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**VULNERABILITY SCIENCE:
A RESPONSE TO A CRITICISM OF THE
BALLISTIC RESEARCH LABORATORY'S
VULNERABILITY MODELING STRATEGY**

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MICHAEL W. STARKS

JUNE 1990

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U.S. ARMY LABORATORY COMMAND

BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

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I. WHAT IS V/L ASSESSMENT?

There is a certain kind of technical work performed by several DoD Laboratories and Activities as well as by aerospace firms and consultants. The work is traditionally called "vulnerability analysis"; about 150 of the workers toil in the Vulnerability/Lethality Division (VLD) of the Ballistic Research Laboratory (BRL). This paper will try to illuminate issues about what these people are doing and should be doing, especially with respect to ground vehicles. The arguments will have an important bearing on the question of what we should be trying to accomplish when we develop computer simulations in support of our vulnerability/lethality (V/L) mission.

A recent statement of BRL's V/L mission is as follows:

- Provide *Objective, Quantitative* Vulnerability and Lethality, Assessment Data for Decision and Operational Analysis

and

- Means to Reduce Vulnerability and Enhance the Lethality of BLUE systems.

This mission statement is probably not very different from those of other DoD elements with V/L responsibilities. Note that of the two parts of the mission statement one is essentially *scientific* (Objective, Quantitative ... Data) while the other is essentially *practical* (Reduce ... and Enhance). For the benefit of non-specialists, I would like to briefly discuss the practical aspects of the mission first.

A competent and experienced worker in ground vehicle V/L has been involved with both V/L testing and V/L simulation modeling. The testing could range from individual fragments fired against vehicle components to firings of large caliber munitions against fully combat-loaded targets. The simulation experience could also vary over an equally broad range. It is fairly clear that our idealized competent worker is uniquely placed to give helpful practical advice to developers of both ground vehicles and munitions designed to defeat ground vehicles. Examples of this kind of advice are as follows:

- Put more armor around the gunner's sight
- Make the hatches thicker
- Lower the fuel cells and ammunition
- Separate back-up wiring harnesses
- Add redundancy for fire control
- Change the built-in-standoff of a developmental shaped charge
- Change the intended hit point of a smart munition
- Shock mount key electrical components if possible

There are several points I wish to emphasize about this mission of giving useful practical advice. First, it is important. Developers often take the advice with an immediate reduction of vulnerability or enhancement of lethality as a direct result. Second, I estimate (an estimate corroborated in discussions with senior V/L managers) that no more than 20% of VLD's effort is directed towards the role of giving practical advice. Third, I believe that this mission is the fundamental reason why workers on V/L problems have traditionally been called "analysts" rather than "scientists". The label "analyst" was at one time scientifically honorific and was used in the sense of "one who divides into parts". In more recent years, however, the label is sometimes used in a contrastive sense with "scientist"; we do analysis when there is insufficient information available to do science. People who do wargaming are analysts, for example, while those who do fluid mechanics are scientists. For the role of giving practical V/L advice, the mixture of science, experience, engineering judgment, and rules of thumb with ill-defined regions of applicability is indeed traditionally characterized as "analysis" with its implicit connotation of a strong subjective or judgmental component.

Unfortunately, the term "vulnerability analyst" is also used for the 80% remaining effort which truly is -- or should be -- scientific. This is unfortunate because it carries the implication that development of objective quantitative vulnerability estimates is as subjective and judgmental as the practical advice. I believe that this implication should be regarded as false; that is, I believe that when we are trying to fulfill our mission of developing objective, quantitative vulnerability data we should be doing science purged of subjective judgment to the maximum extent possible.

Since I have learned from experience that this claim is bitterly contested by some V/L workers, it is worth discussing in more detail. Perhaps it is best to begin by avoiding spurious objections through clarification of what is *not* being claimed. I am not claiming that objective, quantitative vulnerability assessments can be conducted without exercise of good judgment on the part of V/L workers. (It is equally true that objective, quantitative assessments of the stars can be made only by astronomers with good judgment.) Good judgment is clearly a prerequisite for success with any rational activity; my claim is only that we should limit, to the maximum extent possible, our appeal to subjective judgments when we make V/L assessments.

