VULNERABILITY ASSESSMENT OF AIRCRAFT

A Review of the Department of Defense Live Fire Test and Evaluation Program

Committee on Weapons Effects on Airborne Systems
Air Force Studies Board
Commission on Engineering and Technical Systems
National Research Council

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Preface

The combat vulnerability of a military vehicle, that is, the inability of the vehicle to withstand the damage caused by a man-made hostile environment, is a critical system characteristic. A vehicle's vulnerability can be assessed or evaluated by the use of analytical models and by empirical live fire testing. Many within the Department of Defense (DoD) hold the opinion that live fire testing can be very expensive relative to the value of the results obtained. Consequently, there has been a reluctance within DoD to conduct realistic tests on new systems during their development. This reluctance was brought into the public domain in the mid-1980s when the U.S. Army was accused of not conducting realistic vulnerability tests on its Bradley Fighting Vehicle.

As a consequence of this reluctance by DoD to conduct realistic live fire tests on systems in development, Congress passed legislation in fiscal year 1987 that requires realistic vulnerability testing of covered weapon systems, including aircraft, before they can proceed beyond Low Rate Initial Production. This legislation is known as the Live Fire Test (LFT) law. The realistic vulnerability tests mandated by the LFT law must be conducted on the system, configured for combat, using weapons likely to be encountered in combat. A waiver from these mandated tests is possible if the Secretary of Defense certifies to Congress, prior to entry into engineering and manufacturing development, that such tests are unreasonably expensive and impractical. An alternate plan for assessing vulnerability must be submitted if a waiver to the mandated system tests is given.

In response to the LFT law, the position of Director, Live Fire Testing, was established under the Office of the Deputy Director of Defense Research and Engineering (Test and Evaluation) [DDDR&E(T&E)] and was given the responsibility for implementing the law. The Live Fire Test & Evaluation (LFT&E) Guidelines were written in 1988 by the Test and Evaluation Committee, and the LFT&E Planning Guide was written in 1989 by the Director, LFT, to assist the system program managers in the preparation of test plans that satisfy the law. In spite of these efforts, the historical reluctance to conduct realistic vulnerability tests on aircraft systems in development has persisted. Furthermore, ambiguities in the wording of the law, and in the published guidance for satisfying the law, have resulted in different interpretations of the law's requirements regarding what must be tested and what weapons must be used. Considerable controversy between the LFT Office and the Services has developed as a consequence of these different interpretations of the law's requirements.

In an attempt to resolve the controversy regarding the law's requirements, and to obtain an independent opinion regarding the total vulnerability assessment process and the law's contribution to that process, the DDDR&E(T&E), now the Director, Test and Evaluation, requested that the National Research Council (NRC) conduct a study of aircraft vulnerability assessment. The NRC appointed the Committee on Weapons Effects on Airborne Systems to conduct this study. This report is the result of the committee's deliberations.

The committee was asked to review the two methodologies used to assess the vulnerability of airborne systems (i.e., analysis/modeling and live fire testing) and to identify and evaluate the costs and effectiveness of these methodologies. Recommendations regarding the most appropriate methodology for each application were requested. In particular, the current direction of the congressionally mandated LFT&E program was to be reviewed and recommendations for change were requested, if appropriate.

The tasks assigned to the committee were carried out by examining the two aircraft vulnerability assessment methodologies and the LFT law from the general point of view that the purpose of any assessment and of the law is to obtain information on the vulnerability of aircraft. This information can be described in terms of the information attributes of (1) types, amounts, and applications; (2) the accuracy of, or level of confidence in, the information; and (3) the cost required to obtain the information. In addition, the LFT law was considered to be a mandated application of the live fire test methodology. Accordingly, Chapter 1 presents a review of the two methodologies and identifies the applications of the results from these methodologies. Chapter 2 presents an evaluation of the cost, effectiveness, and deficiencies of the two methodologies based upon the three information attributes described above. Chapter 3 presents a review of the LFT&E program directed by the LFT Office. Chapter 4 contains the LFT programs of the three Services and the views of the Services' LFT test community and of industry. Chapter 5 presents the committee's view of the future of vulnerability assessment, and Chapter 6 gives the committee's conclusions and recommendations. The LFT law and the major issues and conclusions of two earlier studies of vulnerability assessment and live fire testing of military vehicles by the U.S. General Accounting Office and the Board on Army Science and Technology are presented in Appendixes A, B, and C, respectively. The committee believes that its recommendations merit serious consideration and that the results of this study should eliminate, or at least significantly reduce, the controversy that has revolved around the LFT law.

The committee, in its deliberations, discovered that the controversy over the LFT law was aggravated by several inconsistent definitions of important words and terms used in vulnerability assessment. Consequently, the committee has included the various published definitions as well as those selected for use in this report in the following chapter entitled "Definitions." The key definitions used in the report are live fire test (any test that involves the firing of actual munitions at a target); Live Fire Test (a live fire test that is part of the congressionally mandated LFT&E program); full-scale or complete system test (a test conducted on the complete or total system, with or without the full complement of fuel, ammunition, and hydraulic fluid carried into combat); sub-scale or partial system test (a test conducted on a part of the system, such as a component, a subsystem, or a subassembly, with or without the full complement of fuel, ammunition, and hydraulic fluid carried into combat); and full-up test (a test conducted on a complete or a partial system with the full complement of fuel, ammunition, and hydraulic fluid carried by the system into combat).

The committee held four meetings. The first meeting was in July 1991 in Washington, D.C. The committee received briefings from the study sponsor, the Live Fire Test Office, the Tactical Warfare Programs Office, the Joint Live Fire Test Program Office, and the aircraft vulnerability analysis/modeling community. This was followed by a meeting in September 1991 in Washington, D.C., when the committee heard briefings from the Army, Navy, and Air Force Live Fire Test officials, the Ballistic Research Laboratory, the Institute for Defense Analyses, and the program offices of several major systems. In January 1992, the committee met at the Arnold and Mabel Beckman Center in Irvine, California, and heard briefings from several industry representatives involved with Live Fire Testing and from the Director, Live Fire Testing. During this month, several of the committee members also met with the congressional staffer who drafted the LFT law. The committee conducted a report writing session in April 1992.

The individuals who contributed to the work of the committee during the course of this study are too numerous to be listed separately here. However, in addition to the initial guidance provided by Mr. Charles Adolph, the study sponsor, the committee would like to acknowledge with gratitude the assistance received from personnel from the Live Fire Test Office, the Joint Live Fire Test Program Office, the Institute for Defense Analyses, the Ballistic Research Laboratory, the Army/Navy/Air Force Live Fire Test Offices and major Program Offices, and representatives from Boeing, General Dynamics, McDonnell-Douglas, and Northrop. The committee also wishes to thank the staff of the Air Force Studies Board and the sponsor liaison, COL Bernard (Chip) Ferguson, for providing excellent support throughout this study.

Robert E.Ball
Chairman

Contents

List of Figures

List of Tables

Definitions

Many of the important words and terms used in the survivability, lethality, and live fire test disciplines have been defined in several public documents. The published definitions of the words and terms of particular interest to this study are given in the Table below.

Previously Published Definitions	
configured for combat	The term "configured for combat," with respect to a weapon system, platform, or vehicle, means loaded or equipped with all dangerous materials (including all flammables and explosives) that would normally be on board in combat (U.S. Congress, 1986–1989).
covered product improvement program	A program under which a modification will be made to a covered system that (as determined by the Secretary of Defense) is likely to affect significantly the survivability of such system (U.S. Congress, 1986–1989).
covered system	A vehicle, weapon platform, or conventional weapon system that includes features designed to provide some degree of protection to users in combat and is a major system (see section 2303(5) of title 10 U.S. Code for the definition of a major system) (U.S. Congress, 1986–1989).
damage mechanism	The output of a warhead that causes damage to the aircraft (Ball, 1985).
damage process	The interaction between the damage mechanism and the aircraft components (Ball, 1985).

full-scale tests	Those conducted on complete weapons systems rather than components or mock-ups (GAO, 1987).
full-up testing	Firings against a full-scale target containing all the dangerous materials (e.g., ammunition, fuel, hydraulic fluids), system parts (e.g., electrical lines with operating voltages and currents applied, hydraulic lines containing appropriate fluids at operating pressures), and stowage items normally found on that target when operating in combat. Full-up testing includes firings against full-up components, full-up subsystems, full-up subassemblies, or full-up systems. The term "full-up testing" is synonymous with "realistic survivability testing" or "realistic lethality testing" as defined in the legislation covering Live Fire Testing (OSD, 1988; DDDR&E, 1989).
full-up tests	Those conducted with the full complement of fuel, ammunition, and hydraulic fluid carried by the system into combat (GAO, 1987).
Live Fire Test	A test event within an overall Live Fire Test & Evaluation program that involves the firing of actual munitions at target components, target subsystems, target subassemblies, and/or full-scale targets to examine personnel casualty, vulnerability, and/or lethality issues (OSD, 1988; DDDR&E, 1989).
Live Fire Test and Evaluation (LFT&E) Program	The program conducted by the Director, Live Fire Testing, Office of the Director of Defense Research and Engineering and described in (DDDR&E, 1989).
Live Fire Test law	Legislation in the fiscal year 1987 Department of Defense Authorization Act that requires realistic survivability testing before a covered system can proceed beyond low-rate initial production (U.S. Congress, 1986–1989).
realistic survivability testing	The term "realistic survivability testing" means testing for vulnerability of the system in combat by firing munitions likely to be encountered in combat (or munitions with a capability similar to such munitions) at the system configured for combat, with primary emphasis on testing vulnerability with respect to potential user casualties and by taking into equal consideration the susceptibility to attack and combat performance of the system (U.S. Congress, 1986–1989).
simulants	Fabricated substitutes for unavailable threat weapons or targets (GAO, 1987).
sub-scale tests	Any tests conducted on less-than-full-scale target weapon systems, such as component vulnerability tests or behind-armor-debris studies (GAO, 1987).
surrogate	Any existing munition or target substituted for one that is unavailable for testing on the basis of similarity (GAO, 1987).
survivability	The capability of an aircraft to avoid and/or withstand a man-made hostile environment (Ball, 1985).

	The ability of a weapon system to avoid being killed in battle, including its vulnerability if hit, but also taking other factors such as maneuverability and the ability to avoid detection into account (GAO, 1987).
susceptibility	The inability of an aircraft to avoid the radars, guns, ballistic projectiles, guided missiles, exploding warheads, and other elements that make up the hostile environment. It can be measured in a general sense by P_H, the probability the aircraft is hit by one or more damage-causing mechanisms, such as a bullet, fragment, or blast wave (Ball, 1985). Comprises all the capabilities and characteristics of a target and threat that influence or determine the probability that the target is hit, including the threat capability to detect, lock on, track, and fire, and the target capability to evade the threat (GAO, 1987).
vulnerability	The inability of an aircraft to withstand the damage caused by the hostile environment. Vulnerability can be measured by $P_{K/H}$, the conditional probability that the aircraft is killed given a hit by a damage mechanism, such as a bullet or fragment, or by $P_{K/D}$, the conditional probability that the aircraft is killed by a warhead detonation (Ball, 1985). The inability of a weapon system to withstand damage from a specific attack, given that it has been hit (GAO, 1987).

The committee notes that the definitions for several of the words and terms given above either are not consistent or do not conform with conventional usage. This inconsistency and lack of conformity has created considerable confusion. The committee has reviewed these definitions and has selected the definitions given below as the ones to use throughout this report.

Definitions Used in This Report	
live fire test	Any test that involves the firing of actual munitions at a target.
Live Fire Test	A live fire test that is a part of the congressionally mandated LFT&E program.
full-scale or complete system test	A test conducted on the complete or total system, with or without the full complement of fuel, ammunition, and hydraulic fluid carried into combat.
sub-scale or partial system test	A test conducted on a part of the system, such as a component, a subsystem, or a subassembly, with or without the full complement of fuel, ammunition, and hydraulic fluid carried into combat.
full-up test	A test conducted on a complete system or a partial system, with the full complement of fuel, ammunition, and hydraulic fluid carried by the system into combat.

inert test	A test conducted on a complete system or a partial system, without the full complement of fuel, ammunition, and hydraulic fluid carried by the system into combat. A semi-inert test is one in which some of the combustibles are on-board.

Note the important distinction between a live fire test and a Live Fire Test. Also note that a "complete system test" is equivalent to a "full-scale test," and a "partial system test" is equivalent to a "sub-scale test." Furthermore, the term "full-up test" does not imply that a complete system is tested.

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- U.S. Congress, 1986–1989. Survivability and Lethality Testing of Major Systems, DoD Authorization Acts, FY86—Sec. 123, FY87—Sec. 910, FY88-89—Sec. 802, Washington, D.C.
- U.S. General Accounting Office (GAO), 1987. LIVE FIRE TESTING, Evaluating DoD's Programs, GAO/PEMD-87-17, Washington, D.C., U.S. Government Printing Office.

Statement of Task

There is concern by the Director, Test and Evaluation, for evaluating airborne systems level vulnerability assessment methodologies. Several methodologies such as computer modeling, engineering analysis, and live-fire testing are available to the Services.

The committee will:

1. review current methodologies used by the Army, Navy, and Air Force to determine the vulnerability of airborne systems to enemy conventional weapons and identify the applications of the results;
2. evaluate the costs and the effectiveness of these methodologies and identify deficiencies;
3. recommend the most appropriate methodologies for the applications, weighing the confidence in the results versus costs;
4. in particular, review the current direction on live fire testing and evaluation, compare this direction to the committee's recommended methodologies, and recommend changes, if appropriate.

EXECUTIVE SUMMARY

Background

Aircraft vulnerability refers to the inability of the aircraft to withstand the damage caused by one or more hits by the damage mechanisms associated with air defense weapons, such as warhead fragments and blast. Vulnerability assessment or evaluation is a part of every U.S. military aircraft acquisition program. The assessment can be accomplished by using two methodologies: (1) analyses or computer models that simulate the various reactions of the aircraft and its components to the hits, and (2) live fire testing.

The Live Fire Test Law. As a result of the controversy over the vulnerability testing of the U.S. Army's Bradley Fighting Vehicle, Congress passed a law in fiscal year (FY) 1987, known as the Live Fire Test (LFT) law, which mandates realistic survivability and lethality testing of covered systems or programs. The law was modified in 1988. In the current version of the law, realistic survivability testing is defined as "testing for vulnerability of the system in combat by firing munitions likely to be encountered in combat (or munitions with a capability similar to such munitions) at the system, configured for combat, with the primary emphasis on testing vulnerability with respect to potential user casualties and taking into equal consideration the susceptibility to attack and combat performance of the system." (Note that survivability is used when vulnerability is intended.)

According to the LFT Guidelines in the law, the live fire tests are to be carried out sufficiently early in the development phase of the system to allow any design deficiency demonstrated by the testing to be corrected in the design of the system before proceeding beyond low-rate initial production (LRIP). The system acquisition program cannot proceed beyond LRIP until the testing is completed. The FY 1988–1989 Department of Defense Authorization Act Conference Report states that Congress intended that the Secretary of Defense implement the LFT law "in a manner which encourages the conduct of full-up vulnerability and lethality tests under realistic combat conditions, first at the sub-scale level as they are developed, and later at the full-scale level mandated in the legislation."

A waiver from the requirement for realistic survivability testing is allowed if the Secretary of Defense notifies Congress, prior to entry into full-scale engineering development, that live fire testing of the system would be unreasonably expensive and impractical. The notification of the waiver must be accompanied by a report describing an alternate program for evaluating the survivability of the system and assessing possible alternatives to realistic survivability testing of the system.

When the Live Fire Test law was passed, the position of Director, Live Fire Testing, was established under the Office of the Deputy Director, Defense Research and Engineering (Test and Evaluation) [DDDR&E(T&E)] and was given the responsibility for implementing the LFT legislation. The tests specifically associated with the congressionally mandated Live Fire Test and Evaluation (LFT&E) program are referred to herein as Live Fire Tests, whereas other tests using live ammunition that are not specifically part of the LFT&E program are referred to as live fire tests.

Study Tasks. The tasks assigned to this committee were (1) to review and evaluate the current vulnerability assessment methodologies for aircraft, including both analysis/modeling and live fire testing; (2) to review and evaluate the current direction of the congressionally mandated Live Fire Test programs within OSD and the Services; and (3) to recommend changes to these methodologies and programs, if appropriate. The committee was instructed to consider all aspects of the vulnerability assessment methodologies, programs, and the Live Fire Test legislation.

The committee met four times between July 1991 and April 1992 and received presentations from personnel from the Office of the Secretary of Defense (OSD) LFT&E Office, the DDDR&E(T&E)/Tactical Weapons Programs Office, the U.S. Army's Test and Evaluation Management Agency and Comanche Program Office, the U.S. Navy's Survivability Branch, Naval Air Systems Command, the U.S. Air Force's Test and Evaluation Office and F-22 and C-17 System Program Offices, and the live fire test organizations of the three Services, as well as vulnerability assessment experts from four U.S. aircraft companies and the Institute for Defense Analyses. Several committee members also interviewed Mr. Joseph Cirincione, the congressional staff member who drafted the LFT legislation in 1987.

The study was divided into six parts: (1) review of the analysis/modeling and live fire testing assessment methodologies and identification of the applications of the results of the assessments; (2) evaluation of the cost, effectiveness, and deficiencies of the two methodologies; (3) review and evaluation of the OSD LFT&E program; (4) review and evaluation of the LFT&E programs of the three Services; (5) examination of the future of vulnerability assessment of aircraft; and (6) conclusions and recommendations.

Review and Evaluation

Methodology Review and Applications of the Results. The study reviewed both of the methodologies used by the Army, Navy, and Air Force to determine the vulnerability of airborne systems to guns and guided missiles, and identified the applications of the results. The weapons considered include the nonexplosive armor-piercing (AP) penetrator or fragment, the contact-fuzed high-explosive (HE) warhead, and the proximity-fuzed externally detonating HE warhead. The target aircraft is either full-scale (the complete system) or sub-scale (a partial system consisting of one or more components and/or subsystems) and inert (no combustibles) or full-up (with combustibles).

The committee identified six applications for the results from analysis/modeling and live fire testing. They are (1) to aid in the design and design validation, (2) to satisfy the vulnerability assessment requirements contained in DoD MIL-STD 2069,[1] (3) to develop data bases in support of subsequent analytical assessments, (4) to predict test outcomes, (5) to satisfy the requirements of the Live Fire Test law, and (6) to support acquisition decisions.

Cost, Effectiveness, and Deficiencies of the Methodologies. The committee notes that the primary objectives and applications of the two methodologies are, in general, different. Analysis and modeling are primarily used to aid in design and to quantify vulnerability, whereas live fire testing is conducted to gain insight into the major types of physical damage, including cascading and synergistic effects; to develop component vulnerability data bases; to aid in design; and to validate the design and the model, when appropriate.

The committee selected the information or results provided by the methodologies as the basis for comparison with respect to cost, effectiveness, and deficiencies. In particular, the information attributes of (1) type, amount, and applications; (2) accuracy, or level of confidence; and (3) cost were evaluated for both analysis/modeling and testing. The testing methodology was divided into two categories, tests on sub-scale targets and tests on full-scale targets.

In general, the results from analyses and models consist of numerical values of vulnerability for the components and the aircraft for all weapons and all threat directions. These results can be used in all six applications listed above. The overall level of confidence in the analytical results is relatively low because of the inadequate modeling and supporting data base of some damage processes and vulnerabilities, and the omission of others. The cost of analysis/modeling is also relatively low.

The live fire tests on both sub-scale and full-scale targets produce information on what actually happened for a particular set of test conditions but only for a relatively small number of shots under these conditions. The applications of the test results are to aid in design and design validation, to develop vulnerability data bases, to satisfy the Live Fire Test law, and to support acquisition decisions. The level of confidence in the results is relatively high, and so is the cost, particularly for the full-scale aircraft tests. However, using other full-scale test articles, such as prototypes, for the full-scale vulnerability testing can significantly reduce the cost. Any Live Fire Tests on prototypes must be carefully audited for their applicability to production articles since the differences between the two may be large.

One of the most important findings of this study is that on-board ordnance has been neglected in both analyses and live fire testing as a contributor to vulnerability. One of the basic requirements of the Live Fire Test program is to test full-scale vehicles with the full load of on-board ordnance. External ordnance may shield components from projectiles and fragments, or it may react violently to a ballistic impact, possibly destroying the aircraft. Adverse reactions of any internally carried ordnance have an even greater probability of destroying the aircraft.

In general, the committee believes that the combination of analytical models, supported by live fire tests on components and subsystems, and the full-scale Live Fire Tests are mutually compatible in the vulnerability assessment and design of aircraft. They complement each other, and the whole is superior to the sum of the parts. However, more work is needed to unify these approaches in order to obtain the maximum benefit.

Review of the Requirements of the Live Fire Test Law. The committee notes that there is a major controversy among the various participants in the DoD Live Fire Test program regarding the law's requirements. One point of contention is the requirement for testing the system. One interpretation is that the law does not explicitly state that a complete system must be tested; hence the law is satisfied by an LFT program only on components and

[1]DoD MIL-STD 2069, "Requirements for Aircraft Nonnuclear Survivability Program," contains the requirements and guidelines for establishing and conducting aircraft survivability programs.

subsystems. Another interpretation is that the word "system" refers to the complete or full-scale system. Based upon the evidence gathered by the committee and its study of the law, the committee is unanimous in the opinion that the LFT law requires a full-scale, full-up aircraft to be tested, unless a waiver is granted. The committee bases its opinion upon the events that led to the law, the wording in the law, the accompanying discussion of the law in the FY 1988–1989 DoD Authorization Act Conference Report, the opinion of the congressional staff member who drafted the law, and the fact that a waiver is allowed. If full-scale, full-up tests were not required, no waiver would be necessary, and any live fire tests would suffice, provided they were realistic.

Review of the OSD Live Fire Test and Evaluation Program. Two OSD documents have been provided to the Services and their Program Managers to assist them in the planning and conduct of a Live Fire Test program: (1) the 1988 Live Fire Test and Evaluation Guidelines issued by the Test and Evaluation Committee, Office of the Secretary of Defense, and (2) the 1989 Live Fire Test and Evaluation Planning Guide issued by the Live Fire Test Office. The committee is concerned that the written guidance provided by the LFT&E Office does not provide sufficient detail, particularly with respect to the full-scale tests, to ensure that the Program Manager can satisfy the requirements of the OSD policy and the LFT law, and also design a cost-effective test plan that will ensure the system requirements are satisfied. The various definitions given in the 1988 LFT&E Guidelines have been interpreted by some to imply that full-scale, full-up Live Fire Tests do not have to be conducted, that is, the OSD LFT policy is satisfied by Live Fire Tests only on sub-scale targets, such as major portions or subassemblies of an aircraft. Furthermore, the committee is concerned about the official status, or lack thereof, of the LFT&E Guidelines and the Planning Guide.

Review of the Service Live Fire Test and Evaluation Programs. The committee reviewed the LFT&E policies and programs of the three Services, including the Army's RAH-66, the Navy's V-22 and A-12, and the Air Force's F-22 and C-17. The committee believes it is important to point out the facts that, except for the RAH-66, all of these programs were well under way when the law was passed and the C-17 development had proceeded beyond the deadline for the application of a waiver. Furthermore, Congress did not provide transitional guidance for these programs or additional money to fund the tests.

The Navy and the Air Force have interpreted the 1988 LFT&E Guidelines to imply that full-scale, full-up tests are not required. Furthermore, the LFT&E policies presented to the committee by the Services do not consider such tests to be cost-effective, particularly if on-board ordnance is included. Consequently, they have not developed LFT&E programs that contain full-scale, full-up Live Fire Tests. However, both Services strongly support the conduct of sub-scale inert and full-up tests throughout the development process. The Army policy on LFT&E supports a "building-block" approach consisting of component testing through full-scale, full-up system testing that satisfies the Live Fire Test law. The emphasis of its LFT&E program is on sub-scale testing, with limited full-scale, full-up testing to confirm the results obtained from sub-scale testing. However, the Army LFT&E program for the RAH-66 did not contain firm plans for testing a full-scale, full-up helicopter. The full-scale testing was going to be conducted only if the sub-scale test results showed it to be necessary.

In addition to the controversy regarding the requirement for full-scale testing, there is a controversy regarding the munitions to be used in the Live Fire Tests. The specific munitions to be used for a particular aircraft are selected by the aircraft Program Office as part of its LFT&E program plan. Typically, the threats selected by the Program Office for Live Fire Testing are the threats the aircraft was designed to withstand, such as a single hit by an AP projectile or small-caliber HE round. The assumption is made that the more lethal overmatching threats, such as the larger gun projectiles and missiles, will be avoided and hence should not be a part of the LFT&E program. The Live Fire Test Office has interpreted the phrase "munitions likely to be encountered in combat" to mean that those munitions the aircraft may encounter, including the latest directed energy weapons, should be included in the LFT&E program, regardless of the design threat for the aircraft.

The representatives from the live fire test organizations of the three Services and the vulnerability experts from industry appear to be in general agreement about the efficacy of the Live Fire Test law as it applies to aircraft. They do not consider it necessary to conduct full-scale, full-up tests in order to determine most of the design vulnerabilities. However, they do consider it essential to conduct many sub-scale live fire tests on components and sub-systems, both inert and full-up, in the development cycle of an aircraft. They believe the full-scale, full-up tests may be conducted too late in the development cycles to be of much value to the designer, and that the amount of information obtained from the tests is limited. The representatives do recognize the possibility of an unanticipated reaction, cascading damage, or synergism occurring in the full-scale aircraft. However, they believe that nearly all of the kill modes of an aircraft are known and can be anticipated.

The committee notes that not everyone who has observed live fire tests on sub-scale and full-scale test articles shares the views held by these testers and vulnerability experts. They believe that there have been unanticipated results from these tests. Furthermore, even when the response is as expected, the difference in the expected magnitude of the response and the observed magnitude often is too large to be acceptable. The testers have also overlooked the fact that the information from the full-scale tests is a valuable input to the acquisition decision makers at milestone reviews.

Perceptions of the LFT Law. The committee is aware of the strong differences of opinion held by various individuals and organizations concerning the efficacy of the Live Fire Test law and of the level of mutual distrust that has evolved as a result of these opinions. This distrust between the various participants of each other's motives and actions is probably responsible for the ever-increasing tensions within the current Live Fire Test program. In the committee's opinion, the attitudes of the major participants concerning the Live Fire Test law and its place in the acquisition process may be those described below.

