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COMPARISONS OF FIELD TESTS WITH SIMULATIONS: ABRAMS PROGRAM LESSONS LEARNED

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The onset of full-scale, live-fire testing (LFT) has provided vulnerability workers with unprecedented opportunities to examine field results in the light of model predictions. Pre-Abrams experience with LFT showed, however, that the extant vulnerability models lacked 1] the capability to predict component damage states and 2] the ability to reflect at least the principal forms of randomness which are intrinsic to the vulnerability process.

To remedy this shortcoming, the BRL/VLD developed a new stochastic point-burst vulnerability code, called SQuASH. SQuASH has been used to predict 48 shots in the Abrams LF program. Both subjective and statistical tests have been performed in an effort to compare field observations with computer predictions. In this paper, the vulnerability framework is described, the kinds of results yielded by the SQuASH predictions, and the lessons learned from efforts to "calibrate" the model based on the statistical tests performed.

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1. INTRODUCTION

The National Defense Authorization Act for FY 1987[1] requires that all major weapon systems undergo live-fire testing (LFT) prior to entering full-scale production. The intent is to establish the baseline for either system response to expected threats (vulnerability) or the effectiveness of an offensive weapon against a particular class of targets (lethality). Planning for the Abrams Live-Fire program began late in 1985 and culminated in a series of 48 firings in the period between July 1987 and July 1988.

The Abrams LFT Program was preceded by testing of a number of other systems including the M113 Personnel Carrier and the Bradley Fighting Vehicle (M2/3). As such, considerable experience had been gained both in testing procedures and pre- and post-shot modeling practice. It had become clear to vulnerability workers at the BRL that the extant vulnerability tools were inadequate to describe vehicle damage in a manner consistent with the field-assessment process. To remedy this shortcoming, the BRL/VLD developed a new stochastic point-burst vulnerability code called SQuASH (Stochastic Quantitative Analysis of System Hierarchies),[2,3] in which 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 generation, and 5] individual component-kill assessment.

SQuASH was used to predict 48 shots in the Abrams LF program. Both subjective and statistical tests have been performed in an effort to compare field observations with computer predictions. These comparisons have been made both for component damage as well as Mobility-, Firepower- and Catastrophic-Kill criteria and will be summarized below.

Just as with prior point-burst models and LFT assessments, substantial subjectivity exists in four areas: a] the identification of system-critical components, b] the binning of partially functioning (post-shot) components into kill/no-kill categories, c] the characterization of component interconnectivity *via* the fault tree synthesis and d] the Damage Assessment List (DAL) mapping process (by which M- and F-Kill values are inferred). In order for comparability to exist between field tests and computer simulations, LFT observations must be assessed within the same analytical paradigms of a] through d].

In Reference 3 much of the background of LFT was described and many of the algorithmic details of the SQuASH model were presented. Familiarity with that work may aid in the understanding of these results. In the present paper extensive elucidations of the operational aspects of SQuASH including the means of predicting damage are eschewed; rather, a detailed bottom-up description is given of the vulnerability assessment process. This process begins with the characterization of individual component damage, moves through a system of detailed fault-tree analyses, and finally to the Mobility and Firepower Loss-of-Function (LoF) calculations.

As each step in the process is described, the necessary similitude between model representation and actual field assessment will be emphasized. SQuASH outputs include a series of statistical estimates of warhead penetration performance, individual component probability-of-kill (PK) and component damage-state vectors. Various statistical tests have been applied to the field data *vis-a-vis* the model statistics. We will describe the tests and state our current conclusions concerning them.

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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.
2. 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.
3. Paul H. Deitz and Aivars Ozolins, *Computer Simulations of the Abrams Live-Fire Field Testing*, **Proceedings of the XXVII Annual Meeting of the Army Operations Research Symposium**, 12-13 October, 1988, Ft. Lee, VA; also **Ballistic Research Laboratory Memorandum Report BRL-MR-3755**, May 1989.

2. COMPONENT DYSFUNCTION

Consider an Armored Fighting Vehicle (AFV) component characterized by a Loss-of-Function (LoF) on the interval (0.0,1.0) where:

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

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

Most classes of components exhibit LoFs which are Bernoulli in nature; that is, they either operate fully or not at all. An example of such a component might be a portion of a fire-control system with optical elements. Such a component might be able to absorb fragments up to certain mass/velocity combination and suffer no damage until a certain threshold is reached. Then an optical element breaks and the component utterly fails. Such a component would then have only two possible states: 0.0 and 1.0.

We also note that in the case of complex components which must perform multiple functions, the use of a one-dimensional LoF characterization can represent an unrealistic simplification. Such a situation occurs in the description of personnel vulnerability to striking fragments. For people, the term LoF is exchanged for *Level of Incapacitation* (LoI),[4] but the notion is similar. And in such a case, various combinations of limb, torso and head trauma might possibly map to the same LoI and yet reflect entirely different operational capability (e.g. ability to view a battlefield and passively direct fire over a radio *vice* maneuver a vehicle slowly through the use of hand-controls only). Thus the first step in the critical problem of characterizing the potential loss of components is to relate various threat conditions (fragments masses, velocities, blast levels, etc.) to (normalized) LoFs.

However for vulnerability analyses such as SQuASH, component characterization must be Bernoulli in nature, i.e. functional/non-functional. Thus in a conceptual sense, a minimum performance threshold for each component must be applied against a LoF following interaction with a threat. If the LoF is sufficiently small that this threshold is at most equaled, the component is considered fully functioning (or alive). If not, it is considered killed.

This process thus yields a crisp binary decision process for each component and can be characterized by a single-pole, single-throw (SPST) electrical switch (either closed 'alive' or open 'nonfunctional') as in Fig. 1. This concept of the behavior of individual components becomes the basis upon which the analyses of the functionality of systems and sub-systems of the vehicle are based and ultimately the notions of Firepower and Mobility Kills.