In particular, I believe we should avoid subjective and overly global V/L assessments which rely on vague interpretive procedures, functional relationships of dubious relevance or provenance, intuitive hunches, semantically ambiguous outputs, or rules of thumb regarded as dogma. Avoidance of these difficulties requires "analysis" in the good sense; the V/L assessment problem must be broken into intellectually digestible chunks so that the phenomenologies associated with various kill mechanisms, classes of components, and target classes can each be treated in the most careful and auditable way possible. In short, V/L assessments, whether executed in the field or with a computer, should be conducted less as art and more as science.

For that portion of the V/L assessment process that involves testing, few would argue that we should not attempt to meet scientific standards of measurement. When we test a developmental bullet against a ground vehicle or a ground vehicle component we keep careful photographic and numerical records concerning the initial conditions of the test. Experiments typically involve a wide variety of measurement instrumentation including high speed photography, x-ray, thermal, blast, and motion sensors, as well as careful observation of the exact state of the target after the shot. Clearly, scientific standards of measurement are met for the empirical part of V/L assessments.

It is the theoretical portion of V/L assessments where there is apparent disagreement on the issue of whether we can or should meet scientific standards. Here, I would argue, we are trying to achieve *scientific understanding* of vulnerability phenomena by developing *explanations* of observed events and *predictions* of events not yet observed. Those who have argued that we cannot or should not attempt this rely on the belief that V/L phenomena are "too hard" to understand and that we are therefore constrained to rely on judgmental analysis.

It must be conceded that we do not have a physical paradigm for conduct of scientific V/L assessments which is as robust as the Newtonian, relativistic, or quantum, paradigms. This does not imply, in my view, that we should throw up our hands and settle for subjective and judgmental analysis. There is a clear sense in which the problems of classical mechanics were "too hard" for Kepler and Galileo and the problems of electrodynamics were "too hard" for Lorentz. None of these individuals obtained a completely satisfactory scientific account of the entire set of phenomena he brought under study. Still, perusal of the historical record clearly reveals that much of the careful scientific work accomplished by these men eventually was embedded in that complex of laws and initial conditions which constitutes the scientific truth at time *t*.

Scientific progress takes time with respect to any phenomena. Vulnerability phenomena are extremely complex, are at least partly stochastic, are difficult and expensive to measure, and often seem unstable with even small changes in initial conditions. When these difficulties are considered in conjunction with the fact that vulnerability phenomena have been under scientific study for only a short period of time, it is easy to see why a general physical theory concerning these phenomena is not yet available.

Sometimes it is argued that because there is no first principles general theory of V/L phenomena, V/L cannot be pursued as science. It is certainly true that many of the premises embedded in our explanations are empirical in the sense that they express functional relationships developed from experiment rather than derived from higher order physical law. Moreover, we are often in the uncomfortable position of extending these functional relationships beyond the region for which they were actually measured. Clearly, it is very difficult to determine the extent to which this procedure is adequate without the help of first principles guidelines.

Despite these difficulties, I would argue that there is every reason to link together our explanatory premises in as rigorous a way as possible. If we force ourselves to codify relations of dependence in the central phenomenologies relevant to V/L studies, then we will be forced to face our own ignorance in those areas where we feel that the postulated relations of dependence are on shakiest ground. In turn, this will lead us to focus our efforts on exactly those areas which are most in need of further work.

There are also excellent further reasons why we should regard our attempts at providing objective, quantitative vulnerability data as science, *even if for various reasons we fall short of this goal*. To begin with, there is grounds for optimism in that only recently has sufficiently powerful computing machinery been available to allow simulation of complex and stochastic phenomena at an appropriately high level of resolution. So at the very least, we must be permitted some time to prosecute V/L work as science.

