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Rationale for the Modular Air-System Vulnerability Estimation Network (MAVEN) Methodology

Lisa K. Roach

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The air community has long had a need for a new vulnerability/lethality (V/L) methodology, one usable by the tri-service community. Current models range from manual calculations of total vulnerable area (A_v) to complex models of incendiary functioning, fragment penetration, and fire initiation with component fault tree damage modes. Most, if not all, of these models make use of expected value, or deterministic, methods which do not accurately reflect the actual, observed phenomenology. In addition, technological advances in system design and weapon lethality have outpaced the growth of these models. While the community has tried to come to grips with these more complex systems and phenomenology, clearly, the existing models have not.

The purpose of this report is to describe the rationale behind the development of a new stochastic, point-burst vulnerability model for air systems which supports the myriad of analyses the air community must perform, as well as to discuss, in general, the technical requirements which generated this need.

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1. BACKGROUND

The air community has long had a need for a new vulnerability/lethality (V/L) methodology, one usable by the triservice community. Current models range from manual calculations of total vulnerable area to complex models of incendiary functioning, fragment penetration, and fire initiation with component fault tree damage modes. Most, if not all, of these models make use of expected value, or deterministic, methods which do not reflect accurately the actual, observed phenomenology. In addition, technological advances in system design and weapon lethality have outpaced the growth of these models. While the community has tried to come to grips with these more complex systems and phenomenology clearly, the existing models have not.

Currently, there is only one joint-service endgame model (JSEM) computer code which is available for a wide community of Government and contractor uses (Joint Technical Coordinating Group for Munitions Effectiveness 1991). This model was developed by piecing together several existing service submodels on a very limited budget. Users have complained that because of its size and lack of modern data structure, JSEM is limited in its ability to adapt to new applications and very difficult and costly to validate. These limitations and deficiencies also apply to the large number of older, separate service models now in use.

Furthermore, there is a wide variety of analyses which must be supported within the air community (these apply to the ground community as well). Of primary concern is the need to support live-fire test and evaluation programs. Clearly, these programs require metrics which allow the analysis community to provide pre- and post-shot predictions which are measurable or observable. The need for accurate ballistic vulnerability data on U.S. aircraft and missiles, and, conversely, the ballistic lethality of U.S. munitions (to include missiles) is a continuing mission of the U.S. Army Research Laboratory (ARL), Ballistic Vulnerability/Lethality Division (BVLD). Other analyses which must be supported are battle damage repair (BDR) and reliability, availability, and maintainability (RAM), which can be related to vulnerability analyses (Roach 1993). The vulnerability/lethality data generated by the air community provide input to a number of force-level models/simulations such as those used by the Army Battle Labs; these models and simulations require a more robust set of data then currently generated. Finally, there is an ever increasing need for tools which support the myriad of research, design, and development analyses conducted within the community.

The purpose of this report is to describe the rationale behind the development of a new stochastic, point-burst vulnerability model for air systems which supports the aforementioned analyses as well as to discuss, in general, the technical requirements which generated this need.

2. GENERAL DESCRIPTION

The Modular Air-system Vulnerability Estimation Network (MAVEN) is a stochastic, point-burst methodology, applicable to rotary wing, fixed wing, and missile systems, capable of both V/L and BDR analyses. It is applicable during all phases of the system acquisition cycle; thus, it represents a research, design, and development tool as well as a production tool for test and evaluation analyses. Most importantly, it will provide results, at all stages, which are observable and/or measurable. It should be noted at this point that MAVEN provides the basis of the Advanced Joint Effectiveness Model (AJEM), a joint development project of the Joint Technical Coordinating Group for Munitions Effectiveness (JTCG/ME), the Joint Technical Coordinating Group for Aircraft Survivability (JTCG/AS), and ARL.

The MAVEN methodology is being developed as an approximation method in the Modular UNIX-based Vulnerability Estimation Suite (MUVES) environment and which follows the ARL-BVLD V/L Process Structure (Walbert, Roach, and Burdeshaw 1993). The basis for the process structure comes from the recognition that V/L analyses pass through four distinct levels of information in a precise order. These levels are:

- Level 1: Threat-Target Interaction, or Initial Configuration (including initial conditions),

- Level 2: Target Component Damage States,

- Level 3: Target Capability States, and

- Level 4: Target Combat Utility.