To summarize, component dysfunction can be characterized by the following steps:

1. Let a defined threat (fragment, blast wave, etc.) interact with a given component.

2. Characterize any reduction in component capability on a normalized interval as a Loss-of-Function.

3. Bin the (possibly continuous) LoF into crisp Kill/No-Kill binary states.

All point-burst codes accomplish such characterization through the notion of component conditional

4 William Kokinakis and Joseph Sperrazza, *Criteria for Incapacitating Soldiers with Fragments and Flechettes (U)*, **Ballistic Research Laboratory Report #1269**, January 1965.

Closed Switch → Live Component Open Switch → Killed Component

Figure 1. All components of an Armored Fighting Vehicle (AFV) start in a working state indicated here as a closed single-pole, single throw (SPST) switch. After interaction with a threat, if the functionality of the component is insufficient to support a minimal capability, the component is considered killed and the switch is opened.

kill probability or component Probability of Kill, given a Hit ($P_{K/H}$). Whether such a process uses fragment mass/velocity/shape-factor/orientation or the notion of lethality*, the component $P_{K/H}$ analysis effectively concatenates all three steps into one.

— CAVEATS RE: COMPONENT DYSFUNCTION —

- Components with complex or multimodal capability may not be well described by a one-dimensional Loss-of-Function.
- The LoF interval may be continuous or discrete.
- The threshold for minimal component operation (to be considered non-killed) is likely to be a function of a specific mission requirement. Thus a component with a fractional LoF might be "alive" in one scenario while "killed" for another.

3. SINGLE-SYSTEM FAULT TREE

The analytical determination of whether a particular system (or sub-system) is functional starts with connecting all of its components together in the form of a series/parallel circuit. These circuits are normally called *fault trees* and an example is given in Fig. 2. Before a shot occurs, all switchs are closed (fully operational). After a live-fire shot, some components may have lost enough capability to be defined as killed (switch open). Three components are killed in this example. The bold line shows the (single) functional path through this system, so this system is considered fully functional.

— CAVEATS RE: FAULT-TREE DEVELOPMENT —

Note well, this process gives rise to a number possible sources of subjectivity both in the analysis and in the field assessment; for example:

- What constitutes a switch (i.e. component)?

  The subjectivity here has two parts; how is the component defined, and is the component critical to system effectiveness? Only the critical components define the circuit.

- What constitutes a proper subsystem definition?

  Clearly considerable subjectivity enters into this decision process as well.

4. CRITICALITY ANALYSIS FOR AN AFV

A complete *criticality analysis* of an AFV consists of the determination of 1) which components, if lost, *might* result in a reduction of system mobility or firepower capability and 2) the structuring of

* See Reference 3, Section VI, for a discussion of the PKs used in the SQuASH model.

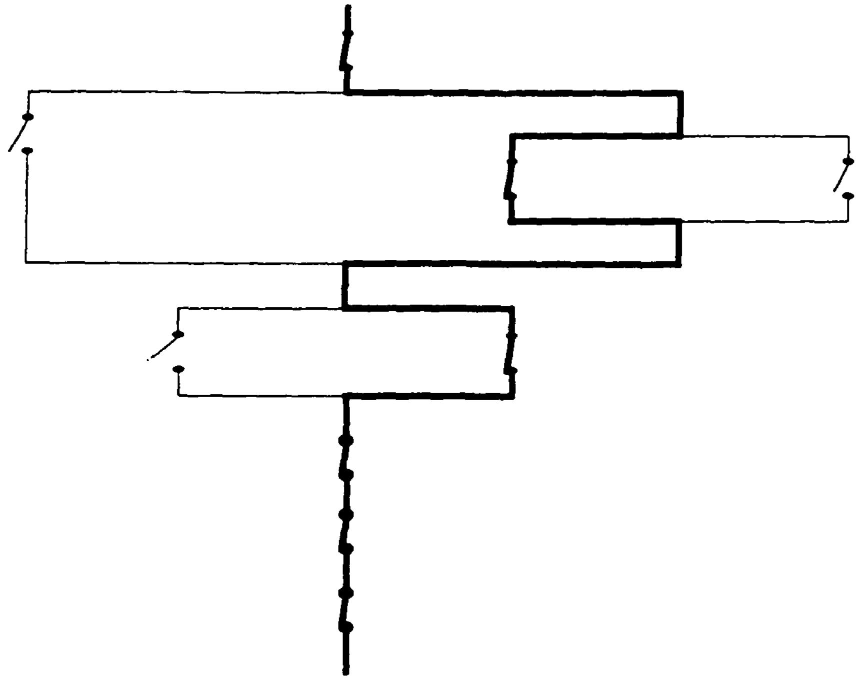

Figure 2. An example of a fault tree used in vulnerability analysis. Parallel components exhibit redundancy; series components do not. An overall system is either fully functional - at least one unbroken path exists from top to bottom, or is killed - no unbroken path exists.

those "critical" components into fault trees as described above. In the case of the Abrams tank, the criticality analysis[5] resulted in the generation of 76 individual fault trees built from approximately 750 critical components.

— CAVEATS RE: CRITICALITY ANALYSIS —

The issues here are:

- What sub-set of AFV components should be classified as critical?
- What *n* fault trees constitute a proper representation of the AFV?

In addition to the unavoidable subjectivities connected with this process it is further critical that both the live-fire *field-assessment* process *and* the live-fire *modeling* process use the identical fault-tree framework. Otherwise there is no comparability between the two processes and thus no basis for comparing field and predicted results.

