Army Research Laboratory
Aberdeen Proving Ground, MD 21005-5068

ARL-CR-450 **April 2000**

Vulnerability and Lethality Assessment: The Role of Full-Up System-Level Live-Fire Testing and Evaluation

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under contract

DAAH04-96-C-0086

Abstract

In this era of decreased defense budgets and limited resources, it is important for decision-makers to determine the optimal strategy for assessing the vulnerability or lethality (V/L) of a weapon system and the role of Full-Up System-Level Live-Fire Test and Evaluation (FU SL LFT&E) in that strategy. This report presents a foundation for a methodology to (1) identify, measure, and categorize the costs and benefits of FU SL LFT&E; (2) determine the relative significance of FU SL LFT&E to the V/L assessment plan of the weapon system; and (3) compare competing V/L assessment plans for a system.

Descriptions of the activities of FU SL LFT&E, the costs and benefits (i.e., impacts) of those activities, the complexities encountered in the reporting of the impacts, and approaches for addressing the complexities are presented. A discussion of the contributions of FU SL LFT&E to a V/L assessment strategy and suggestions for improving the cost-effectiveness of FU SL LFT&E are included.

The Taxonomy of the V/L Analysis Process (Deitz and Ozolins 1989) is proposed as a framework for identifying the data voids to be addressed in a V/L assessment plan. The potential of adapting the principles of the Cost as an Independent Variable methodology to the evaluation of competing plans of V/L assessment is explored.

Acknowledgments

This work was supported by the Survivability/Lethality Analysis Directorate, U.S. Army Research Laboratory, Aberdeen Proving Ground, MD, under the auspices of the U.S. Army Research Office Scientific Services Program administered by Battelle (Delivery Order 31, Contract No. DAAH04-96-C-0086).

The author wishes to acknowledge the contributions made to this study by personnel of the following organizations:

- U.S. Army Research Laboratory, Survivability/Lethality Analysis Directorate.
- Headquarters, U.S. Army Test and Evaluation Command.
- Project Manager, Abrams Tank System.
- Project Manager, Bradley Fighting Vehicle System.
- Product Manager, Improved Army Tactical Missile System Block IA.
- U.S. Army Materiel Systems Analysis Activity.
- U.S. Army Operational Test and Evaluation Command, Evaluation Analysis Center.
- U.S. Army Test and Evaluation Command, Aberdeen Test Center.

Special appreciation is expressed to Contracting Officer's Technical Representatives Mr. Dennis C. Bely, Chief, Engineering Analysis Branch, Survivability/Lethality Analysis Directorate, and Dr. Paul H. Deitz, Technical Director, U.S. Army Materiel Systems Analysis Activity, for their considerable assistance in completing this research effort.

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1. Introduction

U.S. congressional legislation requires weapon systems in certain categories to undergo Full-Up System-Level Live-Fire Testing and Evaluation (FU SL LFT&E) prior to the system entering full-scale production, unless a waiver is requested by the Service acquiring the system and granted by the Secretary of Defense [1]. The waiver request must show why FU SL LFT&E is unreasonably expensive and impractical and include an alternative strategy for assessing the survivability/lethality of the system.*

Significant resources are consumed in the planning, execution, and evaluation of a Full-Up System-Level Live-Fire Test (FU SL LFT). In this era of decreased defense budgets and limited resources, it is important for decision-makers to determine the optimal strategy for assessing the vulnerability or lethality (V/L) of a weapon system and the role of FU SL LFT&E in that strategy.† The selection of the optimal assessment strategy requires that a consistent methodology be in place for the identification and measurement of the costs and benefits of potential assessment plans, the weighing of the costs against the benefits for plans considered, and the comparison of alternative competing plans.‡

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* U.S. Code requires Full-Up System-Level Live-Fire Test and Evaluation to be conducted on a covered system (any vehicle, weapon platform, or conventional weapon system that includes features designed to provide some degree of protection to users in combat and that is an Acquisition Category I or II program), a major munitions program, a product improvement to a covered system or a major munitions program, or a missile program before it can proceed beyond low-rate initial production [1].

The Secretary of Defense may waive the application of tests, if the Secretary, before the system enters engineering and manufacturing development (EMD), certifies to Congress that a FU SL LFT of such system or program would be unreasonably expensive and impractical. A waiver and alternative LFT&E plan must have been submitted and approved by Milestone II (i.e., approval to enter EMD).

† FU SL LFT&E, as described in this report, addresses questions of vulnerability and lethality, not the broader concepts of system survivability, effectiveness, and susceptibility.

‡ In Live-Fire Test (LFT) legislation, an *alternative* strategy is a strategy that does NOT include FU SL LFT&E. In this report, however, the term *alternative*, as in *alternative strategy* or *alternative plan*, is defined more broadly and is used to indicate more than one option or a choice among options. Therefore, one or more alternative vulnerability or lethality (V/L) assessment plans or strategies may include FU SL LFT&E as an element.

The ultimate goal of the Live-Fire Test and Evaluation (LFT&E) process, which includes analysis, experimental, and testing activities in addition to FU SL LFT, is to quantify the V/L characteristics of the platform or munition. Each activity of the LFT&E process may provide an important element(s) to the V/L assessment of the system, and some data critical to the assessment may be provided by alternative activities. When designing strategies for V/L assessment, it is therefore important to consider the whole acquisition cycle and all potential sources for the data needed by evaluators in the assessment process.

1.1 Research Objectives. This study seeks to establish a foundation for the development of a methodology to (1) identify, measure, and categorize the costs and benefits of FU SL LFT&E, (2) determine the relative significance of FU SL LFT&E (one element of a V/L assessment plan) to the V/L assessment plan taken as a whole, and (3) compare competing V/L assessment plans for a system. The comparison of assessment plans should consider the costs, benefits, and uncertainties associated with each of the alternative plans presented.

It is proposed that the development of the aforementioned methodology will provide information needed for

- Ranking alternative plans of V/L assessment.

- Budgeting resources for the FU SL LFT&E element of a V/L assessment plan.

- Making specific decisions, including the appropriateness of a FU SL LFT&E waiver for systems covered by Live-Fire Test (LFT) congressional legislation.

1.2 Research Approach.

1.2.1 Systems. The FU SL LFT&E programs of three U.S. Army weapon systems included under the LFT congressional mandate are analyzed in this study:

- Abrams M1A2: FU SL LFT&E, an element of the vulnerability assessment plan of the weapon system, completed in 1993.

- Army Tactical Missile System Block IA (ATACMS Block IA): FU SL LFT&E, an element of the lethality assessment plan of the weapon system, completed in 1996.

- Bradley Fighting Vehicle System-A3, M2A3/M3A3 (Bradley A3) FU SL LFT&E, an element of the vulnerability assessment plan of the weapon system, scheduled to be completed in 1999.

1.2.2 Impacts of FU SL LFT&E. The specific activities that define the FU SL LFT&E element of a system's assessment strategy are identified. For each system, the components of each identified activity and the *costs* related to those components are determined. In addition, the following practices and procedures are examined:

- Current procedures used in the measurement of the costs related to identified activities.

- Current practices used in reporting the computed costs.

- Current practices used in budgeting for the costs of FU SL LFT&E and computing and reporting the variances between actual and budgeted costs.

Identifying the *benefits* of FU SL LFT&E, as well as the benefits of other elements of alternative assessment plans, is an important part of the methodology that compares competing assessment strategies. Although there is a large element of subjectivity in describing these benefits, several broad categories of FU SL LFT benefits are identified through discussions with individuals associated with the V/L assessment plans of the systems studied. The capabilities of an element of a V/L assessment plan to address the critical evaluation issues of the system are considered to be the *benefits* of that plan element.

Complexities encountered in identifying, measuring, and reporting the costs and benefits or impacts (i.e., *costs and benefits* are often described by the term *impacts* in the cost-benefit literature) of FU SL LFT&E and its associated activities are recognized, and approaches for addressing these complexities are suggested.

It is proposed that the methodology used in identifying and measuring the impacts of FU SL LFT&E is applicable equally to the computing of the costs and benefits of other elements of the assessment strategies for weapon systems.

1.2.3 Comparison of Competing Strategies. The Taxonomy of the V/L Analysis Process (V/L Taxonomy)* provides the framework for identifying (1) the specific data set required for an adequate assessment of the critical V/L issues of a weapon system, (2) the subset of the required data set available from existing reliable sources, and (3) data voids to be addressed in a V/L assessment plan.

The potential of adapting the principles of the Cost as an Independent Variable (CAIV) methodology to the evaluation of competing strategies of V/L assessment is explored. The analyses of the identified impacts of alternative assessment strategies, the uncertainties (i.e., risks) associated with these impacts, and the priorities assigned by analysts to the critical data voids expected to be produced by these assessment strategies serve as inputs to the evaluation approach grounded in CAIV principles proposed in this report.

Complexities encountered in predicting the data or information to be obtained from a V/L assessment plan prior to completing the plan and prioritizing the information needs of decision-makers are discussed.

1.3 Organization of Report. The remainder of the report is organized as follows. The research methodology employed in this study is developed in section 2 and includes a description of the three weapon systems studied and the identification of the

* The Taxonomy of the V/L Analysis Process was first introduced in Deitz and Ozolins [2].

agencies that provided much of the information upon which this report is based. The results of the research, including descriptions of the activities of FU SL LFT&E, the impacts of those activities, the complexities encountered in the reporting of the impacts, and approaches for addressing the complexities are reported in section 3. A discussion of Project Manager (PM) personnel's perceptions of the role of FU SL LFT&E in the survivability/lethality assessment process and their suggestions for improving the cost-effectiveness of the assessment process complete this section of the report. Section 4 includes a discussion of the application of the V/L Taxonomy framework and CAIV principles to the decision-making process of selecting the optimal V/L assessment strategy. The report concludes in section 5 with a discussion of the relationship of FU SL LFT&E, cost-effective assessment strategies, and the acquisition process.

2. Research Methodology

2.1 Systems. A description of the three weapon systems examined in this study and a brief review of the FU SL LFT&E events related to those systems are provided in the following paragraphs.

2.1.1 Abrams M1A2. The M1A2 Abrams Main Battle Tank system is described as follows in the "FY 1996 Annual Report of the Director, Operational Test and Evaluation [3]:"

> The mission of the M1A2 Abrams tank is to close with and destroy enemy forces using firepower, maneuver, and shock effect. The M1A2 is an upgrade of the Abrams M1A1 intended to improve target acquisition and engagement rates, improve survivability, and maintain operational suitability at the level of the M1A1. Many of the enhancements were made by replacing or modifying previous items to take advantage of the introduction of digital distributed data and power architecture of the M1A2. The Inter-Vehicular Information System and the Position/Navigation equipment are designed to improve battlefield command, control, and communications. The Commander's Independent Thermal Viewer increases the rate of target acquisition so that the gunner is able to engage targets more rapidly.

The FU SL LFT, an element of the vulnerability assessment plan of the Abrams M1A2, was conducted from April to October 1993 at the U.S. Army Aberdeen Test Center (ATC) at Aberdeen Proving Ground (APG), MD.* A total of 11 shots (i.e., 10 shots planned, 1 shot repeated) were fired against 2 of the initial 62 M1A2 vehicles produced in the Low-Rate Initial Production (LRIP) contract. The Office of the Secretary of Defense (OSD) submitted the Abrams M1A2 Live-Fire Test & Evaluation Report to the U.S. Congress in May 1994.

The Abrams M1A2 FU SL LFT was designed to investigate the effects of non-perforating and perforating threats likely to be encountered in combat. The M1A2 Abrams Live Fire Vulnerability Test objectives include [4]:

- To determine the vulnerability of the M1A2 vehicle and total system (crew and vehicle) along with the corresponding loss of mobility and/or firepower function as a result of nonperforating or perforating threats likely to be encountered.
- To determine the vulnerability of the crewmen in the modified crew compartment.
- To investigate the survivability improvements incorporated into the M1A2 as a result of previous testing.
- To determine if there were unexpected or unacceptable M1A2 vulnerabilities and determine how these vulnerabilities might be reduced or eliminated if they were significant.
- To assess the repairability of the vehicle.

2.1.2 ATACMS Block IA. The ATACMS Block IA system is described as follows in the "FY 1997 Annual Report of the Director, Operational Test and Evaluation [5]:"

> The Army Tactical Missile System (Army TACMS) is a family of long-range, near all-weather guided missiles fired from the Multiple Launch Rocket System (MLRS) M270 launcher and deployed within the ammunition loads of corps MLRS battalions. ... The Block IA is an upgrade intended to double the range of the current Army TACMS Block I missile.

* The Aberdeen Test Center (ATC) was formerly known as the Combat Systems Test Activity (CSTA).

> Army TACMS Block IA will dispense M74 Anti-Personnel, Anti-Materiel (APAM) bomblets, as does the Block I. ...
>
> The primary changes in Army TACMS Block IA are a reduced payload (from 950 to 300 bomblets) and the addition of a Global Positioning System (GPS) navigation aid to the inertial guidance system. The reduced payload is necessary to achieve the extended range. To compensate for the reduced payload, the accuracy of the missile has been improved with inflight GPS updates. If GPS is rendered inoperable, the Army TACMS Block IA reverts to inertial guidance only and maintains Block I accuracy.

The FU SL LFT&E of the ATACMS Block IA did not include vulnerability tests of the chassis and launcher of the missiles. The evaluation of the FU SL LFT&E of the ATACMS Block IA includes the results of 3 test events: (1) the full-up live-fire arena tests, conducted from May to June 1996 and designed to observe effects of 23 M74 bomblets detonated at various ranges against 3 operationally representative threat targets, (2) the 2 developmental and operational test live-fire launcher-to-target firings (previously referred to as end-to-end firings), conducted in August and September 1996 against an array of 9 and 15 nonoperating targets and designed to provide a demonstration of ATACMS potential to inflict damage upon a multiple-vehicle area target, and (3) the tire fragment tests, conducted from June 1994 to June 1995 and designed to test the capability of M74 and other munitions with small fragments to inflict damage on tires (the tire tests were not an official part of the LFT plan, but their results were included in LFT evaluation). The arena and tire fragment tests were conducted respectively at ATC and the Survivability/Lethality Analysis Directorate, U.S. Army Research Laboratory (SLAD/ARL) at APG, and the launcher-to-target flight tests were performed at White Sands Missile Range (WSMR), NM. Milestone III for ATACMS Block IA was deferred to allow more time to address issues related to acquisition, in-flight survivability, and lethality. Follow-on tests were conducted both at SLAD and ATC, and the ATACMS Block IA LFT&E report was submitted by OSD to the U.S. Congress in April 1998.

The ATACMS Block IA FU SL LFT was designed to provide information to assess the ability of the system to eliminate and/or degrade the operational functions of representative threat-target systems, thus providing insights into the principal damage mechanisms and target failure modes occurring as a result of munitions and target interaction. The "Live Fire Independent Evaluation Plan/Test Design Plan (IEP/TDP) for the Army Tactical Missile System (ATACMS) Block IA" reports the critical test and evaluation issues of the ATACMS Block IA program as follows [6]:

- Bomblet lethality ... What is the lethality of the M74 bomblet against personnel and light materiel targets? Subissues include: What are the M74 fragmentation characteristics? What are the penetration characteristics of the M74 fragments? Can the M74 fragments routinely damage components of the desired targets? How is the performance of the M74 bomblet affected by degraded conditions such as uneven terrain and various impact media?

- Pattern lethality ... What is the lethality of the ATACMS Block IA missile against the required target elements, given the element is in the bomblet pattern? Subissues include: What is the density and distribution of the M74 bomblets within the bomblet ground pattern? What is the M74 bomblet dud rate and distribution within the ground pattern?

- System Effectiveness ... What is the system effectiveness of the ATACMS Block IA system against the required target sets to include both point and area targets? Subissues include: What is the system accuracy relative to the aimpoint? What are the pattern dimensions? What are the target dimensions (area targets)? What is the Target Location Error for the target of interest?

2.1.3 ***Bradley A3.*** The Bradley A3 system is described as follows in the "FY 1998 Annual Report of the Director, Operational Test and Evaluation [7]:"

> The M2A3 and M3A3 Bradley Fighting Vehicle Systems (BFVS) are improved versions of the M2A2 and M3A2 BFVS. The BFVS-A3 includes enhancements intended to improve lethality, mobility, survivability, and sustainability. Additionally, these enhancements are intended to provide increased situational awareness and digital command and control capabilities necessary to provide information superiority to the dominant maneuver force. . . .
>
> The mission of the BFVS is to provide mobile protected transport of an infantry squad to critical points on the battlefield and to perform cavalry scout missions. The BFVS will also provide overwatching fires to support dismounted infantry and suppress or defeat enemy tanks and other fighting vehicles. BFVS-A3 enhancements include:
>
> - Incorporation of Force XXI Battle Command, Brigade and Below Embedded Battle Command to share command and control and situation awareness with all components of the combined arms team.

- The improved Bradley acquisition system and commander's independent viewer, ... , to improve target acquisition and target engagement.

- A position navigation system with a Global Positioning System receiver to enhance situational awareness.

The following comparison of the Bradley A2 and the Bradley A3 is provided in the LFT&E Strategy included in the "Bradley Fighting Vehicle System, A3 Test and Evaluation Master Plan (TEMP) [8]:"

> Although much of the ballistic protection is the same as on the Bradley A2, some changes have been made to both internal and external configurations: electronic systems have been changed and upgraded, new subsystems have been added to the vehicle both internally and externally, armor covering most of the roof and some of the upper portion of the sides has been improved, a pontoon system is being developed and a 10th crew member has been added.

The Bradley A3 FU SL LFT, an element of the vulnerability assessment plan of the system, began in December 1998 at ATC in Aberdeen Proving Ground, MD, and is scheduled for completion in 1999. Eighteen shots are planned against two production qualification test (PQT) vehicles, upgraded to production configuration with 3.0Z software end product, and an LRIP vehicle.

The Bradley A3 FU SL LFT is designed to investigate the effects of nonperforating and perforating threats likely to be encountered in combat. The critical test and evaluation (T&E) issues are defined as follows in the LFT&E Strategy included in the "Bradley Fighting Vehicle System, A3 Test and Evaluation Master Plan (TEMP) [8]:"

- What is the vulnerability of the Bradley A3 system to the spectrum of expected threats and how does this compare to previous Bradley Fighting Vehicles? Subissues [include:] How are the vulnerabilities of the Bradley A3 changed ... by the additional roof armor? What impacts do the A3 modifications have on Bradley system vulnerabilities? ... What is the impact of the A3 modifications on the Bradley system's vulnerability to ballistic shock?