The mappings by which one passes from one level to the next are dependent on different kinds of information at each level. For example, going from Level 1 to Level 2 (threat-target initial configuration to target damage) essentially involves physics; going from Level 2 to Level 3 (target damage to capability) requires engineering measurement. The process is shown pictorially in Figure 1.

It is important at the outset to differentiate between "Levels," which are composed only of states of existence, and the "Mappings," operators (with the data and algorithms to which they have access) which relate a state at one level to a state at another.

A *Level* contains all the information required to define the state of the system at the associated stage of a V/L analysis/experiment. At each level, one can define a space of points, each point being a vector whose elements correspond to the status of a particular entity related to the target. For example, in Space 2 (Damage States), each element may refer to the status of a particular component/subsystem. The spaces thus defined are the "V/L Spaces," and represent, at each level, the state of the target system.
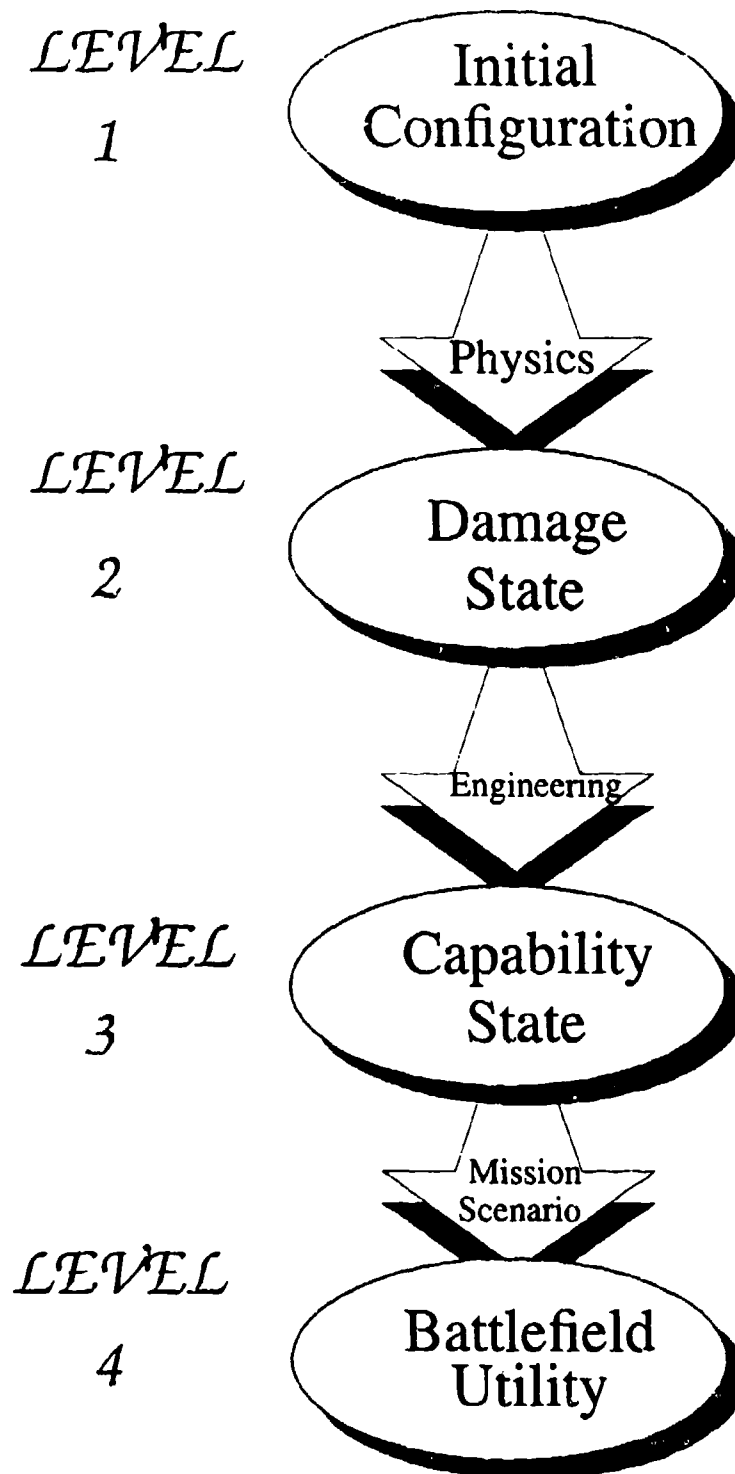
Figure 1. The Vulnerability/Lethality Process Structure.