5. 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. VULNERABILITY MODELING & LIVE-FIRE TESTING

The analytical estimation of vehicle vulnerability and the assessment of a live-fire test are both characterized by a two-step process:

- **STEP 1:**[†] Fire a warhead against the target and observe which switches are thrown open by the event.

At this stage, we first predict (or observe) whether the munition breached the armor (perforation) and with what residual energy; then examine the effects of that residual energy on individual components; compile the resultant state of all of the critical components; and decide whether the vehicle suffered total irreparable damage (catastrophic failure or K-kill).

- **STEP 2:** Take the switch states together with the fault-tree logic and process this information in a precisely consistent (but possibly subjective) fashion to infer one or more Measures-of-Effectiveness (MoEs).

For armored fighting vehicles, the MoEs are characterized in terms of loss of the vehicle's primary functions: Mobility (M LoF), Firepower (F LoF), and the greater of the two, *Mobility/Firepower* (M/F LoF).

— CAVEAT: MODEL VS. FIELD DATA —

- If both the field and modeling processes differ in the precise processing phases of **STEPS 1 & 2**, then comparability is lost.

5.1 Observations re: STEP 1:

If there are n switches (critical components) represented in the criticality process, then there exist 2^n possible unique switch (damage) states. However, LF damage is typically constrained to localized regions of an AFV. Thus, for a single shot, only a subset of all critical components are candidates for damage. This reduces significantly the potential number, but from the results of the current model, our simulations typically reveal $\simeq 10^6$ distinct component damage states for a given shot.

If the criticality analysis *and/or* component (binary) kill assessments are inconsistent between the modeling process and live-fire field assessments, then there is no basis for comparability between the test results and model predictions.

5.2 Observations re: STEP 2:

The process of **Step 2** currently involves the Damage Assessment List (DAL).[3] The DAL contains a listing of some 150 major components/AFV systems. If a single major component or system is nonfunctional following a shot, then the M- and F-LoF values are given directly by the DAL. If two or more major components/systems are nonfunctional, LoF values for each are extracted *via* the DAL and survived[‡] to get single M- and F-LoF values. Typically the M- and F-LoF values resulting from **STEP 2**-processing are binned into twenty intervals. Since the damage state dimensionality resulting from **STEP 1** is $\simeq 10^6$, agreement between predicted and field-derived LoFs, ***even if processed by the same methods***, does not imply validation or even support calibration.

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† STEP 1 and STEP 2 can be related identically to the mapping processes shown in Fig. 2, Ref. 3. **STEP 1** here is the mapping process from Space 1 to Space 2; **STEP 2** here is the mapping process from Space 2 to Space 4.

‡ The *Survivor Rule* states that the overall LoF of an AFV consisting of n independent systems each with its own LoF_i is given by:

$$LoF = 1 - \left[(1 - LoF_1) \times (1 - LoF_2) \times \cdots (1 - LoF_n)\right]$$

6. EXAMPLES OF SQuASH OUTPUT

Figure 3 gives a view of the computer model[3] of the M1A1 looking at the front-left of the vehicle. For this display the armor and main armament have been removed to reveal some of the interior details of the computer description. This modeling effort has produced one of the largest target-description files ever assembled, consisting of over 5000 objects. In addition to this high level of geometric modeling required for the Abrams Live-Fire Program, the stochastic nature of the calculations leads to a complex set of outputs which can best be displayed in the form of summarizing tables and histograms. The samples of these outputs, given in the APPENDIX,[+] exemplify this complexity. Briefly, they show:

- A histogram of residual armor penetration for 1000 computer replications of a warhead/armor encounter.
- The SQuASH prediction for all critical components killed on at least one of the 1000 replications.
- Listings of component-damage states for several important classes of critical components. They are ranked according to expected frequency of occurrence.
- Distributions of Mobility, Firepower, and Mobility/Firepower LoF, plus probability of Catastrophic Kill (K-Kill).

7. COMPARISONS: ABRAMS TESTS/SQuASH PREDICTIONS

In the following sections we discuss comparisons between these predictions and the results of the Abrams Live-Fire Tests.[6] In order to keep these discussions unclassified, various detail will necessarily be omitted.

7.1 Perforation

Does the attacking munition succeed in perforating the armor of the vehicle? The answer to this question becomes a first-level input to an estimate of the vulnerability of a tank. Of the 48 shots fired, in 25 tests (52%) the perforation results were predicted ***exactly*** by SQuASH; that is for each encounter either ***all*** 1000 replications predicted penetration and penetration was observed in the test or ***none*** of the 1000 simulations predicted penetration and the field test did not result in penetration. In 43 (90%) of the shots fired, the field outcome occurred in consonance with the larger percentage of computer predictions. Three of the shots were predicted by SQuASH, however, not as the most likely outcome having probabilities of occurrence of 0.36, 0.34, and 0.23. Only two (4%) of the shots were not predicted by SQuASH. One shot gave a result not predicted because the round happened to pass through a component that was not modeled in the computer target description. SQuASH failed to predict the perforation outcome of the other shot, due to incomplete information about the performance of that munition.

When input data is adequate, the model seems to predict warhead/armor penetration well.

7.2 Catastrophic Kill

To produce a Catastrophic Kill (K Kill), the munition must cause damage that is irreparable on the battlefield and renders the vehicle completely incapable of carrying out its mission. In every case SQuASH predicted as the most likely outcome the K-Kill result observed in the field. SQuASH also reminded us that for certain shots the complementary outcome *might have occurred* if the field sample size had been larger.

+ These figures and tables were taken from Ref. 3.

6. C. J. Dively, S. L. Henry, J. H. Suckling, J. H. Smith, W. E. Baker, D. W. Webb and P. H. Deitz, *Abrams Live-Fire Test Program: Comparisons Between SQuASH Predictions and Field Outcomes (U)*, **Ballistic Research Laboratory Special Publication, BRL-SP-81,** September 1989, SECRET.