In the committee's opinion, the Program Manager (PM) may consider the full-scale, full-up testing mandated by the LFT law to be an unquantifiable, but potentially catastrophic, risk to his program. LFT has no quantitative contractual specifications or acceptance criteria at program initiation. No quantitative criteria for acceptable or unacceptable damage are included in the requirements process, milestone commitments, or contractor performance documents. LFT of the full-scale aircraft occurs late in the development phase of the program, and there may be neither adequate time nor money to conduct the tests or to make any changes required as a result of the tests. Further, the PM may believe that neither the definition of the tests, nor the conduct of the tests, nor the interpretation of the test results is totally under his control. The perceived jeopardy to his program created by LFT is exacerbated by the severe requirement to fit the program into a somewhat inflexible overall resource schedule, both in time and in dollars. In summary, LFT represents a considerable source of problems to the PM, in the form of an uncontrollable, potentially catastrophic uncertainty, as he attempts to successfully complete the development of a system, and should be avoided if at all possible.

In the committee's opinion, the Services may believe that, as system developers and users, they know what is needed in the equipment they will take into the field, and that they, the Services, are directly responsible for the fate of the military personnel who use this equipment in combat. They are very apprehensive about any outside organization that can dilute their ability to define the necessary equipment testing and the procedures required to accomplish this testing. They appear to further believe that the Live Fire Test law gives to others not directly responsible for the delivered product inordinate control without any accompanying responsibility for the quality of the product or its cost.

In the committee's opinion, the OSD may believe that there have been a sufficiently large number of prior experiences in the area of live fire testing to indicate that pressure by one of the Services for successful and rapid certification of its products under development can lead to inadequate live fire testing and to subsequent unnecessary combat vulnerabilities. The OSD, therefore, has chosen to exercise close control over the Live Fire Test programs and assumes the ultimate authority for approval of the equipment based on the program results.

In the committee's opinion, the Congress may believe that there are sufficient proven instances of unnecessary combat vulnerability in DoD equipment previously delivered to the field to warrant legislative direction of DoD test certification to include live fire testing of full-scale, full-up systems using munitions likely to be encountered in combat. Congress further believes that it has the ultimate responsibility for the programs it authorizes and therefore has the obligation to exercise that legislative direction.

The committee believes that the current assessment procedure, which is supposed to result in an improved aircraft, does not guarantee that the U.S. armed forces will field cost-effective systems designed for reduced vulnerability. The intent of the LFT law to contribute to the creation of less vulnerable aircraft designs is valid; its execution to achieve this intent has been flawed. The committee believes that the problems with the LFT law are (1) ambiguities in the wording of the law's requirements; (2) the lack of a clear and binding LFT policy directive; (3) the Services' reluctance to ask for a waiver from full-scale, full-up LFT for those programs for which they believe LFT to be unreasonably expensive and impractical because of the fear of a stigma associated with the waiver; and (4) the absence of a formal waiver process that includes a procedure for identifying when the full-scale, full-up testing is or is not unreasonably expensive and impractical, which would eliminate any stigma associated with the waiver.

The Future of Vulnerability Assessment. The committee recognizes the limited prospects for both new program starts and product improvements as a result of the declining DoD budget. Although this new environment will lead to austere budgets for vulnerability assessment, the requirements for a vulnerability assessment of any particular system should not decline. However, the overall total requirements for vulnerability assessments will most likely decline due to the reduction in the number of active aircraft programs. In addition to individual program cost containment issues, the committee anticipates a reduction in both the analytical/ modeling and the test and evaluation infrastructure within OSD and each of the Services as the total DoD budget declines.

Three categories for cost reduction in vulnerability assessment while maintaining or improving the current capabilities were examined. The first consists of an increased reliance on analysis/modeling. The committee believes that there appears to be a sufficient start of a modeling capability, and of a weapons effects and materials data base, to warrant an increased dependence on analysis/modeling for future vulnerability assessments as an aid in design. However, the committee also believes that the current analytical methodology and supporting data bases are not yet sufficiently robust, correct, precise, and representative to permit a total dependence on this methodology. Much work needs to be accomplished in model development and in the accumulation of weapons effects and material vulnerability bases.

A reduction in assessment costs can be obtained by requesting a waiver from the full-scale tests. The major factor in the cost of vulnerability assessment is the requirement for the full-scale Live Fire Test program mandated by the Live Fire Test law. The law offers a waiver from the full-scale, full-up tests when they would be unreasonably expensive and impractical. Under the current LFT&E Guidelines and Planning Guide, there is no guidance as to what constitutes an unreasonably expensive and impractical Live Fire Test program. In the future, a procedure must be established for gathering the facts necessary to determine if the full-scale, full-up Live Fire Tests are unreasonably expensive and impractical with respect to the critical vulnerability issues and, if they are, what other assessments should be conducted in place of the complete system tests.

A third possibility for cost reduction involves a consolidation of the vulnerability assessment infrastructure. Although the committee did not review in detail this aspect of the vulnerability assessment activities and capabilities in each of the three Services, the committee believes that until the recent DoD budget downturn, there were sufficient aircraft programs to warrant the continuation of more or less similar Service live fire test capabilities. However, in the decades ahead, the expected requirements for the vulnerability testing of new Service equipment will probably fall below the level at which a critical mass of broad-based facilities and knowledgeable staff can be maintained within any of the individual Services. Because considerable cost savings could be achieved by consolidating the capabilities of these facilities, some form of consolidation beyond that currently contemplated appears inevitable.

The future of vulnerability assessment will most likely involve one or more of these three categories.

Conclusions

After reviewing the vulnerability assessment methodologies; evaluating the cost, effectiveness, and deficiencies of these methodologies; and reviewing and evaluating the Live Fire Test law and the OSD and Service Live Fire Test & Evaluation programs, the committee has come to the following conclusions.

- *Conclusions Regarding the Live Fire Test Law & DoD Programs*

1. **The committee believes that the requirements in the Live Fire Test law have been interpreted in several ways and that these different interpretations have caused confusion and tension in the Live Fire Test programs. Nevertheless, the committee believes that the law is a valuable contribution to vulnerability assessment and to the design of survivable aircraft. Furthermore, it is satisfactory in its present form because of the waiver process.** The committee believes that the law has had a positive impact on the vulnerability design of aircraft and is sufficiently flexible, due to the waiver process, to apply to all aircraft. Furthermore, the committee believes that verification of vulnerability by live fire testing is necessary and that this law ensures that verification.
2. **The committee believes that the 1987 congressional Live Fire Test law mandates live fire testing of full-scale, full-up aircraft, including on-board ordnance, unless a waiver is granted by the Secretary of Defense.**
3. **The committee believes that the 1988 Live Fire Test & Evaluation Guidelines and the 1989 Live Fire Test & Evaluation Planning Guide are not consistent with its interpretation of the LFT law.**
4. **Because all three Services apparently believe that an LFT&E program plan that contains only sub-scale testing is in compliance with the law as interpreted by the OSD 1988 LFT&E Guidelines, no current LFT program contains plans to conduct full-scale tests and no waivers have been requested.** (The committee has been informed that on May 11, 1992, the Under Secretary certified to the Congress that live fire testing of the F/A-18E/ F aircraft would be unreasonably expensive and impractical. The alternatives to the statutorily prescribed survivability testing are being prepared by the Navy.)
5. **The committee believes that a waiver is required to omit the full-scale, full-up tests.**
6. **The committee believes that there are aircraft for which a full-scale, full-up test program is unreasonably expensive and impractical, and that there are aircraft for which a full-scale, full-up test program is neither unreasonably expensive nor impractical.**
7. **The committee believes there should be no stigma attached to a waiver because the waiver is an acceptable alternative LFT&E path.**

8. **A serious problem in both the analyses and the Joint Live Fire Testing of aircraft has been the omission of on-board ordnance as a critical component.**

9. **The stated intent of the system tests mandated by the Live Fire Test law is to aid in design by providing information on possible weaknesses sufficiently early in the design process to allow the weaknesses to be corrected.**

10. **The implied intent of the Live Fire Test law is to force the consideration of vulnerability during the design process.**

11. **The lack of a definition of the specific threat munitions to be used in design and in Live Fire Testing has resulted in considerable controversy regarding which threat weapons to use in the Services' LFT programs.**

12. **The apparent separation of the oversight of vulnerability analysis from the oversight of live fire testing, both of which are part of the testing and evaluation process, has created a situation that is detrimental to the overall OSD vulnerability program.**

- *Conclusions Regarding the Vulnerability Assessment Methodologies*

13. **Based upon its review of the two methodologies, the committee concludes that both vulnerability analysis and live fire testing, including the mandated Live Fire Testing, are essential in a mix peculiar to each aircraft development program.**

14. **The committee believes that both methodologies need to be improved and that these improvements should be mutually beneficial.**

- *Conclusions Regarding the Vulnerability Programs for Aircraft*

15. **The vulnerability of currently fielded U.S. aircraft will become more important in the future.**

16. **There is insufficient attention given to the requirement to design for vulnerability.**

17. **The collection of actual combat data on the vulnerability of U.S. aircraft is not given proper emphasis.**

- *Conclusions Regarding the Vulnerability Infrastructure*

18. **The process of designing and testing for vulnerability is extremely complex and would benefit from continuous input and oversight from a broad range of experts in the vulnerability community.**

19. **The vulnerability community of the future most likely will become smaller in both the number of programs and the size of the infrastructure.**

Recommendations

Based upon the results of the committee's study and the conclusions given above, the committee makes the following recommendations:

- *Recommendations Regarding the DoD Live Fire Test & Evaluation Program*

1. **The committee recommends that the Director, Test and Evaluation, issue Guidelines that replace the 1988 Live Fire Test & Evaluation Guidelines and that more clearly conform with the requirements for the full-scale, full-up tests mandated by the Live Fire Test law.** The recommended directive should completely define the procedures and requirements for planning and conducting the LFT&E program for both sub-scale and full-scale tests. The directive should require the conduct of vulnerability tests under realistic combat conditions, first at the sub-scale level as sub-scale systems are developed, and later at the full-scale level mandated in the legislation. In addition, the directive should describe a formal process for requesting a waiver.

2. **The committee recommends that the Director, Test and Evaluation, formalize the waiver process by developing a risk-benefit assessment methodology that can be used uniformly to determine whether a full-scale, full-up test program for any particular aircraft is "unreasonably expensive and impractical." The methodology must also be applicable to the evaluation of the alternative Live Fire Test program for the sub-scale targets.** The process for requesting a waiver, described in the DoD directive recommended above, should include a risk-benefit assessment methodology that quantifies the benefits

associated with full-scale, full-up Live Fire Tests and the risks associated with waiving these tests. Once the benefits and risks have been quantified, a decision can be made as to whether the full-scale, full-up tests are unreasonably expensive and impractical. The committee strongly believes that such a methodology would significantly improve the process of requesting a waiver.

3. **The committee recommends that the Secretary of Defense take measures to ensure that (a) the LFT&E Guidelines are properly enforced by requiring either that covered systems be subjected to full-scale, full-up testing or that a waiver be obtained; (b) that any waiver be fully justified; (c) that the waiver process be uniformly applied; and (d) that no stigma be attached to the use of the waiver process.**

4. **The committee recommends, for the full-scale, full-up Live Fire Tests, that the specific "likely to be encountered" munitions referred to in the Live Fire Test law be the weapon(s) specified in the requirements documentation for the system, projected forward to the time when the system is to be fielded. Furthermore, the threat should be reviewed and updated periodically at the milestone decision points to ensure that the specified design weapon(s) is representative of the major "likely to be encountered" threat(s) to the system.**

5. **The committee recommends that the Director, Test and Evaluation, expand the charter of the Live Fire Test and Evaluation program from its current oversight of those tests that are part of the congressionally mandated Live Fire Test program to include oversight of vulnerability assessment.**

• *Recommendation Regarding the Vulnerability Assessment Methodologies*

6. **The committee recommends that both the analysis community and the live fire testing community routinely include on-board ordnance in their assessments.** A waiver to allow full-scale Live Fire Tests without on-board ordnance should be granted only after an examination of the results from alternate live fire tests of sub-scale components and their integration into analyses of the full-up aircraft carrying such ordnance.

7. **The committee recommends that the Under Secretary of Defense, Acquisition, direct the multi-Service coordinated development and authorization for use of improved analytical vulnerability assessment models that are applicable to all military aircraft.** The current Joint Technical Coordinating Group on Aircraft Survivability (JTCG/AS) approved models could form the basis for the new models. The 1987 General Accounting Office study on Live Fire Testing provides many suggestions on how to improve these models.

8. **The committee recommends that a long-term live fire test program be funded in which realistic components, subsystems, and systems are specifically tested to develop a data base to support the analytical models.**

9. **The committee recommends that the Secretary of Defense (a) establish a program to examine the combat data collected from Desert Storm for "lessons learned" regarding the susceptibility and vulnerability of U.S. and allied aircraft; and (b) develop formal, institutionalized procedures for collecting data in future conflicts, for ensuring that the data collectors have access to the theater, and for permanently storing the data.** The combat survivability data collection program should reflect the importance of collecting and preserving the data and should be coordinated among the three Services through a joint agency, such as the JTCG/AS.

• *Recommendations Regarding Vulnerability Programs for Aircraft*

10. **Because of the expected service life extension of currently fielded U.S. military aircraft, the committee recommends that the Under Secretary of Defense, Acquisition, establish a formal vulnerability assessment and reduction program for these aircraft.** This program should require that all product improvement or upgrade programs to existing aircraft include vulnerability assessment and, if appropriate, reduction as major goals of the program.

11. **The committee recommends (a) that a vulnerability assessment program be an**

integral part of every aircraft acquisition program; (b) that vulnerability assessment and evaluation be a specific item examined at each formal milestone review; and (c) that adequate funds be appropriated to the program.

12. **The committee recommends that aircraft programs that become "prototype" programs, such as the RAH-66,** *not* be excluded from live fire testing. The committee is concerned that the RAH-66 might be developed as a prototype without adequate consideration or testing of its vulnerability. If the decision is made at a later date to go into production with the prototype, it will be too late to correct any design weaknesses.

13. **The committee recommends that specific vulnerability requirements on the design be a part of the survivability objectives defined at Milestones I and II.** These vulnerability requirements should be identified as part of the survivability characteristics and incorporated in the aircraft development contracts.

- *Recommendations Regarding the Vulnerability Infrastructure*

14. **The committee recommends that the Director, Test and Evaluation, establish a permanent Senior Vulnerability Assessment Board comprised of senior Services' technical leaders, high-level OSD officials, and nationally recognized experts from industry and academia.** This board would be advisory to the Director, Test and Evaluation, and chartered to review annually the proposed vulnerability assessment programs and budgets of DoD and to review the vulnerability assessment programs on specific aircraft as the need arises. This board would be similar to the boards already formed for conduct of coordinated 6.1, 6.2, and 6.3a Tech Base programs in the DoD.

15. **The committee recommends that studies be conducted to determine if the existing Army, Navy, and Air Force vulnerability analysis community, test facilities, and infrastructure can be reduced proportionally to the expected overall infrastructure reduction within DoD.** Project Reliance, the existing senior joint Services' R&D cooperation group, should be charged with conducting the studies of how best to accomplish a meaningful infrastructure reduction. The committee believes that this drawdown should be carried out very carefully to ensure that essential vulnerability assessment personnel, capabilities, and facilities are not lost in the process.

The Future

The committee recommends to the Secretary of Defense that the broad issue of how to both design and test for vulnerability in an austere future be studied. Present concepts of analyses and live fire testing for vulnerability may not be adequate in a future of reduced budgets, fewer fielded aircraft, fewer program starts, smaller procurement numbers, and more "storage on the shelf" of technology capabilities with less time to react to emergencies. When such a study has been completed and an effective process has been developed for vulnerability design and validation, OSD should consult with Congress regarding revisions to the LFT law that reflect this new process.

1 Review of Current Methodologies Used to Assess Aircraft Vulnerability and Identification of Applications of the Results[1]

What Are the Threats to Military Aircraft?

When the military began to use aircraft in war, the opposing forces began using weapons in an attempt to destroy them. In the first half of the twentieth century, guns were the primary weapons used against aircraft. These guns were either surface-based or carried by enemy aircraft. They ranged from the small arms weapons, such as the 0.3/0.303-inch (7.62/7.7-millimeter) and 0.50-caliber (12.7-millimeter) machine guns, to anti-aircraft artillery (AAA), such as the 40-millimeter and 88-millimeter caliber guns of World War II (WW II). Contemporary guns that can be used against aircraft include the 5.56-millimeter, 7.62-millimeter, 12.7-millimeter, 14.5-millimeter, and 20-millimeter small arms, and the 23-millimeter, 30-millimeter, 37-millimeter, 57-millimeter, 76-millimeter, 85-millimeter, and 120-millimeter AAA. The small arms weapons typically fire ball ammunition, or armor-piercing projectiles, known as AP rounds, or AP projectiles with incendiaries, known as API rounds. The AAA weapons and the larger-caliber aircraft guns usually fire ballistic projectiles with a high-explosive (HE) core and a surrounding metal case. These are referred to as HE warheads or HEI warheads when incendiaries are included.[2] The HE warheads may detonate on contact with the aircraft (contact-fuzed HE warheads), after an elapsed time since firing (time-fuzed HE warheads), or in proximity to the aircraft (proximity-fuzed HE warheads).

After World War II, guided missiles, both surface-based and airborne, were developed to kill aircraft. These anti-air weapons typically carry contact- or proximity-fuzed HE warheads designed to kill aircraft with fragments and blast. Guns and guided missiles are still the primary threat faced by aircraft today. However, several new threats to aircraft are in development. Directed energy weapons, in the form of low-to-medium power lasers and high-power microwaves, have the potential to damage or destroy sensors on the aircraft and the weapons they are carrying; and high-power lasers can damage major aircraft structure. Chemical and biological weapons pose a threat to aircraft, particularly on the surface, and nuclear weapons are a threat to aircraft on the surface and in the air.

What Is Aircraft Vulnerability?

Aircraft survive a mission into hostile territory by “avoiding” the damage-causing mechanisms of the enemy’s air defense and by “withstanding” the damage caused by these mechanisms when they cannot be avoided. The aircraft attribute known as susceptibility refers to the inability of

[1]Much of the material presented in this chapter is based upon Ball (1985).

[2]Some of the small-caliber AAA also fire API rounds.

the aircraft to avoid (being damaged by) the man-made hostile environment and is measured by P_H, the probability the aircraft is hit by a weapon while on its mission. The aircraft attribute known as vulnerability refers to the inability of the aircraft to withstand (the damage caused by the) hostile environment and is measured by $P_{K/H}$, the probability the aircraft is killed[3] given that it is hit. The probability the aircraft is killed by a particular weapon while on the mission is P_K, which is equal to $P_H \bullet P_{K/H}$. The probability the aircraft survives the encounter with the weapon is P_S, which is equal to $1–P_K$, which is the same as $1–P_H \bullet P_{K/H}$. Thus, reducing an aircraft's susceptibility (P_H) and vulnerability ($P_{K/H}$) to the weapons likely to be encountered in combat increases its survivability. An aircraft's susceptibility can be reduced by destroying the enemy air defense elements, by reducing the aircraft's signatures (stealth), by employing on-board and off-board threat warning systems and electronic countermeasures, and by the tactics employed. An aircraft's vulnerability can be reduced by using redundant and separated components, by locating components to minimize the possibility and extent of damage, by designing components to contain or withstand the effects of damage, by adding special equipment to suppress the damage, by shielding components, and by removing vulnerable components from the design. A very important aspect of vulnerability reduction is that many design features are effective against a number of different threat weapons. For example, locating redundant flight control hydraulic components on opposite sides of the aircraft and inerting the fuel tank ullages will provide protection from both gun projectiles and proximity-fuzed missiles in most situations. Thus, in many situations it is not necessary to consider all of the individual threats when designing the aircraft.

Critical Components and Essential Functions. Each component in the aircraft has a level, degree, or amount of vulnerability to the damage-causing mechanisms[4] generated by the threat weapon; and each component's vulnerability contributes in some measure to the vulnerability of the total aircraft. The critical components on an aircraft are those components whose kill result in the loss of an essential function. Essential functions are those functions required to prevent an aircraft kill. The essential functions that prevent an attrition kill are lift, thrust, and control of flight, and the ability to land safely. Navigation and weapons delivery are two possible essential functions for a mission abort kill. An example of a critical component for the attrition kill is the single pilot who controls the flight of the aircraft. If the pilot is killed (i.e., he/she is unable to perform the essential function of control of the aircraft) the aircraft is also killed. An example of a critical component on an attack aircraft for the mission abort kill is the weapons delivery computer. If the computer is killed, the weapons cannot be released at the correct time; consequently, the pilot will return to base prior to mission completion.

Components that do not contribute to any of the essential functions become critical when their response to a hit (i.e., their kill mode) causes the kill of another component that is critical because it contributes to an essential function. For example, consider the bombs carried on-board an attack aircraft. The bombs do not contribute to the essential functions for flight of lift, thrust, and control. However, if one of the bombs explodes when hit by a fragment or bullet, and the explosion kills the pilot or any other critical components on the aircraft, the bombs are critical components because their kill mode (explosion) eventually leads to a kill of the aircraft.[5] The propagation of damage from the hit component to other components is known as cascading damage. Pyrotechnic items, such as infrared flares, are also critical components when their reaction to a hit leads to a fire and the eventual loss of the aircraft.

The critical components can be nonredundant, such as the single pilot and single engine on a single-piloted, single-engined aircraft, or redundant, such as the two engines on a two-engined aircraft. When the critical components are redundant, a kill of more than one of the redundant components is required for a kill of the aircraft. In general, the critical components on a particular aircraft depend only upon the selected kill category (and level, if appropriate) and the assumed kill mode(s), and not upon the threat weapon.[6]

The procedure used to determine all of the nonredundant and redundant critical components on an aircraft is known as the critical component analysis. Two different types of analyses can be used, the Failure Mode and Effects Analysis (FMEA) and the Fault Tree Analysis (FTA). In the FMEA, all possible failure, damage, or kill modes of a component or subsystem are identified and the consequence of each

[3]The word kill is used here in a general sense. The vulnerability assessment community uses several definitions of kill. Two categories of kill are the attrition kill and the mission abort kill. There are several levels of attrition kill based upon the elapsed time of kill after the hit. For example, the K-level attrition kill is defined as a kill in which the aircraft falls out of control within 30 seconds after the hit, and the A level is defined as a kill in which the aircraft falls out of control within 5 minutes after the hit.

[4]Damage, threat, or kill mechanisms are the output of the threat warhead that cause damage to the aircraft. The types of damage mechanisms associated with penetrator and high-explosive warheads are penetrators, fragments, incendiaries, and blast. Damage processes refer to the interaction of the damage mechanism with the aircraft and its components. The damage processes associated with the damage mechanisms listed here include ballistic impact, penetration, combustion (in the form of a fire or explosion), hydraulic or hydrodynamic ram, and blast loading.

[5]The treatment of the on-board munitions when assessing aircraft vulnerability is a major concern to the committee, particularly for aircraft with internal ordnance storage. This concern is examined in detail in Chapters 2 and 4.

[6]Refer to footnote 3 for several examples of kill definitions.

TABLE 1-1 List of Some Subsystem Damage-Caused Failure (Kill) Modes [Ball, 1985]

Fuel Subsystem	*Propulsion Subsystem*	*Flight Control Subsystem*
Fuel supply depletion	Fuel ingestion	Disruption of control path
In-tank fire/explosion	Foreign object ingestion	Loss of control power
Void space fire/explosion	Inlet flow distortion	Loss of aircraft motion data
Sustained exterior fire	Lubrication starvation	Damage to control surfaces
Hydraulic ram	Compressor case perforation	Hydraulic fluid fire
	Combustor case perforation	
Power Train/Rotor Blade/Propellor Subsystem	Turbine section failure	*Structural Subsystem*
		Structural removal
Loss of lubrication	Exhaust duct failure	Pressure overload
Mechanical/structural damage	Engine control/accessories failure	
		Thermal weakening
Electrical Subsystem		Penetration
Severing or grounding	*Crew Subsystem*	
Mechanical failure	Injury, incapacitation, or death	*Avionics Subsystem*
Overheating		Penetrator/fragment damage
	Armament Subsystem	Fire/explosion/overheat
	Fire/explosion	

component failure/damage/kill mode upon each of the essential functions is determined.[7] In the FTA, those component or subsystem kill modes required to cause the loss of the essential functions are determined.

Kill Modes. For many years, the aircraft vulnerability community has observed the results of live fire testing of components, subsystems, and aircraft and has examined the combat data on damaged and killed aircraft in order to determine all of the kill modes associated with each of the aircraft subsystems. For example, there are five kill modes associated with the fuel subsystem. When a fuel tank is holed by a penetrator or fragment, a catastrophic explosion or major fire may occur inside the tank, or fuel may leak from the hole in the tank into an adjacent void space or dry bay and catch fire, or hydraulic ram damage to the fuel tank wall may cause a major structural failure of the tank or allow fuel to dump into engine intake ducts, causing an engine kill. A list of some of the possible kill modes for each of the major subsystems on an aircraft has been compiled based upon these observations and studies. This list is presented in Table 1-1.

The kill modes listed in Table 1-1 describe different types of reaction that components or subsystems in the aircraft exhibit when the aircraft is hit. In some of the kill modes, the component hit is the only component killed, whereas in others, the component hit reacts to the hit in a mode that kills other components. An example of the former is the loss of flight control due to a hit in a hydraulic power actuator that causes a jam of the actuator and a loss of control of the control surface. An example of the latter is a fuel ingestion kill of an engine due to a hit on a fuel tank adjacent to the air inlet. Reducing the vulnerability of an aircraft to the threat weapons and their damage mechanisms involves reducing the likelihood the kill modes given in Table 1-1 will occur when the aircraft is hit.

The Failure Mode and Effects Analysis (FMEA). As an example of the FMEA process, consider a single-engine aircraft with only two fuel tanks, one in each wing. The tanks are partially full, and there are fuel vapors in the ullage[8] of the tanks. The possible kill modes for the fuel subsystem are given in Table 1-1. One fuel tank kill mode is an explosion inside the tank. If the consequence of the internal explosion in either wing tank is the destruction of the wing containing the tank, which then causes a kill of the aircraft due to loss of lift, both wing fuel tanks are nonredundant critical components for the attrition kill for the internal explosion kill mode. On the other hand, suppose the kill mode of the tanks is a loss of fuel storage capability due to one or more holes in the bottom of the tank. If this kill mode occurs in only one tank, this will not lead to a loss of thrust due to fuel supply depletion when the undamaged tank can provide fuel to the engine. However, if both tanks are holed and lose their storage capability, then a fuel supply depletion

[7]The relation between a component or system failure mode and combatcaused damage or kill modes is developed in the Damage Mode and Effects Analysis.

[8]The ullage is the volume of the tank above the fuel level. Fuel vapors accumulate in the ullage.

kill will occur, the aircraft will lose thrust, and an attrition kill will result. Thus, for this kill mode, the fuel tanks are redundant critical components.