A *Mapping* represents all of the information (physics, engineering, etc.), known or unknown, required to associate a point in a space at one level with a point in a space at the next level. Mappings have access to information such as fundamental data (penetration parameters [Level 1 to Level 2], leakage rates [Level 2 to Level 3], etc.); intermediate data generated by the mapping (line-of-sight thicknesses [1 to 2], temperature rise in an uncooled engine [2 to 3]); and algorithms (depth of penetration [1 to 2], fault trees [2 to 3 or 3 to 4]). These are referred to as the $O_{1,2}$ (Level 1 to Level 2), $O_{2,3}$ (Level 2 to Level 3), and the $O_{3,4}$ (Level 3 to Level 4) mappings.

The V/L experimental and analytical processes then can be expressed as a series of mappings which relate a state vector in one space (the domain) to a resultant state vector in a next higher-level space (the range).

Note that at each transition to the next level, some detail about the target system may be lost; a broken bolt in Level 2 may be the cause of degraded mobility influencing mission effectiveness, but at Level 3, the bolt is no longer recognized as an entity. It is now widely acknowledged that skipping over levels (such as inferring remaining combat utility directly from the size of the hole in the armor) loses so significant an amount of information that continuity and auditability are lost.

3. SHORTCOMINGS OF THE CURRENT METHODOLOGIES

There are a number of service models available for a variety of applications and analyses. Each model provides differing capabilities and results, which are thus not comparable. It is also difficult to extend or modify these models for other applications. Consequently, no one model currently exists to play the myriad of target and threat combinations now available. As an example, the advent of tactical ballistic missiles (TBM) extends the realm of threat-target pairings which analysis models are only now starting to address. Newly identified threat mechanisms such as hit-to-kill (HTK) must be included in any new air system model or, minimally, hooks included to allow new threats to be added with relative ease.

Vulnerability analysis models (for example, COVART3.0 [JTCG/ME, undated]) provide a variety of analytical techniques, but no one model provides the complete set of tools needed to analyze rotary-wing, fixed-wing, and missile systems. These models all provide input to the endgame models yet the algorithms employed are not consistent nor are the results they generate. They also make use of performance-oriented measures of effectiveness (MOE) such as "Forced Landing," "Mission Abort," and "Time-Dependent Crash Landings." These measures are not truly observable as they are subjective decisions, at best. In the missile community, models such as PEELS (Ballistic Missile Defense Organization 1993) are deterministic where stochasticism is clearly required. Target descriptions are hardwired into the model instead of being in a commonly used format such as BRL-CAD. Their outputs, while referred to as probabilities of kill (P_k), are not true probabilities. Finally, for both aircraft and missiles, the existing models are not modular, nor does their architecture support research or the easy and efficient addition of new methodologies. Thus, the vulnerability analysis codes used in the air community suffer from

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logical disconnects between weapon effects and target response (a problem, also, for ground targets).

Most importantly, none of the current models provides outputs which are observable and/or measurable. As a consequence, there is no method available to validate their results. Furthermore, these models violate the fundamental tenet of the V/L Process Structure. Neither a P_k nor a vulnerable area (A_v) can be measured or observed from any type of test, shot, or experiment. One can certainly say that for a munition, a P_k of 0.5 is better than a P_k of 0.1. The point is, 0.5, 0.1, or any other P_k has no empirical basis of support. The same is true of A_vs.