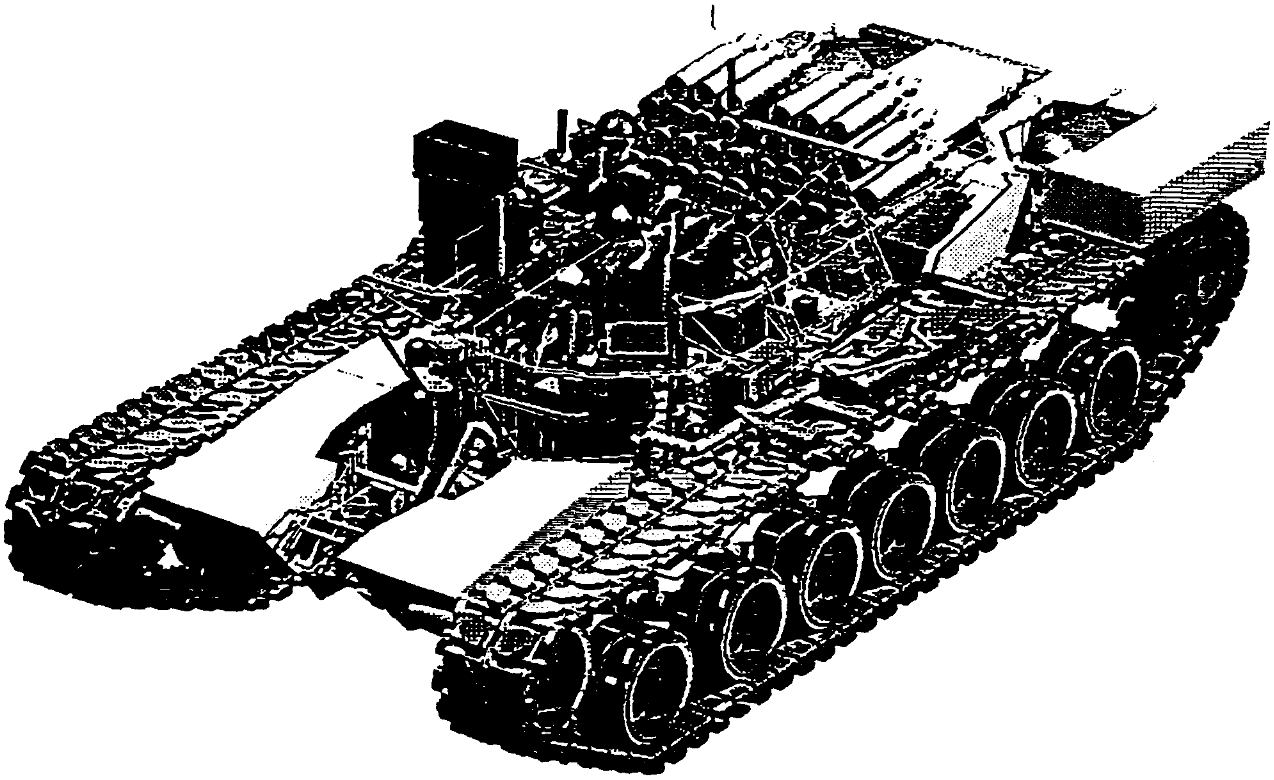

Figure 3. View of the M1A1 produced by the computer description. The armor and main gun have been removed to reveal the level of interior detail. This description contains some 5000 objects of which approximately 750 are critical components.

7.3 Component Kill Assessment

As discussed in the Component Dysfunction Section, all component outcomes are characterized as Bernoulli trials, i.e. functional/nonfunctional. For each field shot (each vector element), a probability of killing the given component is computed equal to the mean of 1000 SQuASH Monte-Carlo replications. Using these 48 probabilities, and assuming statistical independence of the field results, an empirical distribution of the vector is obtained by computing all possible outcomes. The Ordering of Probabilities (OP) Test[7] is used to determine the p-value within that distribution. The p-value reflects the probability of realizing the observed live-fire vector or any vector less likely than the one observed. A p-value of less than 0.05 indicates that the field outcome resulted in a rare vector and causes rejection of the hypothesis that the model output is consistent with the field data.

7.3.1 Initial Individual Component Assessment: Due to the time constraints for analyzing the Live-Fire data, only twenty-six of the components have been analyzed to date for consistency with the model predictions. These components were chosen based upon their relative importance to vehicle Loss-of-Function. Table I gives a listing by system of the components examined.

Table I. Components Evaluated and Grouped by System

Components Evaluated	
Group 1 - Other	**Group 4 - Armament**
receiver-transmitter	commander's control panel
intercom amplifier	gunner's primary sight
	gunner's auxiliary sight
Group 2 - Crew	commander's gps ext.
commander	hydraulic reservoir
gunner	main hydraulic pump
loader	race ring
driver	slip ring
	main gun
Group 3 - Electrical	ammo
turret networks box	
hull distribution box	**Group 5 - Propulsion**
hull networks box	driver's master panel
	alternator
	power turbine
	air cleaner
	electronic control unit
	transmission, main body
	fuel

These 26 components over the 48 tests produce 1248 comparisons between the model predictions and the field results. Of these, 969 (78%) were complete matches. A complete match occurs when all 1000 SQuASH outcomes predict the observed field outcome. Thirty-six (3%) of the comparisons resulted in complete mismatches; that is, SQuASH never in its 1000 replications, predicted the component damage observed. The remaining 243 (19%) comparisons were broken down by threat and

7. David W. Webb, *Tests for Consistency of Vulnerability Models (U)*, Ballistic Research Laboratory Technical Report #3030, August 1989

component into 34 statistical tests. The OP Test was applied to these groupings. Twenty-two (65%) of these tests accepted the hypothesis that SQuASH predicted the component PK correctly. The remaining 12 (35%) failed the test for consistency.

