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ASSESSING THE ACCURACY OF VULNERABILITY MODELS BY COMPARISON WITH VULNERABILITY EXPERIMENTS

MICHAEL W. STARKS

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This paper provides a discussion of "accuracy" in the context of vulnerability modeling and vulnerability predictions. Past practice is criticized, and various levels at which accuracy might be defined are discussed.

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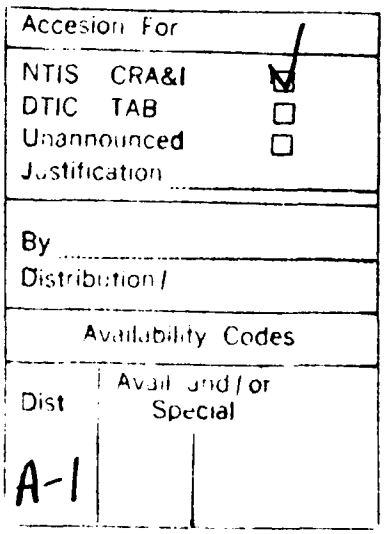

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1. INTRODUCTION

Over the past three decades the business of vulnerability analysis has been conducted more as art than as science. For a number of reasons, there has been recent movement away from art and towards science. One reason is internal to the Ballistic Research Laboratory (BRL). If a substantial work force of scientists and engineers spends several decades doing vulnerability analysis it would be both surprising and disappointing if improved clarity on the foundations of the subject were not achieved. A second reason is the declining *cachet* associated with computer models. Several decades ago it was virtually the case that if a quantitative result issued from a computer model, it was sufficiently warranted as correct. The crude extrapolations which then passed as vulnerability models benefited from that halo effect. Today, people are understandably more skeptical about models. Questions are asked and answers expected about accuracy and validation. The pressure of such questioning has forced vulnerability analysts into seeking greater scientific respectability for the fruits of their labors. A third cause of the scientific turn is the recent explosion of computer technology. Vulnerability phenomena are complex; realistic simulation was out of the question with the tools available to early vulnerability analysts.

Intersection of the three trends mentioned has caused the progress of vulnerability analysis towards science to proceed at an uneven rate. Accurate computerized target descriptions seem clearly to be a necessary condition on scientifically adequate vulnerability modeling and a set of appropriate tools is in hand.[1] The stochastic nature of vulnerability phenomena has been more explicitly recognized, and appropriate modeling tools developed.[2]

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1. Ballistic Research Laboratory CAD Package, Release 3.0. (1 Oct 88), "A Solid Modeling Systems and Ray-Tracing Benchmark Distribution Package," SECAD/VLD Computing Consortium, The US Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD 21005-5066

2. A. Ozolins, "Stochastic High Resolution Vulnerability Simulation for Live Fire Programs," in The Proceedings of the Tenth Annual Symposium on Survivability and Vulnerability of the American Defense Preparedness Association (ADPA), 10-12 May 1988.

Vulnerability measures of effectiveness have been more clearly defined than was traditionally the case.[3] However, one area where less progress has been made has to do with issues of vulnerability model validation and accuracy.

Most of the personnel resources of the Ballistic Research Laboratory's Vulnerability/ Lethality Division (VLD) are devoted to predicting the vulnerability of targets to conventional threat munitions or to predicting the lethality of conventional munitions when fired against various targets. No doubt, some would prefer to say that VLD *estimates* vulnerability rather than *predicts* it. This strikes me as a euphemistic way of avoiding the question of how good our predictions are.

In this paper I will discuss the idea of an accurate vulnerability prediction and related notions. Let me begin by beating the surrounding bushes to clarify what the paper is not about. There is no attempt to answer the question whether current vulnerability models are accurate, or even to lay out the details of a practical program for determining whether they are accurate. Nor do I discuss the empirical data voids which clearly contribute to inaccurate vulnerability predictions. I do hope to provide a consistent framework within which such issues can be coherently debated. This would itself constitute progress.