The Fault Tree Analysis (FTA). In the FTA process, the selected kill category (and possibly level) is defined as the top-level undesirable event, and the component kill required to cause the undesirable event are determined. The component kill that result in the undesired event are linked together in the fault tree by using logical AND and OR gates. For example, consider an aircraft with components A, B, C, and D. An undesirable kill will occur if either component A OR B is killed, or it may occur if both components C AND D are killed. Thus, components A and B are nonredundant critical components, and components C and D are redundant critical components. In using FTA for the fuel tank example given above, one undesirable event leading to an attrition kill is loss of lift. If loss of lift occurs due to an explosion inside the left wing fuel tank, a component A kill, OR if it occurs due to an explosion inside the right wing tank, a component B kill, both wing fuel tanks are nonredundant critical components for the explosion kill mode. On the other hand, a loss of thrust will occur if wing tanks A AND B are killed (by the fuel supply depletion kill mode). Thus, the tanks are redundant critical components for this kill mode. As another example of FTA, consider a two-engined aircraft. The undesired event of loss of thrust, which leads to an attrition kill, will occur when the left engine AND the right engine are killed. Thus, these two components are redundant critical components. A list of the typical critical components on a single-piloted, two-engined helicopter is given in Table 1-2.

The Kill Tree. A visual illustration of all of the critical components and their redundancies is provided by the kill tree,[9] such as the one shown in Figure 1-1 for an attrition kill of a two-engined, two-piloted helicopter. A complete horizontal or diagonal cut through the tree trunk anywhere along the trunk will cause a kill. For example, a kill of the pilot and either the copilot or the copilot's controls will cause a kill, as will a kill of the drive train or any of the three cyclic actuators. If the kill mode of the left- and right-hand fuel tanks is fuel supply depletion, both tanks must be killed to cause a kill of the aircraft. On the other hand, if the kill mode is a fuel fire or explosion, then a kill of either tank will kill the aircraft. Once the critical components have been identified and arranged in the kill tree, a vulnerability assessment can be performed.

What Is a Vulnerability Assessment?

A vulnerability assessment is broadly defined here as the systematic description, delineation, test and evaluation, analysis, or quantification of the vulnerability of the individual critical components and of the total aircraft. When an aircraft is hit by one or more damage mechanisms generated by the threat weapon, the outcome of those hits is not deterministic; it is random or stochastic.[10] For example, when 15 fragments from a proximity-fuzed high-explosive warhead penetrate the upper wall of an aircraft's wing fuel tank, the flammable vapor inside the tank may explode, destroying the wing and killing the aircraft; or the vapor may not

[9]The kill tree is also referred to as the fault tree.

[10]A deterministic process has a repeatable outcome that can be predicted with certainty if all of the influencing parameters and governing laws are known. Random or stochastic processes have multiple or various outcomes, any one of which may or may not occur on any one trial.

TABLE 1-2 List of Typical Nonredundant and Redundant Critical Components on a Single-Piloted, Two-Engined Helicopter (Ball, 1985)

Nonredundant Critical Components	*Redundant Critical Components*
Flight Control Subsystem Components Rods, bellcranks, pitch links, swashplate, hydraulic actuators, collective lever, and control pedals	*Propulsion Subsystem Components* Engines and engine mounts
Rotor Blade and Power Train Components Blades, drive shafts, rotor heads, main transmission, and gearboxes	*Hydraulic Subsystem Components* Hydraulic reservoirs, lines, and components
Fuel Subsystem Components Fuel cells, sump, lines, and valves	*Structural Subsystem Components* Redundant structural elements
Structural Subsystem Components Tail boom	

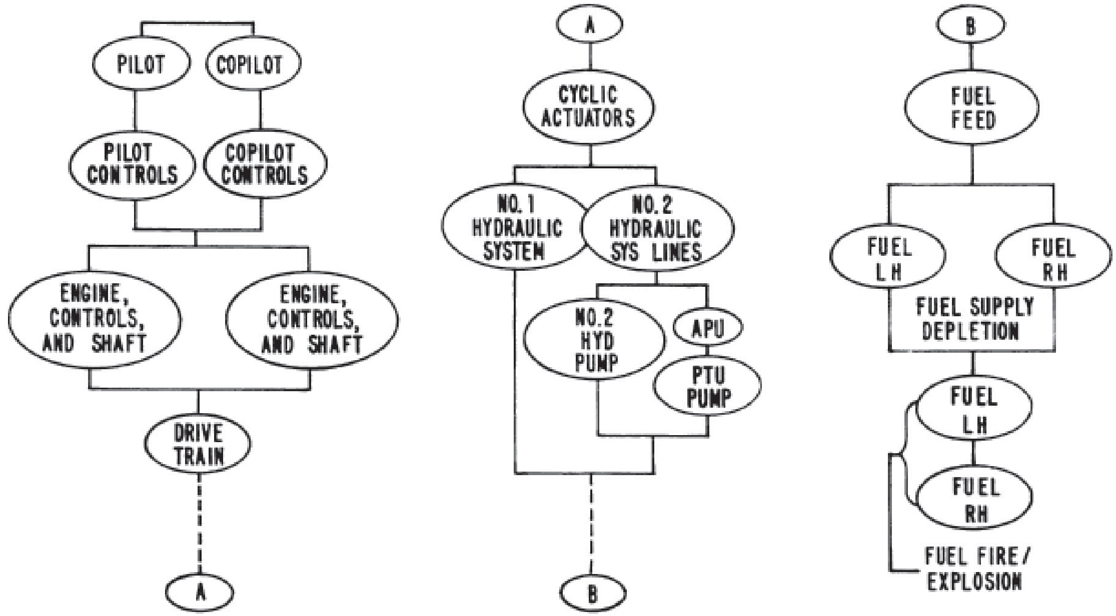

FIGURE 1-1 The attrition kill tree for a two-piloted, two-engined helicopter (Ball, 1985). Copyright © AIAA 1985—Used with permission.

explode, and the aircraft survives the 15 hits. The likelihood of an explosion inside the tank depends upon many random variables, such as the amount of fuel vapor, the oxygen concentration in the vicinity of the fragments, and the temperature of the fragments.

How Is Vulnerability Measured?

As a consequence of the random nature of vulnerability, the metric most often used to quantify the vulnerability of an aircraft's critical components is $P_{k/h}$, the probability the component is killed given a random hit on the component by a threat weapon or damage mechanism.[11] The value of $P_{k/h}$ depends upon the intensity of the terminal effects parameters associated with the damage mechanism, such as mass and impact velocity on the component for penetrators and fragments. The set of component $P_{k/h}$ values for different masses and impact velocities is known as the $P_{k/h}$ function. A second metric used to quantify a component's vulnerability is A_v, the vulnerable area of the component. Component vulnerable area is defined as the presented area of the component that, if hit, would cause a kill of the component and is equal to the product of the component's presented area A_P in the threat approach direction and its $P_{k/h}$, i.e., $A_v = A_P \bullet P_{k/h}$.

[11]Other metrics sometimes used for component vulnerability are $P_{d/h}$, the probability a component is damaged given a hit, area removal, energy density, and blast.

The metrics used to quantify the vulnerability of the aircraft to a single random hit by a penetrator or contactfuzed warhead include $P_{K/H}$, the probability the aircraft is killed given a random hit on the aircraft and A_v, the aircraft's single hit vulnerable area.[12] The metric used to quantify the vulnerability of an aircraft to the proximity- and time-fuzed HE warheads on AAA projectiles and guided missiles is $P_{K/D}$, the probability the aircraft is killed given an external detonation by a high-explosive warhead. The $P_{K/D}$ is a function of the location of the detonation point with respect to the aircraft.

What Are the Two Methodologies Used to Assess Vulnerability?

In general, there are two methodologies used to assess aircraft vulnerability. One method is the a priori prediction of aircraft vulnerability by using analyses or modeling. This method is nearly always supported by prior live fire test data on component $P_{k/h}$ values for the various kill modes. However, the data have often been obtained on older equipment. The other method is the a posteriori observation and

[12]Lowercase subscripts refer to a component and uppercase subscripts refer to the aircraft. Thus, $P_{k/h}$ is the probability a component is killed given a random hit on the component, $P_{k/H}$ is the probability a component is killed given a random hit on the aircraft, and $P_{K/H}$ is the probability the aircraft is killed given a random hit on the aircraft.

possible measurement of aircraft vulnerability by using empirical data obtained from either actual combat, aircraft accidents, or controlled live fire testing.[13] This method is nearly always supported by a priori predictions of vulnerability prior to testing to define the test conditions and by a posteriori analyses or evaluation of the data. A brief review of the state-of-the-art of vulnerability analysis/modeling and vulnerability testing is given below.

Analysis/Modeling. The prediction of an aircraft's vulnerability to the ballistic projectiles and guided missiles likely to be encountered in combat can be accomplished by using standardized computer programs.[14] One set of programs is applicable to a single hit by impacting penetrator or fragment. Computation of Vulnerable Area and Repair Time (COVART) is the Joint Technical Coordinating Group on Aircraft Survivability (JTCG/AS) standard program for computing the critical component vulnerable areas A_v and the aircraft's vulnerable area A_v for a single random hit by a penetrator or fragment (JTCG/ME, 1984). Another set of programs computes aircraft vulnerability to contact-fuzed HE warheads that detonate on the surface or within the aircraft. High Explosive Vulnerable Area and Repair Time (HEVART) (BRL, 1978 and HEI Vulnerability Assessment Model (HEIVAM) (Datatec Inc., 1979) are examples of this type of program. A third set, known as endgame programs, computes the probability an aircraft is killed due to an external burst of an HE warhead. SCAN (Dayton University Ohio Research Institute, 1976) is the current JTCG/AS endgame model for computing an aircraft's $P_{K/D}$. Modular Endgame Computer Assessment (MECA), Joint Services Endgame Model (JSEM), SESTEM II (ASD/WPAFB, 1981), and SHAZAM (Air Force Armament Lab./Eglin AFB, 1983) are four other widely used endgame programs.

All of these vulnerability assessment programs require as input a three-dimensional data base that defines the geometric model of the aircraft. The geometric model may be contained within the vulnerability assessment program, as in SCAN, or it may be developed in a separate program, such as MAGIC, Ballistic Research Laboratory Computer-Aided Design (BRL-CAD) package, or FASTGEN III, which are used as preprocessors for COVART. This model should contain all of the aircraft's components, equipment, and supplies, including such items as fuel, hydraulic fluid, and ordnance. However, because of the limitations on program size, available time, and manpower, many small non-critical components that are not expected to influence the results are often omitted.[15] Another subsystem that has often been omitted in vulnerability assessments is the on-board ordnance in the form of bombs, missile warheads and propellants, and ammunition drums. On most aircraft, bombs and missiles are carried externally. In this position, they may shield other components from projectiles and fragments, or they may react violently to a ballistic impact (e.g., detonate) and destroy the aircraft. The new stealth aircraft carry ordnance internally in order to reduce signatures. Adverse reactions of any internally carried ordnance, such as a deflagration or a detonation, have an even greater probability of destroying the aircraft. The omission of on-board ordnance from the assessment is discussed in more detail in Chapters 2 and 4.

Another input requirement for the assessment is the kill tree (or logical kill expression) for the selected kill category (and level if appropriate). This tree defines the redundant and nonredundant components that if killed individually (the single engine on a single-engined aircraft) or in combination (both engines on a two-engined aircraft) will cause an aircraft kill. Associated with each critical component on the tree is a data base that contains the $P_{k/h}$ or A_v value for the component that is based upon the selected threat weapon or damage mechanism and the possible range of impact velocities on the installed component, for the kill modes considered in the critical component analysis.

Vulnerability to a Single Hit by a Penetrator or Fragment. All of the vulnerability assessment programs contain an assumption as to how the damage mechanisms associated with the weapon proceed through the aircraft. The COVART methodology assumes that the penetrator or fragment from any selected direction[16] is equally likely to impact the aircraft at any location and that it propagates along a straight line, known as a shotline, through the aircraft, slowing down and possibly breaking up as it penetrates the various components. The amount of fragment or penetrator slowdown is determined by the penetration equations that are a part of the built-in data base. Ricochet of the fragment or penetrator is not considered. An additional assumption often made is that only the components that are intersected by one shotline can be killed by the hit along that shotline. This assumption rules out the possibility of cascading damage away from the shotline.[17] In the analysis, the presented area of the aircraft

[13]Combat and accident data are extremely valuable as adjuncts to the other methodologies, but they are limited in scope, limited in the information on the nature of the event, and not always available for direct application.

[14]The Joint Technical Coordinating Group on Aircraft Survivability has established a library of computer programs for assessing the susceptibility, vulnerability, and Survivability of aircraft. The library is maintained and operated by the Survivability/Vulnerability Information and Analysis Center (SURVIAC) at the Wright Aeronautical Laboratories.

[15]The COVART model for the F-22 contains 2,213 components, of which nearly half are critical.

[16]The directions usually selected include the six cardinal views of front, back, top, bottom, left side, and right side, and may include the twenty 45-degree angles between these six views.

[17]It is possible to modify the intersected component's $P_{k/h}$ to account for kills of adjacent components.

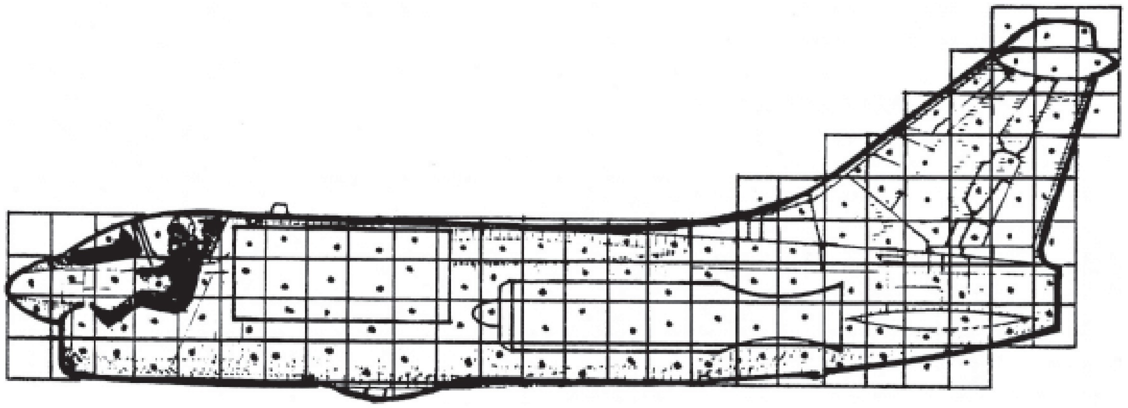

FIGURE 1-2 Example of a grid and random shotlines from FASTGEN for COVART (Ball, 1985). Copyright © AIAA 1985—Used with permission.

from the selected direction is covered by a uniform grid, and one shotline is randomly located within each cell. An example of the random shotlines within the cells for a particular aircraft is shown in Figure 1-2.

The user has the option of selecting the uniform cell size. Typical cell sizes range from 12 inches to 1 inch on a side, with 2 inches being typical. A preprocessor program, known as a shotline generator program, such as MAGIC, BRL-CAD, or FASTGEN III, identifies all of the critical components intersected by each shotline. This information is input data for COVART. COVART computes the vulnerable area of each critical component and the aircraft's single hit vulnerable area, as well as the probability the aircraft is killed by a random hit. For component vulnerable areas, each grid cell containing a shotline that intersects a component has a vulnerable area equal to the product of the presented area of the cell and the $P_{k/h}$ for the shotline through the component. The total vulnerable area of the component is the sum of the vulnerable areas of those cells with shotlines that intersect the component. For the aircraft vulnerable area A_v, each grid cell shown in Figure 1-2 contributes a vulnerable area equal to the product of the presented area of the cell and the probability the aircraft is killed by a hit along the shotline in that cell.[18] The total aircraft vulnerable area is equal to the sum of the vulnerable areas of each of the cells. Consequently, redundant components, if separated, that both are not intersected by one shotline, do not contribute to the aircraft's single hit vulnerable area for that shotline.[19] The $P_{K/H}$ for the aircraft is equal to the A_V of the aircraft divided by A_P, the aircraft's presented area from the selected direction.

Vulnerability to a Contact-Fuzed High-Explosive Warhead. Essentially the same analytical procedure is followed for contact-fuzed high-explosive warheads. A geometric model of the aircraft, the kill tree, and the critical component $P_{k/h}$ or A_v data are required. A grid is superimposed on the aircraft and a shotline is randomly located within each cell. The difference between this analysis for the contact-fuzed HE warhead and the analysis for the single penetrator or fragment is the fact that components in the vicinity of the shotline can be killed by the blast and fragments from the detonation of the HE warhead. Thus, redundant critical components that are relatively close together can be killed by a single hit, causing a kill of the aircraft. Figure 1-3 shows the grid cell and randomly located shotlines for this type of analysis. Note that in this figure the HE warhead detonation can cause a kill of both the fuel tank and the engine even though neither component was hit directly by the weapon.

Vulnerability to an Externally Detonating High-Explosive Warhead. The analysis for the externally detonating HE warhead, shown in Figure 1-4, follows the same procedure used for the single penetrator or fragment, except that the fragment shotlines emanating from the external detonation are radial rather than parallel, and the aircraft can suffer multiple fragment impacts over its surface rather than a single hit. In addition, the blast from the detonation can kill the aircraft. The assessment of the kill of the aircraft by external blast is usually made independently from the fragment assessment. Three-dimensional blast contours around the aircraft are determined as a function of HE weight. Within a particular blast kill contour for particular explosive charge weight, a detonation of a warhead with that charge weight or larger will kill the aircraft.

Results from the Analyses. The results or information obtained from an analytical assessment of aircraft vulnerability

[18] When more than one nonredundant critical component is intersected by a shotline, the probability the aircraft is killed is equal to the union of the component probabilities of kill.

[19] This is the result of the assumption that only those components intersected by the shotline can be killed. A modification of the $P_{k/h}$ value for a component can be made to allow a hit on one component to cause a kill of another component due to cascading damage.

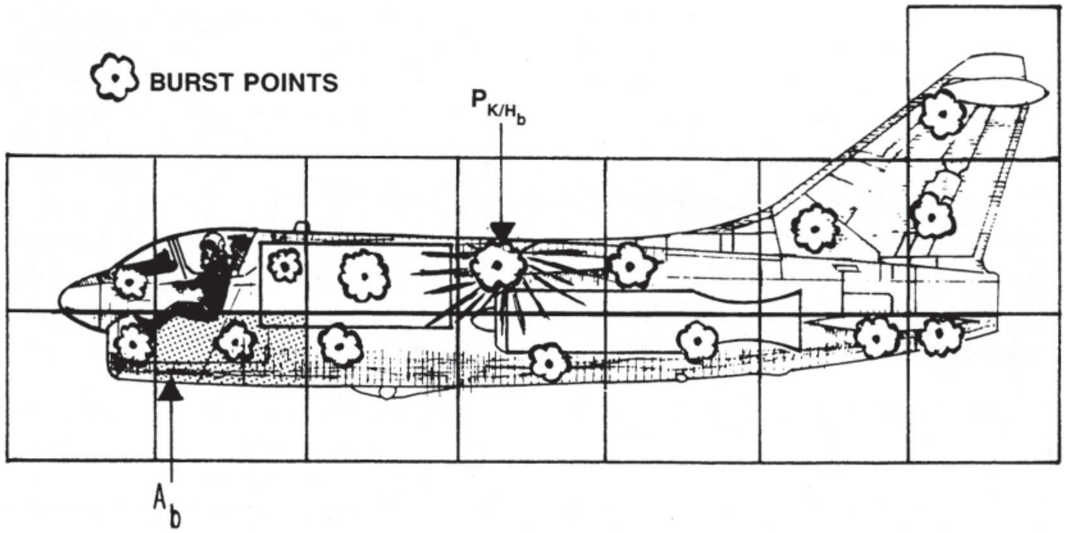

FIGURE 1-3 Grid cells and shotlines for the contact-fuzed high explosive weapon (Ball, 1985). Copyright © AIAA 1985—Used with permission.

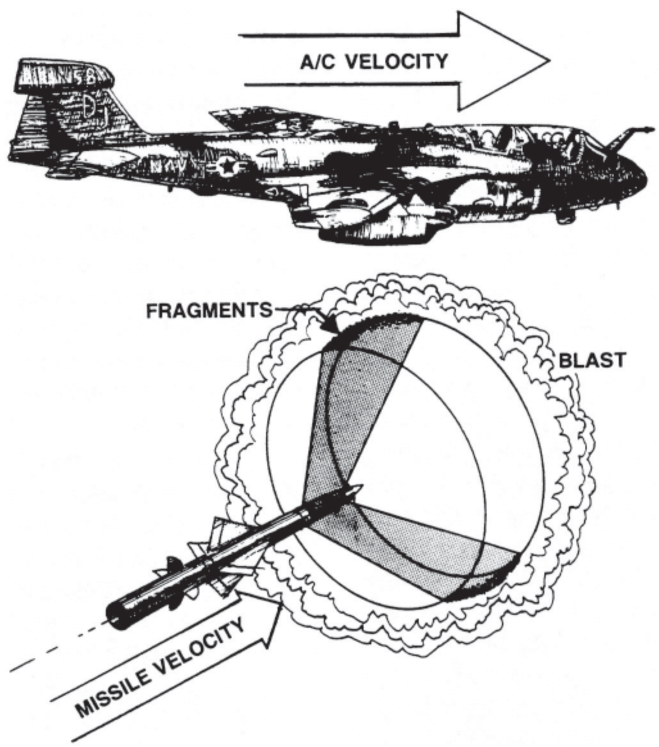

FIGURE 1-4 Aircraft vulnerability to the externally detonating HE warhead (Ball, 1985). Copyright © AIAA 1985—Used with permission.

for the single hit by a penetrator or fragment typically consists of predictions of the values of vulnerable area A_v for all of the critical components, the aircraft vulnerable area A_V, the probability the aircraft is killed given a hit within each grid cell, and the probability the aircraft is killed given a random hit $P_{K/H}$. The assessment results for the single hit by the contact-fuzed high-explosive warhead consist of the aircraft vulnerable area A_V and the probability of kill given a random hit on the aircraft $P_{K/H}$. The results of an assessment for the externally detonating warhead consist of the probability of kill of the critical components intersected by the fragment shotlines from the warhead detonation, the probability of aircraft kill due to blast, and the probability of aircraft kill given a detonation $P_{K/D}$.

The Stochastic Qualitative Analysis of System Hierarchies (SQuASH) Model. One of the primary criticisms of the current aircraft vulnerability models is the straight shotline assumption. Fragments and penetrators usually do not penetrate through the aircraft in a straight line. In an attempt to account for the random, irregular path of penetrators and fragments through armored vehicles, Ballistic Research Laboratory (BRL) developed the SQuASH model (Deitz et al., 1990). SQuASH is applicable to both penetrator and high-explosive weapons. It allows for deflections of the penetrators and fragments from the straight shotline, the creation of spall, and it tracks the pieces of fractured penetrators. The present version of SQuASH was developed for the vulnerability analysis of armored ground vehicles. However, its methodology could be applied to aircraft.

The model introduces the concept of Spaces. All possible warhead and target conditions at the time of the hit form the Initial Conditions Space, or Space 1. A particular set of conditions, such as the type and operational status of the target and the location of the hit on the target, is one point in the Initial Conditions Space. Due to the hit, some components will be damaged, and some will be killed. These damaged and killed components, and all other post-event observables, such as holes in plates and other terminal effects, form the damage vector. All possible damage vectors for the target form the Damage Space, or Space 2, and the specific damage vector containing the components damaged or killed by the hit is one point in the Damage Space. All possible target capabilities after the hit form the Capabilities Space, or Space 4, and the particular target capabilities remaining after the hit represent one point in the Capabilities Space.[20] The vulnerability event starts with a point in the Initial Conditions Space. This point is mapped to the Damage Space either by a live fire test or by the SQuASH model. Note that because the vulnerability event is nondeterministic, one point in the Initial Conditions Space can map to many different points in the Damage Space. The mapping from the Damage Space to the Target Capabilities Space is accomplished currently by using the Damage Assessment List. In the future, the Degraded States methodology will be used for this mapping.

SQuASH is a Monte Carlo model. Each shot at the target is replicated (typically 1,000 times) with slight variations in its initial conditions. For each replication or trial, random drawings determine which events (such as kill of a component that is hit) occur. The resulting damage vector for that shot is computed, and the frequency of occurrence of the elements in these damage vectors is produced as an intermediate result. Input kill or fault trees are used to develop estimates of target and individual subsystem kill probabilities.

Some difficulties associated with SQuASH are the lack of data with respect to the broken paths and component damage, especially synergistic damage, and the problems associated with relating component damage to degradation in performance. Another difficulty is the magnitude of the number of possible outcomes from one event. This number is dependent upon the number of components that can be killed. There may be a large number of components to consider for a particular shot; perhaps between 10 and 100. The number of components in an entire aircraft might be on the order of 1,000. The damage vector consists of these M components, and each of the M components or elements in the vector is either a 0 (no damage) or a 1 (damage), and the sample space is said to have dimension M. The sample space of possible combinations of components that might be damaged by a particular shot is 2^M. Thus, the sample space for a given shot can be quite large. Some sort of metric is needed to reduce the sample space to one with a more manageable size. One approach might be to create some sort of metric that quantifies the "nearness" of various damage vectors (similar to a Hamming distance).

Testing. As a result of the random nature of the vulnerability problem, the multitude of known component or subsystem kill modes, the possible existence of unknown or previously unobserved kill modes or cascading damage, and the difficulty in quantifying the vulnerability of the components and subsystems for each of these kill modes, the use of combat data[21] and the results from controlled live fire[22] tests have always been integral parts of vulnerability assessment. These data provide insight into the component and subsystem kill modes and any cascading damage that can occur. Furthermore, when a sufficiently large number of identical tests are performed, statistical data on vulnerability are generated. However, because of the expenses and difficulty associated with obtaining large quantities of useful results from either combat or testing, there is a general reluctance to engage in large-scale efforts that may provide little useful data or may have little applicability to present or future aircraft or analytical models. Nevertheless, many live fire tests have been conducted since WW II on targets ranging

[20]Space 3 represents objective Measures of Performance and is not modeled.

[21]The combat data gathered in past conflicts is stored in the Combat Data Information Center, which is part of the Survivability/Vulnerability Information and Analysis Center. SURVIAC is located at Wright-Patterson Air Force Base, Ohio.

[22]The term "live fire testing" is used here in the general sense to mean firing live (both explosive and non-explosive) ammunition or fragments at the target (and hitting it).