4. REQUIRED CAPABILITIES OF THE NEW METHODOLOGY

MAVEN can replace a number of existing vulnerability/lethality codes throughout the Department of Defense (DOD). The outputs, at all levels, provide results/information that are measurable or observable. The existence of one triservice code for all air system V/L analyses reduces not only the maintenance costs but allows the services to concentrate their efforts toward the improvement, modification, and documentation of a single code. A single code provides comparable results, not only study to study, but agency to agency.

MAVEN provides better results through the use of better modeling of the physics of the threat-target interaction and appropriate modeling of the variability inherent in the stochastic processes. This section will detail the capabilities that are, or will be, inherent in the MAVEN methodology. Following an introduction to the overall form of the methodology, the specific discussions of MAVEN capabilities will follow the V/L process structure format.

The MAVEN methodology will reside under the BVLD-MUVES environment. MUVES is a software environment under which all vulnerability/lethality analyses conducted by the BVLD will be performed. It is a very general environment that is designed to evaluate the interaction of a threat with a target where the target information is provided via ray-tracing. Currently, the ground systems compartment-level V/L model and a prototype stochastic model have been implemented under MUVES. The environment is written in the C programming language, using structured programming techniques, and includes a user-friendly, menu-driven user interface and a set of post-processors for the textual and graphical display of results (Hanes et al. 1991). In addition, MUVES requires the geometric target description to be in the BRL-CAD format (Muuss 1991). Consequently, as part of the combined MAVEN and AJEM effort, a translator is being developed to convert FASTGEN4 target descriptions into BRL-CAD format; other translator requirements need to be identified and developed.

At Level 1 resides the information pertaining to initial threat-target configuration. Included at this level is the information pertaining to what components are in the system, their location, and material type. A variety of threat information is also detailed at this level. The type of threat is specified, as is the velocity information (speed and direction), orientation (pitch, yaw, roll, and

their associated rates), and altitude. The external burst location is also specified, if applicable. MAVEN will model a variety of threat mechanisms. The main threat mechanisms in the initial release of MAVEN include armor-piercing (AP), high-explosive (HE), the incendiary (I) versions of both, and the FATEPEN2 penetration algorithms. The methodology will be expanded to include the threat mechanisms, detailed in Table 1, as data and algorithms become available.

Table 1: Future Threat Mechanisms for MAVEN/AJEM Modeling

Blast	Fire
Long rod penetrators	Reactive fragments
Hydraulic ram	Fuel-air explosives
Shaped charge	Ballistic shock
Missile debris	Missile body

In some instances, algorithms already exist and will be added according to the needs of the analysis community. Several, though, will require experimentation to generate the data upon which the algorithms can be built (for example, blast and hydraulic ram).

The $O_{1,2}$ mapping provides the mapping from Level 1 to Level 2; it is characterized by the physics of the threat-target interaction. Within MAVEN, this characterization will take many forms, as detailed Table 2.

Table 2: Threat-Target Interactions of Interest

Time dependencies	Multiple rounds
Contact fuzing	Path deflections
Incendiary functioning	HE projectile functioning
Threat mechanism propagation and damage processes	
- body-to-body	- fragments (breakup and spall)
- KE penetrators	- shock
- fire initiation	- penetration
- synergism	- ullage explosion
- hydraulic ram	- internal & external blast
- explosive initiation	- HE projectile combined effects
- momentum transfer	- energy transfer

Initial efforts will be concentrated on those interactions which permit the proper modeling and synergy of attack by AP(I), HE(I), and body-to-body threat mechanisms. The most important requirement during the initial stages of MAVEN development is time dependency; inclusion of this phenomenon will permit more accurate and realistic modeling of the threat-target physical interaction.

The outcome of the $O_{1,2}$ mapping is a vector of damaged critical components of the system at Level 2. MAVEN will output these Level 2 data as both an intermediate output and as the input for the $O_{2,3}$ mapping. The data at Level 2 provide not only the killed critical components but other information which provides insights into the vulnerabilities of the air system. The information should include (but is not limited to): hole size, depth of penetration, explosive reaction level, structural deformation, and structure removed. These data will be required in MAVEN for both the vulnerability and the BDR analyses.