- What is the vulnerability of the A3 crew and troops to the spectrum of expected threats and how does this compare to previous Bradley Fighting Vehicles? Subissues [include:] How is the vulnerability of the

Bradley A3 crew and troops changed ... by the additional roof armor? What impacts do the A3 modifications have on Bradley crew and troop vulnerability? ...

- How effective is battle damage assessment and repair (BDAR) in restoring the A3 to minimum functional combat and full mission capability following a hit by expected threats (direct and indirect)? Subissues [include:] What changes in BDAR procedures are required for the Bradley A3 compared to the Bradley A2? How effective are the applicable BDAR manuals, procedures, tools, and supplies for the A3?

- What are the vulnerabilities of the BFVS A3 system/crew/troops to new and/or emerging threats?

- Are there any unexpected BFVS A3 vulnerabilities? Subissues [include:] What is the operational significance of any unexpected vulnerability? Can these vulnerabilities be reduced?

2.2 Information Sources. The following agencies/organizations provided information for this research study:

- Survivability/Lethality Analysis Directorate (SLAD), U.S. Army Research Laboratory (ARL).

- Evaluation Analysis Center (EAC), U.S. Army Operational Test and Evaluation Command (OPTEC).

- Headquarters, U.S. Army Test and Evaluation Command (HQ, TECOM).*

- U.S. Army Aberdeen Test Center (ATC).

- U.S. Army Materiel Systems Analysis Activity (AMSAA).

- PM Offices (PMOs):

  ◊ ATACMS PMO, U.S. Army Aviation and Missile Command (AMCOM), Redstone Arsenal, AL.

* In a recent command reorganization, EAC, OPTEC, and TECOM became elements of the Army Test and Evaluation Command (ATEC).

◊ Abrams PMO, U.S. Army Tank-automotive and Armaments Command (TACOM), Warren, MI.

◊ Bradley PMO, TACOM, Warren, MI.

- Institute for Defense Analysis (IDA).

Discussions with the personnel from SLAD, EAC, TECOM, ATC, and AMSAA focused on general background information of the respective agency, the role of the agency in FU SL LFT&E and general T&E activities, funding and budgeting for the activities of FU SL LFT&E by the agency, the impacts of FU SL LFT&E activities of the agency, and the complexities encountered in identifying, measuring, and reporting those impacts.

Discussions relative to the application of the V/L Taxonomy and CAIV principles to the analysis of competing V/L assessment strategies were an important part of the conversations with AMSAA, EAC, and SLAD personnel. Limited discussions with IDA personnel focused on the role of IDA in the V/L assessment of weapon systems.

Interviews with PMO personnel included discussions of the history of the system associated with the PMO, congressional funding for the system, contracts associated with various cycles of the acquisition process for the system, the role of the PMO in the acquisition process and the FU SL LFT&E of the system, the impacts of the FU SL LFT&E of the system, and the complexities encountered in the T&E activities of the system.

In total, more than 55 scheduled discussions or interviews were conducted to gather the information needed for this research project with approximately 60 people participating in these conversations. In addition, many informal discussions occurred at defense-related conferences and workshops attended during the most recent 2- to 3-year period.*

* Conferences and workshops included LFT&E—10 Years and Counting Conference, Lawrence Livermore National Laboratory, Livermore, CA, January 1997; Fourteenth International Symposium on Military Operational Research, Royal Military College of Science, Shrivenham, Wiltshire, United

Many documents relative to the three systems, LFT&E and its impacts, the V/L Taxonomy, the CAIV methodology, T&E, and other related topics were reviewed.

3. Research Results

To determine the impacts of FU SL LFT&E, the activities that constitute the FU SL LFT&E program must be delineated. In reality, conducting an Army FU SL LFT&E program results in activities in many agencies, including the Office of the Director, Operational Test and Evaluation (DOT&E), the Office of the Deputy Director, Operational Test and Evaluation, Live-Fire Testing (DDOT&E [LFT]), the Office of the Deputy Under Secretary of the Army for Operations Research (DUSA [OR]), the Office of the Deputy Chief of Staff for Intelligence (DCSINT), the U.S. Army Medical Research and Materiel Command (MRMC), the U.S. Army Training and Doctrine Command (TRADOC) including the U.S. Army Ordnance Center and School (USAOC&S) and the U.S. Army Transportation Center and School (USATC&S), the U.S. Congress and its subcommittees, analysis groups utilized by the aforementioned offices (e.g., IDA), TECOM, SLAD, ATC and other test centers, AMSAA, EAC, and the PMOs associated with the specific weapon system tested. For the purposes of this research project, the FU SL LFT&E program is defined more narrowly and the activities examined are limited to those described in the following section.

3.1 Activities of FU SL LFT&E. The following are identified as the activities completed in a FU SL LFT&E. Specific divisions and agencies with lead responsibilities for the activities are noted as appropriate.

Kingdom, September 1997; Conference on the Economics of Test and Evaluation, TEREC, Georgia Institute of Technology, Atlanta, GA, October 1997; Fourteenth Annual Test & Evaluation Conference and Exhibition, San Diego, CA, March 1998; Fifteenth International Symposium on Military Operational Research, Royal Military College of Science, Shrivenham, Wiltshire, United Kingdom, September 1998; Thirty-seventh Annual Army Operations Research Symposium, Fort Lee, VA, October 1998; Test Plan Optimization Workshop, TEREC, Georgia Institute of Technology, Atlanta, GA January 1999; Simulation and Modeling for Acquisition, Requirements, and Training Conference, San Antonio, TX, January 1999; 10th Annual Army Ground Vehicle Survivability Symposium, Monterey, CA, March 1999; and 67th Annual Military Operations Research Society Symposium, West Point, NY, June 1999.

- Formation of Live-Fire Integrated Product Team (LFIPT)
  EAC leads the working group under the Test and Evaluation Integrated Product Team; members of working group include representatives of the offices of DOT&E, DUSA(OR), a representative of the military intelligence community (e.g., National Ground Intelligence Center), in addition to personnel from EAC, SLAD, TECOM, the PMO, the test center, USAOC&S/USATC&S, and TRADOC.

- Modeling and Simulation
  SLAD performs the extension or expansion, the verification, and the validation of models required to be exercised in FU SL LFT&E of weapon system; exercises the models in pre-shot predictions; and provides full-view V/L estimates to EAC for use in the FU SL LFT evaluation.

- Development of LFT&E Event Design Plan (EDP) that Replaces Prior Independent Evaluation Plan/Test Design Plan (IEP/TDP)
  EAC serves as lead in preparation of EDP; receives input from SLAD and other members of LFIPT.

- Writing of Detailed LFT&E Test Plan (DTP)
  Tester prepares DTP.
    - ◊ *Tester of ground systems: TECOM*
    - ◊ *Tester of aviation systems: SLAD*

  TECOM reviews DTP of LFTs assigned to other agencies for execution.

- Performance of FU SL LFT
    - ◊ Setup and execution
      Designated tester sets up and executes.
    - ◊ Battlefield damage assessment and repair
      USAOC&S conducts the BDAR of ground systems.
      USATC&S conducts the BDAR of aviation systems.
    - ◊ Damage assessment and casualty assessment
      SLAD coordinates damage assessment and casualty assessment.

- Documentation
    - ◊ Damage assessment shot records
      SLAD prepares damage assessment shot records.
    - ◊ Detailed Damage Assessment Report
      SLAD prepares Detailed Damage Assessment Report.
    - ◊ Detailed Test Report (DTR)
      Tester serves as lead in preparation of DTR, receiving input from Damage Assessment Team; TECOM reviews DTR for LFTs assigned to other agencies for execution.

- Independent Evaluation and Preparation of System Evaluation Report (SER), Including the Analysis of LFT&E Activities
  EAC prepares the SER.

3.2 Costs of FU SL LFT&E. A weapon system included in the U.S. congressional LFT&E mandate must conduct a FU SL LFT&E as part of the assessment of the survivability/lethality program of the system, unless the waiver requested by the Service acquiring the system is granted by the Secretary of Defense. The cost of the FU SL LFT&E is an important consideration in determining the appropriateness of a waiver, in budgeting dollars for the execution of a FU SL LFT&E, and in comparing various V/L assessment strategies. Perhaps the most difficult issue faced in determining the cost of FU SL LFT&E is defining the term *cost*. The analyst must determine what components of the FU SL LFT&E activities (listed in the previous paragraph) should be costed and how the costs of those components should be measured. In this process, the analyst must address the following questions:

- How are the costs of the tested systems (i.e., test articles) computed, if systems are damaged but salvageable? How are the costs computed, if the test articles are completely destroyed?

- How are the costs of spare parts used in repairs computed?

- How are the costs of targets used in lethality testing or munitions used in vulnerability testing computed?

- How are the labor costs of individuals participating in the planning; modeling and simulation (M&S); testing; or evaluation process of FU SL LFT&E computed?

- How are the costs of the test ranges and instrumentation used in FU SL LFTs computed or allocated across the many systems tested at the test center or across the multiple time periods over which the test center is in operation?

To make a valid comparison of assessment strategies (e.g., those that include FU SL LFT&E and those that do not), decision-makers must be provided with cost data that are identified and measured according to a consistent methodology employed across assessment plans. Clear descriptions of FU SL LFT&E activities and the separate components of each activity and their related costs must be identified. In situations in which there are alternative ways of measuring the costs of an activity, the measurement method employed should be identified and described. Allocated costs should be so identified, and the bases of allocation or the rates used in allocation should be fully explained. In addition, information that allows the decision-maker to compute the costs in an alternative manner should be disclosed by the cost analysts.

For purposes of this research study, cost sheets of the completed FU SL LFT of both the ATACMS Block IA and the Abrams M1A2 were provided by the ATACMS and Abrams PMOs and TECOM. The cost sheet of the 1993 Abrams M1A2 included costs aggregated in five very broad categories (i.e., Test Center, Repair Parts, ARL/TECOM/AMSAA, Ammunition and Nondestructive Tests, and Contractor Test Support). The time period between the completion of this test and the changes in personnel across agencies made the costs related to the Abrams M1A2 difficult for interviewees to re-construct. The cost sheet of the more recent 1996 FU SL LFT&E of the ATACMS Block IA included a more detailed breakdown of the costs related to work performed by SLAD and the two test centers (i.e., ATC and WSMR) in addition to some target-related costs. Costs for the forthcoming Bradley A3 FU SL LFT&E were available only in total budgeted amounts for the tests. All costs referred to in the following sections were taken from the sheets provided for this study.

Personnel from all three PMOs reported that records are kept of the FU SL LFT&E costs incurred by government agencies and by contractor(s) and subsequently reimbursed by their offices. ATC reports that it provides the PMO with both interim reports of the costs incurred by the test center (i.e., during the execution of the FU SL LFT) and a final accounting of test-related costs at the conclusion of the FU SL LFT. The PMO, however, is not required to produce a formal report detailing the total costs of all FU SL LFT&E-related costs incurred by government agencies and contractors and reimbursed by the PMO.

This research project did not have the objective of critically reviewing the costs incurred or reported by the systems studied but of understanding how the costs of FU SL LFT&E are identified, measured, and reported and what complexities are encountered in accomplishing these tasks. An examination of the information included in the available cost sheets and discussions with individuals associated with the activities of FU SL LFT&E provided much insight into these issues.

In this report, the costs of FU SL LFT&E are placed in one of two categories: (1) costs of direct materials used and consumed in the FU SL LFT&E or (2) costs of activities, including the costs of indirect materials, labor, and facilities used in the planning, execution, and evaluation of the FU SL LFT and its results.

3.3 Costs of FU SL LFT&E: Costs of Direct Materials. The costs of direct materials used or consumed in the FU SL LFT&E are defined as all material costs that can be feasibly or economically traced to the cost objective (i.e., FU SL LFT&E). The direct material costs of FU SL LFT&E include the costs of the following test assets: (1) the test articles (i.e., weapon systems tested), (2) the spare parts provided for the test articles, (3) the munitions fired (i.e., applicable to vulnerability tests), and (4) the targets fired upon (i.e., applicable to lethality tests). It is assumed in this report that the total cost of all test assets discussed will include the transportation and preparation costs incurred to ready the asset for FU SL LFT at the designated test center.

3.3.1 Cost of Test Articles. The following costs are proposed as alternative reporting values for test articles used in FU SL LFT&E:

- Cost of replacing the test article with an article identical to the original article (i.e., *replacement cost*).
- Cost of returning the test article following FU SL LFT to its condition prior to FU SL LFT (i.e., *restorative cost*).
- Cost of acquiring the original test article (i.e., *historical cost*).

The costs of test articles have been accounted for in various ways in completed FU SL LFT&E programs. For example, the total program costs for the FU SL LFT&E provided by the Abrams PMO do not include the costs of the vehicles used in testing. Both test articles were deemed salvageable at the conclusion of the 1993 LFT program with an expenditure of $1.5 million estimated to return the two Abrams M1A2 LRIP vehicles to combat condition. The PMO requests for dollars to return the articles to combat condition were not funded, and the two tanks are currently in use as training vehicles (e.g., track tests) at APG. Replacement cost or the current cost to convert an Abrams M1 to an M1A2 (cost includes some engineering support for potential production problems) is estimated by the Abrams PMO at $4–5 million per vehicle.* Historical costs or the actual costs incurred to construct the two LRIP Abrams M1A2 vehicles used in the FU SL LFT&E were not available.

Neither the cost of the missiles used in the ATACMS Block IA tests (i.e., launcher-to-target tests) nor the relatively small cost of the M74 bomblets (i.e., approximately 100 bomblets used at $30/bomblet) in the arena tests was included on the LFT&E cost sheet produced by the ATACMS PMO. PMO personnel stated that the missile cost was treated by its office as part of the costs of the developmental and operational tests of the ATACMS Block IA. The PMO quoted a figure of $1.01 million as the cost of producing

* It should be noted that this is the replacement cost estimate in 1998; replacement cost in 1993 is unavailable.

an ATACMS Block IA missile (i.e., replacement cost). This cost includes the costs of contractor, support of PM office, and production testing.

The projected cost figures for the LFT&E program of the Bradley A3 include $2.7 million (of the total $6 million FU SL LFT&E budget of the Bradley PMO) budgeted for the replacement of two PQT vehicles.*

From the aforementioned three examples, it is evident that the total costs of FU SL LFT&E may be significantly affected by the choice of the alternative reporting value chosen for the cost of the test article(s). It is proposed in this report that the restorative cost (i.e., the cost to return the test article to its original condition) is the most appropriate value to report as the test article cost if (1) the test article is in a salvageable condition following testing, (2) the restorative cost is able to be estimated, and (3) the restorative cost is the smallest of the three proposed alternative values. The restorative cost is a *cost of testing*, regardless of whether or not the expenditure is made. If the restorative cost is higher than one or both of the remaining alternative values (i.e., replacement cost and historical cost) or the test article cannot be restored, a choice must be made as to which of the two alternatives will be reported as the test article cost. Each value has its own merits, but it is suggested that the lower of the two values be reported as the cost of the test article.† Regardless of which value is reported, *all* available alternative values for costing the test article should be disclosed in the cost report and made part of the database available to those budgeting for FU SL LFT&E of future systems. The computations of all reported values, including the amounts attached to

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* An LRIP vehicle was added to the test articles planned to be used in the FU SL LFT. The PMO stated that all Bradley A3 vehicles were expected to be remanufactured from used vehicles, and there were no current plans to build any new BFVS vehicles for the U.S. Army.

† In general, an asset is reported at its *historical cost* under generally accepted accounting principles because the historical cost is assumed to be objectively determined in an arm's length transaction between two independent parties and therefore reflects the fair value of the asset at the transaction date. In the case of FU SL LFT&E, however, the historical cost of the prototype test asset used in FU SL LFT could be relatively high in comparison to the *replacement cost* of the asset. It is hard to defend the position that if the test asset is lost in the FU SL LFT, the entire *historical cost* of the prototype should be reported as a cost of FU SL LFT&E instead of reporting the *replacement cost* of the asset. In reality, a system would not be expected to be restored IF its replacement cost were lower than its restorative cost (i.e., given enough time for replacement). Therefore, the suggested rule reduces to report the lowest of the three values available: *restorative cost, replacement cost*, or *historical cost*.

these costs (e.g., engineering support costs), should be explained in full to facilitate the processing of this information in comparative analyses of assessment plans and in future budgeting activities.

The costs of assets other than the test articles include the costs of the spare parts provided for the repairs of the test articles made during the FU SL LFT&E, the munitions fired (i.e., vulnerability tests), and the targets fired upon (i.e., lethality tests). As in the cost of test articles, there are often alternative values (e.g., historical cost, restorative cost, and replacement cost) available for assets included in this category.

3.3.2 ***Cost of Spare Parts.*** The accounting for spare parts for test articles in the FU SL LFTs of two of the systems studied raises the question, "Are spare parts provided to the test center as part of a larger contract, and are those costs able to be separated from the major costs of the contract and reported as a line item in a FU SL LFT&E cost report?"* In the Abrams M1A2 FU SL LFT&E, the spare parts were provided at a fixed cost as a test system support package attached to the LRIP Contract for 62 tanks with General Dynamics Land Systems, and ATC accounted for the spare parts as used. The Abrams FU SL LFT&E cost sheet reported a cost of $1.6 million for repair parts, but the Abrams PMO stated this estimate could be as high as $2 million. The attachment of the spare parts cost package to the LRIP contract made this cost more difficult to estimate.

The Bradley PMO reported that it plans to acquire spare parts needed for the FU SL LFT&E of the Bradley A3 from Army depots (i.e., Bradley common parts) and the LRIP contractor, United Defense Limited Partners (i.e., Bradley A3 unique parts). Pre-shot predictions have allowed the PMO to project parts that will be needed in the FU SL LFT. The LRIP contractor will provide the parts as needed from vehicles completed in its contract, and a contract modification will be added following the completion of the FU SL LFT to account for parts required during the testing phase.

* Costs for spare parts of test assets are not applicable to the lethality tests of the ATACMS Block IA (with the exception of launcher spare parts).

