Complete (1.0) LoF means there is no component capability. The notion of a (one-dimensional) LoF is quite natural for describing a component with a single functional characterization such as a pump or electric generator; here the ability to pump fluid or induce current flow can be described on a (single) normalized interval. After being struck by one or more fragments, some classes of components might be operational in a partially functioning state; in the case of a pump, maybe it can supply fluid at half the normal rate so that its LoF would take the value 0.5. For this class of components, the LoF may reflect any value in the interval.

Some classes of components exhibit LoFs which are Bernoulli in nature; that is, they either operate fully or not at all. An example of such a component might be a portion of a fire-control system with optical elements. Such a

Table II. Functional Subcategories for Six Major Tank Functions [4]

— MOBILITY —

M0 → No mobility damage	M2 → Reduced speed (significant)
M1 → Reduced speed (slight)	M3 → Total immobilization

— FIREPOWER —

F0 → No firepower damage	F10 → F2 and F5
F1 → Loss of main armament	F11 → F3 and F5
F2 → Unable to fire on the move	F12 → F4 and F5
F3 → Increased time to fire	F13 → F2 and F3 and F4 and F5
F4 → Reduced delivery accuracy	
F5 → Loss of secondary armament	F14 → F2 and F3 and F5
F6 → F2 and F3	F15 → F2 and F4 and F5
F7 → F2 and F4	F16 → F3 and F4 and F5
F8 → F3 and F4	F17 → F1 and F5 (total loss of fire power)
F9 → F2 and F3 and F4	

— ACQUISITION —

A0 → No acquisition damage	A2 → Unable to acquire while moving
A1 → Reduced acquisition capability	A3 → A1 and A2

— CREW —

C0 → 0 crew casualties	C3 → 3 crew casualties
C1 → 1 crew casualty	C4 → 4 crew casualties
C2 → 2 crew casualties	

— AMMUNITION —

K0 → No ammo lost	K3 → K1 and K2
K1 → Bustle ammo lost	K4 → K Kill
K2 → Hull ammo lost	

— COMMUNICATIONS —

X0 → No communication damage	X3 → No external communications
X1 → No internal communications	X4 → X1 and X2
X2 → No external communications > 300 ft	X5 → X1 and X3

component might be able to absorb fragments up to certain mass/velocity combination and suffer no damage until a certain threshold is reached. Then an optical element breaks and the component utterly fails. Such a component would then have only two possible states; 0.0 and 1.0.

We also note that in the case of complex components which must perform multiple functions, the use of a one-dimensional LoF characterization can represent an unrealistic simplification. Such a situation occurs in the description of personnel vulnerability to striking fragments. For crew, the term LoF is exchanged for Level of Incapacitation (**LoI**) [7], but the notion is similar. And in such a case, various combinations of limb, torso and head trauma might possibly map to the same LoI and yet reflect entirely different operational capability (*e.g.* ability to view a battlefield and passively direct fire over a radio *vice* maneuver a vehicle slowly through the use of hand-controls only). Thus the first step in the critical problem of characterizing the potential loss of components is to relate various threat conditions (fragments masses/velocities, blast levels, *etc.*) to (normalized) LoFs.

However for vulnerability analyses such as SQuASH, component characterization must be Bernoulli in nature, *i.e.* functional/non-functional. Thus in a conceptual sense, a minimum performance threshold for each component must be applied against a LoF following interaction with a threat. If the LoF is sufficiently small that this threshold is at

