UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED

1b. RESTRICTIVE MARKINGS

2a. SECURITY CLASSIFICATION AUTHORITY

2b. DECLASSIFICATION / DOWNGRADING SCHEDULE

3 DISTRIBUTION / AVAILABILITY OF REPORT Approved for Public Release; Distribution Unlimited.

4. PERFORMING ORGANIZATION REPORT NUMBER(S) BRL-MR- 3755

5. MONITORING ORGANIZATION REPORT NUMBER(S)

6a. NAME OF PERFORMING ORGANIZATION US Army Ballistic Research Laboratory

6b. OFFICE SYMBOL *(If applicable)* SLCBR-VL-V

7a. NAME OF MONITORING ORGANIZATION

6c. ADDRESS *(City, State, and ZIP Code)* Aberdeen Proving Ground, MD 21005-5066

7b. ADDRESS *(City, State, and ZIP Code)*

8a. NAME OF FUNDING / SPONSORING ORGANIZATION

8b. OFFICE SYMBOL *(If applicable)*

9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER

8c. ADDRESS *(City, State, and ZIP Code)*

10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO.

11. TITLE *(Include Security Classification)* Computer Simulations of the Abrams Live-Fire Field Testing

12. PERSONAL AUTHOR(S) Deitz, Paul H. and Ozolins, Aivars

13a. TYPE OF REPORT Final

13b. TIME COVERED FROM ________ TO ______

14. DATE OF REPORT *(Year, Month, Day)*

15. PAGE COUNT

16. SUPPLEMENTARY NOTATION Presented as a paper at the Army Operations Research Symposium XXVII, Ft. Lee, Virginia, 12-13 October 1988.

17. COSATI CODES

FIELD	GROUP	SUB-GROUP

18. SUBJECT TERMS *(Continue on reverse if necessary and identify by block number)*
Behind-Armor Debris, Live-Fire Testing, BALLISTICS,
Compartment Model, ARMOR, Point-Burst Modeling, (JES)
Criticality Analysis, ~~SQuASH~~

19. ABSTRACT *(Continue on reverse if necessary and identify by block number)*

Over the years the vulnerability community has developed an array of computer models to predict munition/target interactions. These models range in complexity from the so-called Compartment Model, in which interior behind-armor debris damage is treated by lumped parameters, to the highly detailed Point-Burst (or Component-Code) models in which these effects are assessed explicitly.

Unfortunately neither type can provide truly useful modeling support for Live-Fire Testing. The fundamental difficulty here is that both types provide *first-moment* or *expected-value* estimates of vulnerability, whereas combat damage can be highly stochastic. Single-shot (unreplicated) Live-Fire test results are single realizations of many possible and varied outcomes. To compare first-moment values on a shot-by-shot basis with single test samples can be a meaningless exercise. In addition, the Compartment Model lacks the necessary

(Continued on reverse side)

20. DISTRIBUTION / AVAILABILITY OF ABSTRACT
☐ UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☐ DTIC USERS

21. ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED

22a. NAME OF RESPONSIBLE INDIVIDUAL Paul H. Deitz

22b. TELEPHONE *(Include Area Code)* 301-278-6644

22c. OFFICE SYMBOL SLCBR-VL-V

DD Form 1473, JUN 86 *Previous editions are obsolete.*

SECURITY CLASSIFICATION OF THIS PAGE
UNCLASSIFIED

18. SUBJECT TERMS (Cont'd):

Stochastic Modeling
Vulnerability Assessment

19. ABSTRACT (Cont'd):

spatial resolution to identify and compare damage at the component level.

To remedy these shortcomings, the Ballistic Research Laboratory (BRL)/Vulnerability/Lethality Division (VLD) has made significant extensions to the Point-Burst Methodology in preparation for supporting the current set of Abrams Live-Fire tests. In a new stochastic model, the following parameters are varied in a Monte Carlo replication of warhead/target encounters: 1] slight variability in hit location, 2] warhead depth-of-penetration, 3] deflection of residual penetrator, 4] spall characteristics, and 5] individual component-kill assessment.

The result of a given assessment is a prediction of all *component damage combinations* along with the probability that each specific damage state will be encountered. These various damage states are mapped into loss-of-function histograms giving Mobility and Firepower "kills."

In this paper, the new BRL stochastic model called SQuASH will be discussed and examples of the output will be shown. Calculated probability distribution functions will be used to derive non-parametric uncertainty estimates which impact the issue of model "validation."

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I. INTRODUCTION

The vulnerability of a combat system 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 studies including:

- Cost & Operational Effectiveness Analyses (COEAs)
- Data for Decision Makers
- Inputs to War Games
- Vulnerability Reduction & Lethality Optimization
- Spare Parts Requirements for Repair of Battle Damage
- Logistics
- Concept Tradeoffs

From the earliest assessments performed some 40 years ago, the discipline of vulnerability has involved the use of field-derived data bases woven into a set of algorithms to calculate figures of merit. It has always been true that the quality of vulnerability estimation can be no better than the quality of the input data, and, as will be shown latter, there still exists a marked paucity of data critical to the vulnerability estimation process. Redressing these data shortfalls has been the objective of the National Defense Authorization Act for FY 1987[1] in which all major weapon systems are required to undergo testing prior to entering full-scale production. This program is contributing to the modernization of various data bases which are critical to vulnerability assessment. In addition, the requirements for full-scale live-fire predictions prior to the actual field shots, as well as detailed assessments afterwards, have focussed wide attention on the capabilities and limitations of current vulnerability methodologies. Such issues first arose with the Bradley Live-Fire Test program. The experience gained in that program prompted an evaluation of the methodology tools and their particular relevance to live-fire testing. As the Army began testing the Abrams tank, a new vulnerability assessment code was developed and has been used for some 50 preshot predictions.

The purpose of this paper is manifold. First we will discuss briefly the kinds of threats and damage mechanisms that are relevant to Armored Fighting Vehicle (AFV) assessment. Next we will review some history on full-scale field testing, discuss the key analytic frameworks which are at the heart of both field and analytic assessment procedures, and summarize the experience gained from testing the Bradley. Then the development of a new stochastic vulnerability model will be described and illustrated with a "generic" shot against the M1A1. The kinds of inputs required by this model and the plethora of statistical outputs will be illustrated and discussed. Finally some observations will be made concerning both this particular form of stochastic modeling as well as live-fire testing in general.

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1. "Live Fire Testing", National Defense Authorization Act for FY 1987, contained in Chapter 139, Section 2366 of Title 10, United States Code.

II. CONVENTIONAL AFV DAMAGE MECHANISMS

In terms of conventional munitions that confront AFVs, we give the following list:

- Kinetic-Energy (KE) Rounds
- Chemical Energy (CE) Munitions
  - ☐ Shaped-Charge (SC) Rounds
  - ☐ Explosively Formed Projectiles (EFPs)
  - ☐ Artillery Fragments
  - ☐ Mines

Of the five munitions of threat to AFVs, the KE and SC rounds are the most important. To derive some insight into possible damage mechanisms, we refer to Fig. 1. Here we have listed various phenomenologies which can lead to AFV damage, broken out by KE *vice* SC threats and by damage location, exterior *vice* interior.

—KE Threats/Exterior—

Taking first the KE class of threats, damage to exterior components can occur directly from penetration as well as indirectly from shock waves propagated from the point of impact. In addition, it sometimes occurs that when a KE penetrator strikes the glacis of a tank, eroded material is splashed up and beyond the point of impact. This spray of material can degrade or destroy relatively sensitive components such as vision blocks and also jam turret rings.

—KE Threats/Interior—

If a portion of a KE main penetrator breaches the armor package, the residual can cause significant damage to interior components. Behind-armor debris (BAD), irregularly shaped material exiting from the back surface of the armor, can also cause significant damage to interior components. BAD can be divided into three categories: (a) *direct,* debris which flies directly to a component causing damage, (b) ***secondary***, debris which is generated at an internal barrier, and (c) ***indirect***, deflected debris (ricochet).

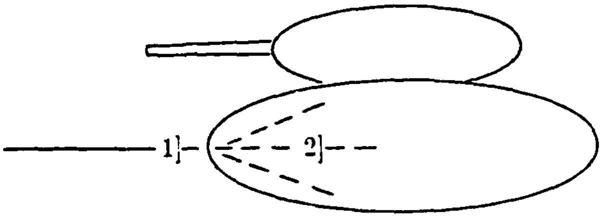
Other phenomenologies contributing to interior damage are shock propagated from the exterior KE striking point into internal components, the initiation of fire, hydraulic ram, and pyrophoric effects. Hydraulic ram effects can be observed when fluid volumes are impacted; the intense pressure spikes that result can disable critical components contiguous to the fluid.

—CE Threats/Exterior—

In contrast to a KE round, when a CE round strikes, a blast wave is created by the action of the warhead initiation. Although by design the kill mechanism is penetration by a jet, the blast wave created by the detonation, even on heavy vehicles, can damage suspension and other external components which are relatively delicate (e.g. sighting devices). In the case of lightly armored vehicles, the warhead delivery system can cause significant damage due to the ballistic impacts of rocket-motor housings, etc. As with KE rounds, hydraulic-ram damage can occur with CE warheads, and the blast effects can breech light armors.

—CE Threats/Interior—

As in the case of KE penetration, CE rounds can generate residual main penetrator elements (here jet residual) and BAD. Shock damage can occur due to blast waves from warhead detonation. As in the KE case, fire and hydraulic ram effects can be generated. CE rounds have some other phenomenologies which sometimes accompany impact: when a jet enters or exits an enclosed volume, a blast wave is generated which reflects within the enclosure. Such waves have the potential of causing damage chiefly to personnel (ears, lungs). Some tests have indicated that when CE jets penetrate aluminum armor, toxic gases may be produced. At the same time intense flashes of light can be produced (luminosity); this phenomenon has the potential to cause temporary (flash) blindness in crew members. Finally, CE jet entry into interior compartments



Kinetic Energy	Shaped Charge
1] EXTERIOR EFFECTS	
• Ballistic Shock (Structural/Ext. Component Damage)	• Blast Effects (Structural/Ext. Component Damage)
• Depth of Penetration	• Depth of Penetration
• KE Splash	
2] INTERIOR EFFECTS	
• Residual Penetration	• Residual Penetration ☜ *PRIMARY*
• Behind-Armor Debris (Direct, Secondary, Indirect)	• Behind-Armor Debris ☜ *PRIMARY* (Direct, Secondary, Indirect)
• Shock (Int. Comp. Damage)	• Shock (Int. Comp. Damage)
• Fire	• Fire
• Hydraulic Ram	• Hydraulic Ram
• Pyrophoric	• Interior Blast (Entry & Exit Points)
	• Vaporifics
	• Luminosity
	• Thermal Spikes

Figure 1. A listing of conventional Armored Fighting Vehicle (AFV) damage mechanisms for the two principal AFV threats, Kinetic-Energy (KE) projectiles and Shaped-Charge (SC) jets. The phenomenologies are further divided into 1] EXTERIOR and 2] INTERIOR effects. Some phenomenologies are common to both threats; others are unique. Based on the preponderance of AFV test experience, the majority of damage comes from warhead residual penetrator entry into interior AFV volume together with Behind-Armor Debris. For both kinds of threats these are labeled *PRIMARY*. All other phenomena are *in general* considered *Secondary*, but in specific warhead/target encounters may contribute to significant damage.

can generate thermal spikes which have the potential to cause burns to crew members and to initiate fires.

In the past, the preponderance of experience in the vulnerability community has been that the *primary* cause of damage to AFVs occurs due to the effect of warhead main penetrators and BAD. Thus these two mechanisms are labeled *PRIMARY* in Fig. 1. By default all of the other mechanisms are considered *secondary* in importance. This is not to say that in specific threat/target encounters the so-called secondary kill mechanisms may not become the principal or, indeed, the only causes of loss-of-function.

In part, the live-fire test programs are providing much needed data that may help to further delineate the issue of secondary kill effects. Even if they do not provide all the data needed to generate accurate algorithms, they will, at least, point the way to phenomena which must be included in future damage assessments.

III. HISTORICAL BACKGROUND ON TESTING

The roots of the analytic methods used in today's studies of AFVs can be found in the analyses of tests performed during the 1950's. This period of vulnerability testing and analysis culminated in a set of full-scale firings performed in Canada in 1959. Referred to as the CARDE tests,[2] 400 antitank rounds were fired against M47s and M48s. Most of the shots were performed with CE rounds in the 5"-8" diameter size. The results of the tests were used to refine a lumped-parameter model called the Compartment Code,[3] developed in the prior year. The Compartment Code was first generated from a group of tests performed between 1950 and 1954. This code relates certain warhead parameters to three kinds of expected-value "kills", Mobility (M), Firepower (F), and Catastrophic (K). The definitions of these kills[4] follow:

> **Mobility**: *An armored vehicle experiences a mobility (M) kill if it becomes incapable of executing controlled movement within a very short time (0 to 10 minutes) after being hit, and it is not repairable by the crew on the battlefield.*
>
> **Firepower**: *An armored vehicle experiences a firepower (F) kill if it becomes incapable of delivering controlled fire within a very short time (0 to 10 minutes) after being hit, and it is not repairable by the crew on the battlefield.*
>
> **Catastrophic**: *An armored vehicle experiences a catastrophic (K) kill if it is totally lost through burning or explosion.*

It is critically important to appreciate that the M, F, and K-Kill values yielded by the Compartment Code are *expected value* or *first-moment* parameters. That is, there is a distribution function associated with each of these parameters. In the case of a K-Kill, the outcome space is bivalued, i.e. the vehicle either *is* or *is not* catastrophically distroyed. This kind of outcome is of the class of a Bernoulli trial.[5]

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[2] Canadian Armament Research and Development Establishment, "Tripartite Anti-Tank Trials and Lethality Evaluation, Part I," November 1959 (UNCLASSIFIED).

[3] C. L. Nail, E. Jackson and T. E. Beardon, "Vulnerability Analysis Methodology Program (VAMP): A Combined Compartment-Kill Vulnerability Model", Computer Sciences Corporation Technical Manual CSC TR-79-5585, October 1979.