The cost incurred at the time of purchase (i.e., historical cost) is generally reported as the cost of spare parts. In addition, the reporting of this cost should include a description of the contract agreement (e.g., pay contractor a fixed amount for all parts needed, pay contractor an amount that varies with the type and number of spare parts needed, etc.). Disclosure of the spare parts used vs. spare parts purchased (i.e., in fixed-dollar contract) and related costs may prove useful in planning of subsequent FU SL LFT events.

3.3.3 ***Cost of Munitions and Targets.*** The costs of some assets related to FU SL LFT&E are particularly difficult to determine. The costs of munitions used in vulnerability tests or targets used in lethality tests may not be readily available or easily estimated. Munitions and targets may have been obtained without exchanging dollars, if acquired in prior combat or in nonmonetary trades with other agencies. ATC reports that munitions are often *free* or obtained at a relatively insignificant cost from a foreign source.

No cost information relative to the munitions used in the completed Abrams M1A2 FU SL LFT&E (i.e., vulnerability test) is included on the cost sheet provided. Neither the costs of the targets used in the launcher-to-target and arena tests of the ATACMS Block IA (i.e., lethality tests) nor the costs of the repairs to the targets used in those tests were totally accounted for on the FU SL LFT&E cost sheet provided.* Additional targets in the launcher-to-target tests conducted at WSMR were required and funded by OSD and were not included in the costs reported on the cost sheet as reimbursable by the PMO. The cost sheet does include a portion of the cost of transportation for targets used in the arena tests.

Target repair costs were not included on the ATACMS Block IA cost sheet. The cost sheet does not include the sum requested by the Project Manager, Instrumentation,

* Of the 3 targets used in the arena tests of the ATACMS Block IA, only 1 was a target included in the Operational Requirements Document (ORD) list of 11 targets; the other 2 targets had characteristics similar to the other 10 ORD target types. Targets used in the launcher-to-target tests included some target surrogates, some foreign targets with elements representative of ORD targets, and some targets that were less vulnerable than ORD targets.

Targets and Threat Simulators (point of contact for obtaining, controlling, operating, and sustaining threat equipment or surrogates for use in LFT) for restoring the targets used in the ATACMS Block IA FU SL LFT. The PMO reported the intent to pursue some "trading" of other target assets with the Target Management Office to compensate the Office for damage sustained to borrowed targets. It may be difficult to obtain an historical cost or to estimate a replacement cost for the munitions used in lethality tests or the targets used in vulnerability tests. A complete accounting of the costs of test assets, however, should include, if available, an estimated cost of the munitions/targets with the relevant range of values for that estimated cost or a disclosure of the inability to estimate the cost for identified assets.

3.4 Costs of FU SL LFT&E: Costs of Activities. In this report, the costs of activities of FU SL LFT&E are defined as the costs incurred for indirect materials consumed, labor performed, and facilities used in the planning, execution, and evaluation of a FU SL LFT and its results. To compute the cost of an activity, all components of the activity that consume resources and the costs associated with those components must be identified. The agencies associated with the activities of FU SL LFT&E described in the beginning of this section account for their costs in different ways as shown in the following sections.

Labor costs are a large component of the costs of all FU SL LFT&E activities across all agencies. In accounting for the labor costs of employees engaged in activities in an agency, the following questions must be addressed:

- Do labor costs include overhead administrative costs of the employee's agency?

- Are labor costs based on the actual hours worked or the hours estimated to be needed for the required service? In other words, is the cost of labor reported in fact the *budgeted cost* of labor, similar to the estimated or budgeted cost of labor in a contract that is fulfilled with the delivery of the product?

3.4.1 Cost of SLAD (ARL) Activities. There are two major SLAD activities: (1) M&S and (2) damage and casualty assessment, in addition to LFIPT participation.

A closer look at the SLAD M&S activity reveals four components: (1) extension and/or expansion of models to include descriptions and characteristics of the test article, munitions, target(s) of interest, and damage mechanisms not previously modeled, in addition to improvements in damage mechanisms already part of the model (e.g., behind-armor debris); (2) verification and validation (V&V) of existing model(s); (3) exercise of model in pre-shot predictions and reruns of pre-shot predictions (e.g., reruns needed if actual geometry of shots is different than planned shots); and (4) provision of full-view V/L estimates to EAC for use in the FU SL LFT evaluation. Modeling activities related to pre-shot predictions provide important data for decisions related to test planning and execution (e.g., selection of shot lines, stock levels of spare parts, etc.) and a certain measure of quality control for the modeling function. On the other hand, modeling activities related to the production of full-view V/L estimates generate data important to the evaluation of the FU SL LFT and the overall assessment of the V/L of the system.

As stated previously, the cost sheet for the FU SL LFT&E of the ATACMS Block IA system includes a more detailed accounting of costs than is available for the other two systems studied and is therefore used as an example of the costing of SLAD M&S activities. The FU SL LFT of the ATACMS Block IA incurred costs for the development of the inputs to the model including target descriptions, criticality analyses, and the probability of component kill assessments for the three targets of the arena tests. Pre-shot predictions were also accomplished for the 23 planned shots against the 3 arena targets. Following the post-shot analysis, the vulnerability analysis was updated with a rerun of the SAFE model including the target description updates (9 targets included in Operational Requirements Document [ORD]). As part of the follow-on effort, algorithms were developed to characterize damage mechanisms and reactions not previously modeled, such as pyrophonic and fragment effects given fuel and propellant interaction.

Verification, validation, and accreditation (VV&A) of models exercised as part of the FU SL LFT&E must be achieved prior to relying on modeling efforts in FU SL

LFT&E.* SAFE and Stochastic Quantitative Analysis of System Hierarchies (SQuASH) models, as exercised in the FU SL LFT&E of ATACMS Block IA, have recently undergone model calibration exercises in which the models are compared to existing test results. The costs of these exercises for the ATACMS Block IA FU SL LFT&E were absorbed by SLAD mission funds. The FU SL LFT&E of the Abrams M1A2 relied on the results of model FORTRAN SQuASH, but VV&A, as it is now known, was not performed for the Abrams system in 1993. The SQuASH and SAFE sections of the Modular UNIX-based Vulnerability Estimation Suite (MUVES) have been consolidated into a new combination model, MUVES-S2. The V&V of MUVES-SQuASH for Bradley A2 has been completed by SLAD in preparation for the Bradley A3 LFT, but V&V for SAFE relative to Bradley A3 is ongoing. The costs of the effort for V&V required for Bradley A3 have again been absorbed by SLAD mission funds. SLAD personnel expect that in the future PMOs will be asked to contribute to the V&V effort, including the reimbursement of material and labor costs incurred in the experiments and analyses necessary to support the changes in codes and algorithms associated with the models required for a system's FU SL LFT&E.

The damage assessment team, generally chaired by SLAD personnel, is responsible for the damage assessment at the conclusion of each FU SL LFT shot. Members of the team generally include personnel from SLAD and the test center and may include personnel from the proponent TRADOC school and EAC among others. The damage assessment shot records, in which the damage assessments for all FU SL LFT shots are detailed, as well as ancillary-related data, are prepared by SLAD and test center personnel for inclusion in the DTR produced by the test center. The Damage Assessment Report, which includes the comparisons of the results of the FU SL LFT shots with pre-shot predictions, is also prepared by SLAD personnel.

The personnel casualty assessment effort is also led by SLAD personnel with support from the test center and others as needed (e.g., personnel from MRMC,

* Accreditation of models is not performed by Survivability/Lethality Analysis Directorate (SLAD) personnel.

including Walter Reed Army Institute of Research and Aeromedical Research Laboratory).*

Examples of the costs incurred by SLAD in damage and personnel casualty assessments can be found on the cost sheet for the FU SL LFT&E of the ATACMS Block IA system. Included are the costs for damage assessment at ATC and WSMR, damage assessment support and model verification, and personnel casualty assessment at ATC and WSMR. SLAD employee-years budgeted by branch chiefs include the participation of branch employees in system-related working group meetings. SLAD also budgets for its labor costs incurred in the support of the tester's plans and reports. For example, the ATACMS FU SL LFT&E cost sheet included dollar figures for IEP/TDP support, preparation of DTP, DTR, General Support, and Final Test Report.

A SLAD branch chief budgets labor hours for FU SL LFT&E activities by identifying the employees and the number of employee-years needed by each identified employee in the branch to complete the tasks required for the LFT effort. Labor cost per employee-year is multiplied by the number of employee-years estimated for the LFT-related task, and this product becomes the total estimated costs for that employee on the identified task.

A labor cost per employee-year for each branch employee and an average branch labor cost per employee-year are computed by the SLAD division and directorate offices and provided to each branch chief for the purposes of budgeting and costing services rendered by branch employees. The employee-year cost computation includes the salary and fringe benefits of the employee plus an amount (based on rate per employee-hours worked) to cover overhead associated with division and directorate administrative offices.† Projections for SLAD costs related to LFT are made often with a 5-year horizon, but estimates are generally revised on an annual basis.

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* Most test centers provide some form of data collector support (e.g., photography and assistance with post-shot component and subsystem checks). Generally, ATC is enlisted to perform data reduction and analyses for damage and personnel casualty assessment.

† The SLAD overhead hourly rate has three components, including the direct and indirect overhead rates of the division office and the general and administrative rate of the directorate office.

In addition to the costs incurred in LFT&E activities reviewed in preceding paragraphs, SLAD employees also incur travel costs related to LFT&E activities. By law, the PMO of the tested system is responsible for the reimbursement of all costs related to the FU SL LFT&E of a system, including travel-related costs, with the exception of costs incurred by agencies with mission-related responsibilities in the LFT&E program. As previously mentioned, some of the FU SL LFT costs related to M&S have been financed with mission funds of SLAD (e.g., V&V of models for Bradley A3 FU SL LFT&E). SLAD mission funds are delegated to systems at the beginning of the year, based on the priorities of the systems for which the SLAD Mission Area Manager (MAM) has responsibility in the period.

SLAD personnel report that the variance or difference between the number of employee-hours budgeted (basis for request for PMO reimbursement) and the number of employee-hours actually used to complete a FU SL LFT&E task is not tracked in detail. If, however, there are significant changes made in the tasks required of SLAD employees, the budgeted reimbursements are adjusted to reflect the difference in hours needed for completion of assigned tasks. Labor costs associated with the additional hours required are funded frequently with a combination of PMO and mission dollars.

Costs incurred for materials (e.g., experimental materials in modeling) required in SLAD tasks are included in dollar amounts requested by SLAD for PMO reimbursement. The significant portion of the SLAD costs, however, is for employee services (including the overhead administrative costs related to SLAD division and directorate offices).

3.4.2 Cost of Test Center Activities. There are three major LFT activities performed by the test center: (1) planning for the FU SL LFT, including preparation of the DTP, (2) execution of the FU SL LFT, including instrumentation and target repair and maintenance, and (3) preparation of the DTR. In addition, test center personnel serve as members of the LFIPT led by EAC and the damage assessment team led by SLAD. The test center assembles a dedicated test team, headed by the test director and specifically trained in the operation, maintenance, and repair of the test articles. The test team includes data collectors who provide the required test data to the test director for inclusion in the test report.

The test center typically is involved in planning activities for several years prior to the actual execution of the FU SL LFT. Its planning activities include developing or procuring unique instrumentation as needed for test execution, investigating and developing techniques to fire unique and/or foreign ammunition in accordance with LFT objectives, coordinating training necessary for test execution events, and handling logistics of obtaining and maintaining test assets, spare parts, etc. As part of its participation in the planning for the LFT program, the test center provides cost and time estimates for each of the test center activities that make up the FU SL LFT&E.

As an example of the costs of a (TECOM) test center, ATC costs are discussed in the following paragraphs. The FU SL LFTs of the Abrams M1A2 and the ATACMS Block IA (arena tests) were conducted at ATC at APG. The Bradley A3 FU SL LFT, begun at ATC during the month of December 1998, is scheduled to be completed in July 1999. In addition to test ranges, ATC provides technical shops, performance measurement laboratories, and instrumentation and analysis laboratories. Employing instrumentation designed to evaluate crew survivability, ATC personnel measure crew incapacitation parameters as part of the tests of vehicle vulnerability.

The assigned ATC test director has the responsibility to develop a test plan that meets the technical objectives of the customer at the least possible costs. In preparing its cost estimates for the PMO customer, ATC reports that it conducts a detailed analysis of labor and material costs, relying on historical cost data, expert opinion, and relevant cost estimate methodologies.

ATC is reimbursed by the PMO for costs incurred in FU SL LFT on the bases of the activities required by the LFT program (e.g., setup, repair, analysis, completing test report) and the costs of materials and services required to complete those activities. In computing the expected costs for a specific activity to be performed as part of the FU SL LFT program, the ATC project manager (1) identifies all tasks and subtasks required to complete the activity, (2) determines the skill (e.g., data quality, international imaging, welding) and skill level required to complete the identified tasks, and (3) projects the number of employee-hours needed to complete all identified tasks. Using the project management software, the cost estimate for the FU SL LFT program is established by summing across all required tasks (1) the respective products of estimated hours projected for each skill and average wage rate established for the identified skill and (2) the other nonlabor costs incurred in the task.

ATC charges the PMO customer for labor costs of government and contractor personnel supporting the test program and the costs of materials and supplies; petroleum, lubricants, and oil (PLO); travel; and other test-specific requirements as directed by the PMO. ATC accounts for the cost of each employee's service by multiplying the actual hours worked by the ATC employee engaged in a FU SL LFT task by the specific wage rate for that employee's services. The wage rate is computed by adding the employee's hourly wage rate (i.e., basic salary with fringe benefits) to the hourly *test support distributive rate* identified for services rendered at ATC. *The test support distributive rate* is established by the ATC budget office at the beginning of the fiscal year by determining the relationship of estimated indirect costs of testing for the period (e.g., testing utility costs, maintenance contracts for support vehicles, hazardous waste disposal, ammunition handling, printing, range control, test support supervisors above the working leader level, costs of range control) to projected direct labor hours to be performed by ATC employees for the period. As Department of Defense (DoD) customers, PMOs do not incur any additional charges for the general and administrative costs of ATC operations.

The PMO pays for interruptions and shutdowns that are necessitated by its system, and repeated startup and shutdown cycles increase the costs incurred by the PMO over and above budgeted amounts. In general, ATC attempts to minimize the costs of the PMO by reassigning those support personnel originally designated for the FU SL LFT of a system to other jobs when shutdowns occur.

Vehicle and crew instrumentation (e.g., instrumentation to measure ballistic shock, blast overpressure, crew acceleration, toxic gases, and thermal radiation) costs include only the costs of labor associated with the instrumentation activities, unless the instrumentation is destroyed or damaged during the test (e.g., fire consumes a TV camera in a test article following shot). Expendable supplies used in testing (e.g., wiring, connectors, tubing, transducers) are charged to the PMO. If instrumentation needed in test execution is not owned by ATC, ATC investigates the feasibility of borrowing or renting that instrumentation. If attempts to obtain instrumentation by other means are not successful, ATC purchases the instrumentation and charges the cost to the PMO. Training costs that are generic to instrumentation for multiple systems are budgeted into the test support distributive rates of ATC, but system-specific training costs must be directly reimbursed by the PMO of the system.

ATC provides the PMO with a formal cost estimate prior to test execution and requires the PMOs to front-forward the budgeted costs of ATC activities (i.e., pay prior to performance of FU SL LFT activities) and incrementally fund the program per fiscal year. If the formal cost estimates funded by the PMO exceed actual costs, the PMOs are allowed to withdraw the unused funds or apply those funds to a follow-on test program, an upgrade in ATC's facilities, or the purchase of materials or instruments for a future test program.

ATC reports ongoing LFT program costs to the PMO upon request. Costs are prepared with a software package that computes costs incurred to date on the basis of activities completed and ATC assigned costs for actual employee services rendered and materials used. The liaison officer of the PMO has direct access to the computer system (i.e., TRMS) for tracking costs.

3.4.3 Cost of HQ, TECOM Activities. HQ, TECOM oversees the coordination of the DTP and the DTR of systems designated to be tested by TECOM centers and is responsible for the review of the DTP and the DTR for LFTs assigned to non-TECOM test centers. In addition, HQ, TECOM personnel serve on the LFIPT led by EAC. The TECOM test manager assists the evaluator and the PMO in the development of the LFT&E strategy, the resolution of LFT&E issues such as scheduling and test configuration, and the execution tasking to other test centers. With the exception of limited travel costs, costs incurred by HQ, TECOM are personnel costs and are part of the HQ, TECOM budget. These costs are not reimbursed by PMO funds. Travel costs related to LFT program activities are reimbursed by the PMO.

3.4.4 Cost of USAOC&S Activities. The major FU SL LFT&E activity conducted by USAOC&S is BDAR analysis, in addition to participation on both the LFIPT led by EAC and the damage assessment team led by SLAD. In an effort separate from the damage assessment effort led by SLAD, USAOC&S conducts the BDAR analysis to determine the ability of the system tested to be returned to an operational status after a hit from threat munitions (i.e., vulnerability test) or the ability of the threat vehicles (i.e., targets) to be returned to operational status after a hit from the system tested (i.e., lethality test). Reimbursement by the PMO to USAOC&S for BDAR analysis and participation in damage assessment, activities generally performed by military personnel, is made only for travel-related costs required to accomplish these activities.

3.4.5 Cost of EAC Activities. The three major LFT activities performed by EAC are (1) serving as lead for the LFIPT, working group under the T&E IPT; (2) preparation of the EDP, an independent evaluation of the FU SL LFT; and (3) preparation of the SER. PMOs are responsible for all costs related to FU SL LFT&E except for the costs of those organizations that have mission-related responsibilities in the LFT&E program, including EAC as a division of OPTEC. EAC reports that PMOs are "taxed" a certain amount for evaluation activities performed for certain Acquisition Category (ACAT) systems. The dollar amount in the PM budget line designated for OPTEC activities is determined at the Pentagon level and is part of the original allocation of funds to the PMO. PM personnel report that funds required by EAC and Operational Evaluation Command (OEC) divisions to perform evaluation activities relevant to their systems are part of the PMO budget, and funds are distributed to these agencies during the fiscal year.