Combining the complete matches and those components subjected to the OP Test, we get a 90% consistency in predicting individual component PKs for the twenty-six components evaluated.

SQuASH had the most difficulty predicting damage to cables. The twenty-six components evaluated above did not include cables. It is not surprising that SQuASH would have difficulty predicting damage to cables since they have a very small presented area and the shotlines are infinitely thin. An analysis of all components is needed to assess fully SQuASH's ability to predict component damage.

7.3.2 Initial Ranking of Component Discrepancies: Table II summarizes the components having three or more mismatched shots, i.e. where $< 25\%$ of the SQuASH outcomes predict the field result. It was noted that crew members were four of the top five components having significant mismatches. Investigation of the crew data revealed an incompatibility between the field data collected and the data expected by SQuASH. As noted above (**Section 2.**), the SQuASH model performs a binning of all components following a shot into crisp kill/no-kill states. However in the case of the LF personnel data, the original assessments were based on the notion of continuous fractional incapacitation ($0.0 \leq$ LoF ≤ 1.0). This incompatibility results in incomparable data for the individual crew components, component damage states, and the Mobility-, Firepower- and Mobility/Firepower Loss-of-Function measures of effectiveness.

Table II. Components Showing Three or More Mismatched Shots of the Twenty-Six Components Investigated

Component	Number of Mismatches	Number of Complete Mismatches
Gunner	10	4
Gunner's Primary Sight	8	6
Driver	7	6
Commander	7	2
Loader	5	3
Main Hydraulic Pump	4	4
Hydraulic Reservoir	4	3
Main Gun	4	1
Turret Networks Box	3	0

7.3.3 Revised Individual Crew Data: In order to make comparisons on how well the SQuASH model predicts crew incapacitation, we must first have comparable scoring between the model and the field results. Since SQuASH expects components to be either functional or nonfunctional after a shot, we asked the organization responsible for personnel vulnerability to convert the fractional incapacitations observed in the field into these categories. An assumption had been made originally that if the loss of function was greater than zero the crew member was totally incapacitated (old bins). The personnel vulnerability experts categorized fractional incapacitation greater than or equal to 0.75 as nonfunctional (new bins). Table III reports the agreement between SQuASH and the field data using both the old bins and the new bins. Although the SQuASH model does agree more with the field data in predicting crew incapacitation, we believe that there are other factors that need to be investigated for all components.

Table III. Improvement in Predicting Crew Based on Binary Field Data

OLD BINS†	NEW BINS‡	RESULTS
54%	59%	Complete match
27%	29%	Most likely outcome predicted by SQuASH
10%	9%	Not most probable outcome, not a rare event (probability ≥ 0.05)
-----	-----	
91%	**96%**	**Subtotal**
3%	2%	Rare event (probability < 0.05)
7%	2%	Complete mismatch
-----	-----	
9%	**4%**	**Subtotal**

† If LoF > 0.0, Outcome = Total Incapacitation
‡ If LoF ≥ 0.75, Outcome = Total Incapacitation

7.3.4 Component Damage States: On a given shot, damage of components is not independent. Predicting individual component damage over a set of tests gives no indication of how well we predict component damage state or loss of vehicle functions. All vulnerability measures derived from field tests are a function of the component damage state of the vehicle since that is the field observable. Because of the dependency, *the distribution of component damage state must be derived* through a Monte Carlo process using SQuASH. The critical components were grouped by system categories (**Crew, Major Electrical, Armament, Propulsion** and **Other**) because the vehicle-wide damage state distribution in many cases was too large to compute even using the Cray-2. For each live-fire shot, a Monte Carlo process was invoked (1000 replications) using SQuASH. The results were used to derive the empirical distributions for the (five) sub-system component-damage states. The field result from each test and for each of the five system categories ($48 \times 5 = 240$) was then compared with the empirical distribution. If the probability of observing the field result within the empirical distribution was less than 5%, the hypothesis that the SQuASH model correctly predicted the component damage state was rejected. This procedure is detailed in the Modified Ordering of Probabilities Test.[8] Since SQuASH only printed the 200 most frequent damage states and occasionally the number of outcomes exceeded this number, there were 14 cases where conclusions could not be drawn; 42 (19%) out of the 226 comparisons resulted in rejection. That is, SQuASH predicted component damage state consistently with the field results in 81% of the cases tested.

7.3.5 Revised Crew Component Damage States: The above analyses on component damage states was based upon the old bins for the crew members. Rebinning the data using the 0.75 incapacitation criteria, we find that SQuASH improves at predicting crew component damage as shown in Table IV. The percentage of rare events (probability of occurrence ≤ 0.05) decreases from 27% to 18% in predicting crew component damage state over all 48 tests.

8 David W. Webb, *A Modification to the Order by Probability (OP) Procedure*, Ballistic Research Laboratory Technical Report, To be Published.