There is a sense in which to speak accurately is to speak precisely, but that is not the operative sense here. The probability of throwing snake eyes with fair dice is .0277777777777778. The assertion meets reasonable scientific standards for both precision and accuracy, though depending on the intended application one might argue that it is needlessly precise.

Suppose you are now asked to interpret the stated probability as the Probability of kill (Pk) of the M107 HE round versus the Super Soviet Tank (SST). Arguments about precision will be the same as for the dice throw. With respect to accuracy, though, virtually everyone will agree that our Pk is not so accurate as the stated precision reflects. It will be correctly argued that our models are simply not that good and that the required inputs are not sufficiently well-known. Heads will nod knowingly that

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3. J.M. Abell, L.K. Roach, and M. Starks, *"Degraded States Vulnerability Analysis,"* BRL Report in press.

our Pk is not sufficiently accurate to justify sixteen place precision. Those same heads will also nod approvingly if we say that the Pk=.03. In truth, however, we cannot, or at least have not clearly stated the grounds according to which our answer is accurate to two digit precision. Let us begin with an overview of the vulnerability analysis process.

2. Conceptual Spaces for Vulnerability Analysis

A paper by Deitz and Ozolins usefully divides the vulnerability assessment/analysis process into four distinct spaces.[4] These conceptual spaces are equally applicable to the conduct and analysis of Live-Fire Testing or to a wholly simulated analysis. Points in a lower number space are mapped to higher spaces by experimental processes and/or definitional and mathematical transforms.

As illustrated in Figure 1, Space 1 contains the details concerning interaction of a specific munition against a specific 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 a live-fire experiment or a computer-based simulation is performed to that end, damage to the target *can* occur 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. (See Appendix A) Following a shot, 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 number of possible bullet/target interactions. As noted above each specific bullet/target state is characterized by literally hundreds of

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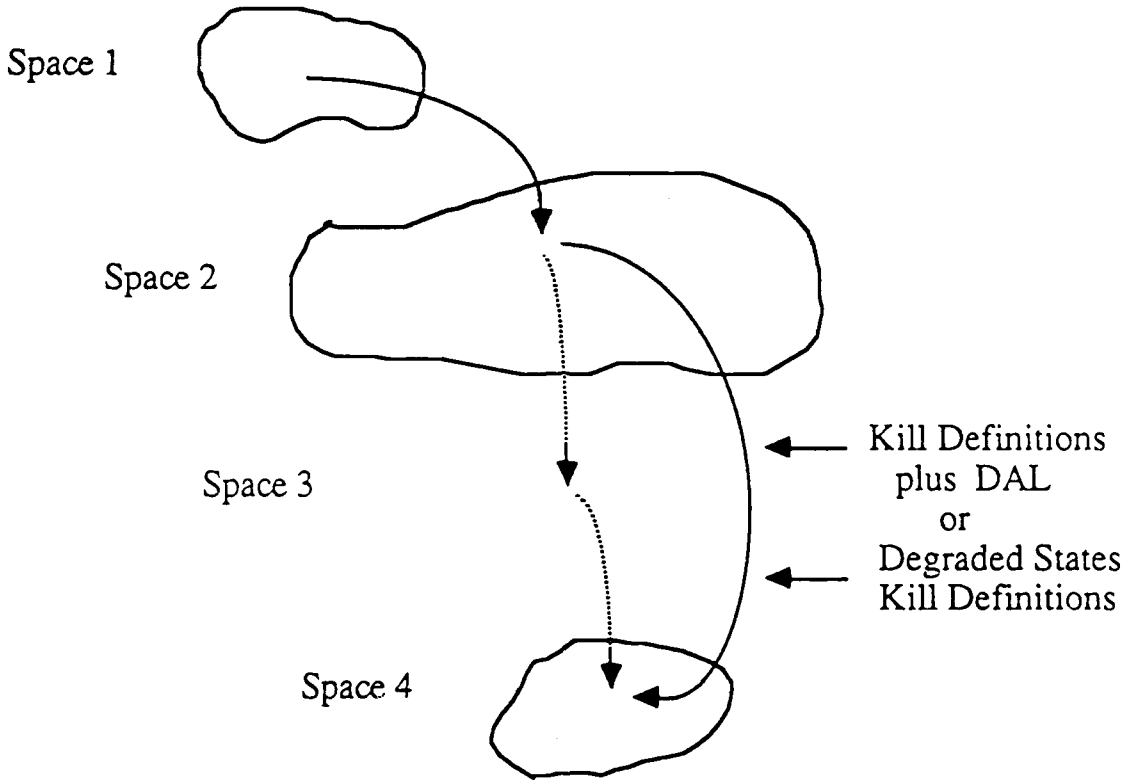
4. P.H. Deitz and A. Ozolins, Computer Simulations of the Abrams Live-Fire Field Testing, in the Proceedings of AORS XXVIII, 12-13 October 1988. (The next four paragraphs closely follow this paper).