[4] J. J. Ploskonka, T. M. Muehl, C. J. Dively, "Criticality Analysis of the M1A1 Tank", Ballistic Research Laboratory Memorandum Report BRL-MR-3671, June 1988.

[5] A. Papoulis, *Probability, Random Variables, and Stochastic Processes*, McGraw-Hill, Inc, 1965, p. 57 ff.

Until the onset of the current live-fire programs, the pre-CARDE and CARDE trials represented the largest collection of full-scale firings against full-up heavy armored vehicles. By 1960 some 1400 firings had taken place with large munitions against heavy AFVs. There were, however, some other full-scale firings performed as the BRL continued to update its vulnerability data base.

Between 1963 and 1976 various full-scale tests were performed including small CEs *vs.* Armored Personnel Carriers (110 shots; 1964), High-Explosive Projectiles *vs.* tanks (228 shots; 1971), Influence-Fused Mines *vs.* tanks (172 shots; 1973), GAU-8 Munitions *vs.* tanks (153 hits; 1975), and Depleted-Uranium KE Penetrators *vs.* tanks (6 shots; 1976).

In 1977, the BRL performed an inhouse study[6] to examine what methods, experiments, and data bases were required to modernize its AFV analytic methods. Already the XM1 main battle tank was in advanced development using various modern armors never fired against in a combat-ready configuration. Although the BRL was not able to obtain M1s for full-scale firing, a set of controlled full-up firings was performed in Soccoro using M-48s.[7] KE warheads were fired and the results used to extend once more the BRL vulnerability data base.

From the time of the Soccoro tests until 1983, the utilization of modern armors (special, spaced, ceramic, etc.) increased in US vehicles. By this time the utility of the CARDE data (obsolete projectiles against monolithic targets) was clearly of diminishing value. In an attempt to modernize its vulnerability data base and methods, the BRL proposed a program called ARBADAM[8] in 1983. Although never funded, this proposal highlighted the critical need for comprehensive testing and set the stage for the current full-scale test programs Joint Live Fire (JLF) and Live Fire Testing (LFT).

The first to get underway was JLF. Chartered in 1984 as a DoD-sponsored and funded program, it employs joint technical coordinating groups for multi-service effectiveness. The overall thrust of JLF is to evaluate combat systems that have already been fielded. To date the types of systems that have been or are being tested include armored personnel carriers, tanks, fixed and rotary wing aircraft, and a wide variety of guided and unguided munitions.

Following the inception of JLF, the Defense Authorization Act of FY 1987[1] mandated LFT to evaluate the performance of all important combat systems prior to their entering full-scale production. An important series of tests took place against the M2/M3 or Bradley class of fighting vehicles.[9] The BRL was tasked with predicting shot outcomes *before* the firings, as well as helping to assess the results of field tests. The results of the shots were also used to upgrade the model used in the Bradley program. That code, called VAST,[10] with origins in the early 1970s, was one of the first of a number of ground vulnerability assessment codes of the *point-burst* class. In contrast to the Compartment Code, which treats interior vehicle damage using lumped-parameter functions, point-burst codes attempt to evaluate explicitly the complex behind-armor debris environment created by overmatching munitions, its interaction with critical interior

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[6] D. F. Menne, G. L. Durfee, R. L. Kirby, J. P. Lambert, M. L. Lampson, J. J. Ploskonka, J. R. Rapp and E. P. Weaver, "Plans for Updating the Armored Vehicle Lethality/Vulnerability Methodology and Data Base", Special Report for the Director, Ballistic Research Laboratory, 22 August, 1977.

[7] D. A. Ringers and F. T. Brown, "SLAVE (Simple Lethality and Vulnerability Estimator) Analyst's Guide", Ballistic Research Laboratory Technical Report ARBRL-TR-02333, June 1981, AD B059679.

[8] G. A. Bowers, P. J. Tanenbaum and S. F. Polyak, "Program Recommendation for Assessment and Repair of Battle Damage to Combat Materiel (ARBADAM)", 7 June 1984.

[9] "Bradley Survivability Enhancement Program, Phase II, Live Fire Test Report", prepared by the USA Test and Evaluation Command, the USA Ballistic Research Laboratory, the USA Materiel Systems Analysis Activity, the USA Combat Systems Test Agency, and the Office of the Surgeon General, 29 June 1987 (Report Classified SECRET).

[10] C. L. Nail, "Vulnerability Analysis for Surface Targets (VAST)- An Internal Point-Burst Vulnerability Assessment Model - Revision I", Computer Sciences Corporation Technical Manual CSC TR-82-5740, August 1982.

components, and the resulting decrease in vehicle functioning. This class of code will be explained in more detail in the next section.

Following the Bradley program, the Abrams Main Battle Tank was scheduled for testing. Based on the Bradley experience, it became clear that a new analytical framework was required to predict and analyze properly the full-scale testing of the Live-Fire Program. In Section V, the key evidence for that conclusion will be presented.

IV. CONCEPTUAL FRAMEWORK FOR AFV VULNERABILITY ASSESSMENT

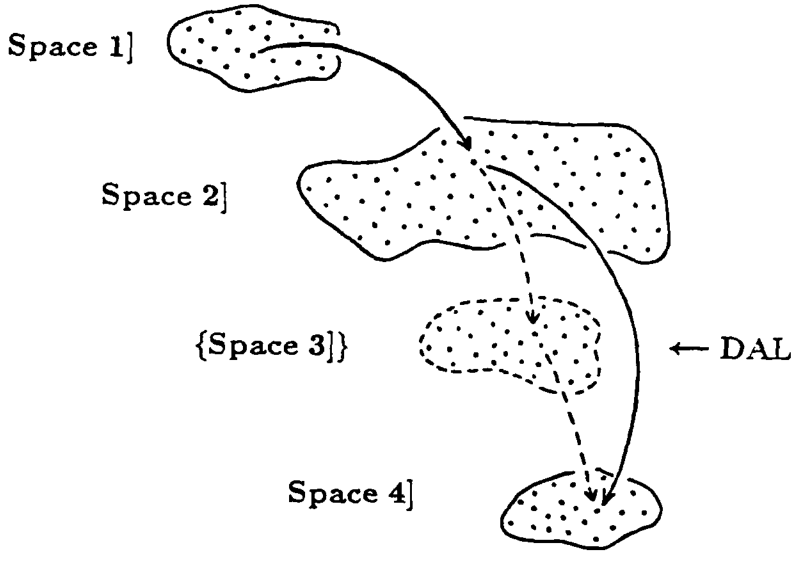
To understand the nature of vulnerability/lethality assessment of AFVs, it is critical to understand the framework within which all assessments for the past 40 years have taken place. This framework is not just implicit to computer-based assessments, but provides a key link to processing live-fire test results as well.

The vulnerability process can be thought of as a transformation or mapping of information among four number domains or spaces. Points in a lower number space are mapped to higher spaces by experimental processes and/or mathematical (modeling) transformations. As illustrated in Fig. 2, Space 1] defines the myriad of details concerning the interaction of a specific munition against a specific AFV target. With respect to a munition, this includes the mass, velocity, shape, orientation, etc. In terms of the target, the specifics include all of the three-dimensional geometry (including armor packages and interior components), material properties, interdependency of system functioning, etc., and the munition impact location.

Whether a real bullet is fired against a target in the course of a live-fire experiment or a computer-based simulation is performed to that end, damage to the target can accrue as a result of the interaction. In the case of an undermatching munition, it may be that no damage occurs. In any case, the state of the target after the interaction is ***defined*** in terms of the vehicle ***critical*** components; a critical component is any component, the loss of which would result in the reduction in a mobility or firepower capability of the vehicle. Past and current practice in vulnerability assessment is to describe individual components in crisp binary states, i.e. ***killed*** or ***not killed***. At the component level no partial functioning is allowed. Following a shot on an AFV the ***damage state*** of the vehicle is defined as the full accounting of all vehicle critical components. Each point within Space 1] represents one of a large (uncountable) number of possible bullet/target interactions. As noted above each specific bullet/target state is characterized by literally hundreds of thousands of numbers representing the state of the system geometry, material constituencies, component interconnectivities, warhead penetration performance parameters, etc. The many points in Space 2] imply a large, but nevertheless countable, number of possible outcomes that may occur following a bullet/target interaction. If an AFV is constructed of n critical components, then the (countable) space of points in Space 2] is 2^n. In the case of the M1A1, the corresponding BRL-generated target description is composed of approximately 750 critical components. Since no individual shot has a significant likelihood of killing all components in the target, the size of Space 2] is far fewer than 2^{750} points. However in just the turret-basket area of the M1A1, there are some 400 components; if only one-fourth of those components were likely candidates for damage, there remain on the order of 2^{100} possible damage states, representing about 10^{30} possible outcomes!

Thus a LF test is an experiment which provides a single transformation from a point in Space 1] to a point in Space 2]. Later we will see that if a LF experiment were repeated, the single point in Space 1] could map to many different points (corresponding to many different damage states) in Space 2]. We will also examine a vulnerability code which can be used to emulate that process.

Given a particular damage state in Space 2], by definition a set of critical components no longer works. Thus there may be some reduction in the firepower or mobility function of the AFV. Space 3] represents an objective measure of this diminution in performance. In the case of firepower



1] Warhead/Target Interaction →

2] Component Damage State(s) →

3] Measures of Performance (MOPs)
[Loss of Automotive/ →
Firepower Capabilities]

4] Measures of Effectiveness (MOEs)
[Reduction in Battlefield Utility,
"PKs", or "Losses-of-Function"]

Figure 2. Four Spaces of Vulnerability. Space 1] represents all combinations of specific warhead/target encounters. Space 2] represents all possible damage states of an AFV. Objective Measures-of-Performance (MOPs) are represented by Space 3], while Space 4] characterizes Measures-of-Effectiveness (MOEs). A Live-Fire shot can be thought of as a mapping from a point in Space 1] to Space 2]. Space 3] is not evaluated in AFV analyses, so the mapping processes and domain are shown in dashed lines. For 30 years standard practice has been to map AFV component damage (states) in Space 2] to Space 4] using the (Standard) Damage Assessment List (DAL).

function, characterization of Space 3] might be in terms of a reduction in rate of fire, an increase in time to acquire a target, or the growth in hit dispersion of the main gun. In the case of mobility, Space 3] might be represented by reduction of top speed, reduction in acceleration, or reduction in rough-terrain crossing ability. Space 3] can be thought of as represented by objective *Measures of Performance (MOPs)*. Although Space 3] is in principle of great interest to many concerned with vulnerability analysis, there is no *implemented* mechanism for this mapping. Hence both the mapping process and the domain are represented with dashed lines in Fig. 2.

Finally Space 4] is a domain which historically was defined as a probability space. It is actually composed of a number of sub-spaces, one describing a K-Kill criterion. Two other sub-spaces describe mobility and firepower. The M and F metrics are constrained to the interval

$$0.0 \leq P_{FK} \leq 1.0$$

and

$$0.0 \leq P_{MK} \leq 1.0$$

where

$$P_{FK} \approxeq \text{Probability of Firepower Kill}$$

and

$$P_{MK} \approxeq \text{Probability of Mobility Kill.}$$

The significance of Space 4] is in terms of a *Measure of Effectiveness (MOE)* where an MOE[11] is driven in terms of the definitions of the Mobility and Firepower Kills given in Section III.

Following the pre-CARDE trials, a mapping artifice was developed (*circa* 1957) called the Standard Damage Assessment List (SDAL). The SDAL is a listing of some 120 major systems and components which comprise an AFV. Later modified by a board of Army officers and armor specialists (*circa* 1959), it represents their best estimates of the *relative* Combat Utility (CU) of a vehicle given the loss of each specified system or component. These estimates assume all possible combat scenarios, both offense and defense, and tank doctrine as then promulgated. The accepted practice has been to equate the Decrement in Combat Utility (DCU)[†] with a probability of kill. However it has been recognized for some time that this process has serious flaws both from a mathematical and an implementation standpoint.[12] For example it is clear that the decrement in combat utility *is not* equatable to a probability function. And there are problems with the massive amounts of mental averaging that are performed by the committees involved in this process. Also, due to the process of averaging over so many scenarios, the effect of the loss of a *particular* system may be washed out for subsequent use in a war game in which a context-specific scenario is being played.

As this problem was identified in the last ten years, some workers dropped the label "Probability of Kill" in favor of "Expected Loss-of-Function" for the respective M and F variables. However, this is a disingenuous stratagem in view of the fact that consumers of vulnerability estimates continue to use them as probabilities. Probably the best that can be said about the SDAL process is that it has been used as an essentially consistent metric for 30 years. On the other hand, it must be noted that *the outputs of the SDAL process, whether called "PKs", "LOFs", or "DCUs", have no assignable meaning except for the extremes of 0.0 and 1.0!* This in spite of the way in which war gamers or any other users of AFV vulnerability data arbitrarily choose to use the numbers.

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[11] P. H. Deitz, "The Future of Army Item-Level Modeling", in the *Proceedings of the XXIV Annual Meeting of the Army Operations Research Symposium*, 8-10 October 1985, Ft. Lee, VA.

[†] The Decrement in Combat Utility is the *complement* of Combat Utility.

[12] J. R. Rapp, "An Investigation of Alternative Methods for Estimating Armored Vehicle Vulnerability", Ballistic Research Laboratory Memorandum Report ARBRL-MR-03290, July 1983.

Nevertheless, because modern tanks have many critical systems/components which were not a part of the original SDAL, other vulnerability workers have generated an updated DAL. This task was completed under the auspices of the AF-sponsored Chicken Little Program.[13, 14] Offense and defense scenarios were examined separately as well as averaged. For the first time the framework for this process was also documented.[13,14] However, the BRL has deferred adoption of the new SDAL values in favor of attempting to define new sets of kill definitions that are both mathematically consistent and directly relatable to field damage states (Space 2]).[15] The Army Materiel Systems Analysis Activity (AMSAA) is assisting the BRL in those objectives.

Thus since the mid-1950s, the standard practice in AFV vulnerability has been to utilize the SDAL to map damage states from Space 2] directly to Space 4]. That standard procedure has been utilized in the Abrams program for the derivation of the Mobility and Firepower LOF estimates reported later. As noted above, no mechanism exists for evaluating Space 3]. It can be seen that the DAL mapping from Space 2] to Space 4] is intrinsic to all vulnerability analyses whether based on field shots or computer simulations.