Table IV. Improvement in Predicting Crew Component Damage State

OLD BINS[+]	NEW BINS[‡]	OBSERVED FIELD OUTCOME
33%	35%	Predicted on all 1000 SQuASH replications (Complete Match)
27%	31%	Most likely outcome predicted by SQuASH
13%	15%	Not most likely outcome, but not a rare event (probability > 0.05)
-----	-----	
73%	**81%**	**SUBTOTAL**
4%	8%	Rare event (probability ≤ 0.05)
23%	10%	Never predicted in the 1000 SQuASH replications
-----	-----	
27%	**18%**	**SUBTOTAL**

[+] If LoF > 0.0, Outcome = Total Incapacitation
[‡] If LoF ≥ 0.75, Outcome = Total Incapacitation

7.3.6 Analysis of Loss-of-Function: M-, F- and M/F LoFs have not yet been analyzed using the new binning for crew members. Analysis of LoF for the old bins confirmed the SQuASH predictions for Mobility Kills in 41 (85%) of the 48 shots. The field results confirmed the SQuASH predictions for Firepower Kills in 16 (33%) of the 48 shots. Because many different component damage states can map into the same LoF, agreement here is not a sufficient condition to infer consistency of the SQuASH predictions. This is a case where it is possible to get the right answers for the wrong reason. SQuASH is a component-level model and if the component damage state predictions agree with the observed field data it necessarily implies agreement of the LoF measures. That is, agreement of component damage states is both a necessary and sufficient condition to validate the models. LoF analyses are summarized here only to give a complete accounting of the usual vulnerability measures reported.

7.3.7 Secondary Kill Mechanisms: Traditionally, component-level vulnerability models, *in the main*, calculate damage due only to the main penetrator and behind-armor debris (BAD). These mechanisms are normally termed the ***primary-kill*** mechanisms. There are well-known conditions under which other phenomena such as blast, shock, etc. (often termed ***secondary-kill*** mechanisms) contribute substantially to AFV dysfunction. Due to the time constraints for developing the SQuASH computer model and generating the Abrams pre-shot predictions, only the primary-kill phenomena were modeled.*

In the actual field results, the secondary-kill mechanisms, when observed, were nearly always (there was but a single exception) accompanied by damage due to primary-kill mechanisms. This observation, if borne out by future tests, indicates that, *in the main*, secondary-kill mechanisms, when present, tend to kill (redundantly) components already killed by the primary phenomena. Clearly, future work is needed to weigh the true importance of secondary-kill phenomena.

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* Provisions have been made in the SQuASH code to evaluate other damage phenomena as new algorithms and supporting data become available

8. SUMMARY

This summary reviews the two major themes of the paper. First, we give the detailed nature of the modeling paradigms utilized in SQuASH and *required* of the LF field assessment procedures for comparability to exist. Second, we summarize our efforts to compare statistically model and test data.

8.1 Similitude of Abrams LF Modeling & Field Assessment:

In **Sections 2.-4.** we discussed the construction of the SQuASH model. The chief issues are 1) what constitutes a critical component and how many such items properly characterize an AFV, 2) how should the decision process be constructed leading to the post-shot assessment of Bernoulli kill no-kill component states, and 3) what is the proper configuration of the fault trees within which the critical components reside?

Without strict adherence to this particular view of the vulnerability world, the field-based assessments cannot be compared properly with the model predictions. We make two related observations: based on the field assessment reports to date, we cannot ascertain that indeed those procedures are comparable. We quickly add that we are not inferring that to assess a AFV in a manner inconsistent with our model is wrong, only inconsistent!

It is worth noting that both the description of the model processes given in **Sections 2.-4.** and the manner in which the SQuASH computer model performs its calculations are bottom-up in fashion. However, the way in which the Abrams field assessors performed their investigations was top-down in manner. Following a shot, the assessors generally attempted to operate all major systems in order to flag possible dysfunction. If abnormal function was observed, then further investigations were performed. This procedure could result in missing killed components for which redundant (parallel) backups existed.

8.2 Statistical Comparisons - Field & Simulation Data:

This paper reports our first cycle of comparing LF field and simulation data. The Live-Fire tests result in many measures that can be analyzed to give insight into the modeling process. The investigation of modifications that should be made to SQuASH to improve its predictive capability are complex. Where disagreements are observed in the measures of performance, many sources for the variance exist and must be investigated systematically.

8.2.1 Perforation and Catastrophic Kill: All Live-Fire data has been analyzed for perforation and catastrophic kill. SQuASH predicted perforation consistently in greater than 95% of the field tests. In every case SQuASH predicted as the most likely outcome the catastrophic kill result observed in the field.

8.2.2 Individual Components: In this first set of comparisons, twenty-six of the most important critical components have been analyzed to evaluate SQuASH's ability to predict individual component damage. SQuASH predicted better than 90% of the component damage correctly. Such estimation abilities are important to the Army studies supporting spare parts inventories and repair parameters.

Over *all* components SQuASH had the most difficulty predicting damage to cables. Possible causes include but are not limited to geometric sampling problems related to the very small presented areas, component $P_{K|H}$ characterization, or the fragment densities used for behind-armor debris. This problem and its effect on the component damage state and LoF measures are under investigation.

The ability to predict individual component damage, although *necessary* for agreement between model and test outcome is unfortunately *not sufficient*. System-wide component damage states, summarized below, provide that sufficiency.

8.2.3 Secondary Effects on Crew Members: Secondary kill mechanisms (e.g. blast, shock, vaporifics) as measured on one of the most critical and sensitive of AFV components, crew, do *not* appear significant. In nearly every case where secondary kill phenomena could be observed, component kill had already occurred *via* primary mechanisms. It would appear that the continuing focus of damage characterization should remain on the primary kill mechanisms.

8.2.4 Component Damage State: This measure of performance is both the prime characterization of post-shot damage from which the other measures of performance (e.g. Mobility LoF, Firepower LoF, and Mobility/Firepower LoF) can be inferred as well as the most difficult to predict. The dimensionality of the damage vector can be very high. For conditions where the munition overmatches the armor, we infer typically between one million and 30 million discrete damage-state possibilities at a given location. And yet an actual test gives us only a single field damage state for comparison with all of these possibilities.