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 1. Conceptual Spaces for Vulnerability Modeling

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 number of possible outcomes that may occur following a bullet/target interaction. If a target is constructed of n critical components, then the number 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 for a given Space 1 event 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. This is too large a number for practical analysis.

Given a particular damage state in Space 2, by definition a set of critical components is no longer functional. Thus there may be some reduction in the firepower or mobility function of the target. Space 3 represents an objective measure of this diminution in performance. In the case of firepower 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 not an implemented mechanism for the mapping from Space 2 to Space 3. Hence the mapping process is represented with dashed lines in Figure 1.

Although it is theoretically possible to map each of the 2^n outcomes of Space 2 into an objective MOP in Space 3, this cannot be practically accomplished with actual targets. For this reason, Space 3 will not be further discussed here.

Various procedures have been used over the years to map Space 2 directly into aggregated vulnerability measures of effectiveness (MOEs) in Space 4. The traditional mapping process has made use of a set of kill criteria (which will be discussed below) and a Standard Damage Assessment List (SDAL) which maps, for mobility and firepower, the killed components of Space 2 into Space 4 MOEs that have variously been called:

- Probability of Kill (Pk)
- Expected Loss of Function (LOF), or
- Decrement in Combat Utility (DCU).

These SDAL mappings are estimates, made by groups of users, of functional disturbance to vehicle capability given a killed

critical component. That there are crippling problems with the SDAL mapping has been documented elsewhere.[5] More recently, some of these problems have been overcome by defining target degraded states explicitly in terms of component-level fault trees. This is an attempt to divide up the impractically large (2^n) states of Space 2 into a number of capability bins in Space 4. Within the Mobility function, for example, component trees have been associated with immobilized, slight mobility loss, severe mobility loss, etc. We will have occasion to discuss the mapping to Space (4) in more detail below.

3. Towards a Definition of Accuracy

Let us return to the accuracy problem by specifying the properties which would have to be true of our vulnerability analysis for us to say that our final vulnerability MOE can be stated with arbitrary precision. Common sense would seem to dictate that we require at least an accurate model and accurate inputs in Space 1; we also require accurate calculation of the damage states of Space 2 and accurate vulnerability estimates as output in Space 4. For our model to be accurate it must have accurate algorithms for the phenomena treated and it must also be complete with respect to the classes of phenomena we claim to treat. For our input to be accurate it must be either the result of an acceptably conducted experiment or derived from physically accepted first principles. For our vulnerability MOEs to be accurate we must be convinced that they compare favorably with the results of experiment.

I believe there are two major problems with the reasoning in the previous paragraph. First, the specific sense of "accuracy" intended for the various parts of the problem is not clear. Second, and this has been a frequent if mostly invisible problem over the years, the task of directly comparing vulnerability MOEs with the results of measurements is impossible. We will return to "accuracy" below. Let us first explain why the Space 4 MOEs from our models cannot be compared with experiment.