3.5 Benefits of FU SL LFT&E. DoD Regulation 5000.2-R reports [9]:

> The objective of LFT&E is to provide a timely and reasonable assessment of the V/L of a system as it progresses through its development and prior to full-rate production. In particular:

- to provide information to decision makers on potential user casualties, vulnerabilities, and lethality, taking into equal consideration susceptibility to attack and combat performance of the system;

- to ensure that knowledge of user casualties and system vulnerabilities or lethality is based on testing of the system under realistic combat conditions;

- to allow any design deficiency identified by the testing and evaluation to be corrected in design before proceeding beyond low-rate initial production; and

- to assess battle damage repair capabilities and issues (... not a statutory requirement of LFT&E, ... assess such capabilities whenever prudent and affordable).

Supporters of mandated testing suggest there are significant *benefits* associated with requiring FU SL LFT&E for major U.S. weapon systems. Discussion of the rationale of proposed benefits is presented in the paragraphs that follow.

- FU SL LFT&E provides an opportunity to identify unknown vulnerabilities of the system, thus allowing design or engineering changes to be made prior to the system entering full-scale production.

- FU SL LFT&E provides insights into BDAR potential.

- FU SL LFT&E provides an opportunity to validate M&S tools developed by analysis groups.

- FU SL LFT&E provides valuable input to doctrine, tactics, and training decisions of system users.

- FU SL LFT&E requirement helps to ensure adequate consideration is given to V/L issues throughout the acquisition cycle.

3.5.1 FU SL LFT&E and System V/L. The General Accounting Office (GAO) reports that FU SL LFT&E provides the opportunity not only to identify unknown unknowns in the tested system, but also to gain insight into the system's known unknowns that are suspected but not well understood. The GAO researchers propose that FU SL LFT&E is the only V/L assessment method that provides direct "visual observation of the weapon/target interaction under realistic combat conditions [10]."

In general, FU SL LFT&E provides an opportunity to gain insights into (1) the synergistic effects of multiple damage mechanisms, (2) the phenomena of blast and shock, (3) the effects of fire, toxic fumes, and the fire suppression system, (4) the effects of secondary and cascading damage (e.g., secondary debris and ricochet) not revealed in component or subsystem testing, (5) the effects of noncritical component damage on critical components, and (6) the effectiveness of redundancy and other vulnerability reduction measures with respect to continued operation of the system tested [11–14]. In addition, LFT provides data to support target signature impact research and the quantification of radiation hazard in target vehicles.

Proponents of FU SL LFT&E argue these insights can lead to the correction of errors and defects through redesign and engineering changes of the weapon system at the component, subsystem, and system levels, thus decreasing the potential for personnel casualties, system and environmental losses and increasing the probability that the system will be able to complete its mission when operating in a hostile environment. Mr. James F. O'Bryon, DDOT&E (LFT), believes LFT&E motivates decision-makers to find feasible solutions for V/L deficiencies [11]. He cites multiple *fixes* that have been implemented as a result of FU SL LFT&E, including the shielding of components, the adjustment of trigger thresholds, and the revision of stowage compartments.

3.5.2 ***FU SL LFT&E and BDAR Activities.*** Although not a statutory requirement of LFT, FU SL LFT&E provides valuable input to decisions relative to BDAR activities. FU SL LFT&E affords insights into the adequacy of current stock levels of spare parts and the effectiveness of current BDAR and troubleshooting procedures [10, 15, 16]. BDAR activities related to FU SL LFT produce experiences from which new repair techniques and procedures are able to be developed and provide realistic time estimates for returning damaged vehicles to combat.

3.5.3 FU SL LFT&E and M&S. FU SL LFT data provide input to the calibration/ validation of lethality and vulnerability models. Because these V/L models are used to develop pre-shot predictions for FU SL LFT&E and may be used to extend the results of testing, the data provided by the FU SL LFT&E of any one system may be significant to the FU SL LFT&E of future systems. In the past, critics of FU SL LFT&E conceded that tests may disclose valuable V/L issues that had been overlooked in existing M&S tools (e.g., toxic fumes or penetrator break-up in BFVS) but submitted that FU SL LFT&E data were unable to provide information of significant value in the validation of models [10, 17]. In recent years, however, FU SL LFT&E data have provided the bases for validation activities. For example, the entire validation of the MUVES-S2 model for the Bradley A3 LFT was based on the results of the Bradley High Survivability (HS) LFT, and the validation of the SAFE model for the ATACMS LFT&E was based on the results of the arena tests that were part of the LFT program. Similar plans exist for validation of models to be used in the FU SL LFT&E of the M1A2 System Enhancement Package (SEP). Data collected from the LFT activities of one system may provide useful data for the V&V of models to be used in the T&E activities of similar systems or later models of the same system.

3.5.4 FU SL LFT&E and Users' Decisions. FU SL LFT&E provides valuable input to the development of both the procedures for preparing crew and system for battle and the doctrine and tactics for a system's operations in hostile environments [13–15]. Data prepared for FU SL LFT incidents furnish information for training simulators and operational tests' assessments [14, 15].

3.5.5 FU SL LFT&E and Survivability/Lethality Assessment Programs. Because the results of testing cannot be the sole basis for V/L assessment, it is important that an appropriate weight is given to V/L issues in the design and engineering phases of the system's development [17]. Supporters of FU SL LFT&E suggest congressionally mandated LFT&E helps to ensure adequate attention is given to V/L issues throughout the acquisition cycle by the PMO and contractor(s) [12, 13].

Proponents of FU SL LFT&E question whether the discipline to proceed with a well-organized program of V/L assessment would continue should FU SL LFT&E

requirements be terminated. Mr. Thomas Julian, Action Officer, DOT&E (LFT), reports the results of a recent survey of PMs, testers, and analysts indicate the majority of those surveyed believe "the old way of doing business" would return if FU SL LFT&E were no longer required of U.S weapon systems prior to entering full-scale production [15]. The high visibility of the FU SL LFT&E mandate appears to provide a certain degree of motivation for PMOs and contractors to consider V/L issues over all phases of acquisition [17]. Some suggest this high visibility also helps to ensure a higher level of congressional funding for V/L assessment activities than may be provided for alternative strategies of assessment that do not include the FU SL LFT element.

3.6 Project Manager Offices: Impacts of FU SL LFT&E. Visits to the ATACMS PMO, AMCOM, Redstone Arsenal, AL, and the Abrams and Bradley PMOs, TACOM, Warren, MI, were part of the information-gathering process for this study. In each location, members of the PMO participated in discussions relevant to the programs of survivability/lethality in operation for their respective systems and the role of FU SL LFT&E in assessment of system V/L. Prior to visits with PM personnel, questions concerning the system and survivability/lethality assessment were sent to the PMOs. Discussions focused on the responses of the PM personnel to those questions and topics that arose from their responses.*

Discussions with PMO personnel covered a wide range of topics, including:

- objectives of the research study,
- current methodologies requiring the identification and measurement of the impacts of competing T&E strategies,
- organization of the PMO and the role of PMO in system acquisition,

* The views of PM personnel described in this report were not expressed by all persons in all three PMOs. Although a group of core topics formed the foundation for all PMO discussions, there were some topics explored in only one or two offices. In general, personnel in any one office did not disagree with the views expressed by other persons in that same office participating in the discussion. Following each PMO visit, PMO personnel were sent a summary statement of the questions asked and the responses recorded during the visit and were asked for comments. PM personnel were also given an opportunity to review this part of the report (i.e., Project Manager Offices: Impacts of FU SL LFT&E) prior to submission.

- phases of acquisition and the activities relevant to each phase,
- history of live-fire testing of earlier models of the identified system,
- contracts for all phases of system development and production, including use of CAIV and target costing in contracts,
- production history of current/earlier models of the system and related costs,
- effects of foreign military sales of system on contractor charges to government,
- responsibilities of the contractor and government agencies in developmental and operational testing,
- budgeting for FU SL LFT&E and follow-on tests,
- activities of FU SL LFT&E and the role of the PMO in those activities,
- costs incurred in FU SL LFT&E, reported and unreported,
- design of the FU SL LFT&E,
- role of M&S in V/L assessment, and
- benefits of FU SL LFT&E or lessons learned from FU SL LFT&E.

Much of the specific system information gathered from the PM discussions has been incorporated into other sections of this report. This part of the report focuses on the perceptions of PM personnel relative to the costs and benefits of FU SL LFT&E as one part of the survivability/lethality assessment process *and* the suggestions of PM personnel for improving the cost-effectiveness of the assessment process.

Discussions related to the impacts of FU SL LFT&E emphasized four main topics: (1) the objectives of FU SL LFT&E, (2) the effect of the system's existing program of survivability/lethality evaluation on the design of the FU SL LFT, (3) the alternatives to

FU SL LFT&E, including M&S, and (4) the lessons learned from a completed FU SL LFT&E.

3.6.1 Objectives of FU SL LFT&E. Guidelines for LFT&E cite the importance of carrying out tests sufficiently early in the development phase to allow for design deficiencies to be detected and corrected in the weapon system tested. Objectives of LFT&E include (1) ensuring that knowledge of user casualties and system vulnerabilities and lethality is based on realistic testing of the system configured for combat against expected threats and (2) gaining insights into potential design flaws so that they can be corrected before the system enters full-rate production [9].

In discussions with PM personnel, questions were raised as to whether FU SL LFT&E, conducted at the conclusion of the Engineering and Manufacturing Development (EMD) phase, occurred too late in the acquisition process to impact design or secure (relatively) inexpensive fixes. The ATACMS PMO argued that if a discovery were made in a FU SL LFT relative to the adequacy of the system's bomblet lethality, subsequent changes in the bomblet would affect the entire production line. Changes in design made late in the production cycle would impact all qualitative tests completed prior to the design change and, in turn, would impact the system evaluation required prior to the system entering full-scale production. PM personnel emphasized that problems related to design and engineering requirements need to be forecasted as early in the acquisition process as possible. FU SL LFT is often too late to afford effective fixes in a cost-efficient manner.

3.6.2 Design of FU SL LFT&E. Does the system's existing program of survivability/lethality affect the plan of the FU SL LFT&E? Is the scope of the FU SL LFT plan more restricted (i.e., less shots) for a system that has a well-developed agenda for evaluating system survivability/lethality built into its acquisition program than the scope of the FU SL LFT plan for systems without such an agenda? Is the FU SL LFT of a system with a building-block program of survivability redundant (i.e., a series of tests repeated at an independent location)?

Abrams PMOs believe the well-managed survivability test program associated with Abrams systems addressed most of the vulnerability issues prior to the M1A2 FU SL LFT&E. The M1A2 FU SL LFT&E in 1993 confirmed the PMO conviction that the M1A2 was a very survivable tank based on the limitations of its 69.9-ton gross weight. The Abrams' PMO reports that from its initial concept, the Abrams was developed with survivability as its first priority, and the results of the 1993 FU SL LFT came as no surprise to the PMO. In its different variants, the Abrams has undergone extensive survivability testing, including tests of its armor, structures, and ballistic hull and turret (BH&T), as well as system-level tests not under independent congressional LFT&E auspices. PM personnel questioned whether congressionally mandated FU SL LFT&E was not a very expensive final check on crew and tank survivability under live-fire conditions. Several interviewees voiced the belief that when EMD includes a well-designed and well-managed survivability/vulnerability program, the results of FU SL LFT&E are predictable and the likelihood of major surprise outcomes is small.

3.6.3 ***Alternatives to FU SL LFT&E.*** Individuals interviewed acknowledge that a LFT program provides insight into the areas of component, subsystem, and system vulnerability/lethality; damage and casualty mechanisms; perforating and nonperforating impacts on the system; and system- or threat-specific subissues such as compartmentalization, stowed munitions, fuel and hydraulics, fire suppression systems, and blast, shock, and incendiary effects. The question, however, remains, "Are there more economical ways than FU SL LFT&E to obtain the information needed by decision-makers or to discover the unknown vulnerabilities?" Is FU SL LFT&E designed with the objective of obtaining information needed by decision-makers that is not available from other sources?

Abrams PM personnel provided an example in which off-line tests were conducted to verify the design of two very important survivability fixes. The tests consisted of seven high-caliber shots on an earlier model with fixes incorporated. The total test cost was reported to be approximately 25% of the cost of one FU SL LFT&E shot. The question then becomes, "If resources are limited, is adequate consideration given to alternative methods (i.e., methods other than FU SL LFT&E) to gather information required for assessment decisions?" Interviewees agreed that the response to this question is different for each FU SL LFT&E. Citing recent technological developments, Abrams PM and Bradley interviewees noted that in the survivability programs of earlier models, some system-level effects were *only* testable in FU SL LFT&E. Currently, however, some of the same effects can be assessed in off-line tests (e.g., effects of blast and shock in WSMR air blast tests).

A second issue raised in discussions concerned the balance of engineering-shot lines (i.e., shots selected to address specific V/L issues) and random-shot lines (i.e., shots generated from likely hit points) in the FU SL LFT program. Interviewees suggested that controlled damage tests (CDTs) and the engineered shots of FU SL LFT&E often produce the data that decision-makers require with minimum test asset repairs. Personnel expressed frustration that in some situations the PMO is aware of and concedes damage with planned random shots, but the random shots remain part of the FU SL LFT&E plan. Frustration was also expressed that attempts by the PMO to modify configurations of the test items to eliminate expensive line replacement units were often unsuccessful. Interviewees hastened to add that they understood random shot lines were a part of the realistic combat setting required in FU SL LFT and that a balance of random and engineering shots was important to the perception of a fair test of the system's V/L. Concern was expressed, however, that many more dollars are now spent on random shots than on engineering shots in which more useful information is often received.

In particular, PM personnel were asked if they believed M&S could serve as an effective substitute for live-fire testing in the assessment of the V/L of a weapon system. Interviewees were in agreement that both M&S and testing are needed in V/L assessment—that they serve as *complements to* rather than *substitutes for* each other. They emphasized that testing is required in the development of M&S tools to ensure M&S robustness and fidelity; in turn, M&S is needed to extend the results of testing to a broad range of weapon system–target encounters.

Although all interviewees expressed the opinion that significant progress in M&S is needed before any substantial cuts in testing would be feasible, interviewees expressed the hope that M&S would eventually be mature enough to allow substantial reduction in the required number of FU SL LFT shots.* They cited the important role that M&S plays in the design of the system (e.g., layouts of interior or placement of armor) and the advancements in modeling of damage mechanisms (e.g., penetrating shots). They strongly encourage testers and modelers to continue to work together to ensure that testers understand the type of information that is required for building models. ATACMS PMO cited the valuable input provided by the tire tests (i.e., tests related to the ATACMS Block IA LFT) to the subsequent modeling of tire effects. In a similar manner, ATACMS PM personnel believed that ATACMS follow-on tests would contribute to the modeling of fire effects.

Although all groups supported the effort to devote more dollars to the development and improvement of M&S tools, all were quick to point out that the funds available for testing and M&S are limited and that tradeoffs are a fact of life. Several interviewees suggested more effort should be made to integrate modeling and testing to provide information needed for decision-makers in a more cost-effective manner. Views were expressed that even with its current limitations, M&S can be combined with nondestructive testing to produce valuable data. All realized that this is a complex situation, as funding of additional tests and experiments to improve the fidelity of models often leads to more questions that must be resolved by additional testing.

In general, there appeared to be consensus across the groups that two major issues related to M&S remain to be resolved: (1) how to obtain the financial resources needed for the development of high accuracy M&S tools and (2) how to ensure the acceptability of an increased role for M&S in the assessment of survivability/lethality of a weapon system.

3.6.4 Lessons Learned from FU SL LFT&E. Although it is difficult to measure the benefits of FU SL LFT *ex ante*, it may be helpful to look at the lessons learned from a

* Some argue that a substantial reduction in the required number of shots has already taken place for a variety of reasons. For example, Phase II of the FU SL LFT of the Bradley M2 and M3 in 1986–1987 included over 80 shots (i.e., random, prescribed, and conceded/repeated shots, as well as repeated Phase I and Development Test shots), as compared to the scheduled 18 shots of the 1998–1999 Bradley A3 FU SL LFT.

completed FU SL LFT&E program as an *ex post* measure of the effectiveness of the FU SL LFT activity. Interviewees in the PMOs of the two systems in this study that had completed a FU SL LFT&E were asked about their perceptions of the benefits of the test and what actions were taken in response to system deficiencies discovered in the test series.

ATACMS PM personnel reported that, while the FU SL LFT for the ATACMS Block IA did not answer all questions about the effectiveness of all M74 bomblet damage mechanisms, it did point out the potential for product improvement. It also pointed out the need for more modeling and analysis in the characterization of the bomblet earlier in the acquisition process. At the time of the interview, the ATACMS PM office was planning follow-on tests (required before full-scale production could begin) to further examine the effectiveness of the M74 bomblet against potential target elements.

Abrams PM personnel reported that the M1A2 Abrams FU SL LFT verified some fixes on problem areas discovered on prior FU SL LFTs and indicated some new vulnerabilities that could be eliminated or minimized with modifications. Problem areas that surfaced were reported to be small. Personnel pointed out that two prior fixes had been verified on off-line tests related to LFT&E and that FU SL LFT basically confirmed what the PMO already knew about the M1A2. They believe the results of the FU SL LFT support their belief that the Abrams survivability test program previously addressed most of the vulnerability issues of the weapon system. Personnel estimated that 80–90% of data uncovered in 1993 FU SL LFT could now be discovered in a test program that did not include FU SL LFT. Personnel acknowledge, however, that some of the technology that is available at this date was not available at the time of the M1A2 Abrams FU SL LFT. For instance, the use of shock simulators currently affords a method of testing off-line that was unavailable in 1993.*

* The ballistic shock simulator developed by ATC is not a replacement for shock testing on a full-up vehicle. Although useful in identifying weak components prior to FU SL LFT, the simulator offers no guarantee that a component that does not fail on the ballistic shock simulator will survive the FU SL LFT.

Abrams personnel reported that potential fixes are briefed as part of MS III deliberations but that modifications or fixes are determined not solely by the PMO but by an oversight committee with input from system users and trainers, system developers, and logistics personnel. Decisions relative to which fixes are implemented are made on the bases of the priorities assigned fixes uncovered in testing and the availability of funds. Often, corrective actions are incorporated into later designs of the system.

The Abrams M1A2 FU SL LFT&E resulted in 12 recommendations, including 9 fixes that were initiated for production retrofit or incorporation into future tank design, 2 that were reviewed but not implemented, and 1 that was not addressed. In addition, some LFT insights were incorporated into the tactics, training, and planning of the system user to improve the survivability of system personnel in the combat environment.