TABLE 1-3 Definitions of Types of Test Articles and Type of Tests (GAO, 1987)

	Loading	
Scale	*Full-Up*	*Inert*
Full-scale (Complete System)	Complete system with combustibles	Complete system without combustibles
Sub-scale (Partial System)	Components, subsystems, or subassemblies with combustibles	Components, subsystems, or subassemblies without combustibles

from individual components to actual aircraft. Of particular interest here are the current Joint Live Fire (JLF) program and the congressionally mandated Live Fire Test and Evaluation (LFT&E) program.

General Procedure for Testing. Before reviewing the JLF and LFT programs, the general procedure for testing that has been established by the vulnerability testing community is described. Briefly, one or more targets and weapons are obtained and prepared for testing. The target can be one component, a subassembly, a subsystem, several subsystems, portions of the aircraft, or the aircraft weapon system. According to the General Accounting Office (GAO), tests conducted on the complete weapon system are known as full-scale tests, and tests on less than full-scale targets are known as sub-scale tests. Corresponding definitions also used in this report are complete system tests and partial system tests. A surrogate target or weapon is an existing target or weapon that is similar to the intended target or weapon. If the target, either the complete system or a partial system, contains all of the appropriate combustibles, such as fuel, hydraulic fluid, ordnance, and stowage items normally found on the aircraft when operating in combat, the tests are known as full-up tests. Inert targets lack all of the appropriate combustibles, and semi-inert targets contain some of the combustibles. Table 1-3 contains these definitions, which are used throughout this report.

The Test Plan and Some Important Considerations. The test plan contains the test objectives and the issues the tests are supposed to provide information on, the weapon to be used, the selection and placement of test instrumentation, the selection of the number of shots, the shotline directions, the impact locations, and any analytical methods that will be used. The test plan may contain a number of random shots as well as a number of selected shots. The tests are scheduled so those shots that are expected to cause minimum damage to the target are conducted early in the program. Those tests that are expected to cause more severe damage are conducted at the end of the program. Particular shots that have the potential to destroy the target, although of vital interest, may not be conducted at all. Preparation for testing consists of the preparation of the test site, the weapon, and the target. After each test, the target is repaired and returned to a condition as similar to the original condition as possible. If the weapon is a non-explosive penetrator or fragment, the amount of damage is usually small, the repairs are relatively simple, and the target can be hit in essentially the same location again. However, if the weapon contains a high-explosive warhead, the damage is more severe and extensive, the repair is more difficult, and it may not be possible to return the aircraft to its original condition. In this situation, the shotline for a second shot must be sufficiently separated from the first shotline so that the damage and subsequent repair of the first shot do not influence the results of the second shot.

Some of the important test considerations are the external and internal environmental conditions at the time of the test, such as the requirements for external air flow over the target, and the proper fuel vapor states and temperatures inside the target; the requirement for jig arrangements to introduce loads on the aircraft structure; and the requirement for all of the equipment to be operating at the time of the hit. For example, must a helicopter rotor blade or tail rotor drive shaft be turning when it is hit by the weapon? Must the hydraulic fluid be at the normal operating temperature when the line is hit? What internal structural loads are appropriate for the test, those associated with normal flight, or those associated with a violently maneuvering aircraft?

The Test Results. The results or information obtained from controlled live fire tests typically consists of a list of the components that were damaged or killed, the nature and severity of the damage, the kill modes observed and any cascading damage, and an estimate or measurement of the ability of the aircraft to continue the operation of essential functions. Specific events, such as the initiation of a fire and the intensity and duration of the fire, are also noted.

Due to the randomness of the reactions to the hit, some of the observed results in one test may not be observed in any of the other tests. For example, firing a 12.7-millimeter API into a partially empty fuel tank may not result in an internal explosion on the first test shot, but the second shot may cause an explosion that destroys the tank. On the first firing of a 12.7-millimeter API projectile into a helicopter engine nacelle, the projectile may ricochet into the cockpit; on the second shot, it may ricochet into the transmission.

What Are the Joint Live Fire and Live Fire Test Programs?

Joint Live Fire. In 1983, the Office, Secretary of Defense (OSD) Director, Defense Testing and Evaluation nominated to the Services a joint test and evaluation initiative for the live fire of munitions, foreign and U.S., made against currently operational full-scale targets, both U.S. and foreign. This program is known as the Joint Live Fire program. The U.S. targets originally included land, sea, and air; however, the sea targets were eventually excluded from the program. Candidate aircraft included the F-15, F-16, F/A-18, AV-8B, fixed wing aircraft, and the UH-60 and AH-64 helicopters. The threats initially considered consisted of armor-piercing projectiles with incendiaries (12.7-millimeter, 14.5-millimeter, 23-millimeter, and 30-millimeter API), warhead fragments (45, 70, 110, and 220 grains), and contact-fuzed high-explosive rounds with incendiaries (23-millimeter and 30-millimeter HEI). A number of specific tests on various components and subsystems of these aircraft have been conducted, such as tests on the UH-60 main rotor blade, the F-15 and F-16 hydraulic fluid, the F-15 and F-16 steady state and quick dump fuel ingestion, and the F-16 emergency power subsystem. In 1989, the results of the JLF tests were presented to more than 100 industry, government, and military specialists in vulnerability and vulnerability testing. The JLF program is still active. The test data gathered during the tests are currently being examined to determine the $P_{k/h}$ values for the tested components, and the empirical values are being compared to the previous values in order to decide whether the previous values should be revised.

The Live Fire Test Law. As a result of the controversy over the vulnerability testing of the U.S. Army's Bradley Fighting Vehicle, Congress in fiscal year 1987 amended title 10 of the U.S. Code, adding Section 2366. "Major Systems and Munitions Programs: Survivability and Lethality Testing; Operational Testing." This legislation, known as the Live Fire Test (LFT) law, applies to covered systems. According to the law, *"A covered system means a vehicle, weapon platform, or conventional weapon system that (A) includes features designed to provide some degree of protection to users in combat; and (B) that is a major system within the meaning of that term is section 2303(5) of title 10"* (U.S. Congress, 1986–1989). A major system is one that costs $75 million in Research Development, Testing, and Evaluation and/or $300 million in procurement, in 1980 dollars, and is determined by the Secretary of Defense not to be a highly classified (i.e., black) program. Several modifications have been made to the law since FY1987.[23]

According to the LFT Test Guidelines established by the law, *"Survivability and lethality tests required under subsection (a) shall be carried out sufficiently early in the development phase of the system or program to allow any design deficiency demonstrated by the testing to be corrected in the design of the system, munition, or missile before proceeding beyond low-rate initial production."* Note that *survivability* is used when *vulnerability* is intended. The primary requirement of the law is that *"a covered system may not proceed beyond low-rate initial production until realistic survivability testing of the system is completed"* Realistic survivability testing is defined as *"testing for vulnerability of the system in combat by firing munitions likely to be encountered in combat (or munitions with a capability similar to such munitions) at the system configured for combat, with the primary emphasis on testing vulnerability with respect to potential user casualties and taking into equal consideration the susceptibility to attack and combat performance of the system." "The term configured for combat, with respect to a weapon system, platform, or vehicle, means loaded or equipped with all dangerous materials (including all flammables and explosives) that would normally be carried in combat"*

A waiver from the law is provided. *"The Secretary of Defense may waive the application of the survivability and lethality tests of this section to a covered system, if the Secretary, before the system or program enters full-scale engineering development, certifies to Congress that live-fire testing of such system or program would be unreasonably expensive and impractical."* Also, *"the Secretary shall include with any such certification a report explaining how the Secretary plans to evaluate the survivability or the lethality of the system or program and assessing possible alternatives to realistic survivability testing of the system or program"* (U.S. Congress, 1986–1989).

The intent of the LFT law is to determine the inherent strengths and weaknesses of adversary, U.S., and allied weapon systems sufficiently early in the program to allow any design deficiency to be corrected. According to the FY1988–1989 DoD Authorization Act Conference Report, Congress intended that the Secretary of Defense implement

[23]The law and the amendments to the law are included in this report in Appendix A.

the LFT law "in a manner which encourages the conduct of full-up vulnerability and lethality tests under realistic combat conditions, first at the sub-scale level as they are developed, and later at the full-scale level mandated in the legislation" (U.S. Congress, 1988). All live fire tests conducted as part of the program to satisfy the Live Fire Test law will be referred to here as Live Fire Tests. Developmental tests using live fire that are not intended to be part of the mandated LFT&E program will be referred to as live fire tests, with no capital letters. The distinction between the two categories of tests is important.

In response to the law, the Department of Defense (DoD) chartered an administering office, the Director of Live Fire Testing, under the Office of the Director of Defense Research and Engineering. The responsibilities of this office include the establishment of policies under which Live Fire Testing is conducted by the Service components, the approval of the Services' Live Fire Test strategy and test plans for each covered program, the review of the test results, and the performance of an independent assessment that is forwarded, via the Secretary of Defense, to the Congress (O'Bryon, 1991).

What Does the Law Require? During the course of the committee's examination of the current direction of Live Fire Testing and Evaluation, it became apparent that because of the ambiguity of the law's requirements regarding the system testing, there were different interpretations of the LFT law. One interpretation was that the law did not explicitly stipulate that a complete system had to be tested, even though no waiver from the law was requested. The opinion was held that the law was satisfied by an LFT&E program in which Live Fire Testing was conducted only on components and subsystems, provided that these tests showed that no complete system testing was necessary; all vulnerabilities had been found in the partial system tests. In an attempt to determine the intent of Congress as to the meaning of realistic survivability testing, members of the committee interviewed Mr. Joseph Cirincione, the congressional staff member who drafted the Live Fire Test legislation in 1987. Mr. Cirincione believes that the intent of the law, as seen by the Congress, is "full-scale, full-up" testing. This, to him, means that the complete aircraft must be tested and must be configured for combat (i.e., engine running, fuel in the tanks, loaded with ammunition, etc.). He believes that anything other than full-scale, full-up testing requires a waiver in accord with the terms of the above paragraph. In support of his position is the statement in the FY1988–1989 DoD Authorization Act Conference report that says "the conferees intend that the Secretary of Defense implement this section in a manner which encourages the conduct of full-up vulnerability and lethality tests under realistic combat conditions, first at the sub-scale level as sub-scale systems are developed, and later at the full-scale level mandated in the legislation" (U.S. Congress, 1988). Furthermore, the events that led to the law and the fact that Congress included a waiver process in the law are further evidence that Congress intended that live fire tests be conducted on full-scale, full-up systems. If tests on the full-scale, full-up system were not intended, no waiver would be necessary, and any live fire tests would suffice, as long as they were realistic. Based upon the evidence gathered by the committee and its study of the law, the committee is unanimous in the opinion that the LFT law requires a full-scale, full-up aircraft to be tested, regardless of the outcome of the sub-scale tests, unless a waiver is granted.

What Are the Applications of the Results of the Assessments?

Vulnerability assessments are a part of the weapon system acquisition process. This process is described in DoD Instruction (DODI) 5000.2, February 23, 1991. According to DoDI 5000.2, survivability is identified as a critical system characteristic and consequently must be addressed in cost-schedule-performance trade-offs throughout the acquisition process. This instruction requires that survivability be considered from all threats found in the various levels of conflict, including the conventional gun and missile threats, the nuclear, biological, and chemical threats, and the advanced directed energy weapons. At Milestone 0, the expected threat environment is identified and discussed in the Mission Need Statement. At Milestone I, the system threat assessment identifies the expected likelihood for each threat. In addition, initial survivability objectives are defined and validation criteria established in the Operational Requirements Document (ORD). Key objectives are included in the Concept Baseline. Critical survivability characteristics and issues that require test and evaluation are identified and included in the Test and Evaluation Master Plan; this includes the Live Fire Test program. Critical survivability technology shortfalls are identified and research requirements established. At Milestone II, survivability issues are addressed in the Integrated Program Summary; at Milestone III, an assessment of how well the survivability objectives have been met has been completed, and all survivability issues should have been resolved.

Vulnerability objectives are part of the survivability objectives required by DoDI 5000.2.[24] If any vulnerability objectives or requirements have been defined in the ORD, they are satisfied and validated by using vulnerability assessments

[24]Note that only survivability objectives are required. Thus, a system could meet the requirements in DoD 5000.2 by requirements on susceptibility alone.

in the form of analysis/modeling and testing. Thus, the primary application of a vulnerability assessment in the weapon system acquisition process is to aid in the design of the aircraft and in the validation of the design. Additional applications are to satisfy program requirements, to develop data bases in support of subsequent analytical assessments, to predict test outcomes, to satisfy the requirements of the Live Fire Test law, and to support acquisition decisions.

Aid in Design and Design Validation. The results of a vulnerability assessment must be available early in the development cycle of an aircraft and used to influence the design. Analytical modeling can provide guidance on the placement of the critical components and the protection that should be given to the various contributors to vulnerability, such as the fuel subsystem, flight control subsystem, and propulsion subsystem. Controlled live fire developmental tests can be conducted on early designs of components, and possibly subsystems, to determine any adverse reactions, either expected or unexpected. Any design vulnerabilities revealed by the full-scale, full-up LFTs should also impact the design. For design validation, the analytical models provide information on vulnerable area, $P_{K/H}$, and $P_{K/D}$; and live fire tests are conducted to verify that certain vulnerability requirements for the design of the aircraft have been satisfied. For example, if an aircraft has a design requirement to be able to take a single hit by a 12.7-millimeter API anywhere on the aircraft and fly for 30 minutes after the hit, live fire testing of the design is the best procedure for verifying the compliance of the design.[25]

Satisfy Program Requirements. The DoD MIL-STD 2069, "Requirements for Aircraft Nonnuclear Survivability Program," requires that analytical vulnerability assessments be made as part of the normal development process. Aircraft development programs that stipulate MIL-STD-2069 will have assessments conducted throughout the development cycle.

Development of Data Bases in Support of Subsequent Analytical Assessments. As data from live fire tests on a variety of components and subsystems are gathered, qualitative information on kill modes and cascading damage effects and quantitative information on individual component $P_{k/h}$ functions can be put into a data base and used to improve subsequent analytical assessments. The JLF program is an example of this application in action. Another application of this type is the use of the results from the analytical vulnerability assessments in trade-off and campaign or similar large-scale war game models that require an aircraft attrition data base.

[25]The design requirement that an aircraft be able to withstand a single hit by a particular weapon and continue to fly for a specified period of time does not automatically mean that the aircraft will be unable to withstand a second hit. Building into the aircraft an ability to take a single hit anywhere also gives the aircraft a significant capability to withstand multiple hits.

Predict Test Outcomes. The results of an analytical vulnerability assessment can be used to predict the possible outcomes of a controlled test prior to the conduct of the test. The particular components that will be damaged or killed by the weapon or by any cascading effects can be identified, and the consequences of the damage or kill of these components to the essential functions can be predicted. However, due to the random nature of vulnerability, no deterministic prediction of the test outcome can be made. Consequently, predictions take the form of statements such as "the flammable vapors in the wing tank have a 0.3 probability of exploding and destroying the wing when the tank is hit by a 12.7-millimeter API."

Satisfy the Requirements of the Live Fire Test Law. The Live Fire Test law requires that a full-scale (the complete weapon system), full-up (configured for combat) aircraft be tested for vulnerability using munitions likely to be encountered in combat, unless a waiver is given from the law. A primary intent of the law is to obtain information on any design weaknesses in time to allow them to be corrected. Thus, the testing required by the law is in some sense an aid in the design (a discovered weakness can be corrected) as well as a validation of the design (if no weaknesses are discovered, the design is presumably validated). Analytical vulnerability assessments can assist in determining the issues that require examination in the Live Fire Test program. The Live Fire Test plan is developed using the information provided in the Live Fire Test and Evaluation Planning Guide. A typical Live Fire Test plan will include early testing of components, sub-systems, and sub-assemblies, both inert and full-up, and later testing of full-scale, full-up targets.

Support Acquisition Decisions. One of the principal applications of both analysis/modeling and Live Fire Testing is to provide information in support of acquisition decisions. This is accomplished by providing timely information on the vulnerability of the complete system to decision-making bodies, such as the Defense Acquisition Board.

Table 1-4 presents a summary of the applications of the analysis/modeling methodology and the Live Fire Testing methodology, including both sub-scale and full-scale testing.

Previous Studies of Vulnerability Assessment with Emphasis on Live Fire Testing

Two previous studies of the vulnerability assessment and live fire testing of military vehicles have been conducted;

TABLE 1-4 Applications of the Methodologies

		Aid in Design	*Design Validation*	*Satisfy Program Require-ments*	*Develop Data Bases in Support of Analytical Assessments*	*Predict Test Outcomes*	*Satisfy Require-ments of LFT law*	*Support Acquisition Decisions*
Analysis/modeling		X	X	X (MIL-STD-2069)	X (War games)	X		X
Live Fire Testing	Sub-scale	X	X		X ($P_{k/h}$ values)		X (with waiver)	X
	Full-scale	X	X				X	X

the 1987 U.S. General Accounting Office study *Live Fire Testing, Evaluating DoD's Programs* (GAO, 1987) and the 1989 Board on Army Science and Technology (BAST), National Research Council (NRC, 1989), study *Armored Combat Vehicle Vulnerability to Anti-Armor Weapons: A Review of the Army's Assessment Methodology*. Both studies addressed vulnerability issues similar to those reviewed here. However, the GAO study, which was conducted at the same time the LFT legislation was enacted, concentrated primarily on the JLF program. The purpose of this study was to answer four questions: (1) What is the status of each system originally scheduled for live-fire testing under the JLF program? (2) What has been the methodological quality of the test and evaluation process? (3) What are the advantages and limitations of full-up live fire testing, and how do other methods complement full-up testing? (4) How can live-fire testing be improved? Of interest here are questions 2, 3, and 4.

The BAST study examined the Army's assessment methodology, including both analysis and live fire testing, for armored vehicles. The committee conducted an independent review to (1) address issues that will help the Army define the objectives of its vulnerability assessment program, (2) define and analyze alternative ways to balance computation and live fire testing in reaching conclusions about vehicle vulnerability, (3) identify technical deficiencies where they exist, and (4) suggest alternatives for improvement as appropriate. All four tasks are of interest here.

Although neither study specifically addressed the Live Fire Test legislation and the DoD LFT&E program, and the BAST study did not consider aircraft, both studies examined issues and arrived at conclusions that are pertinent here. Furthermore, the personnel and organizations involved in the JLF aircraft program also are the ones involved in the LFT aircraft program. Consequently, the major issues and conclusions of these two studies as they apply to aircraft are presented in Appendixes B and C.

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2 Evaluation of the Cost, Effectiveness, and Deficiencies of These Methodologies

Regardless of the specific application(s) of a vulnerability assessment of an aircraft, whether it is to aid in design or design validation, satisfy program requirements, support subsequent analytical assessments, predict test outcomes, satisfy the Live Fire Test law, or support acquisition decisions, the goal of the assessment is to obtain information on the vulnerability of that aircraft. This information can be described in terms of the attributes of the types, amounts, and applications of the information obtained; the accuracy of, or level of confidence in, the information; and the cost required to obtain the information. An effective methodology is one that provides a great deal of accurate information, of all types, with many applications, at very low cost, and with very few deficiencies. Both of the methodologies reviewed in Chapter 1 (analysis/modeling and live fire testing[1]) individually have certain advantages and disadvantages with respect to accomplishing the goal of obtaining information on the vulnerability of aircraft.

In general, the analysis/modeling methodology can provide considerable numerical information on the vulnerability of the total aircraft from all aspects for all threats at a reasonable cost, but the level of confidence placed in the information can vary from very low to high, depending upon the type of information obtained, the model used, the quality of input data, the analyst, and the evaluator.[2] On the other hand, although the live fire testing methodology has the potential to obtain data that can be used to determine numerical information on the vulnerability of the aircraft to a particular weapon for many hits over the entire presented area of the aircraft from all aspects, in actual practice, testing provides information only on the aircraft's vulnerability to hits in relatively few locations,[3] and the expenditure of funds required to obtain this information is relatively large. However, the level of confidence in the test results usually is relatively high. This chapter examines the three information attributes of types (including amounts and applications), accuracy, and cost for both methodologies.

Analysis/Modeling

Type, Amount, and Applications of the Information. The analysis/modeling programs described in Chapter 1 for the

[1]The reader is reminded of the difference between general live fire testing and the congressionally mandated Live Fire Testing.

[2]The committee notes that there are strong differences in opinions concerning the level of confidence to be placed in the analytical results. Some consider them to be very accurate, whereas others believe that there are few, if any, analytical results that are accurate. However, there is consensus in the committee that the present analytical models are flawed in several ways and are weak in their ability to extrapolate beyond their existing data base.

[3]These few locations are selected to maximize the amount of useful data obtained and to answer specific questions concerning the aircraft's vulnerability.

three types of weapons provide numerical values for the vulnerability of the individual critical components and the total aircraft from all aspects around the aircraft and for any selected ballistic projectile or guided missile. The numerical values can be in the form of vulnerable areas or probabilities of kill. This information can be used to aid in design and design validation, to satisfy program requirements, to support subsequent analytical assessments, to predict test outcomes, and to support acquisition decisions.

Accuracy of Analytical Models. There are three aspects of the accuracy of the analytical models that need to be examined: model verification (Are the internal workings of the model in good order—are the equations properly coded?), model validation (Does the model adequately represent the processes it portrays—do the equations adequately represent the actual physical situation?), and model accreditation (Is the model appropriate to the particular application—is the model capable of properly representing the aircraft and the weapon?).

Model Verification. In so far as model verification is concerned, there appears to be little reason to doubt the veracity of the logic and coding of the models described in Chapter 1. They have been widely employed by government laboratories in all three military Services and by a great many nongovernmental users. The committee accepts the fact that the internal workings of the models are in good order.

Model Validation. Credibility problems exist with model validation. Despite all the physical phenomena that the current aircraft vulnerability models attempt to depict (and many are depicted with high confidence), there are some phenomena that are known to exist, but have not been characterized and entered into the model structure, or are poorly modeled. Perhaps the most notable phenomenon not modeled is the random deviation or ricochet of the path of the penetrator or fragment from the assumed straight shotline as it passes through the aircraft components. Another phenomenon not modeled is the synergism that occurs when a portion of an aircraft is hit by a multitude of closely spaced fragments. In this multiple, closely spaced hit condition, the fragments can be far more damaging to the impacted structure than when they are not closely spaced. A third example of a phenomenon not explicitly modeled is spall. The backface spall generated by the impact of a projectile or fragment on a plate is not considered as additional fragments to be tracked through the aircraft by the shotline model.[4]

[4]Spall that is generated within a component is implicitly accounted for in terms of its damage to the component since the empirically determined total damage is the sum of all of the damage mechanisms and processes within the component, including the internal spall.

A poorly modeled phenomenon is the treatment of the remaining parts of an impacting fragment or penetrator after it penetrates a plate. The current model considers only the largest remaining piece in calculating subsequent effects. Another poorly modeled phenomenon is the increase in a component's $P_{k/h}$ that occurs when the component is hit by more than one projectile or fragment or is damaged by both blast and fragments. The assumption is nearly always made that the same $P_{k/h}$ value for the first hit in the component is adequate for subsequent impacts on the component. The increase in a component's vulnerability due to damage caused by prior hits is neglected. For example, a tail rotor drive shaft on a helicopter may not be killed when first hit by a tumbled 12.7-millimeter armor-piercing projectile with incendiaries (API), but a second hit in the vicinity of the first hit may cause the shaft to break due to the synergism in damage between projectiles. This increase in $P_{k/h}$ due to previous hits is usually neglected.

Also, there are known physical phenomena that are modeled, but their numerical values are not well known because they have not been tested, or the test results are for conditions not satisfied in the combat incident. For example, the penetration equations that determine the velocity and mass decay of fragments and penetrators as they penetrate plates on the aircraft may not have the proper decay coefficients for the material of interest. Furthermore, these equations have been developed for specific geometric shapes of impactors, such as spheres and cubes, whereas fragments are usually irregular. Two of the most difficult kill modes to model in aircraft are fire and explosion, This is due to the randomness of fuel sloshing within a tank, fuel leakage into dry bays around the tanks, and fuel migration into distant portions of the aircraft.

Neglect of On-Board Ordnance. One of the most important findings of our study is that on-board ordnance is usually neglected as a contributor to vulnerability. Most of the simulation of internal ordnance aboard the aircraft has been treated by the aircraft vulnerability community as "clutter." Clutter is inert material in a compartment that is considered only as a compartment filler in the calculation of overpressure in the compartment due to its volume. The overpressure from the explosive "clutter" when hit by projectiles and fragments can change the total pressure in the compartment dramatically. One of the basic premises of all development testing is that modeling must precede testing. Any aspect of hardware impact on vulnerability must first be modeled so that the testing can be used to verify the modeling rather than for the testing to be extensive enough to cover all statistical events. One of the basic requirements of the Live Fire Test program is to test full-scale vehicles with a full load of on-board ordnance. The continual neglect of one of the basic vulnerability contributors will make it more difficult to convince anyone that computer modeling can be substituted for the full-up testing of combat-loaded aircraft.

Weapon Lethality Assessments Versus Aircraft Vulnerabil ity Assessments. Some of the programs currently used to compute an aircraft's vulnerability to the various types of weapons were developed by the Joint Technical Coordinating Group for Munitions Effectiveness. Because the munitions effectiveness community wanted conservative estimates for the prediction of a weapon's lethality, its programs were developed so that our weapons were not to be credited with any kill capability that was not clearly justified; a sound policy from the weapon development point of view. However, as a result of this approach, the use of these programs to predict the vulnerability of a U.S. aircraft most likely leads to overly optimistic predictions. Potential vulnerabilities have been ignored unless clearly justified; an unsound policy where the survivability of U.S. aircrews is concerned. Examples of where the vulnerability of aircraft is underestimated are

- the use of the Thor penetration equations, which consider only the largest remaining piece of a penetrator as it passes through the aircraft,
- the lack of synergism due to both multiple simultaneous and sequential hits on a component;
- the lack of direct consideration of spall, and
- the lack of consideration of cascading damage, such as fuel tank damage leading to fuel ingestion.

The Joint Technical Coordinating Group on Aircraft Survivability (JTCG/AS) $P_{k/h}$ Workshop. Even if all other aspects of the model were perfect, some of those portions of the model that portray the results of the physical interactions or damage processes that occur when a threat weapon interacts with an aircraft are inaccurate or incomplete. In order to eliminate some of the model deficiencies, more vulnerability data are needed on component kill modes and $P_{k/h}$ functions. This deficiency in the component vulnerability data base was the subject of a JTCG/AS Component $P_{k/h}$ Workshop held from March 5–8, 1991, at Wright-Patterson Air Force Base (WPAFB).