The Space 4 vulnerability estimates -- the Pks or LOF estimates -- are not physically observable. This is not because the estimates are (or are thought to be) probabilities; an experiment can standardly be regarded as a single sample from an underlying distribution. Even when the experiment is so regarded, it is not

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5. 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.

physically observable whether in a given experiment the target is mobility killed or firepower killed.

One reason why such outcomes are not observable is that whether a vehicle is killed or not is a function not only of the observed state of the target (Space 2) but also of the functional definitions adopted for the various forms of kill, and the specifics of the mapping from Space 2 to Space 4. These definitions are not empirically right or wrong, rather they are *conventions* which are more or less useful in serving the intended purposes of vulnerability analysis.

The much reprinted definitions of the traditional kill criteria are shown below:

- **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.

A little reflection shows that these definitions are not helpful for scientific vulnerability analysis. A useful scientific definition requires the possibility of relatively unambiguous determination, in particular cases, whether the conditions of the definitions are satisfied. Since the definitions contain phrases such as "controlled fire", "controlled movement", "totally lost", and "repairable by the crew", it is fairly clear that there is a great deal of room (too much!) left for disagreement over cases. This particular definitional difficulty is avoided if degraded state criticality trees are regarded as defining the various classes of kill.

Unfortunately, the probability of degraded state MOEs are not any more experimentally observable than are the SDAL MOEs. The fundamental reason for this is that the same probability of being in a degraded state can be obtained in many different ways. An example easily illustrates this.

Figure 2 shows a fault tree that defines the degraded state for slightly reduced speed. Suppose we fire 1000 live fire shots under identical initial conditions with the following outcomes. For 223 shots, none of the components on the reduced tree fault tree were killed, and for 777 shots two right support rollers were killed. Mapping this Space 2 information to Space 4 via the

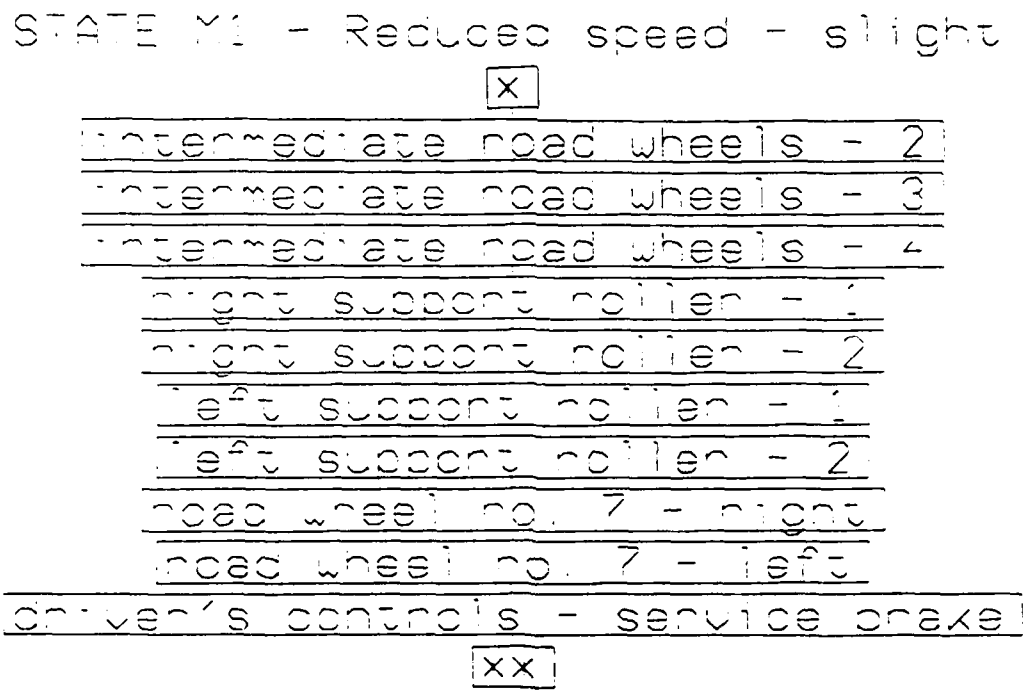

Figure 2. Fault Tree Defining the Degraded State Slightly Reduced Mobility

fault tree we conclude that the probability of the tank being in the slightly reduced speed degraded state is .777.