The effects of the damaged components on system performance are assessed through the $O_{2,3}$ mapping. The $O_{2,3}$ mapping is achieved by mapping the damaged components through mathematical fault trees which represent required functional capabilities of the system. Components, or subsystems, are combined in the fault trees through the use of Boolean operators. Current $O_{2,3}$ methodologies allow only "and" and "or" Boolean operators. As part of the MAVEN development, the inclusion of additional Boolean operators is required and is, therefore, being pursued as one of the initial development modules. At present, only one methodology exists for performing the $O_{2,3}$ mapping, the Degraded States Vulnerability Methodology (DSVM) (Abell, Roach, and Starks 1989). Currently implemented for ground systems, additional work is required to extend this methodology to include air systems. Further, more analog-type engineering performance models (EPMs), such as those developed and used by the Air Systems Branch (ASB) of ARL, must be developed and incorporated into the MAVEN methodology to permit more robust analyses of air systems.

Note, current implementation of the DSVM has been for traditional vulnerability analyses. This methodology can be extended to permit battle damage repair analyses to be conducted in a manner similar to the vulnerability analyses. Some effort has been expended to show the usefulness of this approach for BDR (Roach 1994; Bowers 1994) ,but additional work is required to show the full advantages of this approach. Maturation of the BDR methodology will allow the air community to conduct both vulnerability and BDR analyses within the MAVEN methodology. The Level 2 information makes this possible, as vectors of damaged components are generated which can then be mapped, using the $O_{2,3}$ mapping, into the Level 3 remaining capabilities. If repair priorities, times, and strategies can be established, sensitivity analyses can be performed, within MAVEN, to determine the usefulness of the repairs by attempting to do whatever repairs are possible within the given constraints. This generates a second set of Level 2 damaged components, one which is (possibly) a subset of the original. Using this new damage vector, the $O_{2,3}$ mapping is performed again to determine the remaining capabilities of the system given the

affected repairs. After a comparison is made between the original set of remaining capabilities and the new set resulting from repairs, an assessment of the usefulness of the repairs can be made (i.e., can the system continue its mission, and what capabilities were gained?).

The output of Level 3 is the probability of being in one or more remaining capability states. For a single run, a single remaining capability state is generated, while, for multiple runs, a probability distribution is generated, indicating the probability of being in various remaining capability states. As this metric is different from the traditional A_v or P_k estimates, care must be given to ensure that MAVEN also generates the traditional data which are of use to the air community. Consequently, both remaining capabilities and A_v and P_k estimates will initially be calculated in MAVEN. However, it is envisioned that A_v and P_k generation will eventually be discontinued in favor of the newer, more robust capability metrics.

At all levels, the requirements for animation and graphical results exist. The geometric target description provides the basis for the computer rendition of the air system. Animation is required to provide a visual picture of the threat and the target prior to and during interaction; it is also needed following the interaction to allow the analyst to visually inspect/observe the remaining capability of the system. This ability for visual inspection will allow the analyst to quickly ascertain if the encounter conditions are correct and what, if any, damage has been inflicted on the target. The ability to observe, whether in animation form or a computer snapshot of the system, can provide more useful information in a short period of time than the more time-consuming analysis of numerical results.

Finally, MAVEN will be developed, under UNIX, in a modular format using the standard ANSI C programming language and X Windows system. As MAVEN is being developed under the MUVES environment, the methodology will be usable on any workstation running UNIX and an X server, including, but not limited to, Silicon Graphics Incorporated (SGI) and Sun Microsystems, Inc. workstations.

5. SHORT-TERM MAVEN/AJEM DEVELOPMENTS

A short-term development plan has been laid out for MAVEN to coincide with known and anticipated projects of the ASB over the next 2 years; this plan has been agreed to by the JTCG/ME and will apply to AJEM also. This section discusses the details of both the technical and stochastic modeling aspects required by MAVEN to meet the needs of these projects.