— Compartment Model —

The Compartment Model was based originally on the individual damage states observed from some 1400 firings. For each shot, the observed damage state was mapped to the related P_{FK} and P_{MK}. Lumped parameter curves, called ***damage correlation*** curves were fitted to these data. The result was a ***first-moment*** vulnerability estimate for the specific munition/target combinations tested. The Compartment Model can be thought of as a model which maps bullet/target combinations directly from Space 1] to Space 4].

— Compartment-Model Logic —

The logic of the Compartment Model follows:

1] Intersect ray with target geometry to simulate threat trajectory

2] Check for Exterior Damage (Suspension, Gun Tube)

3] Check for Perforation

4] If Perforation, check for K-Kill due to main penetrator impacting on Fuel/Ammunition

5] If Perforation, then utilize damage correlation curves to estimate magnitude of M and F Kills for each compartment breached. These include K-Kill from fragments impacting ammunition.

6] Assume independence and use probabilistic "survivor rule"[†] to sum up all kill contributions.

The model is only as good as the data base and historically has been based on firings of increasingly antiquated munition/target pairings. In a future effort, the results of a calibrated point-burst model will be used to upgrade variants of the Compartment Model for various combinations of munition/targets.

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13. G.A. Zeller, "Update of the Standard Damage Assessment List (SDAL) for Tanks", Executive Summary, ASI Systems International Report 87-14, October 1987.

14. G. A. Zeller and B. F. Armendt, "Update of the Standard Damage Assessment List for Tanks: Underlying Philosophy and Final Results", Submunition Evaluation Program, Project Chicken Little, Report AD-TR-65, November 1987.

15. M. W. Starks, "New Foundations for Tank Vulnerability Analysis", *The Proceedings of the Tenth Annual Symposium on Survivability and Vulnerability of the American Defense Preparedness Association*, held at the Naval Ocean Systems Center, San Diego, CA, May 10-12, 1988.

[†] Reference 12, p. 16.

It is important to note that there is a long-term requirement for the maintenance of this class of model. Many important vulnerability/lethality studies are required for targets and/or munitions for which detailed information is not available. This situation is encountered, for example, in the study of foreign AFVs for which knowledge is limited or in US concept tradeoffs where only a first-cut design exists.

— Point-Burst Modeling —

During the early 1970s, the first point-burst model was developed. Called VAST,[10] this model attempts to model the behind-armor residual penetration and behind-armor debris environment. Greatly more complex than the Compartment Code, point-burst models require a knowledge of detailed debris data for every warhead/armor pairing that will be encountered in an analysis. For a given shot, VAST gives the probability of killing any critical component (singly) within the vehicle. Although this is a Space 2] parameter, VAST has no capability of calculating the probability of encountering killed components *in combination*. Thus there is no capability of matching the observed damage state of a field experiment with a model prediction of Space 2]. VAST uses the SDAL mapping process to calculate a first-moment estimate of the P_{FK} and P_{MK} as well as the K-Kill (Bernoulli) values.

It is worth noting that in vulnerability assessment there is no truly *predictive* model. All classes of models are built on experimental data. In the case of the Compartment Code, the data involves full-scale firings. After curve-fitting, the "predictions" of the kill probabilities can only be inferred for the particular munition/target combinations tested. The model cannot accommodate changes in the target configuration to examine vulnerability reduction or other modifications. And given the limited statistical sample for any set of full-scale firings, the results may result in considerable arbitrary bias. In the case of point-burst modeling, the vulnerability estimates are actually performed by aggregating the results of various "off-line" experiments involving many tests with warhead/armor pairings as well as component testing to calibrate the susceptibility of components to fragment damage. Although system geometry can be modified, there are voluminous amounts of input data that must be assembled. Often there is insufficient data on particular warhead/armor pairings and concomitant behind-armor debris (BAD) data.

Recently the BRL documented the state of warhead/armor and BAD characterization.[16] These data are replicated in Tables I and II. It can be seen from these tables that many of the newer-threat/modern-armor pairings present combinations for which little or no reliable data are available.

In the next section, we will discuss how the VAST model was applied to the Bradley Live-Fire Program.

V. EARLY LIVE-FIRE EXPERIENCE

When the requirements for vulnerability modeling in conjunction with the Bradley Live-Fire Testing first arose, BRL analysts considered various code options. The Compartment Model was considered and rejected for a number of significant limitations:

- No full-up firings had ever been performed against the Bradley. Thus there were no empirically based Compartment Model damage correlation curves traceable to the test configuration.

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[16] D. L. Rigotti, "Vulnerability/Lethality Assessment Capabilities - Status, Needs, Remedies", *The Proceedings of the Tenth Annual Symposium on Survivability and Vulnerability of the American Defense Preparedness Association*, held at the Naval Ocean Systems Center, San Diego, CA, May 10-12, 1988.

Table I. Status of Penetration Data. The matrix shows the status of penetration for each armor/warhead combination (from Ref. 16).

	WARHEAD				
ARMOR TYPE	Conventional Shaped Charge	Kinetic Energy Penetrators	Shaped Charge W/Crossing Vel	Tandem Shaped Charges	Explosively Formed Penetrators
Homogeneous Steel	3	3	2	2	3
Homogeneous Aluminum	3	3	2	2	3
Spaced Configurations of Steel or Aluminum	3	3	2	2	3
Laminates of Steel and Ceramics or Plastics	1	1	1	1	2
Single Element Reactives	2	2	2	2	2
Multiple Element Reactives	2	1	1	2	2
Reactive Appliques Over Steel/Ceramic Laminates	1	1	1	1	2
Special Armor	3	3	2	2	1

Legend:

1] No analytical penetration models exist. Critical data voids exists.

2] Rudimentary models exist. Additional data are required.

3] Extensive data available. Additional data are of some importance.

Table II. Status of Behind-Armor Debris (BAD) Data. The matrix shows the status of BAD knowledge for each armor/warhead combination (from Ref. 16).

	WARHEAD				
ARMOR TYPE	Conventional Shaped Charge	Kinetic Energy Penetrators	Shaped Charge W/Crossing Vel	Tandem Shaped Charges	Explosively Formed Penetrators
Homogeneous Steel	3	2	1	1	3
Homogeneous Aluminum	3	2	1	1	1
Spaced Configurations of Steel or Aluminum	2	1	1	1	2
Laminates of Steel and Ceramics or Plastics	1	1	1	1	1
Single Element Reactives	2	1	1	1	1
Multiple Element Reactives	1	1	1	1	1
Reactive Appliques Over Steel/Ceramic Laminates	1	1	1	1	1
Special Armor	2	2	1	1	1

Legend:

1] No analytical behind-armor debris models exist. Critical data void exists.

2] Rudimentary models exist. Additional data are required.

3] Extensive data available. Additional data are of some importance.

- Even had damage correlation curves been available for a prior configuration of the Bradley, no parametric excursions from the system baseline would have been possible. This would have precluded examining the effects, for example, of reconfiguring the location and shielding of interior components.
- The Compartment Code does not predict component damage. Thus it could produce no metric directly comparable with a field observable.

Essentially the only available option was to utilize the VAST computer code. This code was used to make some 76 pre-shot predictions.[9]

The results of the exercise are summarized from an analytic perspective here:

- The predictions of VAST were compared with corresponding Live-Fire Field results on a shot-by-shot basis. This was not an ideal choice however, because, as noted above, VAST, like all other vulnerability codes up to this time, is a first-moment predictor; that is, only the expected kill values are produced. At the time, nothing was known about the probability density functions associated with mobility and firepower kills. Lack of appreciation for the possible variability of test results led to a widespread practice of comparing expected-value output of the code to single outcomes from the Live-Fire tests. Based on the most elementary considerations of basic statistics, ***this is an analytic non-sequitur!***
- Nevertheless, model "validation" was carried out by such comparisons. The General Accounting Office[17] performed a detailed summary of VAST and the Bradley test results. The predictions and field results were compared side-by-side. One critic from the Office of Secretary of Defense[†] rated the "validity" of the Bradley predictions on whether they fell within 30% of the expected-value estimates. This in spite of the fact that nothing was known about the probability density functions associated with the PKs.
- As noted above, neither VAST nor any of the other extant point-burst models gave any insight into the probability of encountering specific damage states, and specific damaged components represent the principal yield of the testing process.
- The Bradley tests showed that damaging a single small component can dramatically affect system loss-of-function. In one case the cutting of a single wire by an off-axis fragment resulted in a significant loss-of-firepower function.

Thus as the BRL embarked on the Abrams Live-Fire program it became clear that there was a significant need for a stochastic point-burst model with the following general characteristics:

- The target description modeling would have to be accomplished at an unprecedented level of detail.
- The vulnerability model should be capable of reflecting the chief forms of variability in the vulnerability process that could lead to shot-to-shot variations in damage. This should include both variations in the causes of component damage, given a hit, and random (spatial) deflections of lethal fragments.
- The vulnerability model should calculate damage states on a repeated (Monte Carlo) basis so that probabilities of individual state outcomes could be assessed.

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17. "Live Fire Testing: Report to the Chairman, Subcommittee on Seapower and Strategic and Critical Materials, Committee on Armed Services, House of Representatives", United States General Accounting Office Report GAO/PEMD-87-17, August 1987.

[†] Reference 17, p. 124.

- The vulnerability model should map the damage states to probability density functions in PK space (Space 4]) so that the variabilities in outcome space could be assessed.

The development of the new model is described in the next section.

VI. SQuASH

To meet the requirements of the Abrams Live-Fire program, a totally new class of stochastic point-burst model was developed.[18] Called SQuASH (for Stochastic Quantitative Analysis of System Hierarchies), this code was designed to accommodate the threats enumerated in Section II, including the special case of multiple hits (salvo-fired weapons).

Accommodation was 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 from copy-to-copy in so far as wire routing, etc. The geometric interrogation process involves shooting (zero-width) rays through the target to replicate possible projectile paths. The process only yields 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 was chosen to provide sampling over a six-inch cross section.

- **Warhead Performance:** Normally 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 all warhead/armor calculations; in the course of model exercise, random draws are made from this distribution function.

- **Residual Penetrator Deflection:** In the case of KE projectiles incident at oblique angles, the residual portion of a penetrator can deflect upon exiting armor. The deflection is greatest near the limit velocity when the armor is just being overmatched. A distribution function is utilized here to select trajectories in the vicinity of the expected deflection.

- **Spall Production:** The VAST code uses a spall model based on BAD described in terms of fragment mass, velocity, and shape factor.[10] Since much of this information is lacking (as noted in Table II) for many warhead/armor pairings in the M1A1 program, a spall model based on a notion of *lethal fragments* was used. For the past ten years, the US has standardized spall collection by means of a package of thin metallic plates.[19] Lethal fragments for these purposes are defined as those fragments which penetrate at least the first plate in this combination pack.

  The SQuASH spall model is based on a routine which describes the spatial density of lethal fragments as a bivariate gaussian distribution. The solid angle subtended by any critical component and its location then defines 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 number of fragments. This particular number of fragments is then evaluated against the given component.

- **Component PK/H Characterization:** Each critical component in the target is separately characterized in terms of its probability of being killed by main penetrators and by single

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[18] A. Ozolins, "Stochastic High-Resolution Vulnerability Simulation for Live-Fire Programs," *The Proceedings of the Tenth Annual Symposium on Survivability and Vulnerability of the American Defense Preparedness Association*, held at the Naval Ocean Systems Center, San Diego, CA, May 10-12, 1988.

[19] S. Corbett, J. Suckling, M. Chick, and C. Helleur, "Development of Improved Techniques for the Evaluation of Behind Armour Effects", Report of the Key Technical Areas 9 & 12. The Technical Coordination Program (TTCP), Panel W-1, July 1987.

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. Multiple hits are assessed using the "survivor rule".[†]

- **Secondary Kill Phenomena:** In Section II, both primary and secondary kill mechanisms were described. As mentioned repeatedly, although the primary phenomena are often not adequately characterized, usually even less is known about the myriad of possible secondary effects. In general, secondary kill phenomena are not modeled because, *in the main*, they do not appear to play a consistent and significant role on AFV vulnerability. Nevertheless particular tests have been performed, for example, in which ballistic shock or blast have been shown to cause critical damage in certain circumstances. Unfortunately the relative importance of including this class of assessment in codes like SQuASH is indeterminate at this time, and it is a principal goal of the BRL M1A1 assessment program to gain as much insight into the importance of these secondary mechanisms as possible. Even if such phenomena are shown to be important, there are few dependable algorithms and data bases extant with which to make assessments.

  In the context of the Abrams program there was insufficient time to introduce damage algorithms for these secondary phenomena. However provision was made in the code structure to support any additional damage algorithms that might be required.

Before describing the operation of the SQuASH code further, we will discuss the remaining inputs to the model.

VII. APPLICATION OF SQuASH TO THE M1A1

Prior to exercising the SQuASH code, many inputs had to be assembled. They will now be discussed.

— Geometry —

At the inception of the M1A1 Live-Fire Program, the extant target description was a moderately detailed version of the M1E1 vehicle. Based on the Bradley experience it was clear that the target geometry had to be enhanced to an unprecedented level. Using the BRL-CAD solid geometric modeling software,[20,21] some 25 specific subsystems were added to the target description; these systems are modeled down to the individual wire and hydraulic-line level of detail. Figure 3 shows four of these systems, all from an upper front-left perspective. In Fig. 3a the M1A1 fuel system is illustrated. Critical fuel lines and filters are modeled as well as the larger fuel tanks. Figure 3b gives the powerpack. The turret fire control and communications gear are shown in Figs. 3c and 3d, respectively.

Figures 4 and 5 give views of the aggregate M1A1 system from the front-left and rear-right aspect angles, respectively. For these displays the armor and main armament have been removed. This modeling effort has resulted in the largest target-description file ever assembled, now comprised of over 5000 objects.

[†] Reference 12, p. 16.