The objectives of the JTCG/AS Workshop were to critically review the current state-of-the-art of component $P_{k/h}$ prediction, to recommend a set of $P_{k/h}$ or $P_{d/h}$ values or functions for use in analyses, and to develop plans for improving and validating this set.[5] Working panels were organized as follows:

Fuel System
Flight Controls/Hydraulics (Control and Power)
Crew Station
Engines and Accessories
Stores, Ammunition, and Flares
Electrical and Avionics
Structures, Landing Gear, and Armor
Helicopter Unique Components

The draft reports of the individual panels are currently being integrated into a final report. The findings of the eight working panels are given in Appendix D.[6]

The general conclusion from the workshop is that the component vulnerability data base is the weakest link in the vulnerability analysis chain. Clearly, much remains to be done with respect to validating those sections of the aircraft vulnerability models that deal with component and subsystem damage prediction. The level of confidence placed in the analytical models would be significantly increased if a concerted effort was made to determine the maximum error in A_V that occurs in the model predictions using the current data base, and to what extent this error might be reduced with the availability of new test data.

Model Accreditation. Model accreditation is accomplished by the JTCG/AS. This organization, consisting of representatives from all three Services, has established procedures for verifying, validating, and accrediting models. Despite the deficiencies identified by the aircraft vulnerability assessment community in its analytical models, the community has been exemplary in the exchange of data and ideas among the three Services and industry, in the development of handbooks and design guides for reducing vulnerability, and in the establishment of validated data bases from test data. Although there is still much to learn, more perhaps is known. There will always be a need to update models with new input data as aircraft materials and designs change and as the threat weapons change.

The Cost of Analysis. It is extremely difficult to determine the costs associated with a typical analytical assessment since the cost depends heavily on the type of aircraft being assessed and the particular application for the assessment. However, some rough estimates for the costs to conduct an analysis that would be appropriate for a major milestone decision are given below. The numbers were obtained in a personal communication from a representative from the Ballistic Research Laboratory.

[5]Component vulnerability is sometimes quantified by $P_{d/h}$, the probability the component is damaged given a hit.

[6]These findings are taken from a preliminary copy of a briefing being prepared to be given to the JTCG/AS Central Office and to the Office of the Secretary of Defense. This briefing material was provided by Gerald Bennett, ASD/XRM, WPAFB.

Cost of the Model. The cost of creating a COVART or HEVART model for a helicopter is roughly between $75,000 and $200,000, with the low end for an upgrade to an existing system and the high end for an all new, high detail description of a U.S. system. These costs also include the generation of the shotline data files needed to run the Computation of Vulnerable Area and Repair Time Model (COVART) or High Explosive Vulnerable Area and Repair Time (HEVART) model. The cost of developing appropriate target models for the Stochastic Qualitative Analysis of System Hierarchies (SQuASH) might be two to three times that required for the conventional vulnerable area models.[7] As the design community increases its use of three-dimensional modeling and grid generation, and as computer usage becomes less expensive, the cost of modeling will come down significantly. The major cost will be the preparation of input data.

Cost of Computer Runs. A typical batch of computer runs for a helicopter includes two flight modes (hover and forward flight) and from 6 to 26 attack aspects. The cost of this batch of runs using COVART or HEVART ranges from $45,000 to $100,000. The analysis and preparation of input data account for most of this cost.

Cost of Obtaining Supporting Experimental Data for $P_{k/h}$ Functions. The execution of an analytical model without any live fire test data on kill modes and $P_{k/h}$ functions as input data on component vulnerability could be accomplished, but the level of confidence in the results would be very low. Consequently, the cost of obtaining the necessary data on component vulnerability must be included in the cost of the analysis. If all of these data are available from prior tests, the cost of gathering them is relatively low. If all of the necessary data are not available, supporting tests must be carried out to obtain the missing data. These tests can be as simple as the firing of fragments at pieces of plate to measure penetration or V_{50} velocities, or they can be as complicated as firing several fragments at running engines to determine the severity of damage, or firing at major portions of the aircraft structure that contains fuel tanks to simulate the fire/ explosion and hydraulic ram phenomena. The typical costs associated with two types of live fire tests are given below.

For a helicopter engine and a 23-millimeter HEI threat, basic preliminary testing with components and/or a static engine would cost approximately $30,000. Comprehensive testing with a full-up running engine would cost approximately $250,000. For a tail boom structure, basic shoot-and-look damage characterization tests would cost approximately $25,000. A comprehensive evaluation of the test results, including postdamage controlled structural experiments would cost approximately $150,000.

[7]Note that SQuASH has not yet been applied to aircraft vulnerability assessment.

Live Fire Testing

A live fire test is one in which live ammunition, either explosive or non-explosive, is fired at a target. Live fire testing can be used to assist in the design and design validation of an aircraft, to provide empirical information on component vulnerability in support of the analytical models, to satisfy the Live Fire Test law, and to support acquisition decisions. Live fire testing is part of either developmental testing (DT) or Live Fire Testing. The difference between the two types of tests is that DT is part of the normal design and development process, whereas Live Fire Testing is that testing intended to satisfy the Live Fire Test law. "As currently defined, development test and evaluation (DT&E) is that test and evaluation (T&E) conducted throughout the acquisition process to assist in the engineering design and development process and to verify attainment of technical performance specifications and objectives and supportability. DT&E includes T&E of components, computer software, subsystems, and hardware/software integration. It encompasses the use of modeling, simulations, and test beds, as well as advance development, prototype, and full-scale engineering development models of the system. Technical performance specifications must be validated through DT&E in order for the developer (program manager) to certify that the weapon system is ready for the final phase of Initial Operational Test and Evaluation (IOT&E)" (OSD, 1987).

Of particular interest here is the specific test and evaluation methodology required to satisfy the Live Fire Test (LFT) legislation. The law requires realistic survivability (vulnerability) testing. Although such a test program will in fact involve early component and subsystem or sub-scale Live Fire Testing, the hallmark of this approach is a substantial test program that involves a significant number of shots against a combat-configured, full-scale version of the weapon system (i.e., a full-scale LFT). The early Live Fire Tests on components and subsystems provide information on any vulnerabilities of the individual components and subsystems. Once the information from these tests has been evaluated, the tests on the full-scale aircraft are to be conducted as mandated by the law, unless a waiver has been granted. The full-scale test program will often include a number of shots that are randomly chosen and a number of shots that are selected to address specific issues. Real (or realistic surrogates of) threats likely to be encountered in combat must be used in the tests. These threats can be non-explosive ballistic projectiles, ballistic projectiles with contact-fuzed and proximity-fuzed high-explosive (HE) warheads, and guided missiles with contact-fuzed and proximity-fuzed HE warheads. The three information attributes of types (including amounts and applications), accuracy, and cost for both sub-scale testing and full-scale testing are examined below.

Type, Amount, and Applications of the Information. In general, the Live Fire Tests on both sub-scale and full-scale targets produce information on what actually happened for a particular set of test conditions (e.g., the specific target, weapon, and shotline) and typically for a relatively small number of shots under these conditions.[8] Some typical examples of tests on sub-scale targets are tests to determine the penetration capability of fragments through plates of composite materials, tests on helicopter rotor blades, tail booms, and gear boxes using small arms projectiles and small-caliber HE AAA rounds, tests on fuel tank simulators using small caliber HE AAA to determine the efficacy of a particular fuel tank protection scheme, and stand-alone tests on running engines using several impacting fragments. The information from these tests ranges from measured fragment velocities, temperatures, and overpressures to the ability of the tested article to continue to function after the hit. Tests on the full-scale aircraft will most likely be conducted with the aircraft on the ground or suspended; it can neither crash nor be forced to land as a result of the shot. Thus, the ability of the aircraft to sustain the essential functions for flight after the hit is not observed directly. Furthermore, rather than produce a sufficient amount of numerical data from the full-scale test that can be used directly to determine the kill probability of the aircraft for the shot, each full-scale test provides a list of damaged components along with descriptions of the details of the extent and severity of the damage and the associated damage events for each shot.

With respect to the applications of the information obtained from the tests, the committee notes that the Live Fire Tests are conducted primarily to (1) satisfy the LFT law and its intent (i.e., to determine any inherent vulnerabilities in the design sufficiently early in the program to allow the vulnerabilities to be corrected), and (2) provide information in support of acquisition decisions. They are not specifically intended to provide information that can be used to improve the analytical models for predicting aircraft vulnerability. Nevertheless, previous experience with full-scale Live Fire Tests on ground vehicles has shown that important types of damage and kill modes have been observed that were not included in the analytical models for these vehicles. Thus, the information provided by these LFTs can be used in the other applications. Besides satisfying the letter of the law, the LFT&E program provides (in principle) an opportunity to

- obtain information on the vulnerability of the aircraft;
- find vulnerabilities that were not anticipated by the analyses; and
- gather data on the synergism among the different damage processes and kill modes.

All three aid in the design and design validation, support the analytical models, and support acquisition decisions.

Accuracy of and Level of Confidence in the Informa tion. The level of confidence that is placed in the subscale and full-scale Live Fire Test results depends primarily upon the level of realism of the tests. Certainly, there is a possibility for realism in Live Fire Testing. Some of the vulnerability aspects that are represented in Live Fire Testing are the effects of blast, including structural deformation and component damage, and component damage due to multiple fragment hits, including bending, breaking, and perforating. Other aspects of vulnerability that are represented include the occurrence of spall and the penetration through components. The penetration damage and velocity decay in the test are the result of real penetrators going through real materials, with no assumptions about breakup, ricochet, etc.[9] Synergisms among blast, fire, spall, and fragments are realistically represented to the extent that the other aspects of the test conditions (e.g., air speed and altitude) are adequately represented.

Although full-scale tests have the potential to provide the most realism, there are some problems, particularly with the weapons used, the flight conditions, crew vulnerability, and on-board munitions. The weapons selected for testing will most likely be those that are not overmatching (i.e., they will not have a high probability of destroying the aircraft). Consequently, most of the weapons will be either non-explosive or small-caliber explosive rounds. When larger explosive weapons are used, particularly the large-caliber projectiles and guided missiles, the damage to the aircraft can be severe and widespread, making it very difficult to repair the aircraft and return it to a condition that would be satisfactory for further testing. Associated with the explosive weapon is the location of the point of detonation. Contact-fuzed HE warheads must impact the aircraft in order to damage it, but proximity-fuzed weapons can detonate at distances ranging from the aircraft skin to several hundred feet away. If the warhead is detonated too close to the aircraft, it could destroy it.

With respect to the flight conditions, airflow can be simulated to some extent, although it seems unlikely that an entire

[8]Typically, the smaller the target, the more greater is the number of test shots, and the more detailed is the information.

[9]Although penetration is realistically represented in the test, the information obtained from the test most likely will not provide penetration data per se for the analytical models because there will be few if any data on the parameters associated with the individual penetrations, such as impact and exit velocities, masses, and angles.

transport aircraft would be placed in a uniform high-speed airstream. Static loading conditions can be simulated, at least over a part of the aircraft, but there is some concern about the effects of wind gusts and about transient loads produced by maneuvering and loss of control. Furthermore, altitude and temperature are not simulated. For externally detonating warheads, a static test may result in a different set of blast and fragment impact conditions from those of a dynamic test. In some warhead/target encounters (e.g., in head-on pass or when overtaking at very high velocity), the high-velocity fragments may impact on one part of the target aircraft's structure while the slower blast may affect a different area. In static tests, both affect the same portion of the target.

Clearly, real people cannot be used in the tests. Anthropomorphic dummies, pressure gauges, and gas-sampling equipment can be used to obtain data on vulnerability issues related to personnel vulnerability. On the other hand, the responses of the crew to shock, incapacitation, temporary loss of control, etc., are not directly measured and must be inferred. These responses are critical to both crew and aircraft survivability.[10]

Vulnerability of the Aircraft. Although it is true that certain catastrophic kills, such as an explosion within an aircraft fuel tank, would be observable in a test, it is also true that other types of kills would not be directly observable. For example, would the aircraft actually crash after damage to one of the control surfaces? Even if the actual kill was directly observed, there are the problems of associating the results with the other kill categories and levels, and of extrapolating the results to other threats and tactical conditions. For example, suppose the proximity-fuzed detonation of an 85-millimeter HE warhead near the left differential stabilator of the aircraft removed 90% of the stabilator. Is this a kill, and if it is for the 85-millimeter weapon, would a 57-millimeter warhead detonation in the same location cause the same kill?

Unanticipated Vulnerabilities. The analytic models are presently structured to provide aircraft kill probabilities based upon assumed kill modes, and an aircraft with reduced vulnerability is designed to prevent these kill modes from occurring. However, if a kill mode is unanticipated in both the analysis and the design, the model will underestimate the aircraft's actual vulnerability, and the aircraft will contain this vulnerability. These unanticipated kill modes may be local effects that occur in the vicinity of the original impact, or they may be caused by cascading damage from the impact location to a distant part of the aircraft. For a local effect example, suppose the unanticipated kill mode was an electrical wire bundle that caught fire when hit by a bullet or fragment. This is a local kill mode that could be discovered by component or subsystem testing. On the other hand, suppose the unanticipated kill mode was a fuel ingestion kill of an engine mounted externally on the rear portion of the fuselage. Hydraulic ram pressure in the fuel in the wing fuel tank in front of the engine (due to a penetrator) caused fuel to spew out the top of the tank. This fuel was ingested by the engine, which then died. A test of only the wing fuel tank might not reveal this kill mode because of the absence of the running engine.

Although a full-scale Live Fire Test might reveal a local unanticipated kill mode, such as the burning wire bundle, full-scale testing is not necessarily an efficient methodology for obtaining this information. Furthermore, one can not say with great confidence that if no unexpected vulnerabilities occurred in the full-scale Live Fire Tests, then there are none to be discovered later in combat. Kill modes involving cascading damage may not always occur in a test, and they may be particularly difficult to observe in a full-scale test if they do occur.[11] Some kill modes due to cascading effects are well known, such as the kill of an engine due to the ingestion of fuel from a damaged fuel tank next to an air inlet, and are relatively easy to observe. Others, such as the migration of toxic fumes or flames from one portion of the aircraft to another, are not as well known, may not always occur, and may be difficult to detect if they do occur.

It is not feasible to test all possible combat situations for unanticipated vulnerabilities using full-scale aircraft because of the large number of parameters that affect the target's vulnerability. These parameters include all of the weapons likely to be encountered in combat, the tactical situations of interest, and all of the possible impact locations on the aircraft (i.e., the shotlines). Furthermore, the damaged aircraft should be returned to its original condition after each test if appropriate and possible. Consequently, the test plan may contain a number of random shots, a number of random shots from directions expected in combat, a number of selected shots, and an ordering that schedules potentially catastrophic situations at the end of the program.[12]

Likelihood of Discovering a Particular Vulnerability. Unless a particular vulnerability is relatively insensitive to the parameters associated with a large subset of the conditions and has a relatively high probability of occurring, it may remain undiscovered in a test program. For example, suppose that a particular vulnerability event associated with a

[10]The committee notes that these departures from realism in the live fire tests are more severe in analysis/modeling.

[11]This is the reason that Live Fire Test programs require some random hits and place emphasis on incidents that occur relatively frequently rather than on all unanticipated kill modes.

[12]The number of shotlines in the vulnerability analysis of the F-22 was approximately 300,000 per threat.

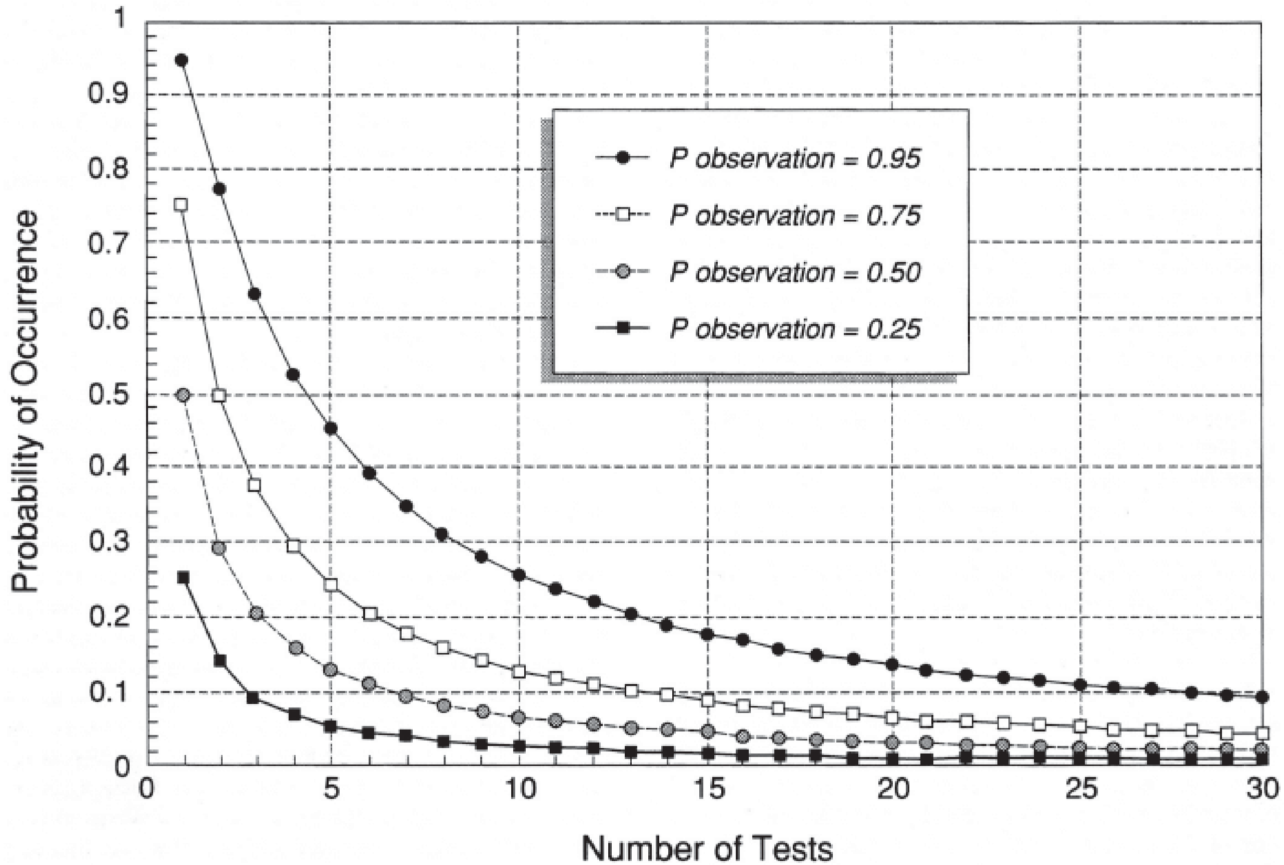

FIGURE 2-1 Relationship among the probability of occurrence on each test, the number of tests, and the probability of at least one observation over the number of tests.

high-explosive weapon had a 0.2 probability of occurrence on any random shot for all test conditions of interest. If the test plan consisted of 10 random shots around the aircraft, the probability the event would occur at least once in the 10 tests is $1-(1-0.2)^{10}=0.89$ and hence the probability it would not occur is 0.11. Thus, this vulnerability would most likely be observed.[13] On the other hand, if the event could only occur on 2 of the 10 random shots with a 0.2 probability (and a probability of zero on the other 8 shots), the probability the event would occur at least once is

$$1-(1-0.2)^2=0.36$$

and the probability that it would not occur is 0.64. Thus, this particular vulnerability would most likely not be observed.

Figure 2-1 shows the relationship among the probability of occurrence; the probability of observation of 0.25, 0.50, 0.75, or 0.95; and the number of tests. This figure can be used to determine the number of tests required to obtain a probability of observation of 0.25, 0.50, 0.75, or 0.95 for a given probability of occurrence. For example, if the probability of occurrence in each test is 0.2 and the desired probability of observance at least once is 0.75 or higher, at least seven tests must be conducted.

Suppose there were 5 independent vulnerability events possible on each of the 10 random shots, and each event had a 0.2 probability of occurring on each of the 10 shots. The probability that any one of the events would occur at least once during the test program is 0.89. The probability that all of the events would occur at least once (not necessarily on the same shot) during the program is

$$0.89^2=0.56$$

Hence, there is a 0.44 probability that one or more of the five kill modes will not be observed. Thus, the test program is essentially equally likely either to reveal all or to miss one or more of the aircraft's vulnerabilities. If each vulnerability

[13]Other known vulnerabilities may also occur during the tests that could obscure the particular vulnerability, and other unknown vulnerabilities could also occur.

could occur on only 2 of the 10 test shots, the probability that one or more vulnerabilities would not occur in the 10 tests is essentially one.[14]

Synergism Among the Damage Processes and Kill Modes. Live Fire Tests are also a valuable source of vulnerability information on the synergism among the damage processes and kill modes, albeit a limited source. Suppose there are two kill modes I and II that exhibit synergism. Mode I has a probability of occurrence of 0.1, regardless of the occurrence of mode II. Mode II has a probability of occurrence of 0.1 if the first mode does not occur and a 0.5 probability of occurrence if the first mode does occur. On one shot, the probability that both modes occur is 0.05. The probability that only mode I occurs is 0.05, the probability that only mode II occurs is 0.09, and the probability that neither mode occurs is 0.81. If these modes were independent, and both had a probability of occurrence of 0.1, mode I only occurs with a probability of 0.09, mode II only occurs with a probability of 0.09, modes I and II together occur with a probability of 0.01, and neither mode occurs with a probability of 0.81. Thus, the probability that neither mode occurs is the same in both the synergistic case and the independent case. In the synergistic case, mode II is more likely to occur (0.14 vs. 0.10) and the probability that both modes occur together is higher than in the independent case (0.05 vs. 0.01).

Validation of the Analytical Model. The analytical models are presently structured to provide kill probabilities and vulnerabilities based upon a selected kill category. The Live Fire Tests do not directly provide the numerical data required to validate the model's predictions; they only provide information on the components that were damaged or killed, the occurrence or non-occurrence of the kill modes, and any cascading damage. Thus, some compromises must be made that require additional analyses in order to relate the empirical test results to actual combat conditions and to determine if the test results correspond to an actual kill of the aircraft. If enough test shots could be made under the identical set of conditions, a statistical inference could be made regarding the probability of an aircraft kill given the test conditions. Unfortunately, the number of identical shots that can be conducted is usually small, and hence the confidence level in the sample mean probability of kill is low. Furthermore, because the models are expected value models, and given the randomness of the empirical results from the limited number of tests, the likelihood that the test results and the model predictions are in general agreement with respect to the components affected and their vulnerability is low. For example, suppose the model predicts a wing fuel tank will explode when hit with a probability of 0.5. If each of three identical tests result in an explosion, does this mean the model is inaccurate? The answer is no.[15] Thus, the Live Fire Tests can not be used in themselves to directly validate the models, and they are not conducted for that purpose. However, they do provide valuable information on damage processes that should be modeled.

Neglect of On-Board Munitions.. The Live Fire Test law requires the aircraft to be full-up when tested. This means that any munitions normally carried by the aircraft must be on-board at the time of the test. This will probably be done in only a very few tests; it is not the intent of the Live Fire Test law to destroy aircraft needlessly. The intent of the law is to obtain information on the vulnerability of the aircraft sufficiently early to allow any design deficiency to be corrected. Consequently, it does not seem reasonable to intentionally create a situation in which the aircraft could be destroyed when essentially the same information on the vulnerability of the aircraft to the on-board munitions can be obtained by using realistic off-line tests of sub-scale models of the portion of the aircraft in the vicinity of the munitions. This is particularly true for aircraft with internally stored munitions. Consequently, inert surrogates most likely will be used for munitions on-board the full-scale aircraft in order to prevent a catastrophic kill. The increase (or decrease[16]) in aircraft vulnerability due to the presence of the munitions can be determined by relating the observed projectile and fragment impacts on these surrogates to the vulnerability data on munition reactions to impacts obtained from the offline sub-scale tests.[17] It is not necessary to load the munitions on the full-scale aircraft in order to determine the likelihood of an adverse munition reaction to a hit or a fire. If a design deficiency with respect to the on-board munitions is discovered and a less vulnerable design can be developed, it can be incorporated without the loss of the test aircraft.

The Cost of Live Fire Testing. No complete Live-Fire Testing program for any aircraft has been carried out as yet. Consequently, the following information is offered only as an indication of the costs involved in full-scale Live Fire Testing. If no waiver has been given from full-scale testing,

[14]These examples are given to put LFT in the same context with the analysis/modeling methodology. It is not the purpose of LFT to find all vulnerabilities.

[15]Nevertheless, a prudent engineer would thoroughly examine the results of the experiment and the analysis in an attempt to determine whether the sequence of three explosions was not indicative of a higher probability of occurrence.

[16]Some munitions may provide a shielding effect, such as the bombs carried below a wing. Projectiles and fragments that do not penetrate a nonreacting bomb are prevented from impacting and damaging the wing.

[17]The off-line tests must provide sufficient information to enable a valid evaluation of the reactions of the munitions and the effects of those reactions on the aircraft, including lower-order effects that are not catastrophic.

TABLE 2-1 Live Fire Test Options for the C-17A (IDA, 1989)

Option	*Test Item*	*Test Item Cost ($ million)*	*Testing Cost*[1] *($ million)*	*Total Cost ($ million)*
1	Full-up aircraft	154	4	158
2	Fuselage & one wing	107	4	111
3	Fuselage section & one wing	60	4	64
4	One wing	36	4	40
5	One wing leading edge	?	?	15[2]

[1]This does not include the cost of repairing the damage for the next shot. Also, some members of the committee believe that $4 million is too low.
[2]An Air Force estimate.

at least one production or preproduction aircraft is required.[18] If the test is carefully designed, and if the target is reparable up to the last shot, one aircraft should be sufficient. The cost of the test aircraft is most likely the major cost of the total program. A question arises as to the proper cost of the aircraft to use when determining the program cost. Should the actual construction cost of the test aircraft, which might be one of the first five or six aircraft built, be used? Should the cost also include the research and development costs, or should the average flyaway cost be used? The particular cost used will have a major impact on the perceived benefit of the Live Fire Test program. If one aircraft is tested out of a total aircraft buy of 400, and the average aircraft cost over the buy is used, the cost of the Live Fire Tests will be less than 0.3% of the total program cost.

Costs for the C-17A. The Institute for Defense Analyses (IDA) has presented a number of test program options, issues, and costs for Live Fire Testing the C-17A in a draft report (IDA, 1989). The report makes no recommendations on which (if any) of the options should be selected. The costs of five options are given in Table 2-1.