Now suppose we wish to calculate vulnerability MOEs in a model for the initial and boundary conditions of the Live Fire Test. If we run 1000 monte carlo cases in our model we might obtain the Space 2 result that for 223 cases no critical component was damaged and for 777 cases left road wheel #7 was killed. Our mapping to Space 4 will once again yield the probability of degraded state result of .777. Our comparison of experiment with theory gives identical kill probabilities even though there are no killed components in common.

In light of the simple example, it becomes clear what can and cannot be correctly inferred from MOE agreement or disagreement in Space 4 concerning damage state agreement or disagreement in Space 2. As the example shows, we cannot infer agreement in calculated damage states (Space 2) from agreement of MOEs in Space 4. Even if we had complete agreement in MOEs between experiment and simulation, this leaves open the possibility that the actual and predicted Space 2 damage states are *completely disjoint.*

Most people will accept as a necessary condition on model validity that critical model calculations be acceptably accurate; it is not an adequate procedure to compare Space 4 MOEs and declare that our model is accurate if they agree. Surprisingly, some workers have come perilously close to doing exactly that.

Pollard **et al** [6], for example, use correlation analysis to relate Space 4 Live Fire Test outcomes to calculated MOEs. After presentation of the correlation technique employed and display of the comparative results, they say:

> "Thus, while additional effort is required on the models to achieve good correlation for all classes of weapons and targets, the use of the expected value model predictions as average characterizations of vehicle vulnerability for wargaming purposes appears reasonable."

This is a very weak conclusion and it is heavily qualified. None-the-less, based on the argument of the last few paragraphs it is simply false that high correlations of the s ort indicated give any warrant that our models and their output MOEs are

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6. R.G. Pollard, G.L. Holloway, D.C. Bely, F. Tyler Brown and J.C Kisko, "An Examination of Vulnerability Predictions in Light of Live Fire Testing of Light Combat Vehicles," The 17th TWG/AOR Quadrapartite Working Group, for AOR, Sydney Australia, December 1987.

"reasonable". As the simple example showed, even a correlation coefficient of one is insufficient to guarantee that our model agrees with experience.

We have seen so far that Space 4 is an unacceptable place to look if the accuracy of our models is to be clarified. It can too easily show apparent agreement between Pks while masking serious defects in the details. The only useful purpose that Space 4 comparisons have for the accuracy issue is a negative one. That is, if there is disagreement in Space 4 MOEs between simulation and experiments, we *can* infer that we have a disagreement in the Space 2 damage states. The natural suggestion arises: why not look directly at Space 2 for measures of model/experiment agreement in the first place? Before exploring this suggestion in more detail, it is worth pointing out that when we change our domain of interest from Space 4 to Space 2 there is no loss of information. We know that Space 2 agreement between model-predicted and experimental damage states strictly implies Space 4 agreement.

It is a natural and understandable chain of reasoning that since the VLD's primary output is probability of kill (Pk), and since we have computer codes calculating Pks, then model accuracy and validation should have to do with Pks. Unfortunately, the reasoning, though understandable, is unsound.

A final heuristic point may further illuminate why we should look to the damage states rather than to the final vulnerability MOEs if we wish to clarify the issue of vulnerability model accuracy. In principle, the modeling work for Spaces 1-3 can proceed according to acceptable scientific standards. The terms that we use to predict component loss of function such as mass, velocity, and drag are certainly familiar from the lexicon of theoretical physics. Thus, even though there is no first principles vulnerability science to use in simulation modeling, there is a rich variety of empirical generalizations available covering many central vulnerability phenomena. This is not to say that we have an empirical law available for each vulnerability phenomenon we are interested in. However, we do have standard modes of scientific experiment, inference, and argument available to help us make further progress and to help adjudicate disputes.