We also note that, given a consistent mapping of component damage state to the LoF measures, agreement between the field and SQuASH component damage state is both *necessary* and *sufficient* to test consistency of the SQuASH model predictions with the test data.[9]

SQuASH currently predicts component damage state correctly in approximately 81% of the cases tested. Considering the dimensionality of the problem and the fact that these were the first predictions made using a newly developed stochastic model, 81% agreement is remarkable. Component damage state is under further investigation for improvements to the SQuASH model.

8.2.5 Loss-of-Functions: The LoF measures have been analyzed for all the Live-Fire test results. Although the LoF measures have not yet been analyzed using the new binning for crew incapacitation, the expected improvement is unlikely to significantly change the overall result. Mobility LoF was predicted consistently in 85% of the Live-Fire shots. Only 33% of the predictions for Firepower LoF were consistent with the field data. The dimensionality of the Loss-of-Function space is twenty bins. Many component damage states map into each LoF bin. Considering the dimensionality of this space, we reject the hypothesis that SQuASH predicts Mobility or Firepower LoF consistent with the observed Live-Fire data.

8.3 Current Status & Follow-on Effort:

On balance, considerable progress has been made in the analysis of the Abrams LF data. From this initial analysis our predictive capability is good in some areas. In other instances, for example certain individual component kills, it is clear that we have not done well, but that good, or at least better, agreement can be achieved by modifying certain component PKs. In other areas of the analysis, particularly in the vehicle damage states, we encounter both the damage characterization of greatest importance and the greatest statistical complexity.

We will continue to study carefully the statistics of these damage states. Their number and diversity taken together with the mapping process to various Loss-of-Function metrics lie at the heart of the vulnerability assessment process and the use to which these related Measures-of-Effectiveness (e.g. M LoFs, F LoFs) can be utilized ***dependably***. The uses, of course, include the assessment of Live-Fire tests, and the application of vulnerability data to wargames, lethality optimization, vulnerability reduction, and spare-parts estimation.

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9. For a discussion of sufficiency conditions for vulnerability model validation, see Michael W. Starks, *Assessing the Accuracy of Vulnerability Models by Comparison with Vulnerability Experiments*, **Ballistic Research Laboratory Technical Report #3018**, July 1989

APPENDIX: SAMPLES OF OUTPUTS FROM SQuASH

Figure A-1 gives a histogram showing the distribution of residual-penetrator overmatch. The warhead is unspecified in order to keep these results unclassified. In general, these curves exhibit complex shapes, sometimes with multi-modal distributions.

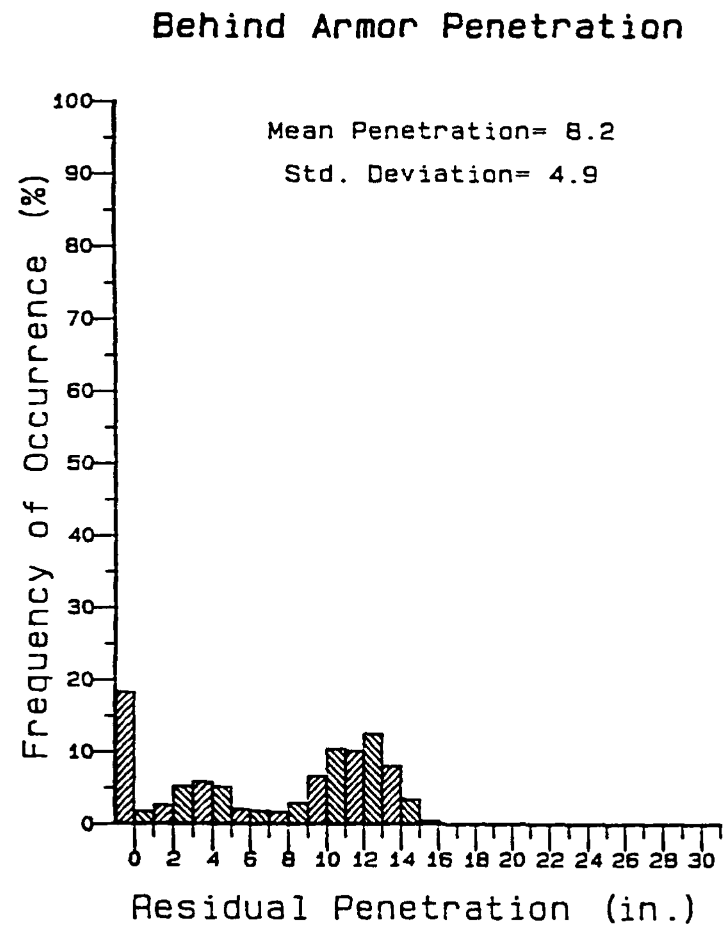

Figure A-1. Histogram of Frequency of Occurrence *vs.* **residual penetration. Because nine different shot lines are used (typically encountering different armor types) together with variable warhead performance, different levels of overmatch are derived.**

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 can lead to significantly different residual magnitudes.

For one sample calculation over the course of 1000 code replications, some 60 critical components were assessed to have been killed at least once. Table A-I lists these components. The remainder of the figures and tables in this appendix were taken from Ref. 3.

Table A-I. 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.

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 mani	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
h.lines TDM to azimuth servo	0.011	0.000	0.011
azimuth gearbox	0.004	0.000	0.004
manual azimuth gearbox	0.004	0.000	0.004
manual azimuth gearbox	0.008	0.000	0.008
manual elevation pump	0.015	0.000	0.015
manual elevation pump	0.005	0.000	0.005
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 bypa	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

The next two tables show how SQuASH output departs radically beyond other point-burst models. Here two classes of components are examined 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 A-II lists the category of **CREW**. For this group, the calculated damage states apply to the personnel located in the turret-basket area. The damage states derived from the 1000 replications were sorted together and then ranked from the most to the least likely in occurrence. Table A-II 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, SQuASH predicted probable outcomes for only six of the eight possible combinations of commander, gunner, and loader.