*3.6.5 **Suggested Actions.*** In discussing the effectiveness of FU SL LFT&E and the lessons learned from tests completed, PMO personnel offered the following suggestions to improve the cost-effectiveness of survivability/lethality assessment and, in particular, the cost-effectiveness of FU SL LFT&E as part of the assessment process:

- Enlist multiple supporters for the development and V&V of M&S tools (OSD, PMO, etc.). Encourage modelers and testers to integrate efforts.

- Provide additional funds in the early phases of acquisition to allow up-front discussions of M&S with SLAD personnel; currently, PMOs are unable to fund this activity prior to the establishment of user requirements.

- Organize a round-table discussion in the early stages of the acquisition process for ARL personnel and all parties of T&E activities to consider carefully alternative methods of obtaining information needed by decision-makers in the assessment of system V/L.

- Enlist involvement of the evaluator very early in the T&E process, using a team approach with the evaluator as a member of the team. PM personnel suggest the oversight of government evaluators in contractor testing allows the positive results of those tests to be included in the government evaluation. PM personnel noted that this cooperation has been more common in recent LFT programs than in prior test programs.

- Consider limiting the scope of the FU SL LFT&E of those systems managed by PMOs with well-established building-block programs of survivability/lethality assessment in place. Scope limitation could serve as an incentive for incorporating V/L assessment into all phases of the acquisition cycle.

- Consider carefully the balance of engineered and random shots in FU SL LFT, weighing the cost incurred for information obtained. Consider alternative tests or forms of analysis and the costs associated with those tests and analyses in designing the number and types of shots in the FU SL LFT&E strategy.

- Consider granting concessions in FU SL LFT&E. In years prior to the congressional LFT&E mandate, critical components of a system often were removed before testing in FU SL LFT, if the PM office conceded the system would fail with hit. Some PM personnel questioned the cost-efficiency of FU SL LFT congressional test requirements that mandate that critical components remain in the test asset.

PMO personnel explained that some of their problems with FU SL LFT&E originate with the fact that PMOs focus on demonstrating that a system is in compliance with the ORD for the system, but FU SL LFT&E often is structured to evaluate a system beyond its requirements. Therefore, PMOs frequently find it difficult to fully support LFT&E and the incorporation of design fixes that the FU SL LFT indicates are needed for the system that has been evaluated beyond its requirements.

In conclusion, it is important to emphasize that the PMOs visited did not discount the benefits of an LFT&E program. Interviewees stated that changes in materials and technology in recently produced weapon systems require a program of LFT&E and that alternative tests may not *catch everything* found in a FU SL LFT. Most of the above suggestions offered by PM personnel attempt to address the question of how limited resources may be employed to design the most effective plan for assessing the survivability/lethality of a weapon system.

4. Framework for Vulnerability/Lethality Assessment

In the current era of constrained resources, the effectiveness and efficiency of a V/L assessment strategy may be increased by the identification of the specific set of data required for assessment, the determination of the subset of the required data currently available from reliable sources, and the selection of a cost-effective *assessment plan* (i.e., M&S, experimentation, FU SL LFT&E, etc.) to fill the data voids. Although the approach described in the following paragraphs is applicable equally to lethality assessment, the discussion offered in this part of the report is limited to vulnerability assessment.

In assessing the vulnerability of a weapon system, analysts evaluate the system's likelihood to sustain personnel casualties, suffer catastrophic losses, or fail to complete its mission when faced with those threats deemed likely to be encountered in combat. Faced with decreased defense budgets, it is important for analysts to employ an assessment strategy that allows vulnerabilities to be detected as early in the acquisition process as possible, thus affording the maximum time to develop *fixes* prior to the system entering full-scale production. An effective vulnerability assessment program begun early in the acquisition process has the potential to detect system vulnerabilities and reduce or minimize not only the costs associated with combat losses but also the costs associated with retrofit of systems in the late stages of production.*

* *Fixes* associated with vulnerabilities detected late in the acquisition cycle are less likely to be able to be achieved through redesign or re-engineering of the system and more likely to be associated with the higher costs of retrofitting of completed systems. Serious vulnerabilities detected late in the acquisition cycle could lead to system abandonment. Although it is acknowledged that not all vulnerabilities can be eliminated, knowledge of a system's vulnerabilities may affect users' tactics and strategies in combat.

Limited resources have led to an increased emphasis on the costs as well as the benefits of conducting vulnerability assessments of weapon systems. It is proposed in this section of the report that an effective vulnerability assessment strategy identifies the specific set of data required for vulnerability assessment, determines the subset of the required data currently available from reliable sources, and then designs a vulnerability assessment plan (i.e., M&S, experimentation, FU SL LFT&E, etc.) to fill the data voids. Alternative vulnerability assessment plans, designed to provide the missing critical data, must be compared on the bases of (1) the capacity of each plan to provide the critical data (i.e., benefits of plan), (2) the cost to accomplish each plan, and (3) the uncertainty (risk) associated with each plan's capacity to provide the critical data at the identified cost within the time constraints of the assessment process.*

An effective vulnerability assessment strategy includes both an analysis of the likely combat scenarios and a determination of the links between the measures of battlefield effectiveness and the measures of capability required of the system to complete its mission. In turn, the vulnerability assessment plan is designed to fill the data voids that exist in the analyses of (1) the relationship between the threat-system interaction and the collection of components associated with system and personnel vulnerability that have been damaged and (2) the relationship between this collection of damaged components and the measures of capability required by the system to complete its mission.

The V/L Taxonomy is suggested as the appropriate framework for identifying the information required in the vulnerability assessment process, as well as the data voids to be addressed in the vulnerability assessment plan [2]. A description of the methodology for the design of cost-effective vulnerability assessment plans and the selection of the optimal plan from those alternatives follows a review of the Taxonomy.

4.1 Taxonomy of the V/L Analysis Process. The V/L Taxonomy provides a framework for examining the elements of the complex vulnerability assessment process.

* Time constraints must consider the availability of hardware required to complete test plan components.

The V/L Taxonomy was first introduced by Deitz and Ozolins in 1989 as a conceptual framework for armored fighting vehicle vulnerability assessment in association with the computer simulation of the Abrams Live-Fire Field Testing [2]. The general description of the V/L Taxonomy that follows is based on the cited publication plus several subsequent publications that have discussed the analytical properties of the V/L Taxonomy [2, 18–24].

The V/L Taxonomy reflects the vulnerability analysis process as a sequence of several levels, each containing specific information about the analysis process.* The information in one level is mapped to the information in the subsequent level by a transformation or a mapping process. A description of the taxonomy includes four levels with associated spaces† as shown in the graphical representation found in Figure 1.‡ Mapping from higher to lower levels (i.e., Level 1 to Level 2; Level 2 to Level 3; and Level 3 to Level 4), the taxonomy can be described as follows:

- **Level 1** defines the initial configuration of the specific threat and weapon system (i.e., target for which vulnerability is assessed) encounter. **Space 1** includes the set (i.e., all combinations) of the initial configurations of the threat and system just prior to threat-system interaction.

- **Level 2** defines the physical state or the damage state of the weapon system that results from the interaction of the threat and system. **Space 2** includes the set (i.e., all combinations) of damage states. Each state, represented by a point in Space 2, is generally expressed as an *n-tuple* with elements describing the status of certain specific *n* number of components of interest. In the V/L Taxonomy,

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* The V/L Taxonomy also applies to lethality analysis. In this report, however, only vulnerability analysis is addressed.

† A *level* includes all the information necessary to define the state of the system at the associated stage of the vulnerability analysis. A *space* of points may be defined at each level to represent the state of the system at that level. Each point in a defined space is a vector with a specific number of elements, each element referring to the status of an entity related to the system (e.g., system components in Level 2). There may, however, be multiple spaces at each level, each space defined by a different set of elements in the vectors that make up that space at that particular level [23].

‡ Figure 1 is adapted from Figure 1: V/L Taxonomy Illustrated via a Mapping Abstraction, as presented in Deitz and Starks [19].

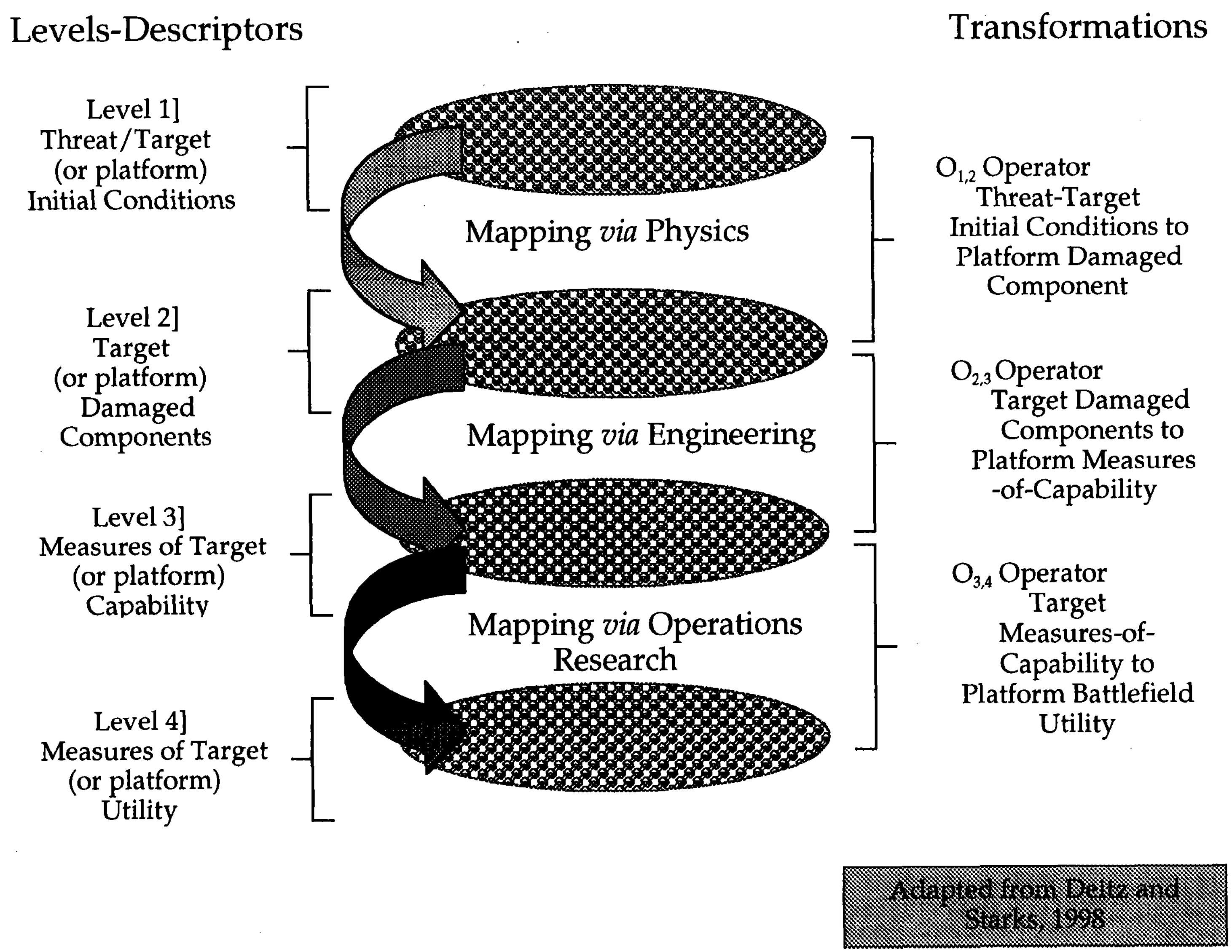


Figure 1. Graphical Representation of the Taxonomy.

each Level 2 state is expressed as a *damage state vector* with each element of the vector representing the status of a component following the threat-system interaction.

The transformation of the undamaged system of Level 1 to the damaged system in Level 2 ($O_{1,2}$) is a physical process and is characterized by physical damage mechanisms, such as threat penetrators, fragments, shock, or fire. The process of mapping a point in Space 1 to a point in Space 2 is generally stochastic, and a single point in Space 1, representing a threat-system configuration, may map to multiple points in Space 2 with each point in Space 2 represented by a different damage state vector. Thus, identical shots by a specific threat against a specific system, when repeated, often result in different damage state vectors for the targeted system. It is important to note that multiple points in Space 1 may map to the same single damage state vector in Space 2 [19, 20].

- **Level 3** defines the capability state of the weapon system that results from the threat-system interaction. **Space 3** includes the set (i.e., all combinations) of capability states. Similar to the damage state of Level 2, the capability state of Level 3 is expressed often as an *m-tuple* with elements describing the status of certain specific *m* number of capability or performance measures (e.g., capabilities related to firepower, mobility, communications, etc.) relevant to the system's mission.* Each state represents a point in Space 3 and is expressed as a *capability state vector* with elements representing specific levels of identified capabilities of the system. The capability state vector represents the aggregate capability of the system to function in areas relevant to the system's mission following threat-system interaction.

  The transformation of a damage state vector in Space 2 to a capability state vector in Space 3 ($O_{2,3}$) is a mapping of damaged components to the resulting reduced capability state. It is important to note that although a single damage state vector

* In this report, capability (not performance) measures are used to describe the metrics of Level 3 of the V/L Taxonomy.

in Space 2 maps to a single capability state vector in Space 3, multiple damage state vectors in Space 2 may map to the same single capability state vector in Space 3.

- **Level 4** defines the operational utility state of the weapon system that results from the aggregate system capabilities measured in Level 3. Data from Levels 2 and 3, combined with information relative to the combat scenario (i.e., threat environment, physical environment, and mission objectives) and users' tactics and doctrine, are used to determine the mission status points or the measures of effectiveness (MOEs) included in **Space 4**.

  The transformation of the capability vector in Space 3 to the operational utility state in Space 4 ($O_{3,4}$) is often perceived as outside of the process of vulnerability analysis and requiring the input of system users and military strategists. In reality, this mapping is often included as part of the vulnerability assessment with input provided by the system user or strategist.

4.2 V/L Taxonomy and Vulnerability Assessment. The V/L Taxonomy presented in the previous section provides a framework for an analysis of the vulnerability assessment process. In the vulnerability assessment of a weapon system, analysts ask the question, "To what extent will the interactions of the weapon system and the threats that the system is likely to encounter in combat result in personnel casualties (i.e., personnel vulnerability) or the inability to complete the system's missions (i.e., system vulnerability)?"

Before analysts are able to design cost-effective vulnerability assessment plans to address the aforementioned question, however, they must ascertain what information is needed to adequately answer the assessment question(s) and determine the subset of that information that is available from reliable sources. A comparison of the required information to the subset of available, relevant, and reliable information leads to the identification of the data voids (i.e., subset of the required information that is unavailable or unable to be relied upon). The data voids define the information that must be gathered in the vulnerability assessment plan.

4.2.1 The Required Data. To determine what data are needed to evaluate the crew and system vulnerability to threats likely to be encountered in combat, the analysts must have a clear definition of personnel and system vulnerability. U.S. Defense acquisition policies define vulnerability as [9]:

> The characteristic of a system that causes it to suffer a definite degradation (loss or reduction of capability to perform its designated mission) as a result of having been subjected to a certain (defined) level of effects in an unnatural (man-made) hostile environment.

In vulnerability assessment, analysts are interested not only in threat-system interactions that render the crew unable to complete its mission but also in interactions that result in injuries to the system's crew members and passengers even though the mission is able to be completed. System vulnerability includes any damage to the weapon system, including the catastrophic loss of the system, that does not allow for mission completion. To provide decision-makers with data characterizing the vulnerability of the system and its personnel, analysts must be able to collect information relevant to the following questions:

1. What are the likely combat scenarios in which this system will operate?

2. Considering the characteristics of the combat scenario (i.e., threat, physical environment, and mission objectives) and users' tactics and doctrine, what activities will the system be required to perform?

3. What enables mission success or completion in the identified combat scenarios? How is battlefield effectiveness of the system or mission success measured?*

* Traditionally, question nos. 1, 2, and 3 have been considered to be beyond the purview of the vulnerability analyst. The methodology described in this report emphasizes the importance of understanding the relationship between the tasks that must be completed to ensure a successful mission and the minimum levels of system capabilities needed to complete those tasks in a cost-effective vulnerability assessment.

4. What specific capabilities (i.e., capabilities in areas of mobility, firepower, communications, etc.) must be evaluated in the assessment of the effectiveness of the system?

5. What levels of the specific capabilities identified in #4 must exist to ensure mission completion?

6. What subsystems of the weapon system must be in operation to produce the levels of capabilities identified in #5 as necessary for mission completion?