20. **Ballistic Research Laboratory CAD Package, Release 1.21 (2-June-1987)**, "A Solid Modeling System and Ray-Tracing Benchmark Distribution Package", SECAD/VLD Computing Consortium.

21. P. H. Deitz, W. H. Mermagen, Jr., and P. R. Stay, "An Integrated Environment for Army, Navy and Air Force Target Description Support", *The Proceedings of the Tenth Annual Symposium on Survivability and Vulnerability of the American Defense Preparedness Association*, held at the Naval Ocean Systems Center, San Diego, CA, May 10-12, 1988.

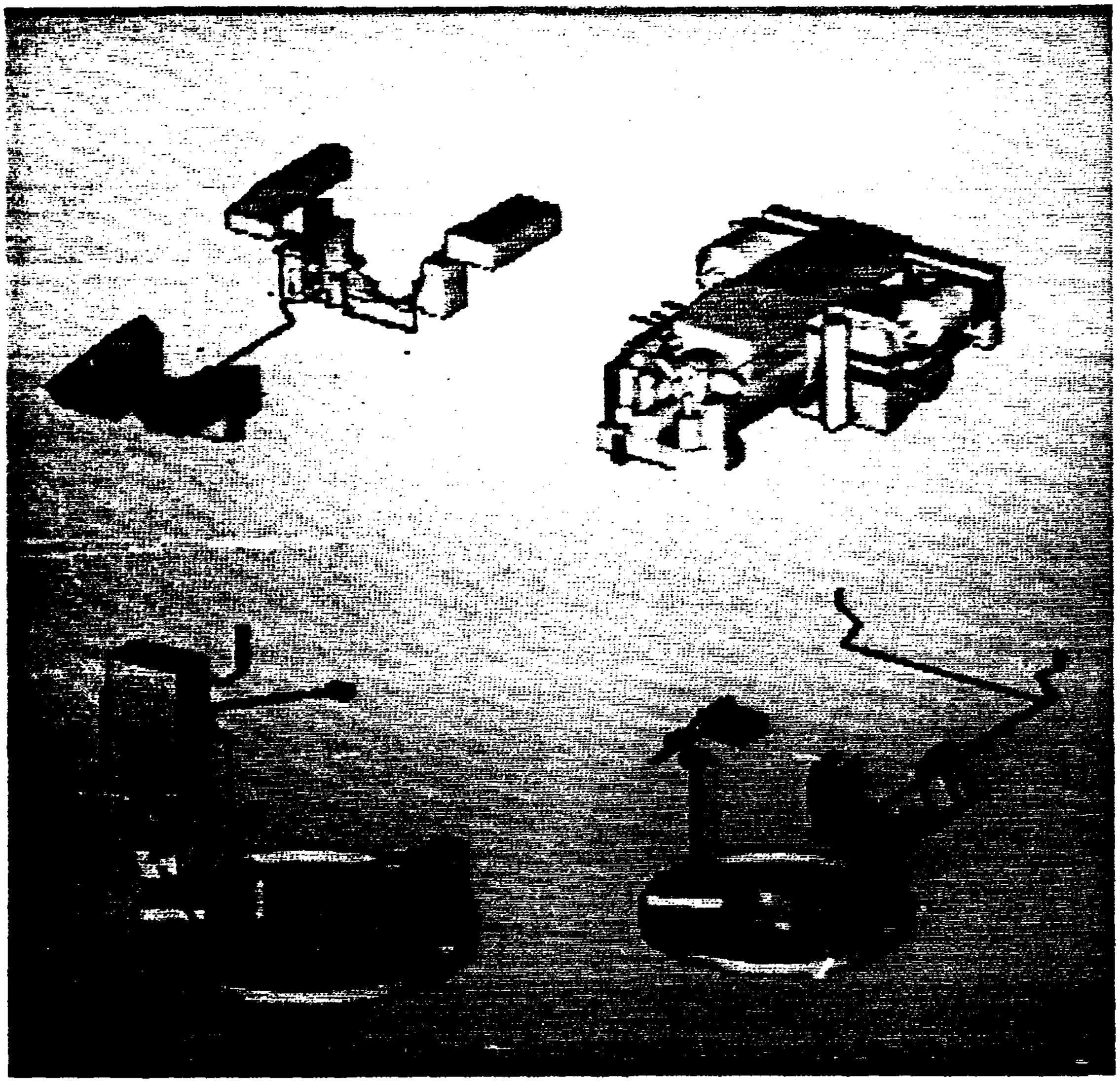

Figure 3. Four of the 25 M1A1 critical systems which support firepower or mobility functions. The fuel system is shown in a), the powerpack in b), the turret fire control and communications gear and are shown in c) and d), respectively. These systems are modeled down to the level of individual electrical wires and hydraulic lines.

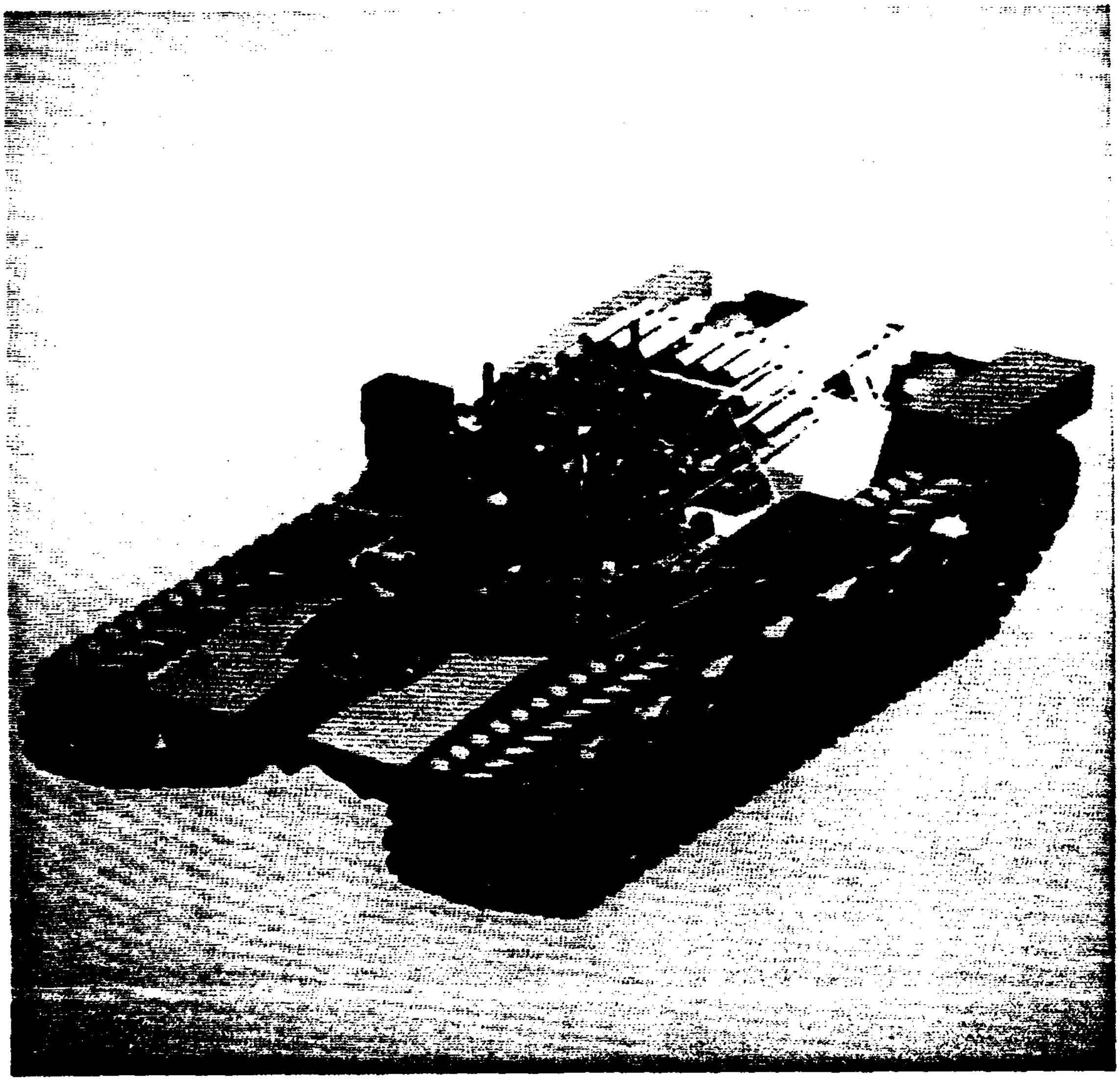

Figure 4. View of the M1A1 from the front left. The armor and main gun have been removed to reveal the level of interior detail. This target description is composed of some 5000 objects of which approximately 750 are critical components.

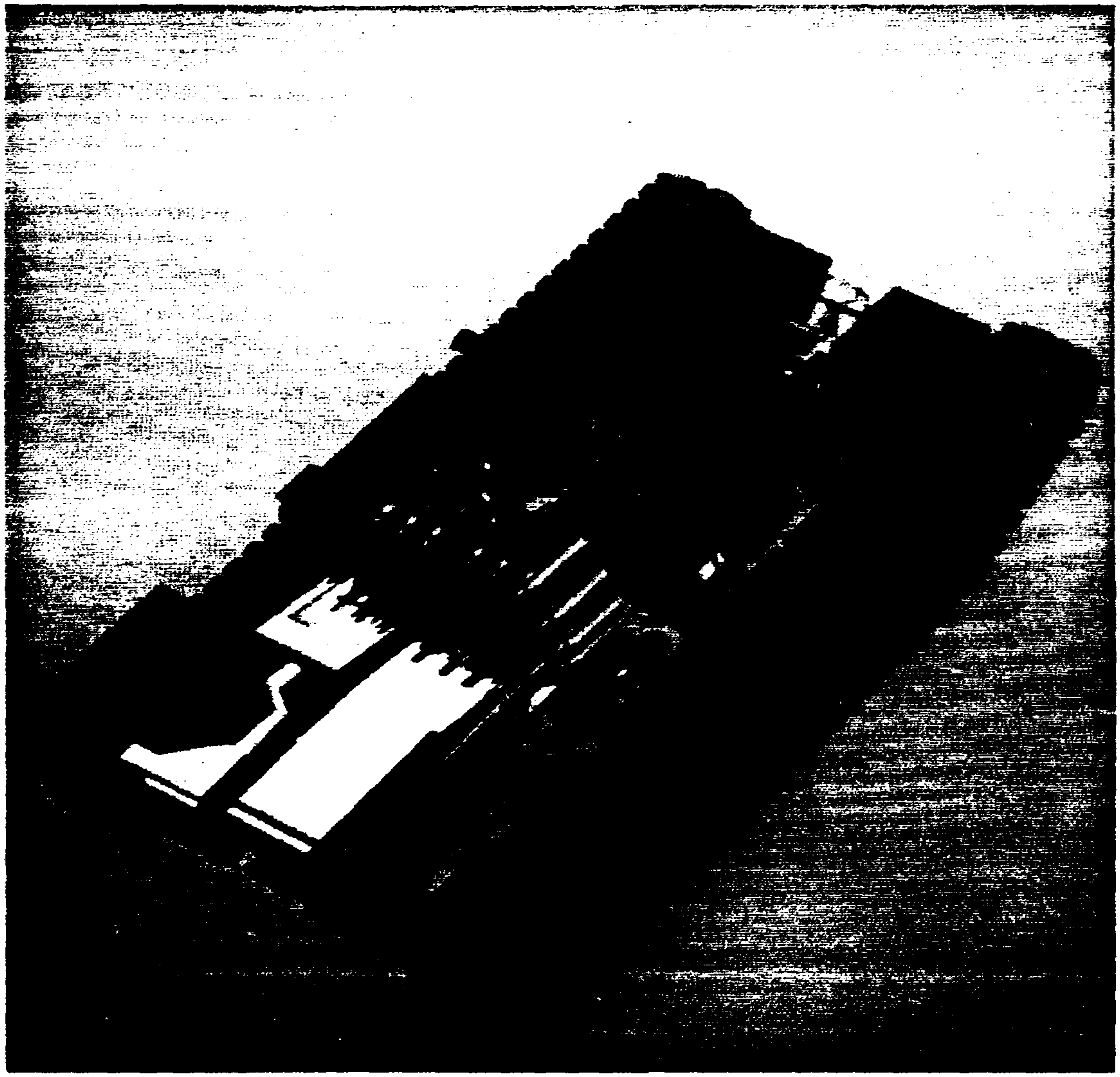

Figure 5. View of the M1A1 from the rear right. As in Fig. 4, the armor and main gun have been removed.

— Criticality Analysis —

Every point-burst analysis code, including SQuASH, requires a criticality analysis. A criticality analysis of a target involves a two-step process. First, every component of the vehicle which supports the mobility or firepower function must be identified. Second, the logical interconnectivity of each component in its respective system or sub-system must be represented in a *deactivation diagram* which is a form of fault-tree analysis. By this process the potential loss of a component on a given system function can be assessed so that the Standard Damage Assessment List can be invoked in the Space 2| to Space 4| mapping process. The details of the M1A1 criticality analysis can be found in Ref. 4. An example for the Fuel System illustrated in Fig. 3a can be found in Fig. 6. In this structure the series layout of components with the lack of redundancy shows that component loss is equivalent to system loss. In contrast, the loss of a single component which operates in parallel with a similar component (e.g. FUEL LINE FROM LEFT REAR FUEL CELL TO TEE) does not affect system capability. Code has been written[22] to assist in the construction of these diagrams and the compilation of the logic structures for the SQuASH input files.

— Threat Characterization-Main Penetrator —

As required in the Detailed Test Plan,[23] some 50 shots have been fired at the M1A1. The M1A1 itself is comprised of some 6 different armor types. Warhead/armor data were assembled for all possible encounters.[24] In all previous vulnerability models, only the nominal (expected-value) performance parameters were utilized. However SQuASH requires an estimate of the *variability* of the warhead/armor performance be included. This information is illustrated in Fig. 7. At the top of the figure, a test configuration is shown for a shaped-charge warhead against a semi-infinite target. This experiment would be repeated many times for a series of standoffs. After plotting data from such an experiment,[25] the curve shown in the bottom of the illustration is derived. This solid curve is the relationship normally utilized in vulnerability models. In the case of SQuASH, data about the variability of penetration depth as a function of standoff were also developed for each round. This is implied here by the error bars on the mean data points. In the course of code execution, nominal penetration values were modulated by random draws from related error functions. For KE rounds, penetration variability is modeled in terms of limit thickness, which is the form data are provided by the Terminal Ballistics Division, BRL. It is worth noting that data were extremely sparse for many of the threat warheads used in the Life-Fire Program.