At least one production aircraft is required for option 1. If the test is carefully designed, and if the target is reparable up to the last shot, one aircraft should be sufficient. The aircraft cost of $154 million is based on a FY1990 recurring flyaway cost of $181 million with engineering, tooling, and avionics costs removed.[19] On the other hand, the FY1997 and 1998 flyaway costs are $78 million. Thus, the cost of the test article depends upon the method of bookkeeping used. The most elaborate test program suggested by IDA is estimated to cost no more than $4 million and involves 100 small arms projectiles, 50 small AAA HE rounds, and 20 man-portable infrared missile shots.

Costs for the RAH-66A COMANCHE Helicopter. The cost of Live Fire Testing the COMANCHE helicopter has been estimated by a representative from the Ballistic Research Laboratory and coordinated with the Program Manager (PM). Based on projected production system fly-away costs for COMANCHE, a full-up low-rate initial production (LRIP) target that is representative of an operational, combat-configured system will cost in excess of $7.5 million. Given the alternative (and planned) use of an engineering test prototype aircraft built up to meet specific Live Fire Test requirements (a minimal configuration), the cost would be less. However, it still is a major percentage of the LFT&E program expense. At least two sets of target components/ subsystems, plus repair provisions, would also be needed. Steps can be taken to attempt to minimize the risks to the hardware, but these may not always work. The operational reutilization of the test articles is unlikely.[20]

The number of shots that can be conducted on one target is highly variable. However, given ideal repair capability and no catastrophes, 25 or more small-caliber API shots

[18]The use of static test articles or prototypes for the LFTs should be considered.

[19]In the committee's evaluation of the cost of full-up, full-scale aircraft estimates are based on flyaway cost without avionics. This would no longer be a "full-up" configuration. In fact, recent testing on aircraft shows avionics provide excellent shielding. In some aircraft, avionics components are themselves vulnerable.

[20]It should be noted that all of the test vehicles used in the U.S. Army's ABRAMS Live Fire Tests were repaired and returned to service.

TABLE 2-2A Relative Advantages and Disadvantages of the Two Methodologies: Type, Amount, and Applications of the Information

Analysis/Modeling	*Live Fire Testing*	
	Sub-scale Testing	*Full-scale Testing*
Advantages • The information is available in the form of vulnerable areas and probabilities of kill given a hit. • The models can provide much information on the vulnerability of the aircraft over a wide range of conditions in which the systems will be used, over a wide range of potential threat weapons, and over a wide range of system design alternatives. • The information can be used to aid in the early design of the aircraft, to satisfy program requirements, to support subsequent campaign/war game assessments, to predict test outcomes, and to support acquisition decisions.	*Advantages* • The type of information from sub-scale testing is in the form of semi-realistic physical outcomes, such as penetration or no penetration, fire or no fire, etc. • The information from sub-scale tests can be used to aid the design (when the tests are conducted sufficiently early in the program), to validate the design, to provide data for component $P_{k/h}$ data bases and new damage processes in support of subsequent assessments, and to support acquisition decisions.	*Advantages* • The type of information from full-scale testing is in the form of realistic physical outcomes, including cascading and synergistic damage, such as which components are damaged, if a fire occurred how far it spread, etc. • The information from full-scale tests can be used to aid the design (when the tests are conducted sufficiently early in the program), to provide information on new damage processes in support of subsequent assessments, to satisfy the requirements of the Live Fire Test Law, and to support acquisition decisions. • The Live Fire Tests that were performed on full-scale armored vehicles provided data on the types of damage that resulted in delayed catastrophic damage. These data were useful in training the crew in emergency exit procedures. Similar data on ejection procedures might come from Live-Fire Tests of aircraft. • Damaged aircraft offer an opportunity for battle damage crews to practice repairing realistic combat damage.
Disadvantages • Model results reflect the assumptions on vulnerability and therefore do not provide any new information on vulnerabilities resulting from new materials and damage processes.	*Disadvantages* • The amount of information is relatively small, is confined to the tested components and subsystems, and is limited to the specific test conditions. • The information from sub-scale tests may not be directly relatable to an aircraft kill.	*Disadvantages* • The amount of information is relatively small, is confined to the tested regions, and is limited to the specific test conditions. An unexpected catastrophic reaction in one of the early tests can prevent the gathering of additional information. • The information from full-scale tests may not be directly related to an aircraft kill. • Because of production-like aircraft must be tested in the full-scale test, it may not be practical to correct design deficiencies discovered in the tests. • Full-scale tests will not be used to produce the necessary broad and detailed data base for supporting the models because of the lack of control over the test outcomes and the costs involved.

TABLE 2-2B Relative Advantages and Disadvantages of the Two Methodologies: Accuracy of, and Level of Confidence in, the Information

Analysis/Modeling	*Live Fire Testing*	
	Sub-scale Testing	*Full-scale Testing*
Advantages • Models can provide estimates of the major vulnerabilities, particularly when they are supported by sub-scale live fire tests.	*Advantages* • Sub-scale tests can provide vulnerability data on new materials, new components, new construction processes, new threats, etc.	*Advantages* • Short of actual combat, full-scale live fire testing is as close to real data on a combat-configured aircraft as is possible to achieve. It accounts for the weapons effects, synergism among damage processes, and cascading damage.
Disadvantages • The models will never be able to totally represent all of the possible vulnerability events that can occur in combat, such as synergism and cascading damage. Some damage processes are modeled poorly, and some are not modeled at all. Thus, the estimates of vulnerability do not have a high level of confidence, particularly for new aircraft. • Current models tend to underestimate vulnerability because of their conservative assumptions regarding weapon lethality (e.g., they neglect spall, fuel ingestion, and multiple hit effects). • There are serious data gaps on componant and subsystem vulnerabilities, such as those identified by the 1991 JTCG/AS $P_{k/h}$ Workshop.	*Disadvantages* • Sub-scale tests can vary from simple component tests to realistic tests on complete subsystems. However, because these tests cannot simulate any interaction between the tested article and the portions of the aircraft not included, they are not fully representative of the actual combat situation.	*Disadvantages* • Those weapons likely to be encountered in combat that can destroy the aircraft are not used in such a manner. They are accepted as overmatching threats. • Altitude effects and the conditions of flying are not included in full-scale vulnerability testing. • Because the air crew is not on board during an LFT, the possible effects of the test on the crew are difficult to determine.

plus four or more small-caliber HEI projectile shots might be possible. The cost per shot is highly variable, ranging from \$500 to \$10,000[21], and is a function of the weapon used, the target configuration, the scope of the test issues, the extent of the instrumentation and data capture, the workup costs, etc.

Advantages and Disadvantages of Analysis/ Modeling and Live Fire Testing

Both analysis/modeling and Live Fire Testing have advantages and disadvantages or deficiencies relative to one another. Furthermore, there are relative advantages and disadvantages of both sub-scale testing and full-scale testing. Table 2-2 presents a comparison of the methodologies for each of the three information attributes of type, amount, and applications; accuracy or level of confidence; and cost.

Conclusion

The committee concludes that the combination of analytical models, supported by live fire tests on components and subsystems, and the sub-scale and full-scale Live Fire Tests are mutually compatible in the vulnerability analysis, evaluation, and design of aircraft. They complement each other, and the whole is superior to the sum of the parts. More work is needed to unify these approaches in order to obtain the maximum benefit. The aircraft vulnerability

[21] Some committee members believe that the cost of the tests would range from \$5,000 to \$50,000.

TABLE 2-2C Relative Advantages and Disadvantages of the Two Methodologies: Cost

Analysis/Modeling	*Live Fire Testing*	
	Sub-scale Testing	*Full-scale Testing*
Advantages • The cost of analysis is significantly less than the cost of Live Fire Testing.	*Advantages* • Sub-scale tests are considerably less expensive than full-scale tests.	*Advantages* • Live Fire Tests are a small percentage of the total program costs. If only one aircraft is tested out of a total aircraft buy of 400, the cost of the Live Fire Test program is less than 0.3% of the total program cost. • The use of static test articles or prototypes can significantly reduce the cost of the tests.
Disadvantages • Although the actual cost of conducting an analysis is relatively low, there are considerable sub-scale test costs required to build up the essential vulnerability data base.	*Disadvantages* • Although sub-scale tests are less costly than full-scale tests, a comprehensive sub-scale test program in support of a particular aircraft acquisition program is not inexpensive, and the program manager may not be inclined to spend the required funds. • The cost of sub-scale testing may preclude testing for basic phenomenological data on damage processes and kill modes.	*Disadvantages* • The cost of full-scale testing is primarily influenced by the cost of the test aircraft. Thus, the cost of testing a full-scale aircraft is considerably more than the cost of analyses or sub-scale testing when the aircraft was procured only for that purpose and cannot be repaired and put into service.

community, based on its plans for the Live Fire Tests, seems to appreciate the need to integrate these approaches, having witnessed the success in using the data from the Live Fire Tests on the Abrams tank and the Bradley Fighting Vehicle to improve both the analytical methodology and the vehicle designs.

References

- Institute for Defense Analyses (IDA), 1989. C-17A Live Fire Test Options Report, Paper P-2228.
- Office of the Secretary of Defense, 1987. Report of the Secretary of Defense on Test and Evaluation in the Department of Defense.

3 The OSD Live Fire Test and Evaluation Program

The Live Fire Test law passed in 1987 stipulates that realistic survivability testing be conducted on covered systems. Realistic survivability testing is defined as *"testing for vulnerability of the system in combat by firing munitions likely to be encountered in combat (or munitions with a capability similar to such munitions) at the system configured for combat, with the primary emphasis on testing vulnerability with respect to potential user casualties and taking into equal consideration the susceptibility to attack and combat performance of the system"* (U.S. Congress, 1986–1989). Systems covered by the law are vehicles, weapon platforms, or conventional weapon systems that include features designed to provide some degree of protection to users in combat and are major systems within the meaning of that term in section 2303(5) of title 10, i.e., Acquisition Category I and II systems. The Secretary of Defense may waive the requirement for Live Fire Testing of candidate systems if, before the system enters full-scale development, the Secretary *"certifies to the Congress that such testing would be unreasonably expensive and impractical"* (U.S. Congress, 1986–1989). The request for a waiver will be prepared by the Service and submitted to the Secretary through the appropriate chain of command. If the waiver is granted, the Secretary shall include with any such certification a report explaining how the Secretary plans to evaluate the survivability or the lethality of the system or program and assessing possible alternatives to realistic survivability testing of the system or program (U.S. Congress, 1986–1989).

Personnel from the Live Fire Test Office and from the Deputy Director, Defense Research and Engineering (Test and Evaluation/Tactical Warfare Program) [DDDR&E(T&E)/TWP] presented the Office of the Secretary of Defense (OSD) Live Fire Test and Evaluation (LFT&E) program to the committee on July 24, 1991, and the Director of the Live Fire Office made a second presentation to the committee on January 15, 1992. Personnel from the Institute for Defense Analyses gave presentations to the committee on September 26, 1991.

Oversight and Published Guidance for LFT&E. When the Live Fire Test law was passed in 1987, the position of Director, Live Fire Testing, was established under the Office of the Director of Defense Research and Engineering (Test and Evaluation) and was given the responsibility for implementing the Live Fire Test (LFT) legislation, developing and issuing guidelines for test plan preparation, reviewing and approving Service-prepared plans, performing independent assessments of the test results, providing liaison with Congress on the test results, and working with the Services and the Department of Defense (DoD) in improving LFT methodology and instrumentation, and in general, ensuring that conduct of Live Fire Testing is within the spirit of congressional intent (O'Bryon, 1987). A series of written documents has been prepared by OSD to provide guidance regarding details not specifically contained in the law.

The first set of guidelines intended to implement the congressionally mandated Live Fire Test program were issued on May 7, 1987 (DDDR&E, 1987). These guidelines supplemented DoD Directive 5000.3-M-1, "Test and Evaluation Master Plan Guidelines," October 1986, in areas pertaining to Live Fire Testing. They also defined the LFT&E plan requirements. According to these guidelines, "the essential feature of Live Fire Testing is that threat munitions are fired against a major U.S. system configured for combat to test its vulnerability, and/or that a major U.S. major munition or missile is fired against a threat target configured for combat to test the lethality of the munition or missile. Each (L)ive (F)ire (T)est plan must include testing of complete systems. However, a limited set of live fire tests may involve production components configured as a subsystem prior to full up testing. In such a case the components must be tested in the context of the complete system in that the test issues must be specific to both a threat system and a target system. In addition, at least a preliminary decision shall have been made to configure the production system with the components tested. Thus, (L)ive (F)ire (T)esting is not synonymous with traditional research and development vulnerability/lethality testing" (DDDR&E, 1987).

The 1988 Test and Evaluation Committee (LFT&E) Guidelines. The 1987 LFT&E Guidelines were superseded by the Live Fire Test and Evaluation Guidelines issued June 1, 1988, by the Test and Evaluation Committee (TEC), Office of the Secretary of Defense, in a memorandum to the Assistant Secretary of the Army (Research Development and Acquisition), the Assistant Secretary of the Navy (Research Development and Acquisition), and the Assistant Secretary of the Air Force (Acquisition) (OSD, 1988). The TEC memorandum stated that the enclosed guidelines implemented the congressionally-mandated Live Fire Test program within the DOD. The guidelines had been reviewed and coordinated by the individual Service deputies responsible for test and evaluation. According to the memorandum, *"the LFT program is a highly visible and sometimes misunderstood program. These guidelines should eliminate much of that misunderstanding"* (OSD, 1988). The guidelines describe the objectives of LFT&E, the scope of the guidelines, the implementation of the program, and the responsibilities of the DoD staff and the Services relative to LFT&E.

The 1989 LFT&E Planning Guide. A *Live Fire Test and Evaluation (LFT&E) Planning Guide* was issued in June 1989 by the Director, Live Fire Testing (DDDR&E, 1989). This Planning Guide is the current primary source of information on LFT&E provided by the LFT office to the Services and industry. The Planning Guide was intended to provide a good foundation for understanding the LFT&E program, and to be useful to system program offices and test agencies responsible for the testing and evaluation of systems identified as Live Fire candidates; nothing in the Planning Guide was intended to be inconsistent with the Live Fire legislation or any related DoD directives. The Planning Guide contains the TEC LFT&E guidelines of 1988; the Live Fire Testing legislation; and guidance concerning the definition of critical issues for Live Fire testing, the development of a strategy for LFT&E, the preparation of a detailed LFT&E plan, and the integration process involving contracting, budgeting, and scheduling. According to the Planning Guide, the intent of LFT&E (with regard to vulnerability) is "to assure that battle damage tolerance and damage control of our crew-carrying combat systems to actual threat weapons is known and acceptable…".

The LFT Program Approach

In concert, the LFT&E Guidelines of 1988 and the LFT&E Planning Guide of 1989 require the services to take an ordered approach to LFT&E on all covered aircraft systems. This approach includes the following steps:

1. identification of the critical issues;
2. development of an LFT&E strategy, which must be an integral part of the Test and Evaluation Master Plan (TEMP) and is subject to OSD review and approval;
3. integration of this strategy into the covered system program plan, budget, and schedule;
4. development of a detailed LFT&E test plan that fully describes the tests to be conducted and criteria for measuring test results and is subject to OSD review and comment;
5. conduct of the tests; and
6. generation of a detailed test report subject to OSD review for submission to the Secretary of Defense and the congressional committees.

The identification of the critical issues is required to form a foundation upon which a strategy for the Live Fire Test program can be developed for each system. To fully understand the system and the threat, information that fully describes the requirements for the system, the environment in which it must operate, and concepts for operation of the system must be gathered. Vulnerability analyses must then be conducted to identify potential weaknesses in the system and to obtain first-order assessments of the ability of the system to meet its operational requirements. Given this information, vital vulnerability concerns can be identified and distilled into the critical Live Fire Test issues. Depending upon the system, there are several sources for Live Fire Test issues. For example, if the system is designed to replace an existing system, a Live Fire Test issue would be, How does the vulnerability of the new system compare with that of the existing system?

The next step in the planning process is the development of a strategy for conduct of the Live Fire Test program. This strategy shall include the establishment of measures of evaluation, procedures for the evaluation of the results, the data requirements, and the test objectives. This strategy shall be a part of the Test and Evaluation Master Plan.

Provision must next be made for the integration of the Live Fire Test strategy into the program plan for the development of the system. The Program Manager will ensure that the overall program plan, budget, and schedule provide adequate resources to assure a successful Live Fire Test program.

A detailed Live Fire Test plan is required that fully describes the tests to be conducted and the criteria for evaluating test results. This test plan shall be in sufficient detail to ensure that the tests will satisfy the strategy objectives. The test plan is subject to review and comment by the Director, Live Fire Test.

The conduct of the tests is to be witnessed by the Live Fire Test Office, which does an independent evaluation of the results. The Services prepare a test report that is reviewed by the Live Fire Test Office. The test report is then forwarded to the Secretary of Defense with the independent OSD evaluation of the results, and from there it is sent to the interested congressional committees.

The 1988 LFT&E Guidelines and the 1989 LFT&E Planning Guide are the current written guidance provided to the Services and their Program Managers to assist them in the planning and conduct of a Live Fire Test program that is guaranteed to satisfy the requirements of the OSD and, through the law, the Congress. In addition to this written material, the staff of the Live Fire Test office is available for regular consultation with the program offices in the preparation of the strategy for the TEMP and of the detailed test plan. Other methods used by the LFT Office to communicate the LFT program to the testing and evaluation (T&E) and acquisition communities include full membership for the LFT Director on the Defense Acquisition Board Committees, periodic one-on-one discussions with the Services' Live Fire Test gate keepers, introduction of the program into the curriculum of the Defense System Management College, preparation of a video containing an overview of the program, public testimony before congressional defense subcommittees, sponsorship of six Live Fire Lessons Learned Workshops, participation in more than 25 T&E symposia, more than 40 on-site overview question-and-answer presentations to the major defense contractors, and publication in the open literature of more than 30 articles on Live Fire Testing (O'Bryon, 1991).

Controversy Regarding the Definition of "Realistic Survivability Testing"

The committee is concerned that the written guidance does not provide sufficient detail, particularly with respect to the full-scale tests, to ensure that the Program Manager can satisfy the requirements of the OSD policy and the law and also design a cost-effective test plan that will ensure system requirements are satisfied. Furthermore, the committee is concerned about the official status, or lack thereof, of the LFT&E Guidelines and Planning Guide.[1]

In addition to the questions regarding the level of detail and the current status of the guidance, there is a question regarding the interpretation of specific mandates contained in the Live Fire Test law. A major issue apparently exists between the Services and OSD, and indeed within OSD itself, regarding the definition and meaning of "realistic survivability testing" given in the law. The definition has been interpreted by the 1988 Live Fire Test and Evaluation Guidelines as follows:

> *a. Live Fire Test: A test event within an overall LFT&E program which involves the firing of actual munitions at target components, target subsystems, target subassemblies, and/or full-scale targets to examine personnel casualty, vulnerability, and/or lethality issues.*
>
> *b. Full-up Testing: Firings against a full-scale target containing all the dangerous materials (e.g., ammunition, fuel, hydraulic fluids, etc.), system parts (e.g., electrical lines with operating voltages and currents applied, hydraulic lines containing appropriate fluids at operating pressures, etc.), and stowage items normally found on that target when operating in combat. Full-up testing includes firings against fullup components, full-up subsystems, full-up subassemblies, or full-up systems. The term "Full-up Testing" is synonymous with "realistic survivability testing" or "realistic lethality testing" as defined in the legislation covering Live Fire Testing.*

The phrasing of these definitions has been interpreted by some to imply that full-scale, full-up Live Fire Tests do not have to be conducted (i.e., OSD policy is satisfied by Live Fire Tests only on sub-scale targets, such as major portions or subassemblies of an aircraft). The essence of the problem is the phrase in the law that states that realistic survivability testing means "testing for vulnerability of the system by." What is the "system?" Does testing only one major subassembly constitute testing for vulnerability of the system? If it does, as some believe, then no waiver from the mandated system Live Fire Testing is necessary.

[1] If action is taken to assign official status to these documents, they should first be modified to ensure that there is no ambiguity in the requirements for full-scale testing (see discussion below). One briefer indicated to the committee that guidelines were good for only one year and, beyond that, the "official status" would not be valid.

Although these definitions in the LFT&E Guidelines are apparently the official guidance on realistic survivability testing provided to the Services' Program Managers, the Live Fire Test Office does not fully accept them. It believes the Guidelines make too liberal an interpretation of the intent of the Congress. It believes that the law requires the testing of complete systems, not just sub-systems or mock-ups, fully configured for combat. However, it appears to recognize that this can be unreasonably expensive and impractical, and that circumstances exist in which the testing of only subscale targets is justified. In those situations, it believes a waiver should be requested.

The committee believes, as stated in Chapter 1, that the Live Fire Test law requires that full-scale, full-up tests be conducted on covered systems, unless a waiver is granted. Furthermore, it believes that the definitions in the 1988 Guidelines and the guidance given in the 1989 Planning Guide are not sufficiently clear as to the law's requirement that full-scale, full-up testing must be conducted. As a consequence of this misunderstanding, the Services have proceeded with sub-scale Live Fire Test programs on several weapon systems without making a provision for testing a complete system and without asking for a waiver because of the belief that no full-scale, full-up testing was required if early tests on sub-scale targets showed no design weaknesses.[2]

Conclusion

The committee believes that the Services, when they consider that full-scale, full-up Live Fire Tests are unreasonably expensive and impractical, should ask for a waiver. There should be no stigma attached to a waiver if a strong case can be made for one. According to the law, *"the Secretary of Defense may waive the application of the survivability and lethality tests of this section to a covered system, munitions program, or missile program if the Secretary, before the system enters full-scale engineering development, certifies to Congress that live-fire testing of such system or program would be unreasonably expensive and impractical"* (U.S. Congress, 1986–1989). If a waiver is granted, the law states that *"the Secretary shall include with any such certification a report explaining how the Secretary plans to evaluate the survivability or the lethality of the system or program and assessing possible alternatives to realistic survivability testing of the system or program"* (U.S. Congress, 1986–1989). Thus, requesting and receiving a waiver from the requirement for a full-scale, full-up test program do not eliminate the requirement for vulnerability assessment; only for the full-scale, full-up testing portion of the assessment.

[2]These programs are examined in Chapter 4.

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4 Live Fire Test Programs of the Three Services, and Views of the Test Community and Industry

The Army, Navy, and the Air Force have developed general Live Fire Test and Evaluation (LFT&E) policies in response to the passage of the 1987 Live Fire Test (LFT) law, and these policies are reflected in the LFT&E programs for the RAH-66 (Army), the V-22 and A-12 (Navy), and the F-22 and C-17 (Air Force). These policies and the individual aircraft LFT&E programs were presented to the committee on September 26–27, 1991, and are summarized below. Also contained in this chapter are the summaries of the presentations given to the committee on July 25, 1991 by the test community from each Service. The presenters represented the offices of U.S. Air Force, Office of the Director, Test & Evaluation; U.S. Army, Office of the Director, U.S. Army Test and Evaluation Management Agency; U.S. Navy, Office of Test and Evaluation and Technology Requirements. The highlights of all of these presentations are given below.

The committee believes it is important to point out before proceeding to the presentations that, except for the RAH-66, all of the programs described below were well under way when the law was passed and the C-17 development had proceeded beyond the deadline for the application of a waiver. Congress had given no transitional guidance for these programs. Furthermore, because the Services had only recently begun to test full-scale, full-up aircraft in the Joint Live Fire (JLF) program, they lacked adequate test facilities for conducting some of the tests; and they did not have any long-term experience in preparing the test plans for, and conducting, such tests.[1] Finally, because of the confusion over the requirements of the law, no waivers were requested for any program because of the belief within the Services that the law was satisfied with less-than-full-scale, full-up tests and that a stigma would be attached to any waiver. This situation has complicated the preparation of a thorough LFT&E program that satisfies the letter of the law as well as its intent.

The Army LFT&E Programs

The Army gave two presentations on its Live Fire Testing program. One, given by a representative from the U.S. Army Test and Evaluation Management Agency, was entitled "Army Philosophy and Policy on Live Fire Testing." The other, entitled "RAH-66 COMANCHE Ballistic Vulnerability DT&E Program Briefing," was given by a representative from the COMANCHE Program Manager's office. The presentations are summarized below.

Army Philosophy and Policy on Live Fire Testing. According to the presenter, the objectives of the Army Live

[1]The 1987 General Accounting Office study presented in Appendix B addressed the issues of the status of the JLF test program, the methodological quality of the testing and evaluation process, and how to improve live fire testing.

Fire test and evaluation (T&E) program are to demonstrate the ability of a system to provide survivability, to provide insight into the principal damage mechanisms and kill modes, and to provide insight into techniques for reducing personnel casualties and enhancing system survivability. The Army policy reiterates the legislative language. A draft policy document AR 73-XX, "Test and Evaluation Policy," was released for interim use in December 1990. According to that document, LFT&E will be integrated into the overall T&E program strategy. The Live Fire Tests are part of technical testing, and the scope of the program will build on early testing of components and on modeling. The LFT&E strategy will be contained in the Test and Evaluation Master Plan (TEMP). A draft document Department of the Army Pamphlet (DA PAM) 73-XX, "Test and Evaluation Procedures Guidelines," is being prepared. This document will incorporate the document "An Army Guide to Live Fire Test and Evaluation," August 1990.

According to the presenter, the Army LFT&E strategy involves a complementary testing and modeling effort. Modeling is an essential part of the strategy for determining system vulnerability since it is impractical to test the total spectrum of weapon/aircraft interactions, and testing is required to provide the necessary data to develop the vulnerability model algorithms. The LFT&E strategy follows a "building-block" approach consisting of component testing; full-up subsystem testing; and full-scale, full-up system testing. The emphasis of the testing program is on front-end testing of the components and subsystems to ensure that the performance of these tested articles is understood. Limited full-scale, full-up testing is conducted to confirm this understanding.

Live Fire Testing of the RAH-66 COMANCHE Helicop ter. The Program/Ballistics Detailed Schedule for the COMANCHE (presented to the committee in September 1991) is shown in Figure 4-1.[2] The ballistic assessment tests began in April 1991 and ended in November 1991. A three-and-half year period of ballistic verification and demonstration tests and Live Fire Tests begins in March 1995 and ends in September 1998.