7. What are the critical components of the subsystems identified in #6?*

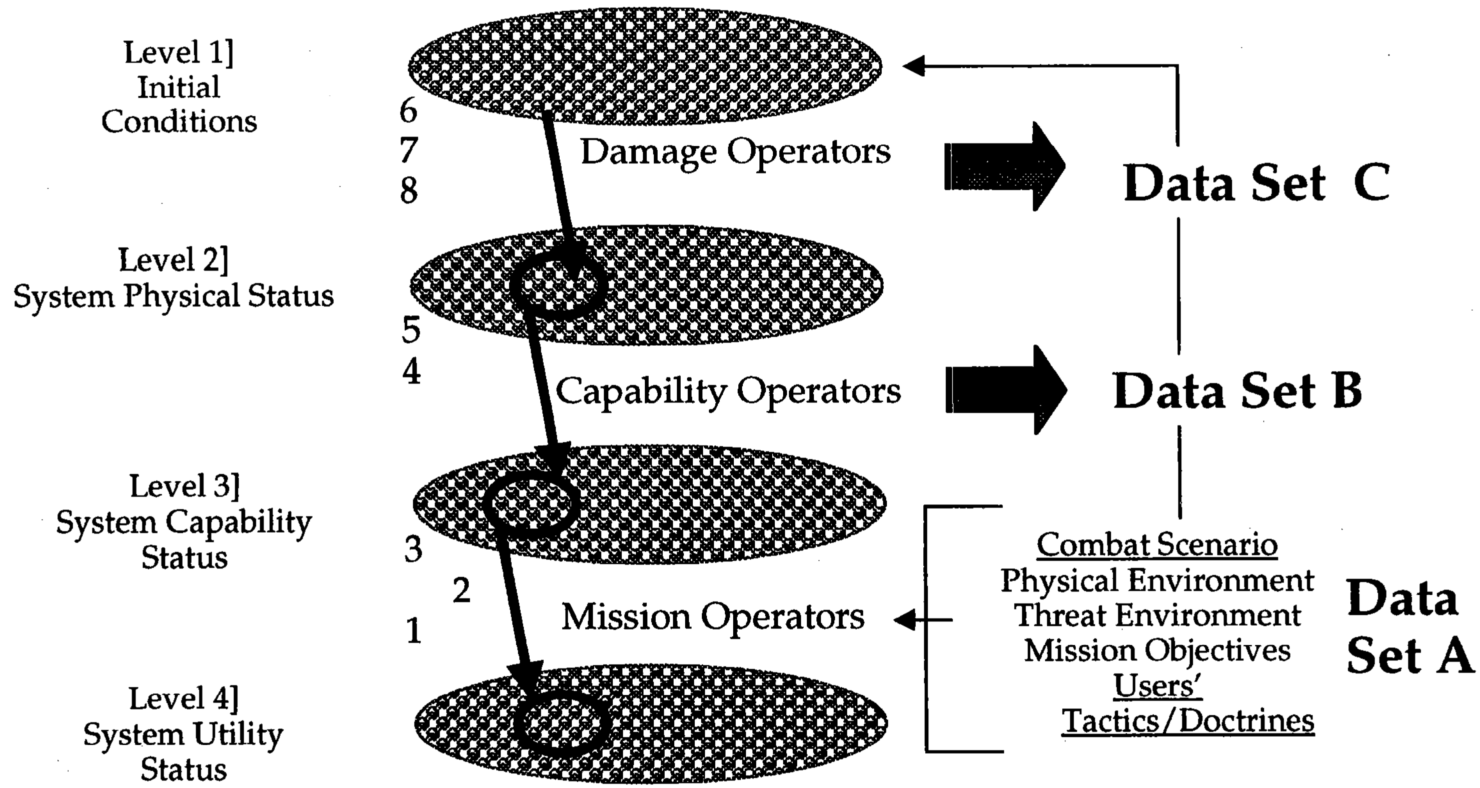
8. What type of damage (i.e., personnel casualties, catastrophic loss of the system, damage to critical components of the system) to the weapon system is expected from the interaction of the system and threats likely to be encountered in combat?

9. Given the damage states identified in #8 and the critical components of the system identified in #7, to what extent are the system and its personnel vulnerable?

4.2.2 The Taxonomy of Vulnerability Assessment. A few changes to the V/L Taxonomy shown in Figure 1 produce the Taxonomy of Vulnerability Assessment (Taxonomy VA) in Figure 2, an appropriate framework for addressing the preceding questions.† The Taxonomy VA provides the bases for describing the activities to be accomplished in the identification of the information required and available for the vulnerability assessment of a weapon system, as well as the information required but

* A system is composed of subsystems, and each subsystem is a set of components. Critical components are those components that if lost will result in a degradation of one or more subsystem functions and, consequently, a reduction in system capability [25].

† Figure 2 is an adaptation of the Mission-Based Acquisition Strategy, chart by Deitz [26].



= Subspace of vectors that map to a "success subspace" at the next level

Activities

1. Define system utility status
2. Develop mission operator(s)
3. Define system capability status
4. Develop capability operator(s)
5. Define system physical status
6. Define initial conditions
7. Develop damage operator(s)
8. Define system physical status
9. Compare system physical status in activity #5 to status in #8

Figure 2. Taxonomy of Vulnerability Assessment.

unavailable or unreliable (i.e., data voids). The activities listed in Figure 2 begin at Level 4 and are described as follows:

1. *Define system utility status (Level 4):* Define the likely combat scenarios and the role played by the weapon system in successful completion of identified mission(s). Define the measures of battlefield effectiveness available to describe the system utility or mission status (i.e., mission complete or not complete). The characteristics of likely combat scenarios (i.e., physical environment, threat environment, and mission objectives), as well as users' tactics and doctrine relevant to the system, serve as input to this activity. In Figure 2, the subspace shown at Level 4 includes those points representing outcomes in Space 4 that are associated with mission completion/success.

2. *Develop mission operators ($O_{3,4}$):* Develop the operators that map the mission-relevant system capability measures in Level 3 to the MOEs in Level 4. The mapping operators establish the link(s) between the *m-tuple* capability state vectors representing the specific *m* number of capability measures to be evaluated, and the MOEs, representing the mission status measures of battlefield success (i.e.,mission complete or not complete). A single capability state vector in Level 3 may map to one or more points or to no points in Level 4, depending on the tasks required in the combat scenarios represented in Level 4. In other words, a set of aggregate capabilities may lead to mission success in one or more given scenarios, but that same set of capabilities may not lead to mission completion in other scenarios that require a different combination of capabilities.

3. *Define (mission-relevant) system capability status (Level 3):* Define the minimum level of each of the *m* specific mission-relevant system capability measures (i.e., measures identified in activity #2) that are required for mission completion. This activity identifies the specific *m-tuple* capability state vectors in Level 3 (shown as subspace of Level 3 in Figure 2) that map to mission completion in Level 4 for a specific combat scenario. Each of the *m* elements in the capability state vector reflects the minimum level of the *m* number of measures of specific capabilities that must be achieved for mission completion.

4. *Develop capability operator(s)* ($O_{2,3}$): Develop the operators that map the damage states in Level 2 to the measures of capability in Level 3. The mapping operators or *degraded state operators* establish the link(s) between the damage state vectors, representing the damage states of the system following threat-system interaction, and the capability state vectors, representing the capabilities required to complete the mission(s). This mapping defines the components and subsystems that must be in operation to deliver the levels of capability identified in activity #3.

5. *Define system physical status (Level 2):* Define the specific critical components that must remain in operation (i.e., not killed) after threat-system interaction to result in the identified capability levels required for mission completion. Redundancies among components must be considered. This activity identifies the specific *n-tuple* damage state vectors of Level 2 (shown in subspace at Level 2 in Figure 2) that map to the required m-tuple capability state vectors of Level 3 (as identified in #3), which in turn map to mission completion.*

6. *Define initial conditions (Level 1):* Define the set of initial configurations of the threat (likely to be encountered in combat) and weapon system just prior to interaction. This set of configurations selected considers the mission objectives, the physical environment of combat, and the users' tactics and doctrine.

7. *Develop damage operators* ($O_{1,2}$): Develop the damage operators expected in interactions of the system and threat (e.g., damage mechanisms, such as threat penetration, fragment penetration, fire, or shock). The damage operators establish the link(s) between the initial conditions (Level 1) of the threat and weapon system prior to interaction and the damage state vectors of Level 2, representing the system's physical status following threat-system interaction.

* This mapping will also identify the specific *n-tuple* damage state vectors in Level 2 that will not map to the identified required *m-tuple* capability state vectors in Level 3.

8. *Define system physical status (Level 2):* Define the specific *n-tuple* damage state vectors (Level 2) that are mapped from the specific points (i.e., initial conditions) of threat-system interaction defined in Level 1. The *n* elements of the damage state vector describe the status (i.e., kill, no kill) of the *n* number of components of the system following a threat-system interaction.

   Analysts need to be able to predict not only the interactions that are likely to result in the loss of critical components, but also the interactions that are likely to result in personnel casualties (i.e., personnel vulnerability). Personnel casualties may also affect the probability of mission completion (i.e., specific number of fully functioning crew members may represent a critical component of system). This activity identifies system vulnerabilities associated with personnel casualties, as well as the potential for catastrophic loss of the system.

9. *Compare system physical status in activity #5 to status in #8*: Compare the physical status of the system required for mission completion (activity #5) and the identified physical status of the system following threat-system interaction (activity #8). This activity compares (1) the specific critical components that must remain in operation (i.e., not be killed) after the threat-system interaction to deliver the identified capability levels required for mission completion to (2) the specific critical components that are expected to remain in operation following the threat-system interaction.

   This activity identifies system vulnerabilities associated with a system's failure to complete its mission.

4.2.3 Data Sources. The Taxonomy VA clearly illustrates that the data required for the assessment of system vulnerability fall in one of three categories: (1) Data Set A (see Figure 2), data that link the mission-relevant capability measures of the system to the mission-status measures of battlefield success ($O_{3,4}$) in combat scenarios likely to be encountered by the system, given users' tactics and doctrine associated with those scenarios; (2) Data Set B (see Figure 2), data that link the damage state vectors resulting from threat-system interaction to the capability state vectors associated with mission success ($O_{2,3}$); or (3) Data Set C (see Figure 2), data that link the initial conditions of the threat-system interaction to the resulting damage state vectors ($O_{1,2}$). Sources for obtaining the required data are explored in this section.

To begin the vulnerability assessment process, the analyst must have a thorough understanding of the combat scenarios in which the system is likely to operate (i.e., the physical environment, the likely threats, and the mission[s] to be completed) and the relevant users' tactics and doctrine. A thorough analysis of likely scenarios forms the basis for determining the minimum levels of capabilities (i.e., Level 3 output) needed in the set of combat scenarios selected (i.e., activities #1–3 in preceding analysis). Sources for this information include the designated users of the weapon system, military strategists, and analysts and operations researchers associated with the evaluation agencies of the military service.

It is proposed that a major objective of vulnerability assessment is to evaluate the extent to which a weapon system retains the capabilities *that were determined at the time of acquisition to be needed for mission success* when the system interacts with threats it is likely to encounter in combat. It is assumed, therefore, that the data defining the relationship between the mission-relevant capability measures and the mission-status measures of battlefield success serve as input to decisions associated with the design and engineering of the system. The operational requirements for the system, incorporating the levels of relevant capabilities needed by the system for mission success, define the minimum levels of those capabilities that must be retained by the system in combat and provide the basis for determining the data required for the vulnerability assessment. These data (i.e., Data Set A in Figure 2) should be readily available to personnel designing the vulnerability assessment plan.

To complete the assessment, the analyst must obtain data relevant to (1) the relationship between the damage vectors and the measures of capability required by the system to complete its mission ($O_{2,3}$) and (2) the relationship between the threat-system interaction and the damage vectors associated with system and personnel vulnerability ($O_{1,2}$). Potential data sources include (1) results of prior tests of materials, components, subsystems of earlier and current models of the system or similar systems, (2) results of prior system-level tests of earlier models of the system or similar systems, (3) combat data relevant to damage mechanisms, system damage, and residual capabilities of system as associated with the identified threats, (4) design analyses of the system with consideration given to the new materials and technologies incorporated into the system, (5) prior engineering analyses or CDTs, and (6) M&S runs that incorporate the system description, threat characteristics, and damage mechanisms expected in threat-system interactions. These data (i.e., Data Sets B and C in Figure 2) would be sought from defense databases, the system contractor, and defense analysis, testing, and evaluation agencies. Information relevant to the $O_{1,2}$ or the $O_{2,3}$ mappings that is either unavailable from the identified sources or is not considered reliable by analysts defines the subset of the required information (i.e., data voids) to be addressed in the vulnerability assessment plan.*

4.2.4 Critical Data Voids. Many resources would be required to design and conduct a vulnerability assessment plan that explores all data voids associated with all possible combat scenarios. To ensure an efficient and effective use of limited resources, analysts must prioritize the data voids to be addressed in the assessment plan (i.e., establish critical data voids). The first cut in restricting data voids to be addressed is achieved by limiting the preceding analysis of activities to the combat scenarios that are more likely to unfold. Analysts must also consider the degree of confidence placed by decision-makers in the subset of required information that is available. Figure 3 provides one representation of an approach in which priorities (one [1] representing high priority and four [4] representing low priority) are assigned to several groups of data voids to be addressed in a vulnerability assessment plan.

A data void in the information set required for vulnerability analysis is assumed to exist if (1) data are not available or (2) the confidence in available data is not high (i.e., low to moderate confidence only in available data). In designing an effective

* It is assumed that the vulnerability assessment program is begun early in the acquisition cycle. Some of the identified information sources may have relevant data in place at the beginning of the planning process; other sources may produce data as part of a vulnerability assessment plan executed to obtain data relevant to evaluators' decisions.

	<======= Likely Combat Scenarios ======>		
$O_{1,2}$ or $O_{2,3}$ Data	Remote Possibility of Combat Scenario	Reasonably Possible Combat Scenario	Probable Combat Scenario
High confidence in available data	[4]	[3]	[3]
Moderate confidence in available data	[4]	[2]	[2]
Low confidence in available data/ no available data	[4]	[2]	[1]

Figure 3. Priorities of Data Voids Addressed in Vulnerability Assessment Plan (High [1] to Low [4] Priorities).

vulnerability assessment plan with limited resources, higher priorities would be assigned to addressing $O_{1,2}$ or $O_{2,3}$ data voids associated with reasonably possible or probable combat scenarios (i.e., likely combat scenarios) in which confidence in available data is not high (i.e., cells labeled [1] and [2]). Gathering data relevant to $O_{1,2}$ and $O_{2,3}$ mappings in likely scenarios in which there is high confidence in available data (i.e., cells labeled [3]) may be part of an assessment plan if funds are obtainable for assurance testing. Generally, a lower priority would be assigned to the analysis of activities and data voids associated with combat scenarios considered only remotely possible (i.e., cells labeled [4]).* Although classifying data voids into four categories may facilitate a systematic approach to addressing data voids, priorities may well need to be defined with finer resolution as resources become more limited.

In this report, it is assumed the data voids to be addressed in an environment of limited resources are restricted to that subset of data voids associated with likely combat scenarios in which information relative to $O_{1,2}$ and $O_{2,3}$ mappings is either unreliable or unavailable (i.e., priorities [1] and [2] in Figure 3). Prioritization of specific data voids within this restricted subset may be accomplished by either engaging in subjective forms of analyses or employing quantitative-qualitative analytical tools, such as the Analytic Hierarchy Process (AHP) or Quality Function Deployment (QFD). A description and discussion of the applicability of these tools to group decision-making may be found in other sources [27–32].

4.3. Vulnerability Assessment Plans. A cost-effective strategy to obtain data needed to assess the vulnerability of a weapon system prior to fielding requires (1) a clear identification of the data required for the decisions to be made, the data available from reliable sources, and the data remaining to be gathered (i.e., data voids) and (2) a vulnerability assessment plan designed to address the data voids with consideration given to the limited resources available. The methodology proposed in this report for the selection of the optimal vulnerability assessment plan from a group of alternative

* It is acknowledged that analysts may choose to assess the vulnerabilities of combat scenarios that are only remotely possible if the scenarios are associated with very costly losses <u>and</u> the resources for assessment are available.

assessment plans incorporates many of the principles of a Cost as an Independent Variable (CAIV) strategy.

4.3.1 ***CAIV Principles.*** *The Defense Acquisition Deskbook* describes CAIV as follows [33]: *

> CAIV is a strategy that entails setting aggressive, yet realistic cost objectives when defining operational requirements and acquiring defense systems and managing achievement of these objectives. Cost objectives must balance mission needs with projected out-year resources, taking into account existing technology, maturation of new technologies and anticipated process improvements in both DoD and industry.

The CAIV methodology supports the setting of realistic but aggressive cost objectives early in the acquisition program and the implementation of cost-reduction strategies throughout the program, including cost-performance tradeoffs, competition among suppliers/contractors, integration of program activities through early planning, and the development of efficiencies in core activities [34].

Characteristics of the CAIV methodology follow [34, 35]:

- Cooperation of PMO, system user, contractor/manufacturer of system, Service leaders, and OSD is required for successful implementation in the production decision. System users play an active role in the tradeoff process throughout the life cycle of the system.

- Analyses of measures of mission effectiveness vs. performance requirements and performance requirements vs. costs of systems are conducted to support production decisions.

- The program budget defines available funds and drives the acquisition strategy for the program. Cost goals must meet objectives of affordability and ability to fund threshold requirements of system.

* Implementation of CAIV, an initiative to reduce life-cycle costs of defense systems, is required of all new ACAT I and IA programs [33].

- System performance parameters (included in ORD) are the designated key performance parameters. Potential for tradeoffs of cost against performance is increased if the number of key performance parameters is minimized. Key performance parameters are not tradable below a threshold value, and parameters must meet users' needs.

- Tradeoff process begins early in the design process with updates to costs and performance requirements incorporated throughout implementation. Metrics to track performance are established. Long-range planning is implemented.

- Risks (uncertainties) in CAIV implementation over program life cycle include the stability of the program budget and the priorities for the system, (2) the stability of the mapping of required measures of effectiveness to minimum performance requirements, (3) the availability of databases and models applicable to cost estimations for systems, (4) the potential for tradeoffs of performance requirements, costs, and schedules, (5) the analysts' capacity to understand the interrelationships of performance requirements, (6) the incorporation of performance requirements in production contract with appropriate incentives, and (7) the developments in technology to enable achievement of program objectives.

The core of the CAIV methodology is the tradeoff process, in which mission needs are balanced against projected resources with consideration given to scheduling issues and identified risks. In production decisions employing CAIV principles, risks are managed to achieve cost, schedule, and performance objectives.

In this report, it is proposed that the selection of the optimal vulnerability assessment plan be made by trading off the plan's performance (i.e., the plan's capacity to assess the critical issues of personnel/system vulnerability) against the budget for plan implementation with consideration given to scheduling issues and risks identified in achieving the plan. Key parameters are identified as the critical prioritized data voids to be addressed in the assessment plan. Major analyses would include performance and cost estimates for the vulnerability assessment plans and the elements of the assessment plans. The methodology proposed employs many of the CAIV principles described in the context of production decisions in the prior paragraphs of this section and emphasizes the exploration of alternative assessment strategies to achieve vulnerability assessment objectives.