5.1 Technical Developments

The most pressing requirement for ASB will be to support the live-fire testing of the Longbow Apache. To this end, the MUVES interaction and evaluation modules (IMs and EMs) for the AP and HE threats will be the first modeled in MAVEN/AJEM in fiscal year (FY) 1994. Simultaneously, the capability categories and levels, for use in the DSVM, are also being
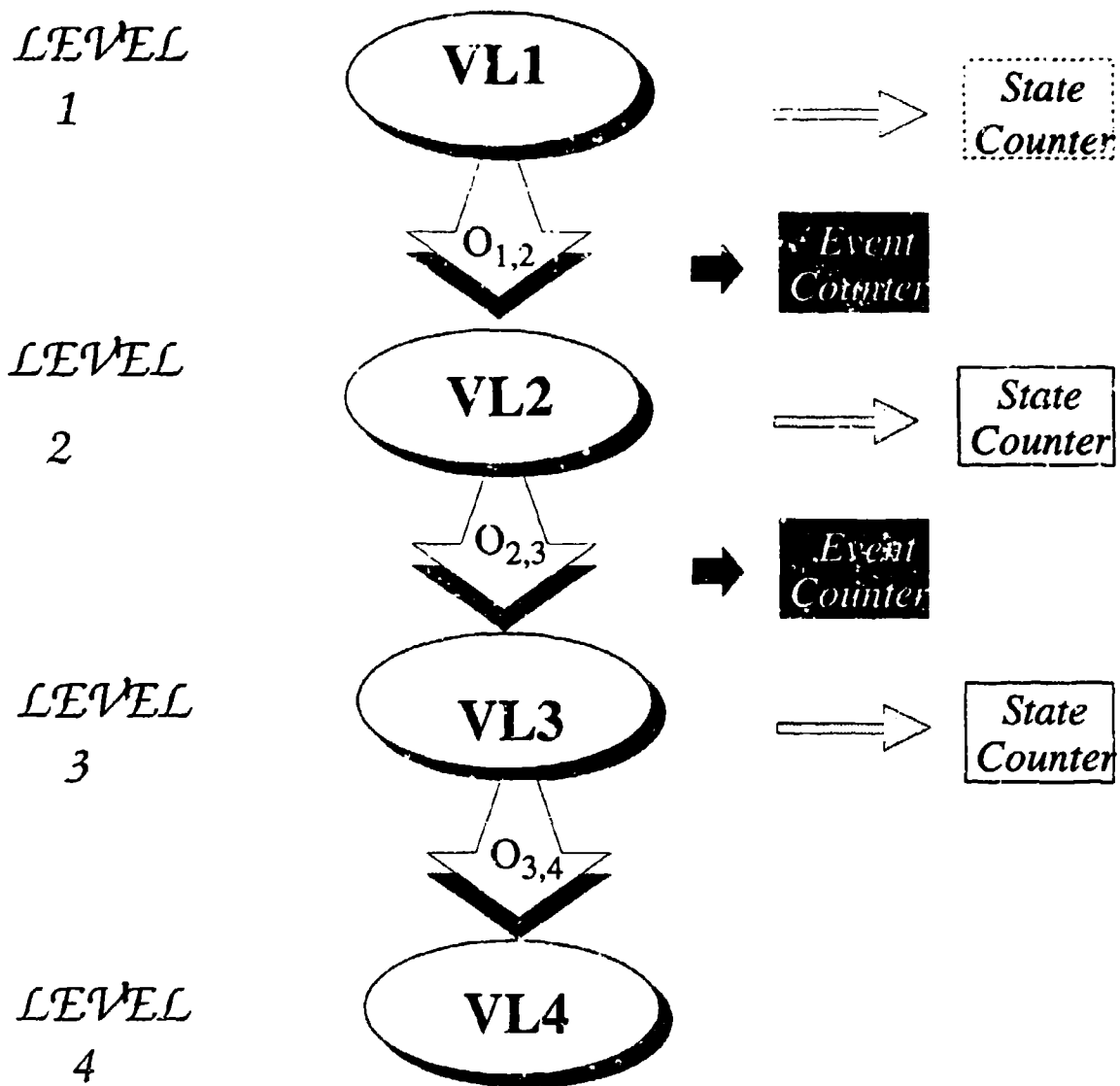
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Figure 2. Probability Distributions in the V/L Process Structure.

developed and modeled. In addition, because the DSVM approach is not yet universally accepted, the traditional A_v estimates will also be provided, consequently, another effort within ASB is aimed at the development of a MAVEN module to perform A_v calculations. These diverse modeling efforts will allow ASB to provide pre-shot predictions for the Longbow Apache in FY95.