The presenter identified three major ballistic vulnerability issues that could result from expected threat encounters. The first issue deals with the hazards to the COMANCHE aircrew, the second issue deals with the vulnerabilities of the flight critical subsystems, and the third deals with the mission essential subsystems. Accordingly, the objectives of the development test and evaluation (DT&E) program for ballistic vulnerability are to verify adequate aircrew and aircraft protection, to reduce the vulnerability of the flight critical components, and to reduce the vulnerability of the mission essential components. All subsystems are to be evaluated in the step-by-step test program, starting from section/ coupon testing, proceeding through static/dynamic component testing and full-up component and subsystem testing, and finishing with full-up complete system Live Fire Testing. The early tests are design support tests, and the later tests are to establish specification compliance. Two examples of design support tests using coupons or engineering mockups are the hydraulic ram tests on fuel tank panels and the ballistic penetration tests on composite panels. Two of the test articles to be examined for specification compliance are the flight control linkage and the anti-torque system drive shaft. Most of the 26 tests scheduled will use the 12.7-millimeter API; five tests are scheduled for a larger-caliber projectile. The Milestone II exit criteria tests are to demonstrate the damage tolerance potential of selected critical components to the specified design threats. Some of the test articles are the main rotor hub, main rotor blade, fantail assembly, and the T800 engine. The focus of these tests is to verify the ability of the helicopter to fly for 30 minutes after a ballistic impact.

According to the presenter from the COMANCHE Program Office, the objective of the dedicated Live Fire Test program is to evaluate the vulnerability of the full-up production configuration components, subsystems, and if necessary, a representative COMANCHE air vehicle. The focus of these tests will be on postdamage tolerance and the evaluation of synergistic effects. According to the presenter, the LFT&E program uses the approved threats; schedules the tests in a sequential "building-block" approach; tests full-up components and subsystems; will test a full-scale, full-up system, if necessary; and is in compliance with the law.

Committee Comments. Several aspects of the COMANCHE LFT&E program are of concern to the committee. First, the schedule shows a Live Fire Test program being completed just before going into full-rate production but after 72 aircraft have been bought in low-rate production contract awards, which is approximately 15% of the planned buy. It may not be possible to retrofit the changes required to correct any design deficiencies discovered in the LFT&E program into these aircraft. Furthermore, if approval is given to go into full production, another 96 aircraft will be produced in the next year while the design changes are being prepared. This is contrary to the LFT law's requirement that testing shall be carried out sufficiently early in the

[2] In early 1992, the Army restructured the COMANCHE program, stretching out the prototype phase by two years through the summer of 1997. Plans for completing the development and going into production after 1997 have been dropped, and the survivability and live fire tests have been deferred. Apparently, this is part of the Defense Department's plans to emphasize prototype research and development of new aircraft (Bond, 1992).

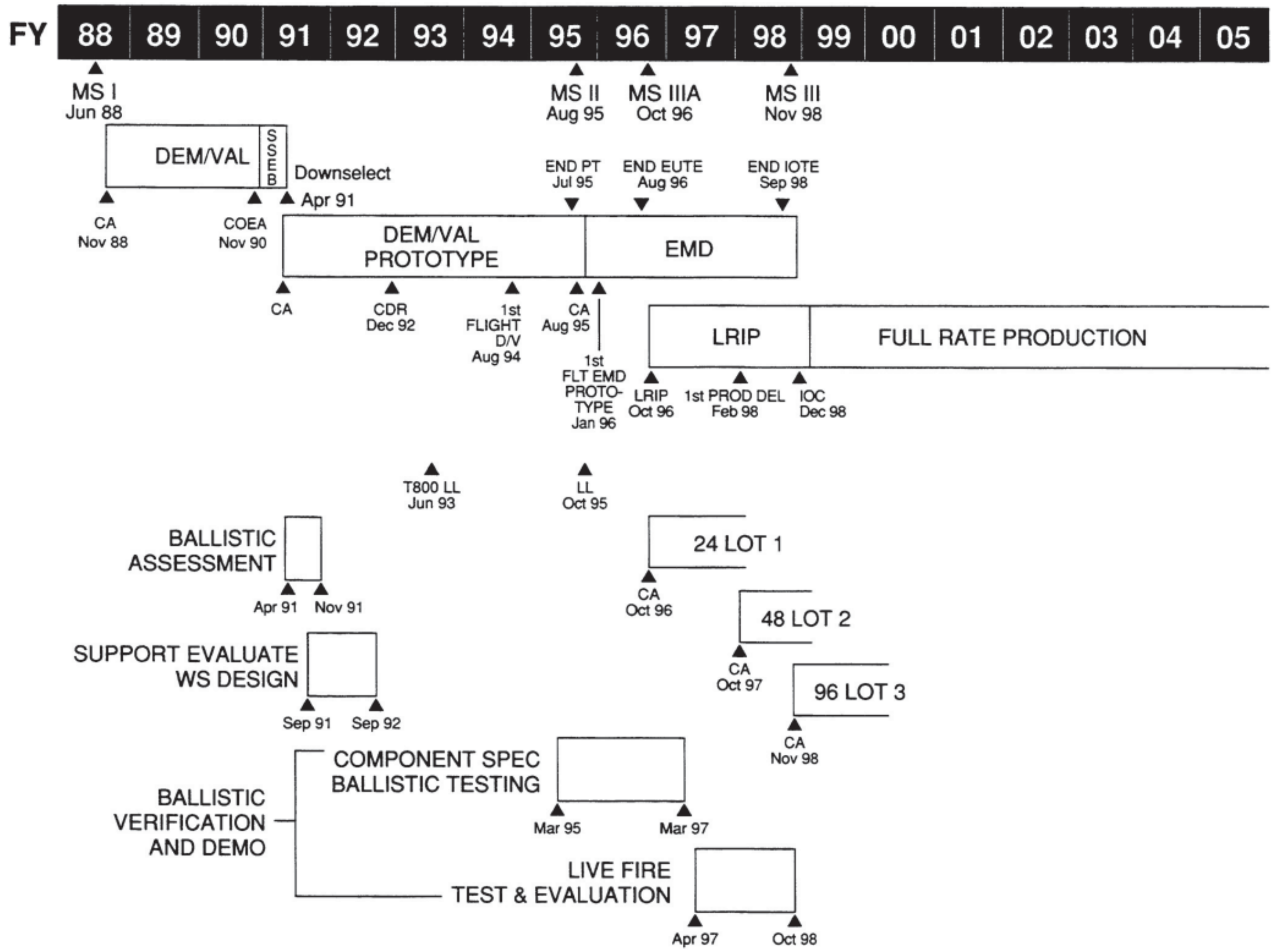

FIGURE 4-1 Program/ballistics detailed schedule for the COMANCHE.

development phase of the system to allow any observed design deficiency to be corrected before proceeding beyond low-rate initial production (LRIP). There are two ways this situation could be improved. One is that the demonstration and validation (DEM/VAL) prototypes will have been flying for several years before the first of the low-rate aircraft will have been contracted for, and one of these could be used for Live Fire Testing. The other way is to slow down the production rate.

Second, the briefer was vague on the actual testing of a full-scale, full-up aircraft and, when questioned, said a full-scale aircraft was not expected to be needed. On the other hand, his summary says the program will operate in compliance with the current Live Fire Test law. The presenter from the Army Test and Evaluation Agency left no doubt of the Army's position; it will do full-scale, full-up testing.

The COMANCHE briefer mentioned the on-board munitions, but did not dwell on its contribution to the vulnerable area of the aircraft. There was little discussion of what the internal stowage of ordnance might do to vulnerability, whether this would be addressed with some kind of protection. The committee believes that the consideration of ordnance in the assessment of vulnerability, both in modeling and in testing, is essential.[3]

It is the committee's opinion that the policy level of the Army supports limited full-scale, full-up testing, but that this support has not been fully recognized at the program level.

The Navy LFT&E Programs

The Navy Live Fire Test philosophy and the program for the V-22 were presented to the committee by a representative of the Survivability Branch, Naval Air Systems Command.

[3]This aspect of vulnerability is examined in Chapter 2.

SURVIVABILITY AND LIVE FIRE TESTING IN THE AQUISITION CYCLE

Conceptual & Preliminary Design Phases	Concept Demonstration/ Validation	Engineering & Manufacturing Development	
No Hardware	Simulator & Subscale Hardware	Full Scale Development Hardware	
• Analysis • Simulation	• Analysis & Simulation • Engineering Trade-Offs • Live Fire Development Testing (Risk Reduction)	• Full Scale Analysis • Design Trade Studies • Live Fire Verification Testing	• Design Feedback if Required • Support Production Engineering
• Mission Threat Analysis • Survivability Objectives Based on Operational Requirements • COEA Support	• Major Trade-Offs • System Specification • Survivability Program Plan • Source Selection • Support Program Changes • Full Assessment • Mission Effectiveness • COEA Support • Live Fire Developmental Testing: Panels, Simulators	• System Specification • Source Selection • Formal Survivability Assessment & Trade Studies • Tactics Development • PDR/CDR Support • COEA Support • Live Fire Verification Testing: Simulators, Surrogates	• Evaluation of ECP's • Survivability Assessment of all Production Changes • Hardness Assurance • Mission Effectiveness • COEA Support

FIGURE 4-2 Live Fire Test and Evaluation of Navy aircraft.

The Deputy Director of the Navy's Office of Test & Evaluation and Technology Requirements was present at the briefing. Preliminary information on the LFT&E program for the A-12 aircraft was provided during several committee meetings. The Navy's presentation is summarized below.

The Navy Live Fire Test and Evaluation Policy. The Navy's view of the Live Fire Test law is that it encourages full-up vulnerability testing, under realistic combat conditions, first at the sub-scale level and later at the full-scale level. Live fire testing is part of developmental testing and is a continuing process that contributes to the development and engineering of Navy aircraft. The Navy policy is to comply with the intent of the law by establishing realistic operational requirements and combat threat scenarios, establishing explicit Survivability and vulnerability design requirements, and requiring Live Fire Testing and Evaluation as part of the development process using a shoot-fix-shootagain approach. The Navy LFT&E program integrates Live Fire Testing with the development of the aircraft, as shown in Figure 4-2. The integration of the tests on simulators and sub-scale hardware early in the development provides design information in time to be useful. Later Live Fire Verification Testing using simulators and surrogates provides information on the design's compliance with the specifications.

According to the Navy presenter, the benefits identified for full-scale, full-up testing are the possible discovery of previously unknown reactions to the weapons and synergistic effects. The disadvantages include the fact that the results are very limited statistically; the full-scale aircraft is at risk on each test; the tests are very costly; and the full-scale, full-up tests do not eliminate the need for all of the earlier sub-scale tests. Furthermore, testing the full-scale aircraft can be accomplished only at a very late stage in the development, and it may not be possible or practical to correct any design vulnerabilities discovered in the tests. This is contrary to the requirement in the law that the testing shall be carried out sufficiently early to allow any design deficiency demonstrated by the testing to be corrected before proceeding beyond low-rate initial production. In summary, Live Fire Testing is a process that begins in the D/V phase; it is not a single pass/fail event. It involves both analyses and testing, with results available sufficiently early to aid in design.

Live Fire Testing of the V-22 Aircraft. A comprehensive plan for the Live Fire Testing of the V-22 was made available to the committee, and though it is somewhat dated it was a useful input. The program is old enough to be grandfathered for Live Fire Testing even though the summary page says the current program meets the Live Fire Test law.

The V-22 aircraft had specific design requirements on the allowable vulnerable area for several specific threat weapons, excluding hydraulic ram. A number of alternative vulnerability reduction designs were identified, and the reduction in vulnerable area and increase in weight were determined for each alternative. The most promising alternatives were tested. Some of the test articles used in the stage I ballistic tests included a wing structure, a fuselage structure, a pylon actuator, and some of the flight controls. Ballistic verification tests have been completed for phase I and phase II wing tank hydraulic ram and the propellar rotor gearbox components. A series of dry bay fire suppression tests has been conducted using a representative three-bay simulator. Four different suppression techniques were tested; a Halon system, power panels, foam, and an on-board inert gas generating system (OBIGGS). The threats were several ballistic projectiles. In the baseline tests without any protection, large, consistent fires with heavy fixture damage were observed. The results using the different suppression techniques ranged from several fires to no fires.

Committee Comments on the V-22. The V-22 aircraft has been under development for several years and has been under a cloud for many of them. The cloud is related to the need for the system rather than anything related to its vulnerability. The cancellation of the program by the Secretary of Defense and the reinstatement of the program by Congress tend to make systematic planning for various phases of Live Fire Testing difficult.

The purpose of the aircraft is to take troops and light material into the vicinity of danger, and for that mission the Joint Services Operational Requirement for ballistic tolerance seems inadequate. Furthermore, there is no discussion of the vulnerable area associated with on-board ordnance. The aircraft will be hauling U.S. Marines into combat, and they will put all of the weapons and ordnance they can load aboard. An analysis that shows how the load could be distributed, or how some light armoring could change the vulnerability of the aircraft to ground fire, would give more credence to the claim that the ballistic protection had been achieved.

The fate of the LFT&E program is dependent upon a decision to enter into low-rate production.

Live Fire Testing of the A-12 Aircraft. The A-12 was a highly classified program, and therefore, it was not a covered system according to the LFT law. Nevertheless, a member of the LFT Office was read into the program because of the fact that the aircraft would become a candidate for LFT when it no longer was a black program. According to one of the briefers, the A-12 live fire test program for components and subsystems was one of the best programs to date. Although the proposed LFT strategy did not include testing on the full-scale, full-up aircraft, it appeared to be reasonable according to the briefer. Apparently, informal approval was given to the proposed LFT strategy, and this strategy was in effect when the program was canceled. Two major criticisms of the program were the omission of testing of the on-board ordnance and the omission of consideration of threats other than projectiles and missiles, such as directed energy weapons.

Committee Comments on the A-12. It is the committee's opinion that the policy levels of the Navy and the Program Offices appear to have no intention of doing any full-scale, full-up test on any aircraft before proceeding beyond low-rate initial production. The Navy considers full-scale, full-up testing of aircraft to be unreasonably expensive and impractical. Apparently as a consequence of this belief and the interpretation of the LFT requirements given in the LFT&E Guidelines, no full-scale, full-up LFT tests were proposed for the A-12. The committee's opinion is that any approval of an LFT strategy for the A-12 that did not include tests on the full-scale, full-up aircraft and did not request a waiver from these tests would have been in error. The committee is concerned that future black programs will face the same problems with respect to the LFT law that occurred with the A-12. The Navy has initiated efforts on a replacement program for the A-12, presently called the AX. Because this also is a black program, it is not a covered system under the LFT law. However, it too will eventually become an unclassified program and at that time will be subject to the law's provisions. This will probably occur after the program enters into full-scale engineering development, the deadline for the application for a waiver. If the requirements in the LFT law are ignored until the program comes out of the black, there most likely will be a confrontation with the LFT Office.

The Air Force LFT&E Programs

The Air Force Live Fire Test Policy. The Air Force policy on LFT&E was presented by a representative from Test & Evaluation, Air Force, and was entitled "Air Force Policy Considerations for Live Fire Test & Evaluation." According to the presenter, the objective of Air Force LFT&E is to provide a timely and thorough assessment of the vulnerability and lethality of a system as it progresses through its development. This is accomplished by a balanced program of analysis and test. It is a systems approach, similar to development testing used in other areas. Because it is prohibitive to test all possible combinations of threat/aircraft/conditions, analysis must be an integral part of the LFT&E process. A general sequence of design-analyze-test is followed and repeated if necessary. The analytical models are those accepted by the Joint Technical Coordinating Group on Aircraft Survivability (JTCG/AS). The LFT&E program is initiated sufficiently early to allow the results to impact the system design. The benefits of LFT&E can be maximized only when the test results are used to aid in the design. The LFT&E strategy, which is included in the TEMP, ensures that all issues are addressed and integrated with the other elements of the system program. According to the presenter, the Air Force policy is in compliance with the reporting requirements of the LFT&E Office. The threat used for the Live Fire Tests is the threat(s) defined by the Operational Requirements Document (ORD). The ORD is the official source of user requirements, and the ORD process places the user in the role of integrating the System Threat Assessment Report (STAR), aircraft characteristics, employment concepts, etc., to derive the expected threat.

According to the presenter, the test hardware will be of sufficient size and quantity so that realistic test results, including synergism and secondary effects, will be obtained. Experience indicates that components, subsystems, and subassemblies are generally sufficient and more desirable than a complete system. Full consideration will be given to the use of actual hardware, replicas, and surrogates. However, use of these items must depend on the technical payoff, availability, and cost. The requirements for additional live fire test facilities are being identified in the Air Force's Test Investment Planning Process. In summary, according to the Air Force, its LFT&E program is integral to the system design, development, test, and evaluation process. The Air Force believes it endorses an intelligent approach to LFT&E that considers all variables affecting aircraft effectiveness. It believes the Air Force T&E approach employs the most prudent combination of analyses and tests, is viable, and is producing positive results.

The Live Fire Test Program for the F-22 Aircraft. The Live Fire Test program was briefed to the committee by a representative from the system program office in a presentation entitled "F-22 Vulnerability Program." The approach to aircraft survivability used by the F-22 is a combination of low susceptibility and reduced vulnerability. Directed energy weapons are considered, as well as the conventional gun and missile threats. The reduction in vulnerability is accomplished through incorporation of redundant subsystems and damage tolerant features. Vulnerability analyses will be used to establish any system weaknesses and to identify vulnerability reduction candidates. Vulnerability testing of materials, components, and subassemblies is used to verify the vulnerability reduction candidates and to identify issues that necessitate Live Fire Testing. The results from the analyses and the lower-level tests will determine the need for, and extent of, further validation tests. According to the presenter, the LFT&E program is a sound development and demonstration program that represents a balance of the technical merits, cost, and schedule. The methodology used in the program is shown in Figure 4-3, and the vulnerability program schedule and funding are given in Figure 4-4. According to the presenter, the budget and schedule supports the conduct of prudent Live Fire Testing. Some of the assessments to be conducted to verify the design include fuel tank inciting using a rig test, redundancy and separation studies using analyses and inspection, verification of the fragmentation resistance of pressure vessels using ballistic tests, and a static test of structure.

Committee Comments on the F-22. In the F-22 presenter's discussion of vulnerability modeling for the engineering, manufacturing and development (EMD) study he stated that internal armament was treated. However, a chart of vulnerability requirements included a column for armaments that discussed vulnerable area as to be determined (TBD) and fire inciting, fire protection, and shielding as not applicable (N/A). The EMD vulnerability program shown in Figure 4-5 has a category for stored munitions, engine, and aircraft availability, but it is under concurrent JLF. When members of the committee questioned the possibility that this was the prototype aircraft, the briefer seemed unaware that a Live Fire Test would be done on a full-scale, full-up aircraft, and that the prototypes were so different from the production model that they would not be representative.

The Live Fire Test Program for the C-17 Aircraft. The program for the C-17 LFT&E was given by a representative from the C-17 System Program Office in a presentation entitled "C-17, Live Fire Test (LFT) Program." According to the presenter, the C-17 is expected to be deployed to within 20 to 40 km of the Forward Edge of the Battle Area FEB A). The vulnerability requirement for the selected design threat in the FEBA is met by using redundancy with separation, damage tolerant components, and fire and explosion suppression. A number of design changes were made to meet the requirement as the result of analytical assessments. These included the relocation of the oxygen converter, rerouting of the hydraulic lines, and changes to the pitch trim actuator and aileron hinge fitting. The test methodology included design, analysis, test, redesign, and retest. The test articles included components, such as crew armor, pressure vessels, the upper wing skin, and a flap

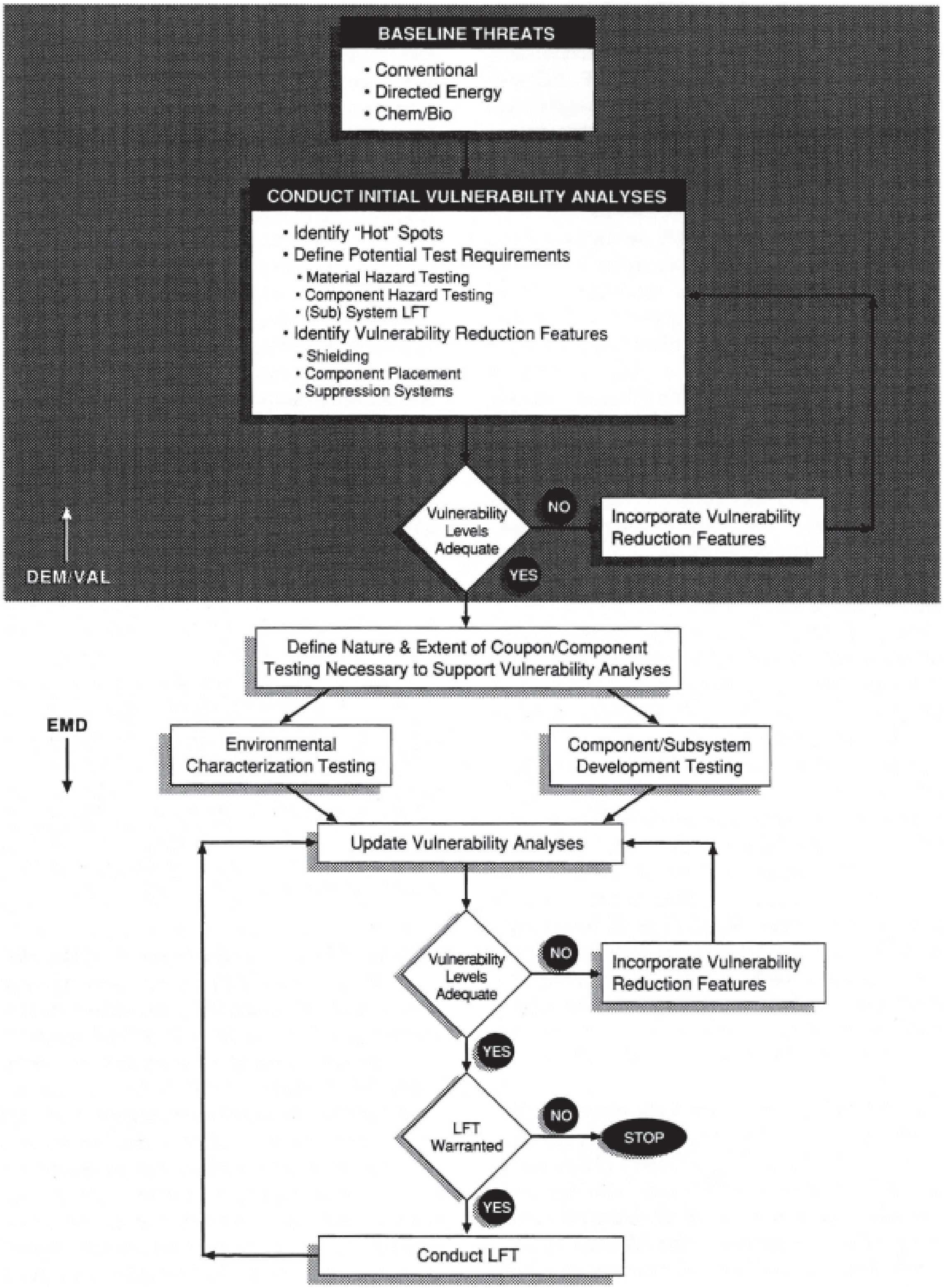

FIGURE 4-3 Vulnerability assessment methodology for the F-22.

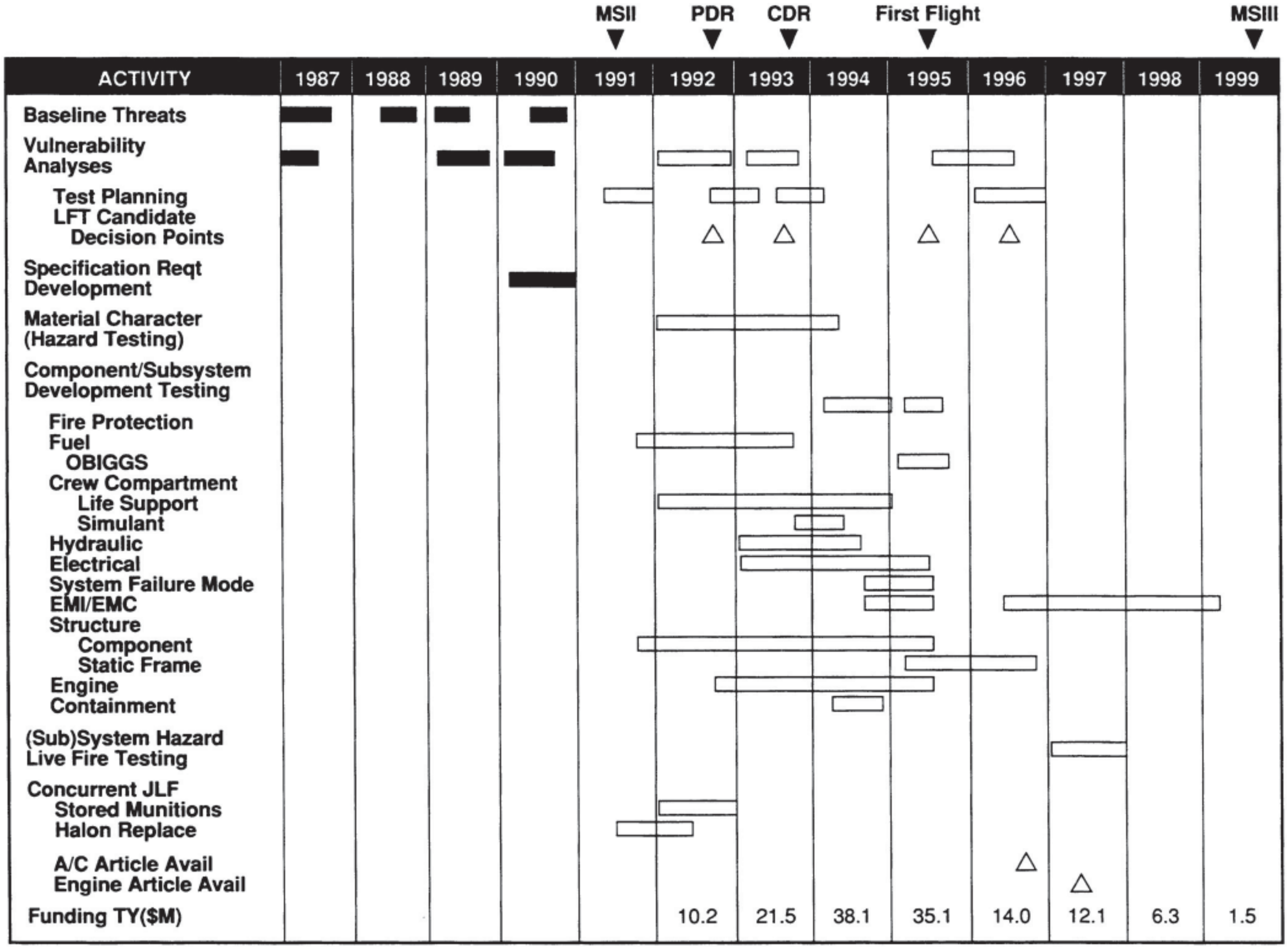

FIGURE 4-4 Vulnerability program for the F-22.

hinge fitting; and a functional 8-foot section of the wing leading edge. The leading edge section is to be Live Fire Tested to determine if there is a leading edge fire problem. The test article is designed from production drawings from the Douglas Aircraft Company and will be built by the 4950th Test Wing Modification Branch. The Live Fire Tests will be conducted by the Wright Laboratory's Flight Dynamics Directorate.