If we strive for a fuller scientific understanding of vulnerability phenomena there are obvious benefits; these accrue from the rigor and clarity with which scientific method requires us to state our premises, methods, and conclusions. This clarity maximizes the likelihood that V/L workers can communicate with a minimum of ambiguity and that they can provide effective and specific criticism of each other's work. Clarity also makes it possible to expose our cognitive claims to the challenge of critically probative data collected under carefully controlled conditions. That is, we can *test* our explanatory schemata and factual premises so that we can improve them if they are mistaken. This central and obvious benefit of regarding V/L assessment as science allows us to assess whether we are making *progress* in developing an improved understanding of V/L phenomena.

The difference between merely judgmental and scientific standards is analogous to differences in standards in marksmanship. Most people would qualify as expert shots if the criterion of expertness were to hit the Pentagon from 100 meters. Fewer individuals could meet the criterion of centering their shots on a 50mm target at that distance. Similarly, a judgment that a tank will become incapable of moving during the next week is more likely to be accurate than a prediction that the tank will become incapable of movement during the next hour due to a specifically stated physical failure. The first prediction will be confirmed if any failure mode develops during the next week; the second will be refuted if the tank is still running at the end of an hour. The latter prediction could be false without the former being so, but not conversely; the latter prediction must therefore satisfy more rigorous standards of experiential control than are assumed for the former.

The point is that rigorously narrow predictions are easier to prove empirically false than broad generic ones. It is by making predictions that turn out to be false that we receive the impetus to improve our understanding such that we can make better predictions. Broad generic predictions are harder to falsify, so

they are less likely to provide such an impetus. Thus it is that predictive rigor is a *sine qua non* of scientific progress.

I have argued that much of what is done in the V/L assessment area can be regarded as science and should be so regarded. The argument has consequences in the V/L modeling area.

II. CONSEQUENCES FOR V/L MODELING

The best scientific theories or models are very often elegantly abstract; they retain just enough structure to satisfactorily explain or predict the observed phenomena which they are intended to illuminate. As was emphasized in Section I of this paper, we are not in possession of simple, general, and elegant models for explaining V/L phenomena. Consequently, our best V/L models are those which empirically capture sufficient physical structure to permit predictions which can be compared to experimental outcomes. I have argued elsewhere¹ that only component-level models pass the test of in-principle comparability with experiment.

The component-level approach is perhaps naturally most appealing to VLD's scientists, since a healthy scientific curiosity motivates them towards obtaining a precise understanding of the vulnerability phenomena under study. With such models² we seek *scientific explanations* of vehicle loss of function in terms of the (possibly stochastic) physical regularities (i.e., "laws", "theories") underlying such phenomena as penetration, spallation, and component dysfunction under loading. In the customary sense in which the phrase is used here, a scientific explanation is a deductively formulated argument in which the premises include both general statements about physical regularities ("laws") and specific statements concerning the initial conditions of interest. The statement to be explained or predicted is specific and concerns particular components killed. By providing a unified explanatory scheme stated with mathematical clarity our high resolution code gives us the hope of scientific progress, one improved subroutine at a time.

This level of vulnerability modeling, it must be acknowledged, is difficult to accomplish in practice. There are several reasons for this. First, we rarely have a

¹Michael W. Starks, "*Assessing the Accuracy of Vulnerability Models by Comparison with Vulnerability Experiments*", BRL-TR-3018, July 1989.

²VLD's current best model for this problem, a stochastic point burst model, is discussed in: Aivars 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 (ADPA)*, held at the Naval Ocean Systems Center, San Diego, CA, 10-12 May 1988, (UNCLASSIFIED) and Paul H. Deitz, Aivars Ozolins, "Computer Simulations of the Abrams Live-Fire Field Testing," presented at the Army Operations Research Symposium XXVII, Ft. Lee, VA, 12-13 October 1988, (UNCLASSIFIED).

fully adequate conjunction of theoretical laws and statements describing empirical regularity to constitute appropriate explanatory apparatus. Otherwise put, we rarely know enough. Second, the information is only sometimes available to develop a three dimensional computer model of a target at the required very high resolution.