ASB also supports the missile community and as a result has identified MAVEN developments in this area. In support of the CORPSAM missile, ASB will begin work on additional IMs and EMs, tentatively scheduled for FY95, to support lethality studies of missile interceptors. Modules to support body-to-body damage mechanisms will be developed as well as modules for the FATEPEN2 equations. Tentative completion dates are November 1994 for FATEPEN2 and September 1995 for the body-to-body work. Additional work will ensue for modules representing the U.S. Army Missile Command (MICOM) MULTIFRAG program. Finally, in the $O_{2,3}$ area, five targets have been identified for which DSVM fault trees will be developed; these include three TBMs and two cruise missiles.

Additional work is ongoing in areas not identified with specific targets or threat mechanisms. One of the main thrusts of the FY94 MAVEN work is the development of an event queue process (Hanes 1994). This process will allow MAVEN to account for, in a physically realistic manner, time-dependent phenomena that occur immediately following threat impact or detonation as well as appropriately model synergistic effects. Because these phenomena happen so quickly, they are treated simultaneously with the threat impact/detonation in current vulnerability analysis models. Examples of these phenomena include buckling plates, aerosolization of fuel, and the punching of holes in components.

5.2 Stochastic Modeling Requirements

Recently, the MUVES environment was expanded to include a stochastic approximation method for ground vehicles. This work provides a starting point for the stochasticism required for MAVEN. Any new air system vulnerability model must address the proper modeling of the stochastic nature of the threat-target interaction and target response. Several areas for which further work is necessary have been identified by ASB. These areas are discussed in this section in terms of the process structure mappings. First, though, is a discussion of the V/L process structure mapping procedure and the generation of probability distributions.

5.2.1 Repeated Mappings and Probability Distributions

Consider the following procedure: Construct spaces at Levels 1 and 2 (VL1 and VL2). Also construct a "scorecard" at Level 2 which allows one to count how many times each damage state point in VL2 is reached. Then select only one set of initial conditions (a fixed point in VL1) and iterate the mapping O_{12}, counting the number of times each point in VL2 is reached. It is clear that, following a large number of mappings, the information in the scorecard provides an indication of the likelihood that a certain damage state point in VL2 will occur from a given set of threat-target

initial conditions in VL1. In fact, it is a straightforward process to infer from the scorecard information a probability distribution associated with the mapping and the initial conditions. The boxes marked "EVENT COUNTER" or "STATE COUNTER" in Figure 2 represent such scorecards.

In principle, the process could be repeated for several sets of initial conditions. In this way, one can arrive at an understanding of the stochastic nature of the physics or engineering underlying the O_{12} and O_{23} mappings. It is essential to appreciate two points:

1. These likelihoods, or probabilities, are functions of the mappings and not of the spaces; if the mappings are changed, the probabilities which they associate with the vectors in the spaces will change.

2. The mappings have their domains and ranges in the V/L spaces, not in the sets of probabilities.

5.2.2 MAVEN Stochastic Needs

Although not previously discussed in this document (it is a level above the V/L process structure), the stochastic nature of the $O_{0,1}$ mapping is of importance as it results in varying initial conditions at Level 1. Three stochastic events have been identified for this mapping. The first is the 6-degrees-of-freedom (6DOF) motion resulting from the trajectory and flyout models. Next is the impact or initiation location which varies as a result of dispersion. Finally, we must include target configuration as it varies simply because of the observed variability in configuration. These variations must be properly modeled in order to obtain realistic initial conditions at Level 1.