Table A-II. 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 cumulati.e 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*

The component damage states for **ARMAMENT**, shown in Table A-III, 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 final stages of calculation of vulnerability involve the various categories of kill. First, catastrophic kill represents the complete loss of the system, which generally occurs in encounters with large-caliber ammunition (warhead and or propellant) or fuel. The probability of this event is shown in Fig. A-2c. For this particular shot, the probability of a catastrophic event is assessed as zero. Note

Table A-III. Component damage states from the SQuASH simulation for the subset *ARMAMENT*. Format and labeling follow the procedure used in Table A-II.

Group: ARMAMENT

Damage States, sorted by likelihood

Damage States																													Relative Occurrence	
Component Number																														
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	state	sum
□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	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

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 bypa*
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*		

that the histogram associated with K Kill can be populated only in the first and last bins. In other words, catastrophic failure either occurs or it does not; the outcome is either zero or one.

The other kill categories are assessed by mapping each of the thousand damage states *via* the DAL 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. A-2a. 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 are a significant number of occurrences away from the mean. The corresponding results for Firepower LoF are given in Fig. A-2b. In this histogram, the mean LoF occurs in a bin with a low population. There is also a significant probability ($\sim$ 18%) that the F LoF will be zero. The M/F LoF histogram is given in Fig. A-2d. 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.

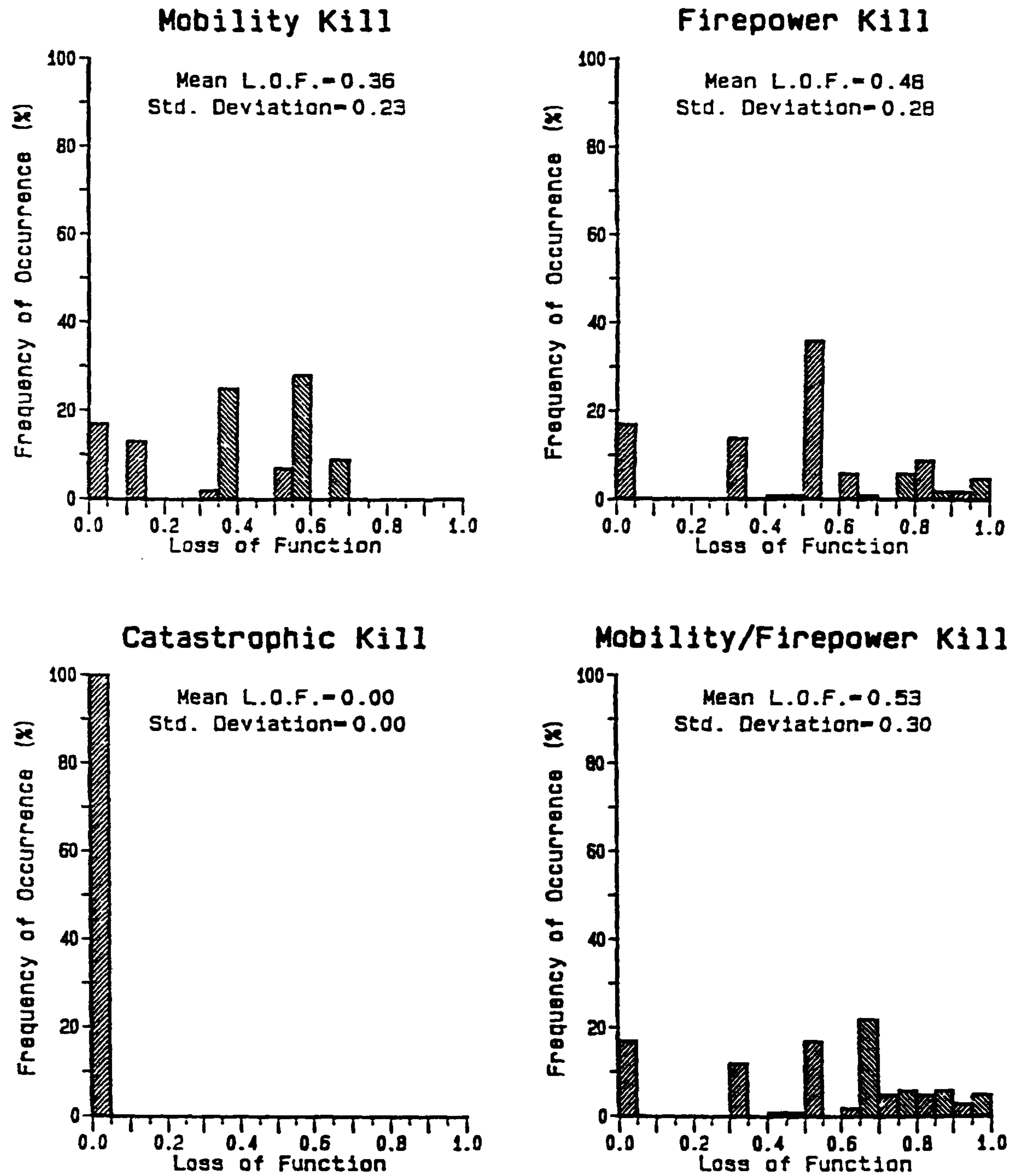

Figure A-2. Histograms of various kill categories derived from the SQuASH simulation. The Mobility Kill Loss-of-Function (LOF) is shown in a), the Firepower Kill in b), the Catastrophic Kill in c), and the Mobility/Firepower Kill in d). The means (expected values) and standard deviations are given for each plot, but are considered relatively immaterial for these non-parametric (i.e. non-gaussian) statistics.

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