Despite the infrequency with which the goal of achieving scientific explanation/prediction has been achieved in practice, it is both theoretically and practically critical that we continue its vigorous pursuit through continual improvement of our high-resolution V/L codes. From a theoretical standpoint, it is when we attempt to code known or postulated regularities into our high resolution vulnerability codes that the shoe of ignorance pinches most acutely. The code serves to illuminate those vulnerability phenomena which are intuitively important and to which our results are known to be sensitive, but about which we are not comfortable with the available general statements concerning underlying regularities. In short, our scientific wish to achieve theoretical understanding of vulnerability phenomena forces us to look hardest at the most important and most poorly charted problems. There could not be a better heuristic principle for focusing V/L research on the right areas.

The theoretical regularities embedded in our high-resolution vulnerability/lethality models constitute the current version of the V/L truth. This truth is perhaps not as timeless or general or as well corroborated as we would wish. Still, it seems clearly to be the only reasonable standard against which we can judge lower resolution models, since it is the only level of model that can be compared with experiment for accuracy.

For both theoretical and practical reasons it is neither possible nor desirable to attempt component-level modeling for every V/L problem. Depending upon the specific question or questions which the modeling is intended to illuminate it might be appropriate to consider only penetration, to consider crude lumped-parameter loss of function (LOF) modeling, or to consider detailed component level modeling of the kind discussed above.

Lumped-parameter LOF modeling is not without its virtues. Since it is less input-hungry than component level models, it is a faster means of developing V/L estimates than is component-level modeling. However, the key disadvantage of this type of modeling is that its output metrics are not empirically observable so that we cannot, even in principle, address the question of how accurate the modeling is. All we can hope for with such simulations is that their results be at least consistent with our component-level models, or better yet, derivable from those models. It follows that we must ground our lumped-parameter modeling in our component-level modeling or abandon all hope of ever being able to quantify the accuracy of our lumped-parameter models.

If we want to pursue scientific understanding of V/L phenomena, there is no alternative to high resolution modeling. This has consequences for a certain criticism of VLD's modeling strategy.

III. CONSEQUENCES FOR OUR CRITICS

Those who have wielded, developed, or analyzed weapon systems often tend to regard themselves as experts concerning vulnerability phenomena. In part, I think this is due to the unfortunate veneer of "subjective and judgmental" which has mistakenly been thought to characterize all V/L work. The "subjective and judgmental" veneer seems to elicit subjective and judgmental criticism of scientific V/L work even from those whose intellectual modesty would forbid expression of offhand opinions with respect to other areas of scientific endeavor. In any case, the V/L community has been reviewed and criticized with remarkable frequency over the past 10-15 years. Much of the criticism is sound and indeed exhibits one form or another of the central point of this paper: that V/L assessment should be pursued in as rigorous a scientific fashion as possible.

It is a specific recent criticism which I wish to discuss here. This criticism was published by a distinguished arm of the National Research Council; it has been made by others as well; and it betrays serious confusion concerning the subjective judgment versus science issues discussed in this paper. The National Research Council group, the Board on Army Science & Technology (BAST), stated ten conclusions/recommendations concerning the Army's V/L assessment methodology. One is shown in its entirety below:³

The committee has reviewed the current BRL approach to more accurate model building. It is, in essence, based on the belief that better accuracy will result from models of increasing detail, i.e., models that incorporate the vehicle exterior and interior geometry in relatively minute detail and that trace behind-armor damage virtually fragment by fragment. It is the committee's opinion that such an approach is not justified because of the inability to forecast with precision the characteristics and performance of ever-evolving threat weapons, and because of the inherently stochastic nature of penetration and behind-armor damage mechanisms. The trend toward increasingly detailed models is not a productive direction and the committee suggests that BRL reconsider its current

³Committee on a Review of Army Vulnerability Assessment Methods, Board on Army Science and Technology, Commission on Engineering and Technical Systems, National Research Council, *Armored Combat Vehicle Vulnerability to Anti-Armor Weapons: A Review of the Army's Assessment Methodology*, National Academy Press, 1989. It should be noted that of the ten conclusions and recommendations in the report only one is discussed here.

direction for model design. A lesser degree of detail, using an approach based on a more generic assessment of the vulnerability of major components, would still provide valid vulnerability estimates with reduced data requirements and shorter computational times.