— Threat Characterization-Behind-Armor Debris —

Since point-burst modeling involves the explicit interaction of BAD with critical components, behind-armor spall clouds must be described analytically. However, as indicated in Table II, even less information is available for warhead/target pairings in the area of BAD than penetrator overmatch.

— SDAL Modifications —

The Standard Damage Assessment List was discussed in Section IV. Minimal modifications in the earlier SDAL were made to include components/systems which were not present on earlier AFVs. These changes were coordinated with the US Armor School, Ft. Knox.[26]

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[22] The program is called *ICE* for Interactive Criticality Estimator, and is documented in the VLD/VMB UNIX Supplementary Manual, D. A. Gwyn, Editor, August 1987.

[23] "Phase I Detailed Test Plan for the Abrams Live Fire Vulnerability Tests", Revision 2, USA Test & Evaluation Command, TECOM Project No. 1-VC-080-4A1-039, 17 July 1987 (Secret, Special Access Required).

[24] T. M. Muehl, "Compilation of Terminal Effects Inputs for Vulnerability Estimates for the Abrams Live Fire Tests", Ballistic Research Laboratory Memorandum Report, In Preparation (Secret, Special Access Required).

[25] R. DiPersio, J. Simon and A. Merendino, "Penetration of Shaped Charge Jets into Metallic Targets", Ballistic Research Laboratory Report No. 1296, September 1965.

[26] "Criticality Analysis of M1A1", letter from D. R. Burgess, COL, Armor, TSM Tank Systems, US Armor School, Ft. Knox, KY, 10 March 1987.

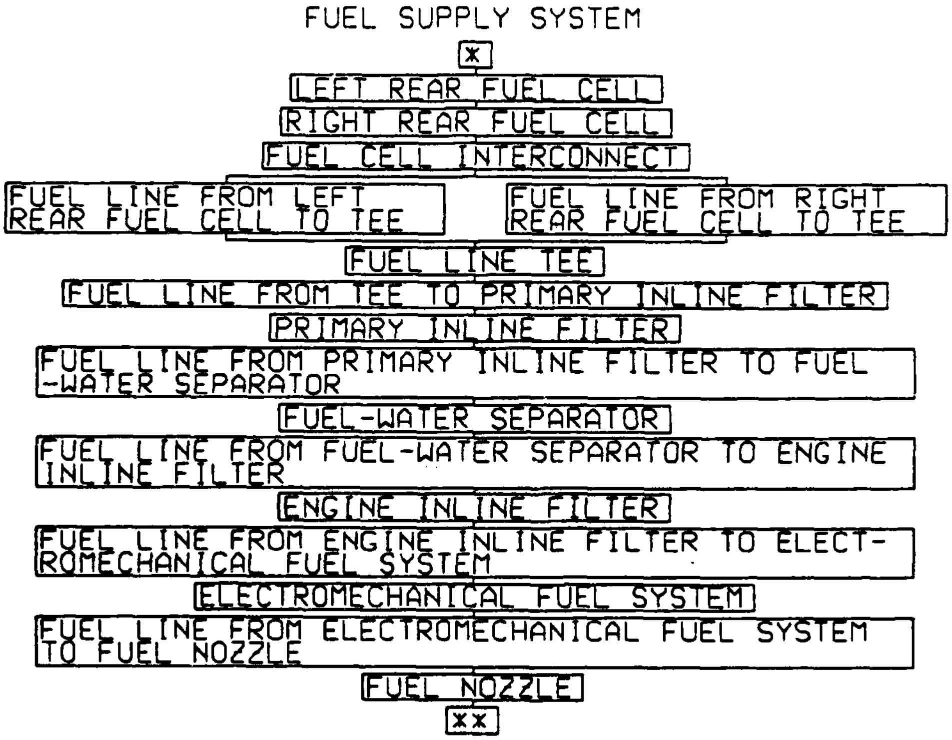

Figure 6. A sample deactivation diagram (or fault tree) for the Fuel Supply subsystem shown in Fig. 3a. Components in parallel have redundancy while those in series do not. Killing a series component defeats the system. Killing a single parallel component does not affect system capability.

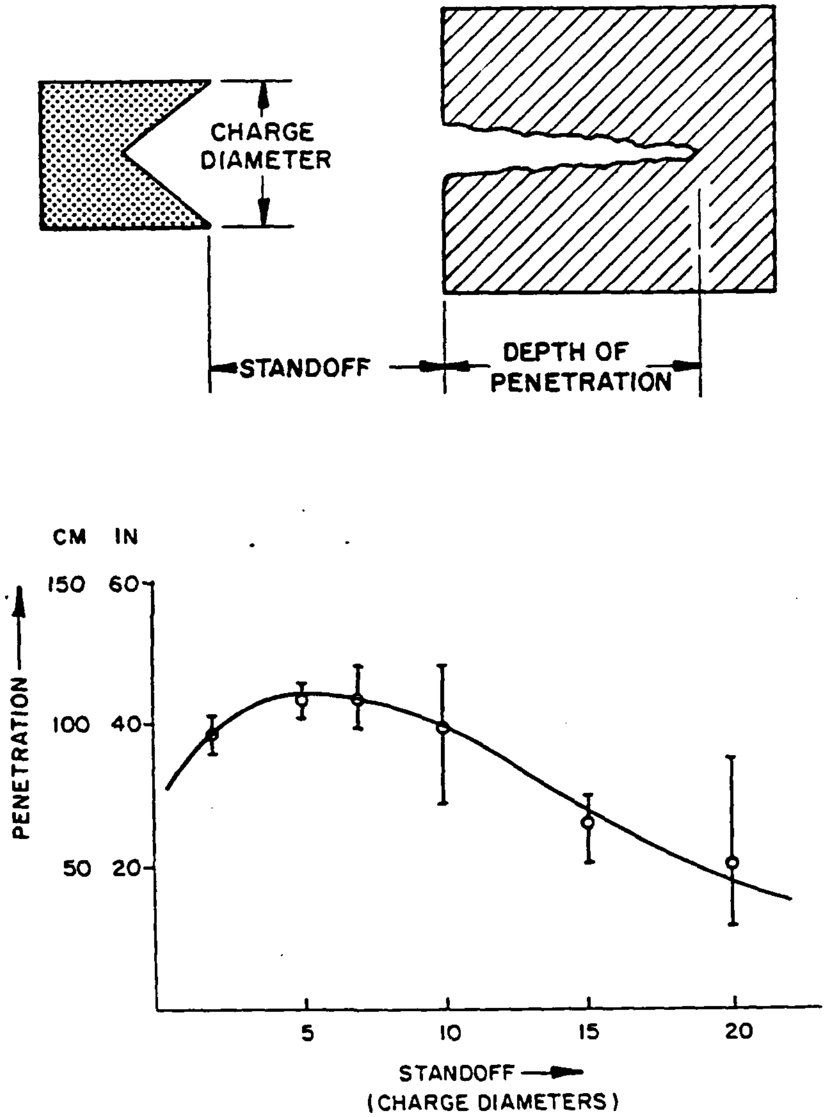

Figure 7. Test configuration (above) and data (below) for a shaped-charge warhead (Ref. 25). A series of tests are performed against semi-infinite armor as a function of standoff to characterize warhead performance. The data at each standoff are averaged and used to fit the solid curve below. The experimental one-sigma deviations (indicated by the error bars) are used in the SQuASH simulation to estimate variability in warhead/armor performance.

— SQuASH Code Logic —

The logic of the SQuASH vulnerability code follows:[†]

1] Intersect nine rays with target geometry to simulate threat trajectory; from each possible interior spall point, burst 10,000 rays

2] Randomly pick one of nine rays and fire threat munition

3] Check for suspension and other exterior damage

4] Check for perforation

5] If perforation, randomly deflect residual penetrator (depending on target & munition)

6] Assess components killed due to residual penetrator

7] Check for K-Kill due to impact on fuel/ammunition

8] Assess presented area and barrier shielding for all critical components in spall domain

9] For each component calculate expected number of lethal fragments from spall model and use Poisson distribution to perform random draw for specific number (n) of fragments

10] Play n fragments individually against the component PK/H ($0 \leq PK/H \leq 1.0$); power up individual PKs using Survivor Rule; take a random draw to calculate a Kill/No-Kill outcome

11] Repeat spall processing for all remaining critical components

12] Record vehicle damage state

13] Repeat the above damage assessment processes 999 times

14] Sort and rank all vehicle damage states

15] Map all (weighted) damage states to "PK" Space to build M, F, & M/F histograms using deactivation diagrams and Damage Assessment List

VIII. GENERIC EXAMPLE OF SQuASH OUTPUT

In this Section, examples will be given of the outputs yielded by the SQuASH code for a typical shot. To keep the results unclassified, various details concerning model input will be omitted. To illustrate the model capabilities, the data will be presented in virtually the same format as supplied by the BRL for the Abrams Detailed Test Plan.[23,27, 28, 29]

A CE shot into the right turret basket will be used to illustrate typical model results. Figures 8 and 9 show the warhead attack geometry. The shotline is illustrated by the addition of an arrow to the normal target description. In Fig. 8, the view is directly along the shot path. Figure 9 gives a perspective view.

Figure 10 shows an interior view of the turret-basket area. Nine cylinders have been added to the actual target geometry to show the nine "grid" rays used to perform the penetration modeling.

[†] For greater detail, see Ref. 18.

27. C. J. Dively, S. L. Henry, T. M. Muehl and J. H. Suckling, "Predictions of Outcomes for the Abrams Live-Fire Tests; First Estimates", Ballistic Research Laboratory Memorandum Report, In Preparation (Secret, Special Access Required).

28. C. J. Dively and S. L. Henry, "Predictions of Outcomes for the Abrams Live-Fire Tests: Revised Estimates, based on Actual Shot Locations" Ballistic Research Laboratory Memorandum Report, In Preparation (Secret, Special Access Required).

29. C. J. Dively, S. L. Henry and J. H. Suckling, "Comparisons between Predicted and Actual Outcomes for the Abrams Live-Fire Tests", Ballistic Research Laboratory Memorandum Report, In Preparation (Secret, Special Access Required).

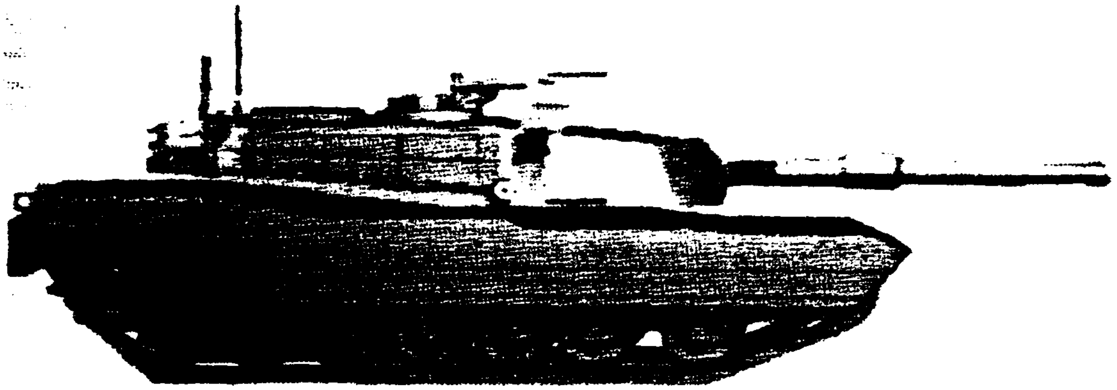

Figure 8. Exterior view of M1A1 showing warhead attack location and orientation. A cylinder has been added to the display to indicate the shotline impacting the right turret front. View is directly along the shotline.

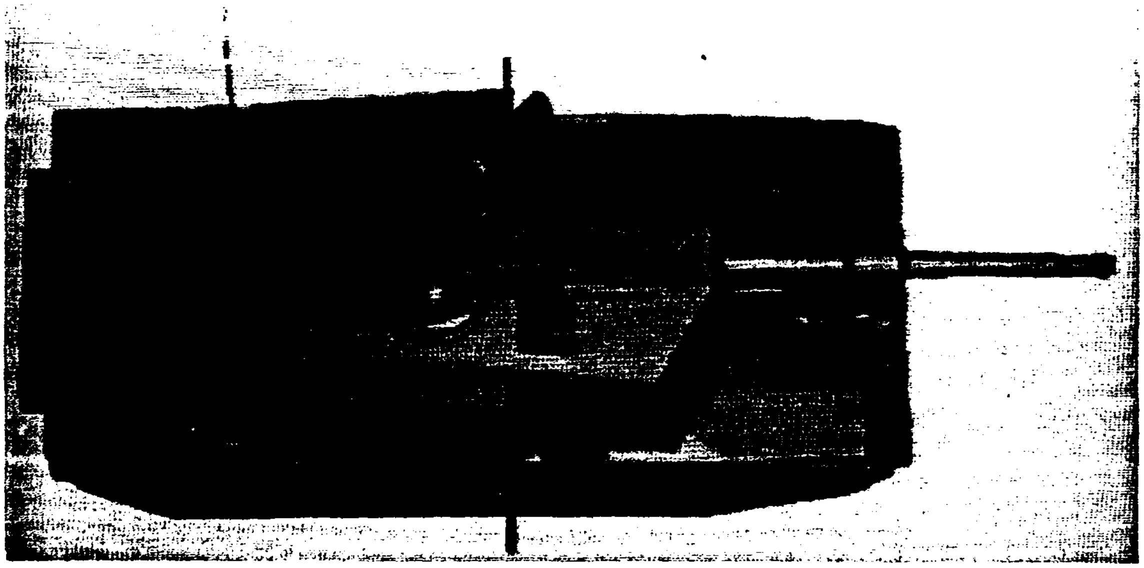

Figure 9. Exterior view of M1A1 as in Fig. 8 but from elevated perspective.