The scientific standards which can be brought to bear when discussing Space 2 damage states are no longer available once these damage states have been mapped to Space 4 MOEs. As was discussed above, these mappings either are or require use of definitions which from a scientific point of view are essentially *arbitrary*. The evaluative criteria for the usefulness of a particular form of Space 4 MOE are not those of empirical science, rather they are *pragmatic*. Does a given MOE illuminate the vulnerability issue or issues that require clarification? As a practical matter, the answer to this question will depend on whether the interlocutor is a commander, a representative of the

user, a vehicle designer, a weapon designer, a war-gamer, a senior decision-maker, a tactician, or is in some other role. Not surprisingly, an MOE may be regarded as useful by some and useless by others. There are sometimes heated arguments. Because the Space 4 MOEs purport to assess the capability of the target in warfare, adjudication of MOE goodness necessarily requires postulations and speculations concerning heretofore unfought wars. This is a long way from masses and velocities.[7]

I do not wish to be understood as arguing that discussions about Space 4 MOEs are useless. BRL must keep an oar in the water here to insure that our MOEs are as useful as they can be to meet the diverse needs of our many types of customer. What I am arguing is that we should distinguish as clearly as possible between the scientific criteria associated with our Space 2 damage-state work, where accuracy can be defined, and our Space 4 MOE work where accuracy cannot be defined. We could say that in Space 2 we aspire to vulnerability science, but in Space 4 we can do no better than pragmatically acceptable analysis.

4. ACCURATE VULNERABILITY PREDICTIONS

We have settled on the Space 2 damage states as the appropriate place for comparisons between vulnerability models and vulnerability experiments. If we can "validate" our model in Space 2 we can guarantee agreement in Space 4.

As noted above, the BRL target description for the Abrams tank is composed of roughly 750 critical components. Under our assumption that for a test event we can regard each component as dead or alive (Appendix A), we can give a complete scientific account of the outcome of a Live Fire shot by specifying an evidence vector E whose components $c_1 \ldots c_n$ take the values 1 (for alive) or 0 (for dead). For each monte-carlo iteration of our vulnerability model we generate a hypothesis vector H whose identically numbered components also take the values 1 and 0.

Suppose we have a statistically significant number of vulnerability experiments with identical initial conditions and have characterized the outcome of each with an appropriate E vector. Suppose further that we also have an appropriate series of H vectors as output from a monte-carlo model simulating those same

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7. Sometimes these MOE arguments are made by scientists. This results in the spectacle of "fog of war" anecdotal musings posed as if they were scientific arguments for or against a particular MOE. Attention to the difference between scientific and pragmatic evaluative criteria would mitigate some of the worst features of these arguments.

initial conditions. For such a case, there are well established statistical methods for answering the question of whether we can be confident that the H and E distributions are the same. The degree of confidence with which we can claim that they are the same characterizes the accuracy of our model for the initial conditions under study.

Unfortunately, large empirical sample sizes for identical initial conditions are prohibitively costly in system vulnerability testing. For problems of practical interest we will often have a single E vector to compare with multiple H vectors. What can we learn about the accuracy of our models when faced with this type of comparison? For a single shot, the emerging answer seems to be "very little", or perhaps even "nothing".

It deserves repeated emphasis, however, that our success or failure in articulating the extent to which our models can accurately predict experimental outcomes is squarely predicated on consideration of the relevant H and E vectors only. Consideration of Space 4 Pks contributes no additional cognitive content once we have assessed the situation in Space 2.

5. A CONSEQUENCE FOR COMPARTMENT MODELS

In the sense of the phrase "accurate prediction" developed here, only component level models can even have the possibility of making accurate predictions. So called compartment models, which map directly from Space 1 to an MOE in Space 4 are neither accurate nor inaccurate. The best that can be hoped for with this class of model is that its Space 4 MOES agree with a component-level model's Space 4 MOES, where the component-level model has been independently judged to be accurate in the Space 2 sense. Unfortunately, for cases where this much information is available, the compartment model is not really needed. It is when we don't have component-level information that the compartment model is most used, and it is precisely for those cases that we cannot assess its accuracy. This forces a conclusion which I believe is true: we do not know how accurate most compartment-level predictions are.