For the $O_{1,2}$ mapping, the variability is inherent in the threat-target interactions. ASB has identified the immediate areas of concern for rotary-winged aircraft and missiles. For AP, perforation, ricochet and breakup must be modeled stochastically; it is felt this can be achieved by making use of the JTCG/ME methodology [JTCG/ME 1977]. More work is necessary for the HE munitions as there is known round-to-round variability as well as variability in the fuzing; however, there is no current methodology which can easily be adapted to allow stochastic modeling of these phenomena. As a result, the JTCG/ME penetration equations will be used up to the burst point. Then, the FATEPEN2 equations will be applied for fragments, and the ASB internal blast envelopes methodology will be used for blast. The inclusion of time dependencies will allow synergistic effects to be investigated. Note, currently there is a triservice group investigating the best available models for HE; it is anticipated that the algorithms the group selects will be incorporated into the MAVEN methodology. Finally, the incendiary versions of these rounds must be modeled stochastically to account for jacket stripping; again, existing JTCG/ME methodology can be adapted for this purpose. In the area of missile work, the missile community (primarily the MICOM) must provide the necessary methodologies and rationale to allow the stochastic modeling of the missile $O_{1,2}$ mappings.
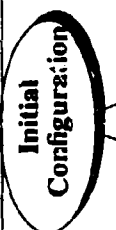
Finally, stochasticism will be added to the $O_{2,3}$ mapping to account for the variability in system response to damage. For rotary-winged aircraft, the areas of interest include leakers (fuel, lubrication, and hydraulics) and structural failure (rotor blades, hub, tail rotor drive, control rods, and other structural elements). The need for stochasticism in modeling these phenomena is based on empirical data and observed variability in system response. For missiles, the concern is also with structural failure (in particular, the aeroshell, control surfaces, airframe integrity, and warhead integrity).

In all these areas, experimental data either exist or must be generated to determine appropriate statistical distributions to represent accurately the phenomena in the MAVEN model. Each of these phenomena represents elements of the threat-target interaction and response. Not only does each element need to be modeled in MAVEN but also how these individual elements interrelate. Thus, the work of identifying these elements and their statistical distributions and appropriately modeling these elements goes beyond merely deciding the correct statistical distribution and including it in the methodology. How the elements interrelate, how the distribution is used, what parameters are required, and what the basis is for the distribution are important factors. Finally, one must note that the outcome of the MAVEN model will, itself, be random and, thus, only representative of all possible outcomes. Confidence in this answer will depend on our confidence in the modeling of the stochastic phenomena in the various mappings.

6. SUMMARY

This document describes the MAVEN methodology's short- and long-term requirements which adhere to the BVLD V/L Process Structure. Included in the requirements are the current FY94 and FY95 strategy for MAVEN as well as the longer range strategy. In addition, areas have been identified for which data and algorithms exist and those for which experimentation is needed to generate the data required to support the methodology development; these requirements are listed in Table 3. MAVEN and, subsequently, AJEM will provide the triservice air community the necessary methodology to perform stochastic, point-burst vulnerability and BDR analyses for rotary-wing, fixed-wing, and missile systems.

Table 3. MAVEN/AJEM Requirements

	ALGORITHMS	SUPPORTING DATA/ EXPERIMENTATION	SOFTWARE	HARDWARE
$O_{0,1}$	Coordinate transforms between threat & target coordinate systems	Distributions of 6DOF conditions for bullets & missiles Distributions of dispersions, input velocities	Interface w/6DOF models Interface w/ FASTGEN Automated input generation/checking Animation	Support animated graphics Support UNIX, MUVES, BRL-CAD...
LEVEL 1 — Initial Configuration				
$O_{1,2}$	Current & anticipated damage mechanisms (Tables 1 & 2) Time dependent phenomena Synergistic effects	Distributions for current and anticipated damage mechanisms	Animation Environment variables for IMs and EMs	
LEVEL 2 — Damage State				
$O_{2,3}$	Time dependencies in fault trees New Level 3 capability metrics	Distributions for leakers, run dry, structural integrity, etc. Capability experimentation	Environment variables for SYS.DEFs Full Boolean support Interactive fault tree generation Animation	Support animated graphics
LEVEL 3 — Remaining Capabilities				
$O_{3,4}$	Conversion of capabilities to Av, Pk, and aircraft categories		Interface with force level models (at least, provide appropriate output)	
LEVEL 4 — Utility State				

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