Figure 10. M1A1 interior view in the turret-basket area. The array of nine cylinders indicates the nine grid rays used for the penetrator/armor calculations in the SQuASH vulnerability model. Some 60 components are illustrated; each was estimated to have been killed on at least one of 1000 stochastic replications in the simulation.

The center ray is the extension of the exterior shotline shown in Figs. 8 and 9. Some 60 critical components are illustrated in Fig. 10 and are culled from the approximately 400 which reside in this general region. They represent those specific components which were calculated to have been killed on at least one of the 1000 replications performed during this simulation.

Figure 11 gives a histogram showing the distribution of residual-penetrator overmatch (in inches). The warhead is unspecified in order to keep these results unclassified. Over the course of many similar computations, these curves exhibit complex shapes, sometimes with multi-modal distributions. This is a natural consequence of the randomness of the overmatch together with the grid ray data derived over nine sample rays. Even though the rays are separated nominally by three inches, different combinations of armor are often encountered. The difference in effective protection levels leads to significantly different residual magnitudes.

To support the spall/component interaction, a matrix of divergent rays was fired from each of the nine potential spall points at the grid-ray entry points. To assure adequate spatial resolution, 10,000 rays were fired from each of the nine spall origins. This hypersampling assures resolution of individual hydraulic lines and wires at large distances from the spall point. The *rtlib* (raycasting) library routines[20] of the BRL-CAD software release were used to make these calculations. The information from these nine processes was used to calculate the solid angle subtended by each critical component with each spall cone as well as any intervening (shielding) barriers.

The same ray file used for the vulnerability calculation can be used to form an image. Figure 12 shows the view from the center grid ray just after entry into the crew compartment. The gunner is directly in the center shotline, the commander is behind, and the loader is across and away from the spall entry point.

The logic for SQuASH was given earlier. Over the course of 1000 code replications, some 60 critical components were assessed to have been killed at least once. Table III lists these components. The columns list the total probability of kill, the contribution due to the jet only, and the fragment cloud only. Of all the components in the target description, it is this particular subset that is displayed in Fig. 10.

Table IV shows where SQuASH output departs radically from other point-burst models. Here the first of five classes of components is listed separately by category. This procedure has been adopted because of the great difficulty in interpreting the results of damage states across the complete vehicle. Table IV lists the category of **CREW**. For this group, the calculated damage states apply to the personnel located in the turret-basket area. The legend for the component numbers is given below. The open square (□) indicates *no calculated damage*. A bullet (•) indicates the component has been killed (or in the case of crewman, *incapacitated*). The damage states derived from the 1000 replications were sorted together and then ranked from the most to the least likely in occurrence. Table IV shows that the most likely crew casualty state is for the commander and loader *not* to be incapacitated and for the gunner *to be* incapacitated. That outcome occurred 461 of the 1000 replications, for a net probability of 46%. The next most likely crew casualty state is for the commander and gunner to be incapacitated but not the loader. The likelihood of this outcome is assessed at 24%. For this component subset, all outcomes occurred over only six combinations.

The damage states for **PROPULSION** given in Table V are relatively simple. Only two components from that group were killed. The three damage states in which at least one of these cables was killed occurred in only 14 of the 1000 replications.

Table VI gives the damage states for the category **MAJOR ELECTRICAL**. Six components are involved over 13 specific outcomes. The most likely damage state involves damage to *none* of the components, estimated at 87%.

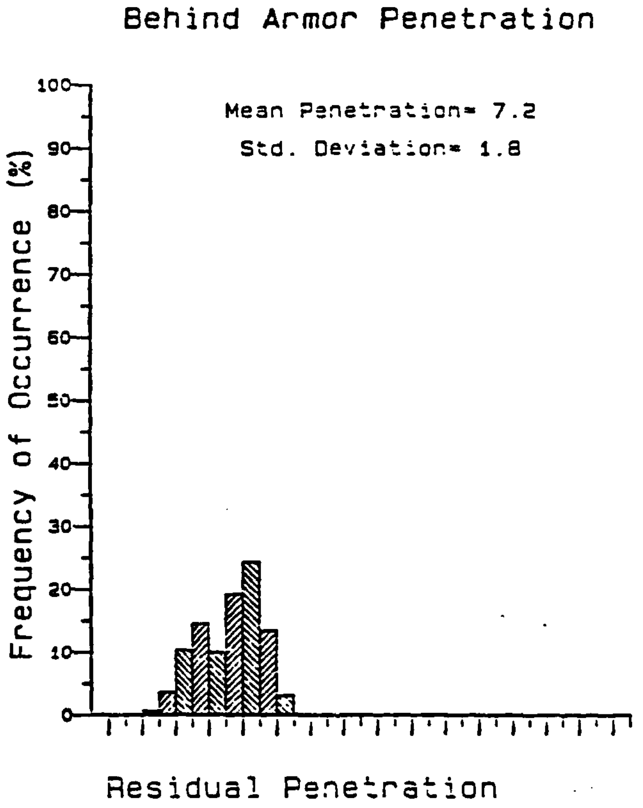

Figure 11. Histogram of Frequency of Occurrence *vs.* residual penetration for the shot configuration illustrated in Figs. 8-10. Because nine different shot lines are used (typically encountering different armor types) together with variable warhead performance, different levels of overmatch are derived.

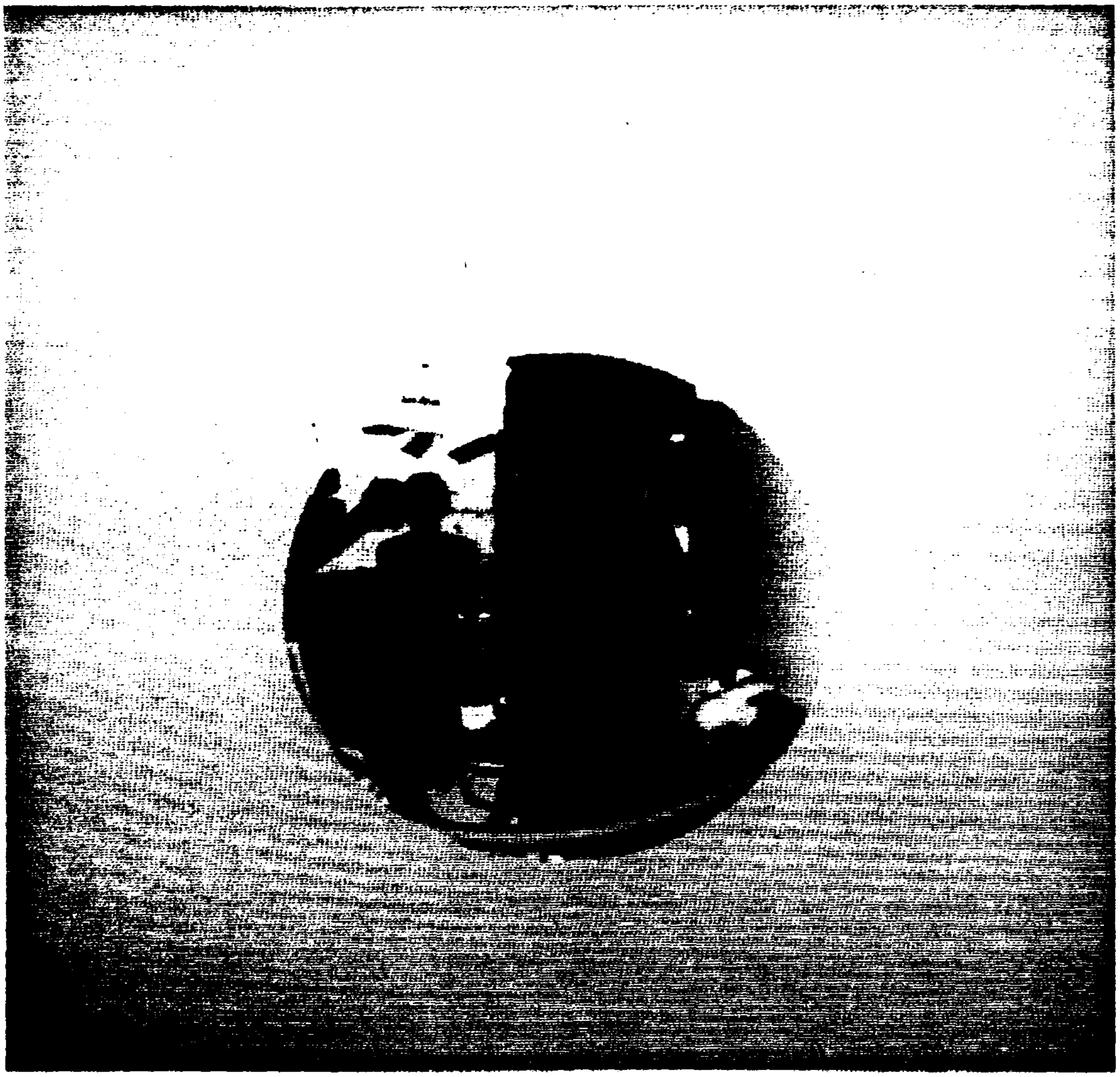

Figure 12. Image of crew compartment from the vantage point of the warhead immediately exiting the interior armor. The information used to form this image is primarily computed to characterize component presented areas and shielding information for behind-armor-debris assessment.

Table III. Listing of all components killed in at least one of 1000 replications of the SQuASH vulnerability model. The columns give the component identification, the total probability of kill, the probability of kill from the jet alone, and the probability of kill from fragments alone, respectively.

SQuASH Component Kills

Component	Relative Frequency of Damage		
	P_k	P_j	P_f
commander	0.399	0.000	0.399
gunner	0.995	0.683	0.594
loader	0.301	0.000	0.301
cable 1w100-9	0.018	0.000	0.018
cable 1w101-9	0.011	0.000	0.011
cable 1w104	0.008	0.000	0.008
cable 1w104	0.137	0.000	0.137
cable 1w105-9 main branch	0.008	0.000	0.008
cable 1w107-9	0.007	0.000	0.007
cable 1w108-9 to main gun	0.034	0.000	0.034
cable 1w200-9	0.552	0.000	0.552
cable 1w201-9	0.011	0.000	0.011
cable 1w202-9 main branch	0.017	0.000	0.017
cable 1w203-9	0.012	0.000	0.012
cable 1w208-9	0.309	0.000	0.309
cable 1w209-9	0.216	0.000	0.216
cable 1w210-9	0.337	0.000	0.337
cable 1w301	0.158	0.000	0.158
cable 1w304	0.039	0.000	0.039
cable 1w306	0.017	0.000	0.017
cable 1w309	0.070	0.000	0.070
cable 1w310	0.027	0.000	0.027
cable 1w311	0.008	0.000	0.008
cable 1w312	0.012	0.000	0.012
cable 1w316	0.035	0.000	0.035
cable 2w105-9	0.044	0.000	0.044
cable 2w107-9	0.009	0.000	0.009
cable 2w108	0.006	0.000	0.006
cable 2w112	0.002	0.000	0.002
cable 2w154-2w155	0.012	0.000	0.012
hull distribution box	0.003	0.000	0.003
hull networks box	0.012	0.000	0.012
turret networks box	0.046	0.000	0.046
gunner's primary sight	0.025	0.000	0.025
commander's gps extension	0.107	0.000	0.107
thermal image control unit	0.208	0.000	0.208
thermal receiver	0.001	0.000	0.001
intercom amplifier	0.024	0.000	0.024
gunner's intercom control box	0.104	0.000	0.104
loader's intercom control box	0.018	0.000	0.018
cable 2w117-9	0.003	0.000	0.003
h.line aux pump to filter manifold	0.003	0.000	0.003
filter manifold	0.013	0.000	0.013
h.lines filter manifold to HDM	0.018	0.000	0.018
h.lines filter manifold to HDM	0.007	0.000	0.007
h.lines TDM to azimuth servo	0.003	0.000	0.003
azimuth gearbox	0.004	0.000	0.004
manual azimuth gearbox	0.004	0.000	0.004
manual elevation pump	0.015	0.000	0.015
gunner's control handle	0.016	0.000	0.016
commander's control handle	0.073	0.000	0.073
race ring	0.013	0.000	0.013
h.line TDM to man elev pump cd	0.004	0.000	0.004
h.line check valve to HDM bypass	0.020	0.000	0.020
coaxial ready ammo box	0.052	0.000	0.052
azimuth gearbox - cws	0.022	0.000	0.022
commander's vision block #3	0.003	0.000	0.003
commander's vision block #2	0.005	0.000	0.005
commander's vision block #1	0.004	0.000	0.004
loader's sight	0.017	0.000	0.017
f.line right bow to manifold	0.001	0.000	0.001

P_k - Total Damage due to all mechanisms
P_j - Damage due to jet
P_f - Damage due to fragments

Table IV. Damage states from the SQuASH simulation for the subset *CREW*. Open squares (□) indicate no component kill. Bullets (•) indicate a component kill. The component numbers correspond to the listing below the table. The relative probability of each damage state is given in descending order of likelihood (column state). The cumulative sum is given in the last column (sum).

Group: CREW
Damage States, sorted by likelihood

Damage States			Relative Occurrence	
Component Number 1	2	3	state	sum
□	●	□	0.461	0.461
●	●	□	0.237	0.698
●	●	●	0.192	0.890
□	●	●	0.103	0.993
□	□	□	0.005	0.998
●	□	□	0.002	1.000

□ - component undamaged
● - component damaged

Number	Component
1	*commander*
2	*gunner*
3	*loader*

Table V. Damage states from the SQuASH simulation for the subset *PROPULSION*. Format and labeling follow the procedure used in Table IV.

Group: PROPULSION
Damage States, sorted by likelihood

Damage States		Relative Occurrence	
Component Number 1	2	state	sum
□	□	0.986	0.986
●	□	0.008	0.994
□	●	0.005	0.999
●	●	0.001	1.000

□ - component undamaged
● - component damaged

Number	Component
1	*cable 2w107-9*
2	*cable 2w108*

Table VI. Damage states from the SQuASH simulation for the subset *MAJOR ELECTRICAL*. Format and labeling follow the procedure used in Table IV.