6. SUMMARY OF MAIN ARGUMENT

System probability of kill is not a field observable; moreover identical probability of kill values can issue from completely different combinations of killed components. Thus, probability of kill is the wrong level at which to compare vulnerability theory with experiment. A better level is the damage state; this is specified by determining (after an actual or simulated shot) which target components are killed and which are alive.

APPENDIX A - Components: Dead or Alive

Our earlier discussion of Space 2 damage states required the simplifying assumption that for given weapon target encounter conditions each component would either be killed or not. Thus, the kills for the components would be ones or zeroes. Unfortunately, the received wisdom on vulnerability analysis does not always divide things so neatly.

One problem is that it is not possible to give a general account of when we should declare an arbitrarily chosen component killed. We might say that a component is dead if it can't fulfill its function in the tank, but this leaves plenty of room for disagreement about cases. I do not believe that this difficulty can be avoided in any practically implementable program for vulnerability analysis. We must just face the fact that we must think through, for each component, what its function is and what level of damage would be required to prevent that function from occurring.

What about the issue of component probability of kill estimates which have historically been regarded as other than binary? There are a few different kinds of cases that seem most problematic. For example, a copper fluid line may be bent by a fragment impact such that fluid flow is restricted but not completely stopped. Our fluid line is neither dead nor alive. Rather, it has a certain fraction of its original capability. Therefore, the argument goes, any theoretical structure for vulnerability analysis which makes the assumption that each component is dead or alive is intrinsically flawed.

First, it must be granted that it is at least sensible to discuss the fractional capability of at least some types of components. If our copper line previously had a capability of 10 liters/minute and now can carry only 5 liters/minute, then it certainly seems sensible to assert that the line has .5 fractional capability. Of course there is still a question about the consequences of a line with .5 fractional capability on vehicle operation. But this should be a question we can satisfactorily answer, at least in theory.

There are points of both similarity and difference between the case of the fluid line and the case of the overall tank. Talk about a tank's fractional capability (combat utility) is vague to the edge of being meaningless. On the other hand, it makes sense to consider the fractional capability of a fuel line. However, for neither case does it make sense to

talk about fractional capability when it is convenient to do so, and to regard the quantities as probabilities when it is convenient. If we were to allow treatment of a fluid line with .5 capability as if it were a fluid line with a .5 probability of destruction, we would be making a serious mathematical error.

Fortunately, I believe that the fuel line can be handled without making such an error; these difficulties can be successfully accommodated within the framework I have been advocating in this paper. How should we handle our critical fluid line with .5 fractional capability? The short answer is: it depends on what it does to the operation of the tank. Suppose we use pliers and crimp the fluid line such that it has .9, .8, .7 ... 0.0 of its original capacity. After each crimping we try to use the tank for the type of task which the damage criterion is designed to illuminate. At some point (possibly only when we get to 0 fractional capability) we will no longer be able to execute that type of task. That is the point at which we declare our fluid line to be dead. What we are essentially doing is defining a threshold of fractional capability beyond which the component is declared legally dead.

Somebody might argue that the questions of whether a fragment of a given mass and velocity crimps the fluid line to exactly the kill-threshold level and whether there even exists a precise threshold level that causes task failure are best answered stochastically. And it must be admitted that our ignorance of the precise initial and boundary conditions of the vulnerability problem are such that stochastic methods are appealing; this is why such models have recently been developed in VLD. However, I cannot see that component kill information is inherently "more stochastic" than other required point burst inputs, for example, penetration. In a Monte Carlo model we should certainly form distributions of every input variable we can, including component PKHs if we have the information to develop the distribution, but for expected value modeling I do not see any harm in regarding component death as a binary matter.

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