*4.3.2 **Construction of Vulnerability Assessment Plan.*** The Taxonomy VA (Figure 2) presents a framework for identifying the data voids, a subset of the information required to conduct a vulnerability assessment of a weapon system. To complete the vulnerability assessment, analysts must design a blueprint, a *vulnerability assessment plan*, to address those data voids. The design of an assessment plan requires the identification of potential sources or activities (i.e., elements of the plan) for obtaining data to address critical data voids and the evaluation of the capacity of each element to produce the critical data within the time constraints of the assessment process. Assuming alternative vulnerability assessment plans to provide the critical data are available and the budgets for obtaining the data are limited, the analyst must select the optimal (i.e., cost-effective) vulnerability assessment plan from the group of alternative plans by weighing (1) the capability or capacity of each plan to provide the critical data (i.e., benefits of plan) and (2) the cost to execute all elements of the plan *with consideration given to* the uncertainty (risk) associated with each plan's capacity to provide the critical data at the identified cost within the time constraints of the assessment process.*

Constructing a vulnerability assessment plan requires the identification of potential sources or activities that could provide data to address the critical data voids. These activities serve as *elements* of the assessment plan and may include modeling and simulation; controlled damage testing; experimental testing; developmental testing; design and engineering analyses; component- , subsystem- , and system-level live-fire testing; and FU SL LFT. Factors that provide input to the design of the vulnerability assessment plan include the nature of the identified prioritized critical data voids, the

* Uncertainty (risk) associated with a plan's capacity to provide the critical data within the time constraints at the identified cost includes the uncertainty associated with the availability of system hardware needed for execution of the plan.

budget for assessment, the availability of hardware, the timetable for the completion of the assessment process, and other constraints unique to the identified data sources.

For example, Figure 4 shows alternative elements that may have the potential to address identified data voids. Each element would be described in detail and the cost of executing the element estimated. Figure 5 illustrates three vulnerability assessment plans, each including several alternative elements to address the identified critical data voids. Each plan includes a different combination of elements and is associated with a different total cost.*

*4.3.3 **Capability of Vulnerability Assessment Plan.*** In designing a vulnerability assessment plan to address critical data voids, an important question arises: "How does one measure the capability or the performance of a plan that is designed to investigate the unknown?" This is a difficult question to answer *ex ante* or *ex post* execution of the plan. An objective measure of capability is not available for this type of analysis, and an appropriate subjective measure is sought to define the capability or performance of the plan. As previously noted, in selecting the optimal vulnerability assessment plan, the analyst must consider not only the capacity of a plan to produce the critical data, but also the uncertainty associated with the plan's ability to supply the required data within the time and financial constraints of the assessment environment.

A subjective metric of risk assessment is proposed for evaluating the capability of a vulnerability assessment plan. Thus, the capability of a plan is rated by the degree of uncertainty a designated panel of experts associates with the plan's capacity to adequately address the prioritized critical data voids within the available time for assessment at the identified cost. A four-point scale of risk assessment is proposed with ratings of high, medium-high, medium, and low risk. An example is provided in the following paragraphs.

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* If the elements of an assessment plan (e.g., modeling, experimental testing, controlled damage testing) differ in detail (i.e., different models are exercised within modeling component, different tests are included in experimental testing), the vulnerability assessment plans also differ.

Data Void	M&S A	M&S B	Exp Tests A	Exp Tests B	LFT A	CDT A
DV #1	…./$	…./$	…./$	…./$	…./$	…./$
DV #2	…./$	…./$	…./$	…./$	…./$	…./$
DV #3	…./$	…./$	…./$	…./$	…./$	…./$
DV #4	…./$	…./$	…./$	…./$	…./$	…./$
DV #5	…./$	…./$	…./$	…./$	…./$	…./$
DV ….	…./$	…./$	…./$	…./$	…./$	…./$

Figure 4. Potential Elements of Vulnerability Assessment Plan to Address Critical Data Voids (DVs).

VAP	M&S A	M&S B	Exp Test A	Exp Test B	LFT	CDT	VAP Cost
VAP #1	x			x	x		$
VAP #2		x	x			x	$
VAP #3	x		x		x		$

Figure 5. Elements and Estimated Execution Cost of Alternative Vulnerability Assessment Plans (VAPs).

Assume an expert panel has assessed the risk associated with the three vulnerability assessment plans illustrated in Figure 5. The described four-point scale is employed to assess the risks associated with each plan's capability to address the specific identified data voids. As illustrated in Figure 6, the expert panel assesses a low risk (i.e., little uncertainty) to be associated with the capacity of Vulnerability Assessment Plan #1 to adequately address Data Voids #3 and #5, but a medium risk to be associated with addressing Data Voids #1, #2, and #4. The low risk assessment assigned to the Vulnerability Assessment Plan #1 and Data Void #3 intersecting cell is interpreted as little uncertainty associated with the capacity of Vulnerability Assessment Plan #1 to adequately address Data Void #3 within the given time frame at the specified cost.

4.3.4 Cost of Vulnerability Assessment Plan. An important consideration in the selection of the optimal assessment plan is the total estimated cost of accomplishing the identified elements of the alternative plans. As discussed in section 3 of this report, a valid comparison of alternative assessment strategies requires the establishment of accounting procedures to ensure consistency and comparability in estimating costs across plans, as well as across periods and systems. Decision-makers must be provided with cost data relevant to all elements of each alternative plan prepared according to a cost methodology applied consistently across all plans. This methodology includes

- Identification of all tasks included in the elements of each plan and the cost components of those tasks (e.g., direct materials and labor, indirect materials and labor, facilities costs, etc.).

- Identification of the behavior of identified costs (e.g., cost varies with volume, cost fixed over relevant range of volume, etc.).

- Identification and description of method(s) employed to measure costs, if alternative methods are available; disclosure of alternative values, if available.

- Identification of all allocated costs and bases for cost allocation.

- Identification and explanation of all incomplete cost data.

	<====================Critical Data Voids ====================>				
Alternative Vulnerability Assessment Plans	**DV #1**	**DV #2**	**DV #3**	**DV #4**	**DV #5**
VAP #1	Medium	Medium	Low	Medium	Low
VAP #2	Low	Low	Low	Medium	Medium
VAP #3	Low	Low	Medium	Medium	Medium

Figure 6. Risk Assessment Measures of Alternative Vulnerability Assessment Plans to Address Identified Critical Data Voids (DVs); High, Medium-High, Medium, and Low Risk Ratings.

There are benefits in identifying the costs of the individual elements of an assessment plan and the costs of the tasks that are included in each element. Activity-Based Costing (ABC), a costing methodology that focuses on the activity or task as the basic cost objective, has been widely used in recent years to determine a more accurate cost of producing a product or delivering a service. Employing ABC to cost the elements of an assessment plan requires the identification of all tasks in each plan element that consume resources and the total costs associated with each task. Tasks must be carefully examined to identify the tasks' cost drivers, the factors that most closely drive or cause the costs to increase or decrease.

The advantage of employing ABC to cost individual elements of an assessment plan is that ABC provides a means to weigh the value added against the costs incurred for each plan element. ABC affords the framework to identify tasks of an element that are non-value-added and are able to be eliminated as well as tasks that are value-added but are able to be made more efficient [36-38].

4.3.5 Selection of Optimal Vulnerability Assessment Plan. To select the optimal (i.e., cost-effective) vulnerability assessment plan from a group of alternative plans, the decision-makers must define (1) the maximum levels of risk in addressing each of the critical data voids they are willing to accept in a vulnerability assessment plan and (2) the maximum cost they are willing to incur in plan execution.

The priorities assigned to the identified data voids serve as input to decisions relevant to the risk assessment levels evaluators require in an acceptable assessment plan. For example, assume analysts (using the four-point scale of risk assessment previously described) have determined certain maximum levels of risk they are willing to accept in a vulnerability assessment plan (i.e., plan addressing five prioritized data voids). Those maximum levels of acceptable risk are shown in Figure 7. Higher priorities assigned to critical data voids would be associated with lower maximum levels of risk acceptable to the analysts. In the example described in Figure 7, a plan is termed acceptable (i.e., with respect to performance), if analysts associate a low risk with the plan's capacity to adequately address Data Voids #1 and #2 and medium

<=========================Critical Data Voids ========================= >

	DV #1	DV #2	DV #3	DV #4	DV #5
Maximum Acceptable Risk Level	*Low Risk*	*Low Risk*	*Medium Risk*	*Medium Risk*	*Medium Risk*

Figure 7. Maximum Levels of Risk Acceptable in Vulnerability Assessment Plan to Address Identified Critical Data Voids; High, Medium-High, Medium, and Low Risk Ratings.

(or less) risk with the plan's capacity to adequately address Data Voids #3, #4, and #5 within the time constraints of the vulnerability assessment process and at the specified cost of plan execution.

The measure of a successful vulnerability assessment depends on which data voids are addressed by the vulnerability assessment plan, the capacity of the assessment plan to address those data voids as measured by the risk assessment metric, and the priorities attached to those data voids by the evaluators of the vulnerability of the system. The capabilities required of an acceptable vulnerability assessment plan as measured by the maximum risk levels allowed must be compared to the capability measures of the alternative vulnerability assessment plans proposed for consideration. Figure 8 provides a comparison of the risk assessment ratings of Vulnerability Assessment Plans #1, #2, and #3 (see Figure 6) to the maximum levels of risk determined to be acceptable (see Figure 7). The comparison reveals both Vulnerability Assessment Plans #2 and #3 are acceptable in terms of expected *plan performance*. A comparison of the expected costs of completing either of the two plans to the maximum amount allowed in the budget for plan execution also finds both plans to be acceptable.

The comparison of alternative assessment plans affords decision-makers an opportunity to look at the tradeoffs in alternative plans relative to cost and performance (i.e., capacity of the plan to adequately assess vulnerabilities associated with the data voids). Although Vulnerability Assessment Plan #3 initially appears to be the optimal plan (i.e., Vulnerability Assessment Plan #3 meets maximum levels of risk allowed of plan and has a lower cost than Vulnerability Assessment Plan #2), possible questions for the decision-makers may be

- Realizing that one remains within the budgetary maximum of $20, is one willing to pay $2 more and adopt VAP #2, thereby decreasing the level of risk in addressing Data Void #3 from moderate to low?

- Is one willing to adopt VAP #1 and accept more risk in addressing Data Voids #1 and #2 (and less risk in addressing Data Voids #3 and #5) to save $3?

<========================Critical Data Voids =======================>

	DV #1	DV #2	DV #3	DV #4	DV #5	Cost of Plan Execution
Maximum Acceptable Level of Risk and Budget	*Maximum Acceptable Level of Risk is Low Risk*	*Maximum Acceptable Level of Risk is Low Risk*	*Maximum Acceptable Level of Risk is Medium Risk*	*Maximum Acceptable Level of Risk is Medium Risk*	*Maximum Acceptable Level of Risk is Medium Risk*	*Maximum Acceptable Budget Is $20*
VAP #1	Medium	Medium	Low	Medium	Low	Estimated $14
VAP #2	Low	Low	Low	Medium	Medium	Estimated $19
VAP #3	Low	Low	Medium	Medium	Medium	Estimated $17

Figure 8. Comparison of Maximum Acceptable Levels of Risk and Budget to Risk Assessment Measures and Estimated Costs of Alternative Vulnerability Assessment Plans (VAPs).

- If the costs of VAP #1 are allowed to increase, are the risk levels of VAP #1 lowered to acceptable levels?*

It is important to realize that the estimated costs of all alternative vulnerability assessment plans may be over and above the amounts allocated or budgeted for the vulnerability assessment program. It is at this point that program managers must carefully weigh the pros and cons of reallocating dollars from other programs to V/L assessment or of requesting additional funds for conducting an assessment plan that meets the performance standards (i.e., allowable levels of risk in addressing critical data voids) determined to be acceptable to decision-makers.

4.4 Complexities of Methodology. There are several complexities inherent in the proposed approach to vulnerability assessment that must be addressed. First, the capability or the capacity of the vulnerability assessment plan to adequately address critical data voids is rated by a subjective measure, the assessment of risk in the plan's capacity. The lack of an objective measure to rate the plan's ability to provide *all of the data* relative to identified data voids or address the unknown unknowns is not a problem unique to weapon system analysis.† In many disciplines (e.g., finance, law, and medicine), opinions of expert panels or groups of individuals with experience in similar decision-making tasks are sought for evaluations in which objective measures are not available.‡ Group assessment or evaluation (i.e., panel of experts) is proposed

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* A complete analysis that includes ALL possible combinations of data source components that have associated costs within the budget range would include the suggested alternative vulnerability assessment plan (i.e., increased costs and decreased risk levels). However, given the limitations in information processing of individuals, this type of comparison affords a check on the completeness of alternatives generated by analysts/testers/evaluators.

† To employ an objective measure to assess the capability of a vulnerability assessment plan to provide *all of the data* relative to critical data voids would require knowledge or definition of *all of the data*. Knowledge of all unknowns would be necessary to answer the question, "Were all the unknown unknowns identified?" Although components of vulnerability assessments plans may be compared (e.g., vulnerabilities detected in component testing versus vulnerabilities detected in modeling), a comparison of even several vulnerability assessment plans would be economically unfeasible. Therefore, the decision-maker must search for the next best solution, the opinions of experts as surrogate for the objective measure of capability.

‡ Recent studies in other disciplines have shown that experts with domain-specific experience often make decisions more compatible with those of statistical models than do experts with more global experience. To avoid unneeded bias, it is imperative that care be given to the choice of experts invited to join the decision process [39, 40].

because numerous studies have established that group information-processing often results in judgments that are superior to the judgments of individuals [41].

A second complexity arises in the determination and comparison of the costs of vulnerability assessment plans. At the present time, the costs of testing and evaluation of weapon systems are not reported consistently across services, weapon systems, or time periods. The computation and recording of costs of components of vulnerability assessment plans according to a single methodology that is consistent across periods and comparable across weapon systems would provide a useful database for analysts designing vulnerability assessment plans in the future. Suggestions for addressing this issue have been discussed in this report.

Finally, it is recognized that implementation of the proposed methodology requires the commitment of time and personnel to the design and evaluation of alternative assessment strategies. A *cost-effective vulnerability assessment strategy* is an important part of a *cost-effective acquisition process.* Failure to commit funds to the prevention and detection of vulnerabilities early in the design and production phases of the system may well result in the expenditure of much larger dollar amounts in system design and engineering modifications or retrofits following production. This issue is discussed in more depth in the Conclusion.

5. Conclusion

5.1 Role of FU SL LFT&E in Cost-Effective Vulnerability Assessment. A methodology to identify, measure, and categorize the costs and benefits of FU SL LFT&E, as well as other elements of a vulnerability assessment plan, is presented in prior sections of this report. As an element of an assessment plan, however, FU SL LFT&E is unique. For many systems, FU SL LFT&E is a congressionally mandated activity conducted by independent agencies* prior to the system entering full-scale production [1]. Evaluating the role of FU SL LFT&E in a cost-effective vulnerability

* Activities conducted by independent agencies are defined as activities not performed under the direction of the manufacturer/contractor(s) of the system or the PMO associated with the system.

assessment strategy requires an understanding of the vulnerability assessment process and the risks inherent in the process.*

5.1.1 ***Cost-Effective Vulnerability Assessment Process.*** A *cost-effective* vulnerability process emphasizes the achievement of assessment objectives within the constraints of resources available. This report proposes the effectiveness and efficiency of an assessment strategy may be increased by the identification of the specific set of data required for vulnerability assessment, the determination of the subset of the required data currently available from reliable sources, and the selection of a cost-effective vulnerability assessment plan to fill the data voids. Because the design of vulnerability assessment plans is based not only on the capacity of the plan's elements to address the critical data voids but also on (1) the time constraints of the assessment schedule, (2) the production schedule and availability of system hardware, and (3) the costs attached to the execution of the plan, there are often tradeoffs among plan performance (i.e., capacity), cost, and schedule that must be explored before the optimal plan is determined.

A cost-effective strategy of vulnerability assessment begins at the Concept Exploration phase and continues through Program Definition and Risk Reduction and Engineering and Manufacturing Development phases of the acquisition process. It may include experimental testing, M&S, design and engineering analyses, controlled damage testing, component and subsystem LFT, FU SL LFT, as well as other activities that address the identified critical data voids relevant to assessment decisions.

Planning early for vulnerability assessment may increase the number of options available to address the critical data voids and may allow assessment activities to be completed early in the acquisition process at a time when design or engineering changes are more feasible and/or more economical. For example, technical tests conducted early give insight into design and engineering issues and often employ test articles (e.g., mock-ups, replicas, etc.) that are less expensive than the realistic test

* To facilitate discussion of the methodology presented in section 4 of the report, the Conclusion is restricted to a discussion of cost-effective *vulnerability* assessment issues.

articles required to be used in an FU SL LFT. There are, however, some critical data voids (e.g., cascading and synergistic damage mechanisms) that are unable to be addressed by alternative activities and unable to be explored until late in the production process when the required hardware for testing is available.

5.1.2 Risks of Vulnerability Assessment Process. There is a risk in the vulnerability assessment process that no matter what actions are taken during the acquisition process by the contractor, the PMO, the IPT committee, or the independent testing and evaluator groups, a serious or significant vulnerability will remain undetected in the fielded system. One objective of a vulnerability assessment strategy is to minimize the risk, a vulnerability assessment risk (VA risk), that a material vulnerability (i.e., one that could result in catastrophic loss of system, failure to complete mission, and/or personnel casualties) will exist undetected in a fielded weapon system. The VA risk could be described as a three-fold risk: *inherent risk, control risk,* and *detection risk.*[*]

Inherent risk is the susceptibility of the weapon system to material or significant system and personnel vulnerabilities. Assessing the level of inherent risk associated with a system requires an understanding of the environment in which the system must function, the expected mission(s) of the system and the tasks required to ensure mission success, the threats the system is likely to encounter, and the potential mitigating effects provided by the tactics and doctrine of the system users. Information relevant to the vulnerabilities of prior models of the system or similar models, the complexity of the design of the system, and the impact of technological developments on the system serve as input to the assessment of inherent risk.

Control risk is the risk that a material or significant vulnerability will not be prevented or detected during the design and production phases of the system under the control structure of the PMO program of survivability or vulnerability assessment. An accurate assessment of the level of control risk associated with a weapon system

[*] *Inherent, control,* and *detection risks* are terms borrowed from a financial auditing context. Although there are parallels between the auditing of financial statements and the assessment of vulnerability in weapon systems, the terminology as used in this report is not strictly analogous to the terminology in auditing contexts.

requires an analysis of the survivability or vulnerability assessment program (e.g., design and engineering analysis, experimental testing, etc.) conducted by the PMO and the critical data voids addressed in this program prior to full-scale production.

Detection risk is the risk that a material vulnerability will not be discovered by analyses, T&E, or other activities conducted prior to fielding of the system by sources independent of the manufacturer/contractor(s) and PMO. Detection risk is a function of the nature, timing, and extent of tests (or other activities) that are performed with the objective of assessing system vulnerability. The level of detection risk is *managed* to a great extent by the independent testers and evaluators of the system.