Group: MAJOR ELECTRICAL
Damage States, sorted by likelihood

Damage States						Relative Occurrence	
Component Number 1	2	3	4	5	6	state	sum
□	□	□	□	□	□	0.866	0.866
□	□	□	□	□	●	0.045	0.911
□	□	●	□	□	□	0.039	0.950
●	□	□	□	□	□	0.014	0.964
□	●	□	□	□	□	0.009	0.973
□	□	□	●	□	□	0.008	0.981
□	□	□	□	●	□	0.008	0.989
●	□	□	□	□	●	0.003	0.992
□	□	●	□	●	□	0.002	0.994
□	□	●	□	□	●	0.002	0.996
□	□	●	●	□	□	0.002	0.998
●	□	□	●	□	□	0.001	0.999
□	●	□	●	□	□	0.001	1.000

□ - component undamaged
● - component damaged

Number	Component
1	*cable 1w100-9*
2	*cable 1w101-9*
3	*cable 2w105-9*
4	*cable 2w154-2w155*
5	*hull networks box*
6	*turret networks box*

The damage states for **ARMAMENT** shown in Table VII reveal the greatest complexity in damage states. This is probably to be expected since nearly half of all the critical components killed during the 1000 replications were part of this group. As seen in other groupings, the most likely damage state assessed for the 29 components in **ARMAMENT** is no damage, this for 28% of the outcomes. The most likely state exhibiting damage occurred for five components (numbers 6, 10-12, 15) on 78 of the 1000 replications for a 7.8% probability. From here on, the 29 components are involved in a slow convergence to the 99th percentile (sum) at the 223rd damage state!

The remaining 11 components involved in damage are listed as **OTHER** and documented in Table VIII.

At this point in the simulation, we have accumulated a full accounting of the statistics of Space 2}. As described in Section IV, the final stage of calculation involves the various categories of kills. First, catastrophic kill involves the complete loss of the system. This generally occurs because of encounters with large-caliber ammunition (warhead and/or propellant) or fuel. The probability of this event is shown in Fig. 13c. For this particular shot, the probability of a catastrophic event is assessed as zero. Note that the histogram associated with K-Kill can be populated only in the first and last bins. This is a consequence of the K-Kill event belonging to the class of Bernoulli trials.

The other kill categories are assessed by mapping each of the thousand damage states *via* the SDAL over to the appropriate M- and F-Kill values. The category labeled M/F (read M **OR** F), by long-standing agreement with the TRADOC community, represents *the larger* of the two values. *It is not the* **OR** *of the logical (Boolean) operation.*

We examine the M-Kill plot in Fig. 13a. Here we find the most likely outcome is for about 0.57 Mobility Loss-of-Function (M-LOF), assessed at about 30% probability. However the distribution is extremely broad with approximately 18% of the outcomes near the 0.0 bin. The expected M-LOF outcome is 0.36; inspection of the histogram shows that there are approximately 26% of the outcomes near this value. However the distribution is broad, and there is a significant number of occurrences away from the mean. The corresponding results for Firepower LOF are given in Fig. 13b. In this histogram, the mean LOF occurs in a bin with a low population. There is also a significant probability (~ 18%) that the F-LOF will be zero. The M/F-LOF histogram is given in Fig. 13d. The M/F value, by definition, is the larger of the M and F-LOFs on a shot-by-shot basis. The F-LOF tends to dominate in this case.

IX. OBSERVATIONS ABOUT RESULTS

From the examples given in Section VIII as well as many scores of other SQuASH calculations made during the M1A1 program to date, significant new insights can be made with respect to the assessment of AFV vulnerability.

- **Complexity of Damage:** Even with only main penetrator and spall damage mechanisms currently invoked in this model, the finite number of possible damage states for repeated shots into the same 6"x6" target area is extraordinarily high. As indicated in Table VII, for the category *Armament*, some 270 damage states were computed before the cumulative probability reached the 99th percentile. When the *finite* damage-state possibilities for the remaining component categories are factored in as well, the number of possible outcomes becomes very large.
- **The Statistics of PKs:** From the histograms of the M, F, and M/F LOFs shown in Fig. 13, it can be seen that the first and second moments (also shown in the figures) are not representative numbers. As noted above, the processes are non-parametric (i.e. do not obey gaussian statistics) and *often it can be observed that the first-moment occurs where not even a single outcome can be found*!

Table VII. Damage states from the SQuASH simulation for the subset *ARMAMENT*. Format and labeling follow the procedure used in Table IV. There are so many components in this class with similar probability of being killed that many different damage states occur, but many with relatively low probability. Convergence to the 99th percentile is slow and doesn't occur until the 223rd damage state.

Group: ARMAMENT
Damage States, sorted by likelihood

Damage States																													Relative Occurrence	
Component Number																													state	sum
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29		
□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	0.275	0.275
□	□	□	□	□	●	□	□	□	●	●	●	□	□	●	□	□	□	□	□	□	□	□	□	□	□	□	□	□	0.078	0.353
□	□	□	□	□	●	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	0.077	0.430
□	●	□	□	□	●	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	0.060	0.490
□	□	□	□	□	●	□	□	□	●	□	●	□	□	●	□	□	□	□	□	□	□	□	□	□	□	□	□	□	0.039	0.529
□	●	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	0.026	0.555
□	□	□	□	□	●	□	□	□	●	●	●	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	0.023	0.578
□	□	□	□	□	●	□	□	□	●	□	●	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	0.013	0.591
□	□	□	□	□	□	□	□	□	□	□	□	□	●	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	0.011	0.602
□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	●	□	□	□	□	□	□	0.010	0.612
□	□	□	□	□	●	□	□	□	□	□	□	□	●	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	0.010	0.622
□	□	□	□	□	□	□	□	□	●	●	●	□	□	●	□	□	□	□	□	□	□	□	□	□	□	□	□	□	0.010	0.632
□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	●	□	□	0.009	0.641
□	●	□	□	□	●	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	●	□	□	□	□	□	□	0.008	0.649
□	□	□	□	□	●	□	□	□	□	□	●	□	□	●	□	□	□	□	□	□	□	□	□	□	□	□	□	□	0.007	0.656
															⋮														⋮	⋮
□	□	□	□	□	●	□	□	□	●	●	●	□	□	●	□	□	□	□	□	●	●	●	□	□	□	□	□	□	0.001	0.998
□	□	□	□	□	●	□	□	●	□	□	□	□	●	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	0.001	0.999
□	□	□	□	□	●	●	□	□	●	●	●	□	●	●	□	□	□	□	□	□	□	□	□	□	□	□	□	□	0.001	1.000

Converges at the 223rd state

□ - component undamaged
● - component damaged

Group: ARMAMENT

Number	Component	Number	Component
1	*cable 1w104*	16	*filter manifold*
2	*cable 1w104*	17	*h.lines filter manifold to HDM*
3	*cable 1w105-9 main branch*	18	*h.lines filter manifold to HDM*
4	*cable 1w107-9*	19	*h.lines TDM to azimuth servo*
5	*cable 1w108-9 to main gun*	20	*manual azimuth gearbox*
6	*cable 1w200-9*	21	*manual elevation pump*
7	*cable 1w201-9*	22	*gunner's control handle*
8	*cable 1w202-9 main branch*	23	*commander's control handle*
9	*cable 1w203-9*	24	*race ring*
10	*cable 1w208-9*	25	*h.line check valve to HDM bype*
11	*cable 1w209-9*	26	*coaxial ready ammo box*
12	*cable 1w210-9*	27	*azimuth gearbox - cws*
13	*gunner's primary sight*	28	*commander's vision block #2*
14	*commander's gps extension*	29	*loader's sight*
15	*thermal image control unit*		

Table VIII. Damage states from the SQuASH simulation for the subset *OTHER*. Format and labeling follow the procedure used in Table IV.

Group: OTHER
Damage States, sorted by likelihood

Damage States											Relative Occurrence	
Component Number												
1	2	3	4	5	6	7	8	9	10	11	state	sum
□	□	□	□	□	□	□	□	□	□	□	0.700	0.700
●	□	□	□	□	□	□	□	□	□	□	0.064	0.764
□	□	□	□	□	□	□	□	□	●	□	0.022	0.786
□	□	□	●	□	□	□	□	□	□	□	0.019	0.805
●	□	□	□	□	□	□	□	□	●	□	0.016	0.821
□	□	□	□	□	□	□	□	●	□	□	0.015	0.836
□	●	□	□	□	□	□	□	□	□	□	0.014	0.850
●	□	□	●	□	□	□	□	□	●	□	0.012	0.862
□	□	●	□	□	□	□	□	□	□	□	0.010	0.872
●	□	□	●	□	□	□	□	□	□	□	0.008	0.880
□	□	□	□	□	□	□	●	□	□	□	0.008	0.888
□	□	□	□	□	□	●	□	□	□	□	0.007	0.895
●	□	□	□	□	□	□	□	□	●	●	0.005	0.900
●	□	□	□	●	□	□	□	□	●	□	0.005	0.905
□	□	□	□	●	□	□	□	□	□	□	0.005	0.910
□	□	□	□	□	□	□	□	□	□	●	0.004	0.914
●	□	□	□	□	□	□	●	□	□	□	0.004	0.918
□	□	□	□	□	●	□	□	□	□	□	0.004	0.922
□	●	□	□	□	□	□	□	□	●	□	0.004	0.926
●	□	□	●	□	□	□	●	□	●	□	0.004	0.930
□	□	□	●	●	□	□	□	□	●	□	0.003	0.933
●	□	□	□	□	□	□	□	●	□	□	0.003	0.936
●	●	□	●	□	□	□	□	□	●	□	0.003	0.939
●	□	□	□	□	□	□	●	□	●	□	0.003	0.942
●	□	□	□	□	□	●	□	□	□	□	0.003	0.945
●	●	□	□	□	□	□	□	□	□	□	0.003	0.948
●	□	□	●	●	□	□	□	□	●	□	0.003	0.951

□ - component undamaged
● - component damaged

Number	Component
1	*cable 1w301*
2	*cable 1w304*
3	*cable 1w306*
4	*cable 1w309*
5	*cable 1w310*
6	*cable 1w311*
7	*cable 1w312*
8	*cable 1w316*
9	*intercom amplifier*
10	*gunner's intercom control box*
11	*loader's intercom control box*

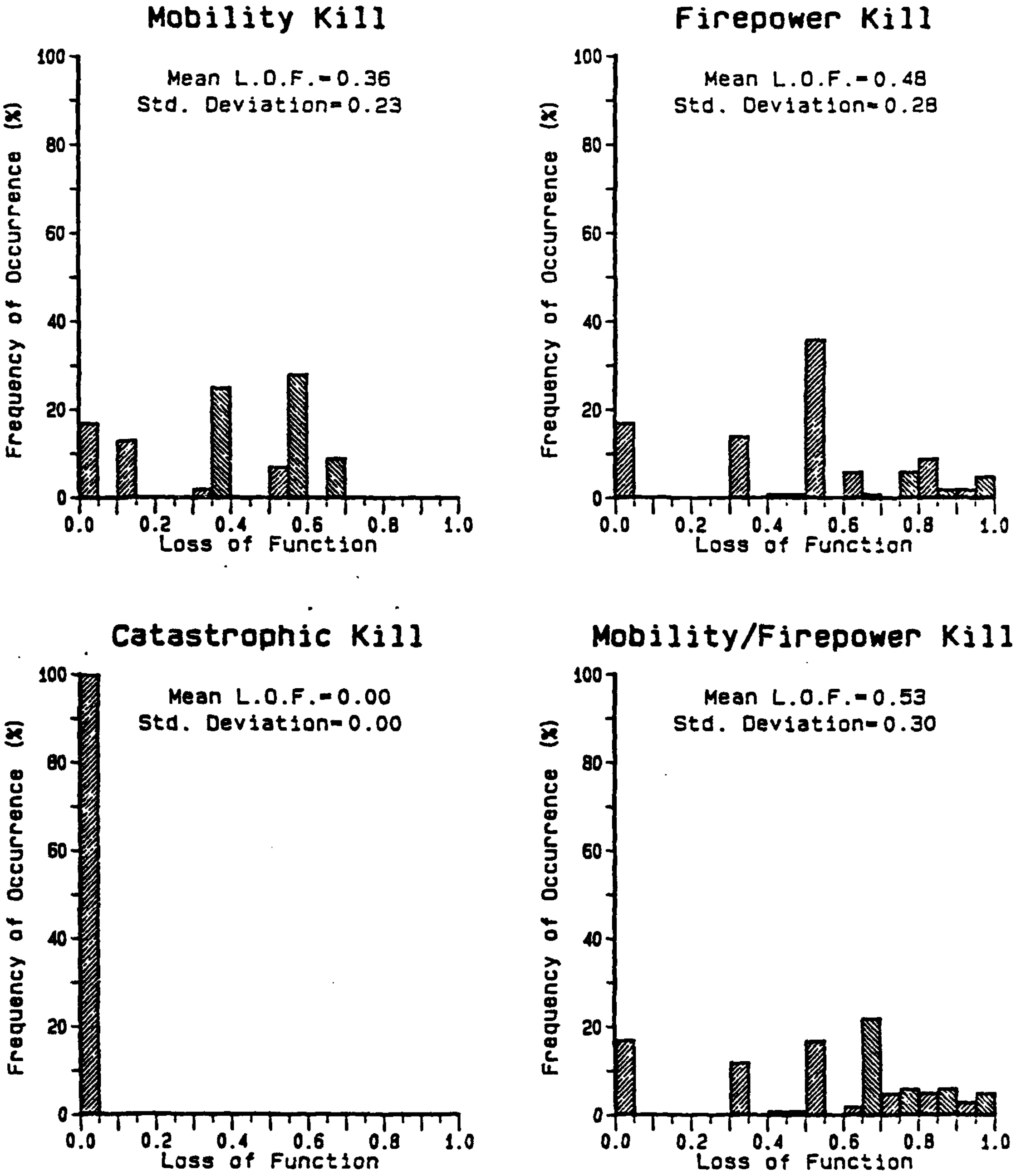

Figure 13. Histograms of various kill categories derived from the SQuASH simulation. The Mobility Kill Loss-of-Function (LOF) is shown in a), the Firepower Kill in b), the Catastrophic Kill in c), and the Mobility/Firepower Kill in d). The means (expected values) and standard deviations are given for each plot, but are considered relatively immaterial for these non-parametric (i.e. non-gaussian) statistics.