I propose to address this reasoning, at first, by indirection. Consider the following suggestion, structurally identical to that of the BAST, which might have been made by a seventeenth century Aristotelian:

The committee has reviewed the current Newtonian approach to more accurate modeling of planetary motion. It is, in essence, based on the belief that better accuracy will result from models of increasing detail, i.e., models that incorporate planetary motions and forces in relatively minute detail and that trace planetary motion virtually moment by moment. It is the committee's opinion that such an approach is not justified because of the inability to forecast with precision the characteristics of planets and their motions, and because of the inherently variable nature of the various heavenly bodies. The trend toward increasingly detailed models is not a productive direction and the committee suggests that Newton reconsider his current direction for model design. A lesser degree of detail, using an approach based on a more generic assessment of the planetary forces would still provide valid estimates of the planetary motions with reduced data requirements and shorter computational times.

Since most of us have more emotional and intellectual distance from seventeenth century natural philosophy than we do from current controversy, let us first note some of the problems with the Aristotelian's criticism of Newton. Notice that the Aristotelian does not come right out and say that Newton is *wrong*; the suggestion is rather that Newton is getting bogged down in unnecessary detail. What the Aristotelian fails to grasp is the fact that Newton was seeking a *deeper understanding* of planetary motion by developing *detailed explanations* of those phenomena which meet much more stringent scientific criteria than can be found in Aristotle's *Physics*.

It also deserves emphasis that the Aristotelian fails to provide a clearly articulated alternative to the Newtonian project. I do not know what a "generic assessment" of planetary forces might look like just as I do not know what a "generic assessment" of component vulnerability might look like. Careful reading of the BAST's paper shows that if they know, they aren't telling. As emphasized in Sections I and II, scientific predictions are intrinsically specific; they are not generic. The suggestion to move toward "generic assessment" is really just an empty exhortation to avoid all that inconvenient and messy detail. This would have been bad advice to give Newton and it is also bad advice to give the V/L community.

It follows that it is not clear whether the generic assessment tools favored by the BAST can provide "valid estimates" or not. It is not even clear what the phrase "valid estimates" might mean in a process stripped of the detail which is required for scientific treatment of the problem. I know what an accurate prediction is; I do not know how the BAST would recognize a valid estimate given that it was developed by an undefined analytical process.

Finally, it is worth brief exploration of the BAST's contention that VLD's pursuit of scientifically accurate component-level models "is not a productive direction". I have already shown that this opinion reflects a peculiar view of science, at best. It is perhaps also worth exhibiting that as a practical matter, the VLD strategy criticized has resulted in clear-cut successes. High resolution stochastic modeling was a cornerstone of VLD's modeling program supporting Live Fire Testing of the ABRAMS Tank, for example. This work not only provided novel and useful quantitative insights into the damage processes modeled; it was also well received by top level Army and Department of Defense decision makers. As a second example, consider VLD's support of the Army's program to determine appropriate spare parts stockages for combat damaged ground vehicles. It is obvious that this valuable program could not be conducted at all without component level modeling. The point here is not that our component-level modeling is perfect, but only that our modeling strategy has already had productive and practical payoff.

To sum up: an unkind paraphrase of the BAST's suggestion might run as follows:

Why bother with V/L science. It's expensive and difficult and the phenomena under study keep changing. Let's just do more "generic assessments"; the resulting V/L estimates will still be "valid".

I hope I have shown that this suggestion is defeatist and anti-intellectual, and that it essentially bids us to stop trying to understand V/L phenomena.

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