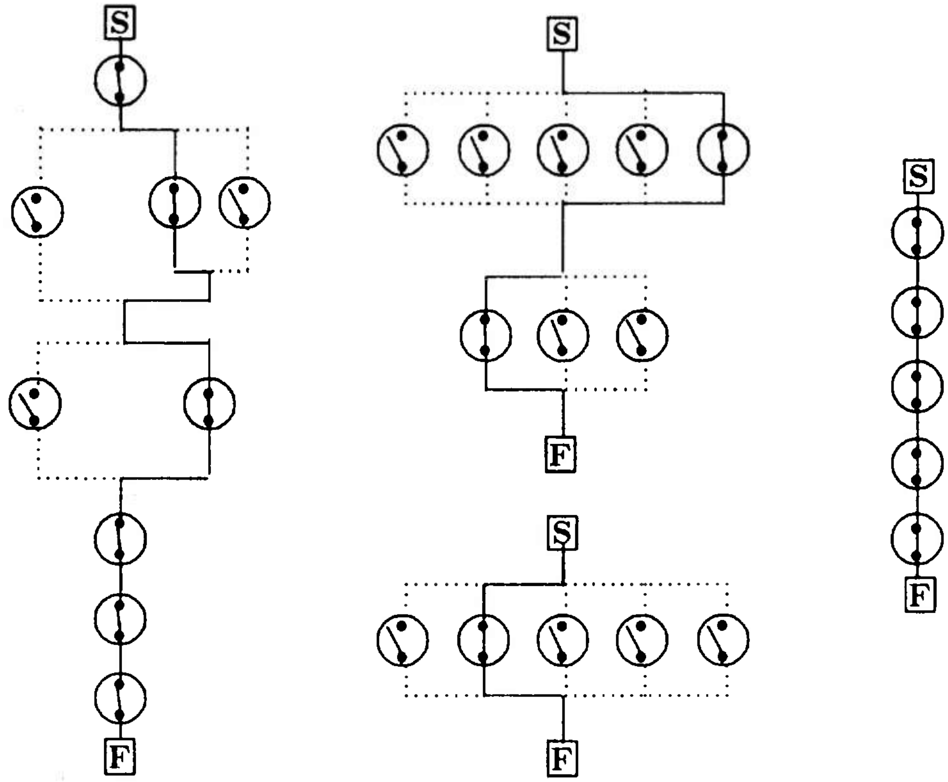

Figure 1. Four Examples of Fault Trees. Functioning components (non-killed) are shown as closed switches; killed components are shown as open switches. Solid paths show continuous (closed) circuits; dotted lines indicate non-functional paths. The $\boxed{S}$ and $\boxed{F}$ symbols indicate the start and finish of the circuits, respectively.

most equaled, the component is considered fully functioning (or alive); if not, it is considered killed. This process thus yields a crisp binary decision process for each component and can be characterized by a single-pole, single-throw electrical switch (either closed [alive] or open [nonfunctional]) as in Fig. 1.

Just as the binning process described for components gives a Bernoulli outcome, the inclusion of such components in the fault trees shown in Fig. 1 gives rise to performance of the same kind. Normally no intermediate forms of system performance are allowed. The application of a strict Bernoulli framework homogeneously at the component level (Level 5) carries directly to the fault trees of Level 4. This convention has been adopted for two principal reasons. First, attempting to predict the fractional performance of components following a ballistic event is extremely difficult. Second, the mathematical means of logically combining *partially* functioning components at the fault-tree level is problematic as well. The complete generalized logic structure for supporting both *Unary Operators* (ABSOLUTE-VALUE, BOOLEAN-VALUE, NOT) and *Binary Operators* (AND, DIFFERENCE, EXCLUSIVE-OR, MAXIMUM, MINIMUM, OR, PRODUCT, SUM) has already been constructed for another project [8]. However, whether such a structure can be properly applied in this context is unknown at this time.

Since the Bernoulli states of Level 4 *define* whether kills have occurred for the Functional Subcategories of Level 3, each Subcategory listed in Table II exhibits binary (0,1) behavior as well. For replicated shots against a target in which the mechanics of damage phenomenology are played stochastically, random collections of components are killed on each shot. From an aggregation of such statistics, a Bernoulli probability for each Functional Subcategory is derived. These "kill probabilities" form the current basis for *characterizing* the vulnerability of a military target.

Finally it is worth noting that the structure just described has potential utility in the areas of reliability, repairability, logistics support and failure analysis.