- **PK Comparisons in Space 4]:** Although the PK histograms are complicated, there are only 20 bins of resolution utilized. This is an extremely small dimension compared with the diversity revealed in component damage space (Space 2]). It is clear that many different damage states can map to the same value in PK space (Space 4]). Thus comparisons between a field PK and a predicted histogram could imply agreement for entirely specious reasons.

  The nature of the PK histograms has been investigated in more detail by decreasing the bin width and increasing the total number of SQuASH replications to 10,000. Close examination of the output shows that this particular nonparametric outcome space is composed of a series of δ functions distributed along the abscissa. In some cases a pair of δ functions can found in close proximity. The nature of these distributions is determined first by which damage states occur and second by the crisp and rather regular numerical values that the SDAL assigns through the Space 2] to Space 4] mapping process.

- **Model Calibration:** Given the complexity of the vulnerability process revealed at this level of detail, it is anticipated that model calibration may prove exceedingly difficult. Particularly because many of the inputs to the model (i.e. penetration, BAD and component-damage algorithms) are poorly known. For the modelers at BRL, one of the key issues in the next phase of analysis is to compare the code predictions with the single outcomes of the field tests. Of great importance is to find what possible damage mechanisms may be evidenced that are not handled in the current code realization.

  A related issue is the "validation"[†] of vulnerability models. There have been attempts to apply statistical tests to compare Live Fire LOFs with model predictions in order to judge the goodness of agreement.[30] This has been problematic for a number of reasons; first, as we have seen above, the LOF metrics are non-parametric (although that fact wasn't known until this work). Thus any method which depends on outcomes being gaussian distributed is inapplicable. Second, it is clearly impractical to derive LOF probability density functions from field tests, and until now, no model was capable of producing an estimate.

  Having now the capability of *estimating* LOF probability density functions, a typical Firepower LOF was used to estimate the rate of convergence of the expected value for repeated tests. Figure 14a illustrates the function used; it has a first-moment of 0.41, a region in which no outcomes occurred. Taking this function as a true representation of the underlying statistics, random draws were made according to this histogram. Thus there was approximately 31% probability of drawing a 0.0 LOF, 9% probability of drawing a 0.27 LOF, and so on. First a sequence of four draws (with replacement) was initiated (as though four field tests had been conducted). The four LOFs were averaged and recorded. The process was then repeated many times. The many averages of four tests were then sorted by LOF, counted, normalized, and plotted in Fig. 14b. This histogram shows the probability of estimating various levels of *mean* LOF, *given the average of exactly four trials*. It can be seen that the highest probabilities are near the true mean of 0.41, but there are substantial likelihoods of estimating significantly different values. This process was also performed for the average of 16 (Fig. 14c) and 64 (Fig. 14d) *exactly* repeated trials. Clearly this process illustrates the central limit theorem in which the envelope of each distribution tends to a gaussian as the number of repeats increases. The peak is also tending to the true mean. However even with the number of repeated tests at 64, the 95% confidence level for the first-

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[†] Validation is a word that should surely be struck from the DoD lexicon. For more than a century, researchers have recognized that experiments don't prove theory, they can only *disprove* it.

30. R. G. Pollard, III, G. L. Holloway, D. C. Bely, F. T. Brown, and J. C. Kisko, "An Examination of Vulnerability Predictions in Light of Live Fire Testing of Light Combat Vehicles", US Army Materiel Systems Analysis Activity Technical Report, In Press.

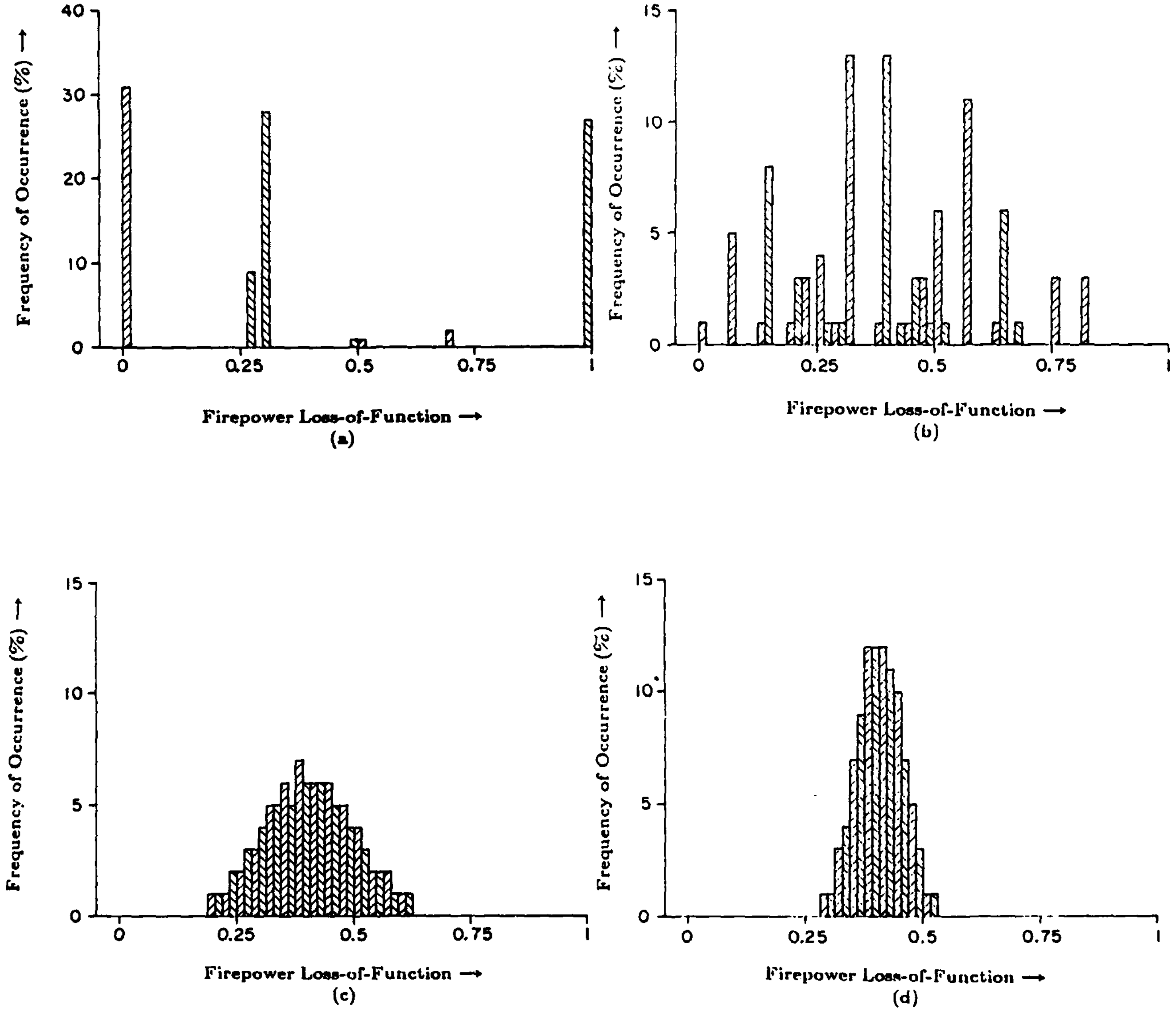

Figure 14. Test for convergence of means of average repeated tests. Histogram in a) is a SQuASH-derived histogram for Firepower LOF with a mean of 0.41. Shown in b) is the histogram for probability of estimating different mean LOFs, given the average of four tests from the population shown in a). The procedure of b) is repeated for averages of 16 and 64 repeated tests and shown in c) and d), respectively.

moment estimate is known to an uncertainty of ±0.09. And we note that there are fewer than 64 shots in the whole Abrams Live-Fire Program and essentially none of the shots is repeated.

X. OBSERVATIONS ABOUT LIVE-FIRE OBJECTIVES

One of the aims of BRL's support of the M1A1 Live-Fire modeling program has been to develop and exercise a vulnerability assessment code which yields more precise insight into the damage process. That objective has been at least partially achieved in the development of the stochastic point-burst code SQuASH. We summarize our observations on these analytic efforts below:

- **Penetration & BAD Data:** Emphasized throughout this paper has been the need for reliable data describing the overmatch phenomena for warhead/armor interactions. Full-up live-fire events are not the place to gather this data since they do not provide calibrated diagnostic media to capture such data. Further, since the most central phenomena in the vulnerability process are themselves often known poorly, it becomes all the more difficult in the post-test assessment to separate out the primary damage phenomenologies from those that are secondary.

- **Limitations of Component PKs:** The basic element for assessing component dysfunction is through component PK characterization. Much "off-line" testing of specific systems needs to be accomplished to generate an adequate data base. Even if the interaction of *single* fragments with components becomes better understood, the problem of *multiple* fragments must be put on a firmer foundation.

- **Secondary Kill Phenomena:** As noted earlier, it is anticipated that the analysis of the Abrams LF test data will provide valuable insight into the importance of this class of damage mechanisms.

- **Damage Synergism:** If and as other damage mechanisms are recognized to be important in this context and can be modeled, a further significant issue will then arise. Just as the multiple-fragment interaction with a single component is modeled in an unsatisfactory fashion, there are no extant algorithms for aggregating damage to a single component from *multiple* phenomenologies. For example if it were possible to model both shock and fragment interaction *individually* with a given component, there is no known method for combining the individual kill assessments.

- **Aggregation of Loss-of-Component Effects:** As noted above, deactivation diagrams are the means by which individual component loss is aggregated up to the major system or subsystem level. This artifice needs to be examined more thoroughly both to learn whether this procedure is reliable in general and further whether the intrinsic subjectivity of the process when applied to a particular system leads to inappropriate biases.

- **System Damage to MOEs:** The historical method for accomplishing this task is *via* the Standard Damage Assessment List. This process is in dire need of replacement, and work to define alternative approaches is ongoing. Taking this procedure as a given, however, it is clear that typical system damage is very complex, and PK histograms ill-behaved. *Certainly comparing a single test PK with the first moment of the associated probability density function is useless. Even showing that the field PK is coincident with a single PK in the predicted PK histogram is irrelevant because entirely different damage states can map to the same point in PK outcome space.*

- **"Objective" (Field-Based) PKs:** From Section IV, the steps involved in deriving final PK values, whether from actual field shots or computer simulations, should be clear. A particular field shot corresponds to a single mapping from Space 1] to Space 2] (see Fig. 2). That same mapping, or transformation process, is simulated in the SQuASH code. However, it is critical to note that *the step from Space 2] to Space 4], where the final PK or LOF value is derived, follows the identical transformation process whether the damage state is "real" or computer simulated.* Although it may be argued that the assessment of post-shot damage (in Space 2]) is an objective process, the criticality analysis[4] and SDAL artifice[13,14] at the heart of the Space 2] to Space 4] mapping are highly subjective in nature. Thus even field data must undergo this somewhat arbitrary transformation. Further, *if meaningful comparisons of field data and simulations are to be made, then the identical mapping process must be used for both sets of data.* There have been instances in which field assessors have examined a vehicle following a live-fire test, made certain subjective conclusions about the level of damage, and then *intuited* a "PK" without regard to either the precise logic of the criticality analysis or the SDAL process. Clearly if this approach were to be utilized, there would be no hope of rationalizing field measurements with predictions.

- **Value of Full-Up Testing:** It is clear that even if all possible off-line tests were performed, the phenomena understood, and the related data bases established, there are other significant effects that can only be tested in a full-up configuration. Included in this category are blast and shock phenomena and ricochet, for example.

  However from the modeler's perspective, the order of Live-Fire testing was initiated in a backward order. For example, the BRL has had to make preshot predictions for the Abrams program before any fragment/component firings have taken place. Although the test plan should be formulated in a top down fashion, the implementation should occur in a bottom up sequence. This is distinctly not the actual order of events.

- **Live-Fire Testing:** The Live-Fire program, not only for the Abrams but other military vehicles, will unquestionably improve the quantity and quality of data with which modelers can make more reliable assessments. However from the complexities of the vulnerability process evident even now with the new class of stochastic modeling *via* the SQuASH model, it is clear that statistical limitations will preclude any kind of rigorous validation. The best that can be expected will be that some uncertainties in the process will be subject to quantitative assessment.

In summary, Live-Fire Testing and analyses for major Army systems are now a reality. In the area of AFVs, many benefits have accrued. Through these programs a wealth of both full-scale and off-line data continues to grow. This process has stimulated the development of a new class of vulnerability analysis tools through which new insights have been gained into the complexity and variability of destructive testing. And the use of these tools in the analysis of Live-Fire data has exposed the inadequacy of expected-value estimates in this milieu.

ACKNOWLEDGMENT

Many people contributed to the SQuASH examples shown in this paper. Mr. A. Ozolins, is the author of the SQuASH code. Mr. L. D. Losie made valuable contributions to the logic of that work. The history on early AFV testing was provided by Mr. R. L. Kirby. The criticality analysis was performed by Messrs. J. J. Ploskonka, S. L. Henry, and Ms. C. J. Dively. The target description was generated by Ms. C. J. Dively and Mr. S. L. Henry. Messrs. J. H. Suckling, T. M. Muehl, J. J. Ploskonka and Dr. R. Shnidman have been responsible for the ballistic inputs. The automatic typesetting output for tables and other documentation integral to the SQuASH code is due to text-processing filters written by Mr. P. J. Hanes. The routines for the shotline interrogation of the target description are due to code written by Mr. G. S. Moss. Ms. C. J. Dively and Mr. S. L. Henry configured the SQuASH code for execution and performed all of the calculations in a secure computing environment installed and configured by C. M. Kennedy, D. A. Gwyn and P. R. Stay.

The authors also acknowledge numerous inciteful comments provided by Dr. M. W. Starks and Messrs. D. L. Rigotti, J. H. Suckling and D. F. Menne.

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