It is proposed that in a *cost-effective* vulnerability assessment process, independent testers and evaluators would (1) determine the level of detectable risk they are willing to accept on the bases of their assessment of the levels of inherent and control risks associated with the system and (2) design the nature and extent of their analyses/tests on the bases of those assessments. In other words, higher levels of detection risk may be acceptable to a tester/evaluator planning the T&E of a system associated with low levels of inherent and control risks. Only very low levels of detection risk, however, may be acceptable to testers/evaluators assessing the vulnerabilities of a system associated with very high levels of control and inherent risk.

5.1.3 Risks of Vulnerability Assessment and FU SL LFT&E. As discussed in the previous section, one objective of a vulnerability assessment strategy is to minimize the risk that a material vulnerability will exist undetected in a fielded system. The level of detection risk that is acceptable in independent tests is contingent upon the assessed levels of inherent and control risks; the level of detection risk associated with a testing activity is determined in a large part by the extent and nature of the testing activities conducted by independent agencies.

As discussed previously, an understanding of the missions of the system, the tasks required to complete those missions, the combat environment, the threats likely to be encountered, and the tactics and doctrine of the system users is important in determining the relationship between the system's capabilities and the measures of mission success ($O_{3,4}$ mapping). The data required for establishing the minimum level of capabilities needed for mission completion are also important to assessing the level of inherent risk associated with the system. The susceptibility of the weapon system to material vulnerabilities (i.e., inherent risk) should be an important consideration in the design of the control structure that is established under the direction of the PMO with the objective of preventing and detecting vulnerabilities in the system produced.

In a *cost-effective* vulnerability assessment plan that includes FU SL LFT&E, independent testers and evaluators might be expected to restrict the scope of the FU SL LFT to a greater extent for a system that has a well-established PMO-directed survivability or vulnerability assessment program (i.e., low control risk assessed) than for a system with similar inherent risks but a less mature or less developed control structure in place.

5.2 Cost-Effective FU SL LFT&E. The manufacturer/contractor(s) of the system and the PMO, as well as independent agencies, participate in the execution of an effective assessment strategy. FU SL LFT&E is one of several possible activities conducted by an independent agency that may be selected as an element of a vulnerability assessment plan. The methodology presented in this report (i.e., section 4) would support the inclusion of FU SL LFT in a vulnerability assessment plan, if it compared favorably with other elements on the basis of identified costs and benefits (i.e., capacities to address critical data voids) and uncertainties associated with the identified impacts. For certain covered weapon systems, however, FU SL LFT&E is a congressionally legislated element of the assessment plan, not a discretionary activity of the assessment process [1]. For that reason, a closer look at increasing the *cost-effectiveness of FU SL LFT&E* is important.

Many of the suggestions to increase the cost-effectiveness of FU SL LFT&E that were offered by interviewees can be better understood in the context of the objectives of cost-effective assessment, the risks of assessment, and the activities of FU SL LFT&E. Generally, suggestions fell into four broad categories: the prioritization of data voids, the consideration of alternative activities for FU SL LFT&E and alternative designs of the FU SL LFT, the evaluation of the control structure under the PMO direction, and the review of the outcomes of prior and current FU SL LFT&E activities. The suggestions of interviewees are summarized in the following paragraphs.

5.2.1 ***Prioritization of Data Voids.*** Prioritize data voids to ensure limited funds are spent effectively in addressing the *most critical* data voids. Consider the benefits (i.e., data to address critical data voids) expected to be received from engineered vs. random shots, as well as benefits from each additional shot planned with attention given to the priorities established for the identified data voids. Consider alternative activities in conjunction with a restriction of the scope of FU SL LFT&E to effectively and efficiently address critical data voids.

5.2.2 ***Consideration of Alternative Activities and Designs of FU SL LFT&E.*** Explore alternative activities to investigate the critical data voids of the system that are planned to be addressed by FU SL LFT&E. Consider substitution of alternative activities if less costly to conduct than FU SL LFT&E and/or occur earlier in the acquisition process than FU SL LFT&E, at a time when fixes may be more feasible and/or more economical.

Consider the cost-effectiveness of the design of FU SL LFT (e.g., random vs. engineered shots, number of shots, etc.). Balance the objectives of sampling efficiency and avoidance of bias perceptions by employing smart testing strategies (e.g., random sampling from combat distribution).

Encourage modelers and testers to integrate efforts in the development and VV&A of M&S tools. Facilitate discussions *early in the acquisition process* among analysts, manufacturer/contractor(s), PMO, and independent testers and evaluators to increase time available to consider, plan, and conduct alternative activities for addressing critical data voids.

5.2.3 ***Evaluation of Control Structure.*** Evaluate the control structure established by the PMO to monitor system survivability/vulnerability. Encourage early involvement of the evaluator in assessment process to ensure minimal funds are spent on redundant testing and analyses. In planning the scope of the FU SL LFT&E, give careful consideration to the activities managed by the control structure to prevent and detect vulnerabilities throughout the acquisition process. An evaluation of the control structure in place that leads to an assessment of low control risk and the subsequent restriction of FU SL LFT scope could serve as an incentive to PMO/manufacturer/contractor(s) to develop and maintain an active agenda for assessment through all phases of acquisition.

*5.2.4 **Review of FU SL LFT&E Outcomes.*** Compile a database relevant to FU SL LFT&E outcomes and actions (i.e., system retrofit, redesign, reengineering, etc.) taken on the bases of those outcomes for all FU SL LFT&E conducted (i.e., *ex post* analyses). Include in the database data relevant to fixes proposed and fixes funded for the current model, as well as alterations implemented in later models. Identify unsuspected vulnerabilities detected in testing. *Require* the costs of FU SL LFT&E components to be recorded and reported according to a consistent methodology.

Outcome data obtained *ex post* T&E could assist in identifying the types of data voids that are addressed most effectively in FU SL LFT&E and the areas in which unexpected vulnerabilities are detected most often. This information would provide valuable input to (1) the design of PMO control structures for the prevention and detection of vulnerabilities in system design and production and (2) the planning of future FU SL LFTs by IPT committees, testers, and evaluators.

For example, FU SL LFT&E is conducted with the expectation of increasing evaluators' understanding of the relationship between the system interaction with threats likely to be encountered in combat and the damage vectors associated with system and personnel vulnerability following the interaction (i.e., $O_{1,2}$ mapping). Assume a review of the outcomes of prior FU SL LFTs finds that a large number of the significant unexpected vulnerabilities or *unknown unknowns* uncovered in FU SL LFT&E can be categorized as data relevant to the $O_{2,3}$ mapping— data that explain the relationship between damage vectors and the measures of capability. Because $O_{2,3}$ data voids can be addressed more efficiently and effectively by other types of assessment activities (e.g., engineering analyses, CDT), this finding may indicate additional resources are needed to direct assessment activities that address $O_{2,3}$ relationships.

Similar to outcome data, cost data gathered *ex post* from completed FU SL LFT&E activities are relevant to the planning of future FU SL LFT&E. Cost data identified by the components of FU SL LFT&E facilitate the identification of value-added and non-value-added components, as well as efficiencies and inefficiencies in the T&E process.

5.2.5 Contributions of FU SL LFT&E to V/L Assessment. Although many offered suggestions for improving the cost-effectiveness of survivability/lethality assessment as a whole and FU SL LFT&E in particular, only a few of those interviewed for this report discounted the benefits or contributions of FU SL LFT&E. Contributions of FU SL LFT&E cited in interviews, as well as published reports and articles, included the capacity of FU SL LFT&E to identify both suspected and unknown vulnerabilities and lethalities; provide insights into potentially significant damage mechanisms and the quantification of their contribution to system V/L; supply data for the calibration and validation of lethality and vulnerability models; provide insights into BDAR potential; and contribute to the development of battle preparation procedures, and operational doctrine and tactics. The importance of the high visibility of FU SL LFT&E to ensuring Congressional funding for V/L assessment and to providing incentive for PMOs and contractors to consider V/L issues over all phases of acquisition cannot be minimized. In addition, the intangible benefits received from T&E conducted by an independent agency that serves as validation for the survivability/vulnerability programs of PMO/contractor(s) must be considered in a weighing of the impacts of FU SL LFT&E.

5.3 Cost-Effective Vulnerability Assessment and Acquisition Process. In this study, the FU SL LFT&E of three separate weapon systems were reviewed with the purpose of identifying the activities of FU SL LFT&E, the impacts of those activities, and the complexities in the reporting of the impacts. Various approaches to address the complexities uncovered were considered. This report describes the current FU SL LFT&E process, including its role in a program of vulnerability assessment, and offers suggestions for improving the cost-effectiveness of vulnerability assessment strategies.

In planning a LFT&E program, the LFIPT brings together the expertise of analysts, testers, evaluators, system PMO personnel, system users, and others to identify and prioritize data voids of the system and to consider alternative data sources in the design of an effective LFT&E strategy. In the review of the current planning process for FU SL LFT&E activities, evidence was found that the V/L community has consistently attempted to implement smarter testing strategies, develop ways to select shots that yield more useful information, and build on the lessons of prior FU SL LFT&E conducted.

It is suggested, however, that more effort is needed in developing cost-effective strategies for improving the assessment programs of new systems vs. systems in the middle of the acquisition process with a majority of budget resources already committed to programs. Developing flexible alternative assessment programs early in the acquisition process affords maximum opportunity to increase the efficiency and the effectiveness of the assessment of the system. Linking vulnerability assessment programs to system design and training programs promotes cost effectiveness in both the gathering and the use of data required by multiple decision-makers.

In conclusion, it is important to consider the relationship of a cost-effective vulnerability assessment strategy to a cost-effective acquisition process. An effective vulnerability assessment strategy includes both an analysis of the likely combat scenarios and a determination of the links between the measures of battlefield effectiveness and the measures of capability required of the system to complete its mission. Understanding the mission of the system and associated tactical utility of the system user in likely combat scenarios is the basis for understanding how users rely on the weapon system—the foundation for vulnerability assessment.

A *mission-based* or *utility-based strategy of system acquisition* advocates the establishment of weapon system performance requirements after a careful analysis of the relationship between system capability measures <u>and</u> battlefield utility measures (i.e., $O_{3,4}$ mapping) [26]. The relevant set(s) of system performance requirements then becomes the basis for weapon system design and engineering.

The information relative to combat scenarios and users' tactics and doctrine gathered for acquisition decisions also serves as valuable input to the supporting vulnerability assessment process. In the assessment process, an evaluation is made of the extent to which a system, interacting with threats likely to be encountered in combat, retains the capabilities that were determined at the time of acquisition to be needed for mission success. The operational requirements for the system, incorporating the levels of relevant capabilities needed by the system for mission success, define the minimum levels of the system's capabilities that must be retained. Therefore, measures of the system's capabilities serve not only as the basis of the system design but also as the core of vulnerability assessment strategies.

The importance of understanding the relationship between the tasks that must be completed by the system to ensure a successful mission and the minimum levels of capabilities needed by the system to complete those tasks is emphasized in the assessment methodology proposed in this report. It makes sense that the operational requirements of new systems incorporate the minimum levels of capabilities needed to complete mission tasks AND that the *objective of vulnerability assessment* be to determine the extent to which the system retains those minimum levels of capabilities it needs to complete its mission(s) when it interacts with those threats it is likely to encounter in combat.

Traditionally, the link between V/L Taxonomy Level 3 (i.e., measures of capability) and Level 4 (i.e., measures of effectiveness) metrics has not been considered to be in the purview of the V/L analyst. The methodology proposed in this report, however, suggests that effectiveness mapping (i.e., $O_{3,4}$ mapping) must be the starting point not only for the design of the weapon system and the development of operational requirements but also for the assessment of the system's vulnerability in likely combat environments.*

The demands of the acquisition process grow with the increase in complex systems with advanced technology attempting to operate in changing combat environments. This report emphasizes the efficiencies that are gained by the mapping of the tasks required for mission success to mission-relevant capabilities and the sharing of these

* There have been some attempts by researchers to identify the tasks that must be completed for mission success (i.e., mission-to-task decomposition) and to model the time-sequencing of task activities [42–44].

data between decisions-makers responsible for the design of the weapon system, the assessment of system vulnerability, the training of system users, and the repair and maintenance of the system. In a similar fashion, the data gathered in vulnerability assessments to evaluate the effect of system damage on the mission-relevant measures of capability ($O_{2,3}$ mapping) provide insights into battlefield damage and repair activities, feed the operational test evaluation, and serve as inputs to programs of training simulators [14, 15].

In recent years, it has become increasingly more evident that the system contractor, user, tester, evaluator, and related analyses groups must join in a cooperative relationship to increase the effectiveness and efficiency of the entire acquisition process. Evidence suggests this cooperative relationship of principal players may lead not only to increased cost-effectiveness in the acquisition process but also to improved readiness for systems in combat.

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Acronyms

ABC = Activity-Based Costing
ACAT = Acquisition Category
AHP = Analytic Hierarchy Process
AMCOM = U.S. Army Aviation and Missile Command
AMSAA = U. S. Army Materiel Systems Analysis Activity
APG = Aberdeen Proving Ground, MD
ARL = U.S. Army Research Laboratory
ATACMS = Army Tactical Missile System
ATC = U.S. Army Aberdeen Test Center
ATEC = Army Test and Evaluation Command
BDAR = Battle Damage Assessment and Repair
BFVS = Bradley Fighting Vehicle System
BH&T = Ballistic Hull and Turret
CAIV = Cost as an Independent Variable
CSTA = Combat Systems Test Activity
DCSINT = Deputy Chief of Staff for Intelligence
DoD = Department of Defense
DOT&E = Director, Operational Test and Evaluation
DDOT&E (LFT) = Deputy Director, Operational Test and Evaluation, Live-Fire Testing
DTP = Detailed Test Plan
DTR = Detailed Test Report
DUSA (OR) = Deputy Under Secretary of the Army for Operations Research
DV = Data Void
EAC = Evaluation Analysis Center
EDP = Event Development Plan
EMD = Engineering and Manufacturing Development
FU SL LFT = Full-Up System-Level Live-Fire Test
FU SL LFT&E = Full-Up System-Level Live-Fire Test and Evaluation
GAO = General Accounting Office
GPS = Global Positioning System
HQ, TECOM = Headquarters, U.S. Army Test and Evaluation Command
HS = High Survivability
IDA = Institute for Defense Analysis
IEP/TDP = Independent Evaluation Plan/Test Design Plan
LFIPT = Live-Fire Integrated Product Team
LFT = Live-Fire Test
LFT&E = Live-Fire Test and Evaluation
LRIP = Low-Rate Initial Production
M&S = Modeling and Simulation
MAM = Mission Area Manager
MOE = Measure of Effectiveness
MRMC = U.S. Army Medical Research and Materiel Command
MUVES = Modular UNIX-based Vulnerability Estimation Suite
OEC = Operational Evaluation Command

OPTEC = U.S. Army Operational Test and Evaluation Command
ORD = Operational Requirements Document
OSD = Office of the Secretary of Defense
PLO = Petroleum, Lubricants, and Oil
PM = Project Manager
PMO = Project Manager Office
PQT = Production Qualification Test
QFD = Quality Function Deployment
SAFE = Stochastic Analysis of Fragment Effects
SEP = System Enhancement Package
SER = System Evaluation Report
SLAD = Survivability/Lethality Analysis Directorate
SQuASH = Stochastic Quantitative Analysis of System Hierarchies
T&E = Test and Evaluation
TACOM = U.S. Army Tank-automotive and Armaments Command
Taxonomy VA = Taxonomy of Vulnerability Assessment
TECOM = U.S. Army Test and Evaluation Command
TEMP = Test and Evaluation Master Plan
TRADOC = U.S. Army Training and Doctrine Command
USAOC&S = U.S. Army Ordnance Center and School
USATC&S = U.S. Army Transportation Center and School
V&V = Verification and Validation
VA Risk = Vulnerability Assessment Risk
VAP = Vulnerability Assessment Plan
V/L = Vulnerability or Lethality
V/L Taxonomy = Taxonomy of the V/L Analysis Process
VV&A = Verification, Validation, and Accreditation
WSMR = White Sands Missile Range

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2. REPORT DATE
April 2000

3. REPORT TYPE AND DATES COVERED
Final, Apr 97–Jun 99

4. TITLE AND SUBTITLE
Vulnerability and Lethality Assessment: The Role of Full-Up System-Level Live-Fire Testing and Evaluation

5. FUNDING NUMBERS
1L622618AH80

6. AUTHOR(S)
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Franklin and Marshall College
Department of Business Administration
P.O. Box 3003
Lancaster, PA 17604-3003

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAMES(S) AND ADDRESS(ES)
U.S. Army Research Laboratory
ATTN: AMSRL-SL-BE
Aberdeen Proving Ground, MD 21005-5068

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
ARL-CR-450

11. SUPPLEMENTARY NOTES
*Franklin and Marshall College, Department of Business Administration, P.O. Box 3003, Lancaster, PA 17604-3003

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13. ABSTRACT *(Maximum 200 words)*

In this era of decreased defense budgets and limited resources, it is important for decision-makers to determine the optimal strategy for assessing the vulnerability or lethality (V/L) of a weapon system and the role of Full-Up System-Level Live-Fire Test and Evaluation (FU SL LFT&E) in that strategy. This report presents a foundation for a methodology to (1) identify, measure, and categorize the costs and benefits of FU SL LFT&E; (2) determine the relative significance of FU SL LFT&E to the V/L assessment plan of the weapon system; and (3) compare competing V/L assessment plans for a system.

Descriptions of the activities of FU SL LFT&E, the costs and benefits (i.e., impacts) of those activities, the complexities encountered in the reporting of the impacts, and approaches for addressing the complexities are presented. A discussion of the contributions of FU SL LFT&E to a V/L assessment strategy and suggestions for improving the cost-effectiveness of FU SL LFT&E are included.

The Taxonomy of the V/L Analysis Process (Deitz and Ozolins 1989) is proposed as a framework for identifying the data voids to be addressed in a V/L assessment plan. The potential of adapting the principles of the Cost as an Independent Variable methodology to the evaluation of competing plans of V/L assessment is explored.

14. SUBJECT TERMS
live-fire test and evaluation, cost-benefit analysis, vulnerability/assessment, lethality assessment, full-up system-level test, vulnerability/lethality assessment strategy cost as an independent variable, vulnerability/lethality analysis taxonomy

15. NUMBER OF PAGES
116

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

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