THREAT/TARGET INTERACTION

The damage phenomenologies associated with the conventional threats listed above include many complicated mechanisms. In addition to the main penetrator and residual fragment generation, they include blast, shock, fire, hydraulic ram, vaporifics, toxic gases, luminosity and thermal spikes. These additional mechanisms ***in the main*** have not been observed significant for direct-fire weapons against heavy tanks as recent tests have illustrated [9]. In this paper, therefore, we will illustrate the core V/L damage processes only by describing the effects of main-penetrator residual and BAD.

The mechanics of exercising the stochastic vulnerability model, SQuASH, involve the assembly of many input files describing geometry, material, warhead performance properties, component $P_{K/H}$'s, and the logic structures described above [1]. Here we briefly review the sources of randomness which lead to the component damage vectors which form the input to Level 5 of the Item-Level Logic. Accommodation has been made to vary stochastically the following variables:

- **Hit Point:** Under the best conditions, the geometric modeling of a complex target cannot perfectly reflect real vehicles. In addition, actual vehicles vary somewhat in configuration. The geometric interrogation process involves shooting (zero-width) rays through the target to replicate possible projectile paths. The process yields only components which would be intercepted by the axis of a projectile, not those that would be impacted by the off-axis body. Thus rather than a single ray normally used to model a striking projectile, a matrix of nine rays provides sampling over a six-inch square cross section.
- **Warhead Performance:** In expected-value V/L models, warhead performance is modeled in terms of its expected (point-value) penetration capability. Repeated warhead/armor experiments using precision components reveal random variations in depth of penetration, *etc.* The SQuASH code associates a distribution function with each warhead/armor combination; in the course of model exercise, random draws are made from this distribution (center-of-mass) function.
- **Residual Penetrator Deflection:** In the case of KE projectiles incident at oblique angles to the armor, the residual portion of a penetrator can shatter and deflect upon exiting armor. The deflection is greatest near the limit velocity when the armor is minimally overmatched. A distribution function is utilized here to select trajectories in the vicinity of the expected deflection.
- **Spall Production:** The SQuASH spall model is based on a routine which describes the *expected* spatial density of lethal fragments as a bivariate gaussian distribution. The solid angle subtended by any critical component and its location then define the *expected* number of lethal fragment impacts. In the exercise of the code for a particular shot, the expected number of fragments is used in a Poisson distribution to draw a specific (integer) number of fragments. To survive, the component must survive all fragment encounters.
- **Component $P_{K/H}$ Characterization:** Each critical component in the target is individually characterized in terms of its probability of being killed by main penetrators and by single lethal spall fragments. For intermediate threats such as fragments from a shattered KE penetrator, intermediate kill probabilities are computed using hole size and penetration capability. The combined effects of multiple sources of damage are assessed using the *Survivor Rule.*§

SUMMARY

In this paper we have described the core structure used in the most advanced Army V/L model. We have reviewed the logical structure used to define system utility. In this paradigm, collections of critical components are organized into fault trees which mirror the series/parallel nature of engineering systems. Based on the definitions of Functional Subcategories given in Table II, engineering judgment is used to construct the supporting fault trees.

§ For this application the *Survivor Rule* states that the Multiple-Hit, Component Kill Probability, $P_{K/MH}$, for a component with Single-Hit Component Kill Probabilities, $P_{K/SHi}$, and n contributing sources of independent damage is given by:

$$P_{K/MH} = 1 - \left[| 1 - P_{K/SH1} | \times | 1 - P_{K/SH2} | \times \cdots | 1 - P_{K/SHn} | \right]$$

When a threat munition is fired against a target, a number of stochastic algorithms are invoked which typically lead to a set of killed, or non-operational, components. Killed components are analogous to open switches in the fault-tree paradigm; if through the action of cutting fault trees *no* continuous path is supported, the system is considered killed, and the related Functional Subcategory *unsupported*. Through repeated Monte Carlo exercise of the model, Bernoulli probabilities are derived for each Functional Subcategory. The record of these Bernoulli outcomes, *singly* and *in combination* defines the vulnerability of the system.

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