Committee Comments on the C-17. The C-17 represents one of the most interesting challenges to the Live Fire Test law of 1987. It was in full scale development when the law was passed and hence could not legally request a waiver. It is a very large and expensive aircraft, although not the largest to enter the inventory. The largest, the C-5A, was delivered during the 1960s and was not subject to any live fire testing. Apparently, Congress considers the C-17 to be a Live Fire Test candidate and expects to see Live Fire Testing conducted on the C-17 aircraft (Bennett, 1991). The contention by Congress is that testing of components from a military vehicle in an essentially inert condition is no substitute for the firing of threat ammunition at that vehicle loaded for combat with the intended fuels, fluids, and ordnance on board and in place.

In the case of cargo aircraft such as the C-17, if the aircraft contains ordnance when configured for combat, the ordnance and its reaction to ballistic impact must be treated in the assessment. A sub-scale, but full-up, Live Fire Test of the C-17 would logically consist of testing a mock-up of an actual cargo compartment, with ammunition loaded in pallets on dunnage. If the shot created significant damage due to a reaction of the ammunition, shielding or armoring could be undertaken to bring the damage expected to an acceptable level.

During a temporary shifting around of personnel in the

Feature	WSS	AVS	STRUC	U&S	C'KPIT	AVIONIC	VMS	ARM	ENGINE
Fuel Inert	X	X	X	X	N/A	N/A	N/A	N/A	N/A
Fire Prot	X	X	N/A	X	N/A	N/A	N/A	N/A	X
Redund & Separate	X	X	X	FUEL HYDLS ELEC	N/A	SMS RADAR CNI CORE P	X	N/A	X
Vuln Area	N/A	X	TBD	TBD	TBD	TBD	TBD	TBD	TBD
Shielding	N/A	X	X	APU	N/A	EC	N/A	N/A	X
Chem Prot	X	X	X	X	X	X	N/A	N/A	X
DE Prot	X	X	N/A	N/A	X	X	X	N/A	N/A
Fuel Ingest	X	X	N/A	X	N/A	N/A	N/A	N/A	N/A

WSS - *Weapon System Spec*
U&S - *Utilities & Subsystems*
ARM - *Armament*
HYDLS - *Hydraulics Subsystem*
TBD - *To be Determined*
N/A - *Not Applicable*
AVS - *Air Vehicle Spec*
C'KPIT - *Cockpit Spec*
SMS - *Stores Mgmt System*
CORE P - *Core Processing*
DE - *Directed Energy*
STRUC - *Structures Spec*
VMS - *Vehicle Management Spec*
CNI - *Comm, Nav, ID*
APU - *Auxiliary Power Unit*
EC - *Electronic Combat*

FIGURE 4-5 Vulnerability requirements for the F-22.

Office of the Deputy Director, Defense Research and Engineering (Test & Evaluation), the Air Force's proposal to test only a portion of the leading edge of the wing was accepted as being in compliance with the LFT law. This enforced the belief that the conduct of full-scale, full-up Live Fire Testing could be avoided by the acquisition arm of the Air Force. The Air Force user should have been put more of a decision-making position on this issue. The size of the C-17 is going to make it an attractive target for various potential enemies who might hold fire from smaller targets in order to concentrate fire on the larger aircraft. If an aircraft is to go into combat, and if combat damage is expected to be encountered, the aircraft is going to have to be tolerant of the damage or a price will be paid in manpower and material losses. Supporters of the Live Fire Test law believe that if the full-scale C-17 is too expensive to be subjected to live fire in a full-up condition, the aircraft is too expensive to risk losing by delivering cargo to a forward military zone. If that is the case, the upper limit on the cost a Service may be willing to put into an aircraft may have been reached. A reasonable question to ask is, would the aircraft be bought if it was to be used only to deliver military cargo to rear areas? If that answer is no, the importance of testing the aircraft against the weapons it is expected to encounter is paramount.

The Test Community's View of Live Fire Testing

The live fire test community of the three Services appears to be in general agreement about the efficacy of the Live Fire Test law as it applies to aircraft. Members of that community do not consider it necessary to do full-scale, full-up tests in order to determine most of the design vulnerabilities. However, they do consider it essential to conduct many sub-scale tests on components and sub-systems, both inert and full-up, in the development cycle of an aircraft. The sub-scale test results are invaluable sources of information that can be used initially to aid the design and later to verify the design. The test community believes that the full-scale, full-up tests are conducted too late in the development cycle to be of much value to the designer and that the amount of information obtained from the tests is very limited.[4] Every time a test is conducted a portion of the test article is damaged, and it may be impossible to restore the article to its original condition. Furthermore, these tests require very large budgets that could go toward the expansion of test facilities and capabilities and the conduct of many more sub-scale tests. The test community does recognize the possibility of an unanticipated reaction, cascading damage, or synergism occurring in the full-scale aircraft. However, its members believe that nearly all of the kill modes of an aircraft are known and can be anticipated; they state that they very seldom see a test result that was unanticipated. The magnitude of the response to the hit may be larger or smaller than expected, but the response was anticipated.[5]

Committee Comments. The committee notes that not everyone who has observed live fire tests on sub-scale and full-scale test articles shares the views held by these testers. They believe that there have been unanticipated results from these tests. Furthermore, even when the response is as expected, the difference in the expected magnitude of the response and the observed magnitude often is too large to be acceptable. The testers have also overlooked the fact that information from the full-scale tests is an input to acquisition decision makers at milestone reviews. The committee also believes that the test community has not given proper consideration to the on-board ordnance problem.

The Industry View of Live Fire Testing

The U.S. aircraft industry does not play a major role in LFT&E. However, the committee solicited its opinion because these are the users of the results of the Live Fire Tests. The four industry representatives were unanimous in their belief that the LFT law as described in the LFT Guidelines and Planning Guide does not require a full-scale, full-up aircraft to be tested. Furthermore, they do not believe it should. One of the major reasons they gave for not recommending full-scale testing of a "production" aircraft is that the design is usually frozen by the time the results become available.[6] However, they were in full agreement with the test community on the necessity of sub-scale testing throughout the program development.

Controversy Regarding Which Munitions to Use in the Live Fire Testing Program

The Live Fire Test law stipulates that *"munitions likely to be encountered in combat (or munitions with a capability similar to such munitions)"* are to be used in the *"realistic survivability testing"* The specific munitions to be used in the Live Fire Testing of a particular aircraft are selected by the aircraft Program Office as part of its LFT&E program plan. Typically, the threats selected by the Program Office for Live Fire Testing are the threats the aircraft was designed to withstand, such as a single hit by an armor-piercing (API)

[4]The test community is not against all testing of full-scale, full-up aircraft; it fully supports this type of testing on existing aircraft in programs such as JLF.

[5]This attitude appears to be in contrast to the experience of the testers of ground vehicles, where the particular response to a hit was often unanticipated.

[6]The committee notes that industry shares the same reluctance as the Services to change a design late in the development cycle.

or small-caliber high explosive with incendiaries (HEI). The assumption is made that the more lethal overmatching threats, such as the larger anti-aircraft artillery (AAA) and the surface-to-air missiles (SAMs), will be avoided and hence should not be a part of the LFT&E program. For example, the Navy and the Air Force are currently developing stealth aircraft whose survivability is strongly related to not getting hit. They believe that some "credit" should be given for this aspect of survivability. Aircraft that do not get hit as often do not have to rely as much on their reduced vulnerability to survive. Furthermore, if these overmatching threats are included in the LFT&E program, they could destroy the only test article(s) available, as well as the test equipment, and perhaps some of the test facilities.

The Live Fire Test Office has interpreted the phrase "munitions likely to be encountered in combat" to mean that those munitions the aircraft *may* encounter, including the latest directed energy weapons, should be included in the LFT&E program, regardless of the design threat for the aircraft. This interpretation of the phrase "likely to be encountered in combat" made by the LFT Office conflicts with the interpretation made by the Program Managers, and this difference in interpretations has been the source of considerable controversy. The LFT Office argues that the user Service's intention to avoid the most lethal threats in combat through susceptibility reduction may not always be achievable. Given that the intent of the LFT law is not to intentionally destroy aircraft, the LFT Office believes that a test involving a "potentially" overmatching weapon can be designed that will provide information on any design weaknesses with little likelihood of destroying the aircraft. For example, suppose the weapon is a guided missile with a large HE warhead and a proximity fuze. The lethality of this weapon depends upon the location of the warhead with respect to the aircraft at the time of detonation. If the detonation occurs next to the aircraft, the aircraft will most likely be killed. On the other hand, if the detonation occurs far from the aircraft, the aircraft will most likely not be killed. Consequently, the LFT Office believes that if information on any design weaknesses can be obtained from a distant detonation with little probability of destroying the aircraft, the test should be considered. The Services counter this argument with the argument that any information obtained from the limited number of tests is not statistically meaningful. This is, in turn, countered by the argument that one purpose of the full-scale tests is to discover vulnerabilities, not to quantify vulnerability.

Committee Comments. Today, military systems are designed to survive the threat they can expect to find in the field at the time they are fielded.[7] The process of defining the future threat is called threat projection. The results of the threat projection appear in STAR. Historically, the threat community has been reluctant to commit to a firm projection of the specific threats a particular system will encounter 10 to 20 years in the future for several reasons. Consequently, a long list of threats that the system may encounter in combat is usually prepared, perhaps with some prioritization. However flawed the threat projection process may be, the user of the proposed system must select a design threat for the system. The developer then designs a system that will survive the threat described in the user's requirements document.[8]

Note that the user is the organization that examines the threat projection and selects the design threat. The design threat selected may or may not be the most likely threat that will be encountered; usually it is but one of many threats that are likely to be encountered. The Live Fire Test Office does not consider the design threat selected by the user as the only threat likely to be encountered and strongly encourages the Program Office to test the system against the other threats that exist, or will exist, in the operating environment. The argument given by the LFT Office is that the threat selected for design is usually one that can be defeated without significant increases in weight and cost. Thus, given that it is important to verify the design's ability to withstand the design threat, it is also important to determine, and correct if possible, any weaknesses in the design when subjected to the other "likely to be encountered" threats before the system goes beyond LRIP. An argument against testing against the other, possibly overmatching, threats is that even though the system was not required to defeat these weapons, any negative results from such tests may jeopardize the program, as well as siphon off much needed funding.

The C-17 LFT&E program is an example of the conflict between testing only against the design threat and testing against other threats that may be encountered in combat. The Operational Requirements Document for the C-17 stipulates a design that will withstand a single hit by a certain ballistic projectile. According to the C-17 presenter, this projectile may be encountered by the C-17 in the region of 20 to 40 km from the Forward Edge of the Battle Area. The Live Fire Test Office, on the other hand, believes that C-17s in the forward area of the battlefield and at austere landing sites near combat zones can expect threats that are

[7]Aircraft have not always had specific design requirements to survive the expected threat, particularly on the vulnerability aspect of survivability. Perhaps the first aircraft to have a vulnerability requirement on the design were the U.S. Army's UTTAS and AAH, now the UH-60 Black Hawk and AH-64 Apache. Both aircraft had to be designed to survive a single hit by a non-explosive ballistic projectile anywhere on the aircraft and fly for 30 minutes after the hit.

[8]As a consequence of this procedure, systems are typically designed against today's threats—and sometimes even against yesterday's threats. Both practices result in systems being designed to survive yesterday's threats when they finally appear in the field.

more much lethal than the design threat selected for the C-17.[9]

A Program Manager's View of the Live Fire Test Law

The committee, after listening to all of the presentations, believes the following description of a Program Manager's (PM's) view of the LFT law may be representative of current opinion:

The full-scale, full-up testing mandated by the LFT law is an unquantifiable, but potentially catastrophic, risk to his program. LFT has no quantitative contractual specification or acceptance criteria at program initiation. No quantitative criteria for acceptable or unacceptable damage are included in the requirements process, milestone commitments, or contractor performance documents. LFT of the full-scale aircraft occurs late in the development phase of the program, and there may be neither adequate time nor money to conduct the tests or to make any changes required as a result of the tests. Further, the PM may believe that neither the definition of the tests, nor the conduct of the tests, nor the interpretation of the test results is totally under his control. The perceived jeopardy to his program created by LFT is exacerbated by the severe requirement to fit the program into a somewhat inflexible overall resource schedule, both in time and in dollars. In summary, LFT represents a considerable source of problems to the PM, in the form of an uncontrollable, potentially catastrophic uncertainty, as he attempts to successfully complete the development of his system, and should be avoided if at all possible.

Issues Relating to Distrust Among the Participants in Live Fire Testing

The committee is aware of the strong differences of opinion held by various individuals and organizations concerning the efficacy of the Live Fire Test law and of the level of mutual distrust that has evolved as a result of these opinions. This distrust between the various participants of each other's motives and actions is probably responsible for the ever-increasing tensions within the current Live Fire Test program. The attitudes of the major participants concerning the Live Fire Test law and its place in the acquisition process appear to be those described below.

In the committee's opinion, the Services may believe that, as system developers and users, they know what is needed in the equipment they will take into the field, and that they, the Services, are directly responsible for the fate of the military personnel who use this equipment in combat. They are very apprehensive about any outside organization that can dilute their ability to define the necessary equipment testing and the procedures required to accomplish this testing. They appear to further believe that the Live Fire Test law gives to others not directly responsible for the delivered product inordinate control without any accompanying responsibility for the quality of the product or its cost.

In the committee's opinion, the Office of the Secretary of Defense (OSD) may believe that there have been a sufficiently large number of prior experiences in the area of live fire testing to indicate that pressure by a Service for successful and rapid certification of its products under development can lead to inadequate live fire testing and to subsequent unnecessary combat vulnerabilities. The OSD, therefore, has chosen to exercise close control over the Live Fire Test programs and assumes the ultimate authority for approval of the equipment based on the program results.

In the committee's opinion, the Congress may believe that there are sufficient numbers of proven instances of unnecessary combat vulnerability in the Department of Defense (DoD) equipment previously delivered to the field to warrant legislative direction of DoD test certification to include live fire testing of full-scale, full-up systems using munitions likely to be encountered in combat. Congress further believes that it has the ultimate responsibility for the programs it authorizes and therefore has the obligation to exercise that legislative direction.

Conclusion

The committee believes the common view of all parties knowledgeable in this business is that the current assessment procedure, including both analysis and Live Fire Testing, does not guarantee that the U.S. armed forces will field cost-effective systems designed for reduced vulnerability. The intent of the LFT law to contribute to the creation of less vulnerable aircraft designs is valid; its execution to achieve this intent has been flawed in several ways as identified in Chapters 2, 3, and 4. The committee believes that the crux of the problems with the LFT law is (1) the ambiguity of the law; (2) the lack of a clear and binding LFT policy directive; (3) the reluctance by the Services to—for fear of a stigma[10]—ask for a waiver from full-scale, full-up LFT for those programs which they believe LFT to be unreasonably expensive and impractical; and (4) the absence of a formal waiver process that includes a procedure for identifying when full-scale, full-up testing is or is not unreasonably

[9]Military airlifters have flown in hostile environments in the past. Examination of the combat data from the Southeast Asia conflict reveals damage and losses to C-7s, C-123s, and C-130s from small arms, AAA, and shoulder-fired SAMs, and 14 airlifters were damaged by small arms in only 400 sorties in 1989 in Operation Just Cause (Ropelewski, 1990).

[10]There is also the possibility that the Services do not consider it appropriate for Congress to become involved in this area of program management and acquisition.

expensive and impractical which would eliminate any stigma associated with the waiver.

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5 The Future of Vulnerability Assessment

Characteristics of the Future Department of Defense Environment

The committee recognizes that there will be a major change in the environment in which the Department of Defense (DoD) will acquire weapon systems in the future, given the dramatic changes in the world socio-political environment and the current difficulties with the U.S. economy. Almost certainly, the future DoD budgets for acquisition of new systems will be significantly reduced, with a concomitant reduction in the number of new program starts. Two recent examples of the types of changes to be expected are the reduction of B-2 aircraft buy from 75 to 20 and the restructuring of the RAH-66 COMANCHE program to postpone production while emphasizing and stretching out the prototype phase. Future budgets for improving existing systems most likely will be below—possibly much below—current levels. Future budgets for the technology base (not counting independent research and development) are difficult to predict at this time, but may be above current levels in order to maintain the current U.S. technology edge.

In spite of the significant reduction in the future DoD acquisition budgets, the requirement to maintain and technologically update fielded platforms over substantially longer lifetimes to counter new threats will remain. When new programs are initiated or prototypes moved into production, it probably will be in response to important new threats not able to be defeated by current platform improvements. In all cases, there will be a requirement to contain the costs of the new or prototype system. Although program cost containment has always been a concern within DoD, the committee believes that minimizing total program costs in the foreseeable future while improving weapon system abilities to counter and survive new threats will be an even more important issue.

In this regard, the committee notes that the restructured program for prototyping the RAH-66 has deferred the survivability and live fire tests. Because there is no intention to go into production at this time, the RAH-66 is not a candidate for Live Fire Testing. The committee is concerned that by deferring the survivability and live fire tests, the vulnerability of the prototype design will not receive the proper attention. A decision could be made in the future to move the prototype into production, with no further vulnerability assessments planned to determine any design weaknesses. However, once this decision is made, the helicopter becomes a candidate for Live Fire Testing. Any attempts to change the prototype design to reduce vulnerability once the decision has been made to go into production may be met with much resistance. This is going to create an adversarial situation again. It would be much better to find and correct any vulnerabilities in the design during development of the prototype than attempt to do so after the development is completed.

In addition to individual program cost containment issues, the committee anticipates a reduction in the test and evaluation infrastructure within the Office of the Secretary of Defense (OSD) and in each of the Services as the total DoD budget declines. In particular, the independent charters, staffs, and facilities of the vulnerability assessment community may have to be changed, as well as the emphasis currently given to the analysis and test communities. The committee believes that new approaches to many of the current DoD weapon acquisition procedures may have to be developed to respond to the new fiscal threat environment, and among these approaches may be changes to the procedures and infrastructure for vulnerability assessment.

Crucial Requirements of Future Vulnerability Assessment Procedures and Infrastructure

The committee believes that it is vital for the future effectiveness of U.S. military aircraft that any changes made to the vulnerability assessment procedures and infrastructure must not degrade the current capabilities for vulnerability assessment within DoD. Vulnerability assessment, which is an integral part of designing for survivability, will increase in importance as the numbers of front line aircraft decrease and the lifetime of each aircraft is extended. Furthermore, because fewer new systems will be developed in the future, the vulnerability of each of these new systems becomes more important. Consequently, more funding for vulnerability assessment may be required for the few systems that are developed, rather than less funding.[1] On the positive side of this situation, as more new starts are prototyped and development time is increased, there are more opportunities for better assessments. For example, the results from live fire tests on full-scale, full-up targets may be obtained sufficiently early in the stretched-out development time to influence the final design. An additional impetus for vulnerability assessment is the close and important connection between combat vulnerability and flight safety. Aircraft designed to take hits in combat and to survive crashes are inherently safer aircraft for the aircrew to fly in. Many design features included to reduce vulnerability, such as fire and explosion suppression, flight control reconfigurability, hydraulic power redundancy and separation, rotor blade toughness, and engine hardness, also prevent the loss of an aircraft due to peacetime malfunctions.

Based on the suppositions given above, the committee believes that the vulnerability assessment capabilities of the future, both analytical and testing, should be developed as follows:

1. Vulnerability assessment will continue to be required to design and validate the vulnerability expectations of new military platforms. Consequently, the current methodologies must be improved. However, the assessments and their improvements must use the available funds in the most efficient way.
2. There will also have to be a cost reduction within the DoD vulnerability analysis and test infrastructure, because there will be fewer aircraft to assess, while still maintaining necessary staff expertise and test facilities for the remaining programs.
3. A vulnerability test and evaluation procedure must be developed that provides, despite any cost reductions, a greater level of trust among the three Services, the OSD, and Congress than exists today.

The committee's view is that unless a procedure for vulnerability assessment and design validation can be developed that increases the mutual trust among participants, there is very little chance that the requirement to reduce the funds expended for assessment while maintaining the capability to produce a less vulnerable and more survivable aircraft will be satisfied. This procedure must be a logically based method that removes all emotionalism and arbitrariness from the assessment process.

Categories for Cost Reduction in Vulnerability Assessment While Maintaining or Improving the Current Assessment Capabilities

Category 1—Increased Reliance on Analysis/Model ing. One method for reducing the costs of vulnerability assessment would be to rely more on the analysis/modeling methodology.[2] Based on its own review, the committee believes that there appears to be a sufficient start of a modeling capability and weapons effects and materials data base to warrant an increased dependence on analysis/modeling for future vulnerability assessments as an aid in design. However, the committee also believes that the current analytical methodology and supporting data bases are not yet sufficiently robust, correct, precise, and representative to permit a total dependence on this methodology. Much work needs to be accomplished in the model development and in the accumulation of weapons effects and material $P_{k/h}$ data bases. Consequently, much of live fire testing in the future should be oriented toward verifying the improved modeling procedures, extending the data base of weapons effects and material responses, and validating proposed design features and equipment for reducing vulnerability.

[1] Even though the funding for each system may be increased, the total expenditure for vulnerability assessment of all new systems may be less than the current level due to the smaller number of new systems in development.

[2] Relying more on analysis does not mean that the full-scale, full-up tests mandated by Congress should be discontinued. Instead, as the models are improved, the number of discovered weaknesses should decrease.

Category 2—Request a Waiver from the Live Fire Test (LFT) Law. The major factor in the cost of vulnerability assessment, which obviously provides the major opportunity for cost reduction, is the requirement for the full-scale, full-up Live Fire Test (LFT) program mandated by the LFT law. This law was written to prevent the neglect of vulnerability in the system design and was the result of the distrust among the Congress, OSD, and the Services examined in Chapter 4. The law offers a waiver from the Live Fire Tests. If this waiver is granted, considerable funds would be freed up to be used in vulnerability analyses and Live Fire Tests at the sub-scale level. Under the current Live Fire Test and Evaluation (LFT&E) Guidelines, there is no guidance as to what constitutes an unreasonably expensive and impractical Live Fire Test program and no instructions on which facts should be gathered together and used to make an unbiased, impartial, and logical waiver decision. Up to the present time, the Services have not applied for a waiver for any program, apparently because of the belief that their LFT&E programs were in compliance with the law and because they have been reluctant to take advantage of the waiver for fear of a stigma attaching itself to their program.

Many people, both in and out of the Services, are of the opinion that full-scale, full-up Live Fire Testing is unreasonably expensive and impractical for all aircraft, that there are more cost-effective ways to obtain a design with reduced vulnerability, and that this conclusion should be obvious to any one who has thought about it. Among the reasons given for this conclusion are the facts that the results come too late in the development cycle to influence the design, that expensive targets are at risk on every shot, that not enough data are obtained for statistical validity, that the wrong conclusion might be reached, and all the other disadvantages associated with Live Fire Testing presented in Chapter 2.

Others believe that full-scale LFT is unreasonably expensive and impractical only for some aircraft, such as large nontactical aircraft that are not likely to encounter threats to their survival, and is not unreasonably expensive and impractical for other aircraft, such as small tactical aircraft that are very likely to encounter threats to their survival; there are some who feel that LFT is not unreasonably expensive and impractical for any aircraft. They believe that only by testing the full-scale, full-up aircraft can certain design weaknesses be discovered, that it is never too late to change a design if it is inadequate, that a test schedule can be designed so that the full-scale target is not at risk for all shots, and all the other advantages associated with Live Fire Testing presented in Chapter 2. All of these opinions and beliefs on both sides of the fence are subjective; none are objective. No quantification of the benefits and risks associated with the combination of analyses and full-scale, full-up live fire tests compared to the benefits and risks associated with the combination of analyses and only sub-scale live fire testing has been attempted. Consequently, a decision to grant a waiver today will be based on subjective arguments.

In the future, a formal analytical procedure must be established for gathering the facts necessary to determine if the full-scale, full-up Live Fire Tests are unreasonably expensive and impractical with respect to the critical vulnerability issues and, if they are, what other assessments should be conducted in place of the complete system tests. With such a procedure in place, requesting and receiving a waiver, which should allow much of the vulnerability assessment budget to be transferred to other assessment tasks, will be an acceptable procedure. No stigma should be attached to the waiver because the procedure for obtaining a waiver is a rational one. Arbitrariness and emotionalism have been reduced or eliminated and replaced with objectivity.

Such a procedure, referred to here as a risk-benefit assessment, could be developed by using the principles of risk analysis. Risk analysis is a procedure that has been developed for projects that involve large capital outlays, significant new technology, uncertainty, and regulatory issues, such as the Live Fire Test law (Cooper and Chapman, 1987). This risk-benefit methodology will formalize and standardize the procedure for deciding if a waiver should be granted. A risk-benefit assessment would identify and quantify the risks and benefits associated with both conducting and not conducting full-scale, full-up testing. For example, the benefits (e.g., a reduction in vulnerability) associated with full-scale, full-up testing of a relatively inexpensive combat aircraft, many of which are very likely to be hit in combat, may outweigh the benefits (e.g., a reduction in expenditures) of not testing the full-scale, full-up aircraft. Not testing the full-scale, full-up aircraft puts too many aircraft at an unacceptable risk of destruction. On the other hand, the benefits associated with such tests on a relatively large support aircraft, very few of which will likely be hit in combat, may not outweigh the risks of not conducting the tests. The committee believes that such a methodology is essential to the process of requesting a waiver. If one is not developed, the arbitrary granting of a waiver will continue to be subject to considerable controversy, and attempts may be made to avoid all live fire testing.

Category 3—Consolidation of the Vulnerability Assess ment Infrastructure. The third category for reducing costs is to consolidate the various Service live fire test facilities and vulnerability analysis/modeling organizations. Although the committee did not review in detail this aspect of the vulnerability assessment activities and capabilities in each of the three Services, it believes that until the recent DoD budget downturn, there were sufficient programs to warrant the continuation of more-or-less similar Service live fire test capabilities. Continuous review within the Services and by

OSD has already led to reduction of duplicative underutilized capabilities. However, in the decades ahead, the expected requirements for the vulnerability testing of new Service equipment will probably fall below that level where a critical mass of broad-based facilities and knowledgeable staff can be maintained within any of the individual Services. If considerable cost savings could be achieved by consolidating the capabilities of these facilities, some additional form of consolidation beyond that currently contemplated should be considered. Furthermore, an overall reduction in the cost of test facilities does not automatically imply a reduction in capabilities at every facility. In fact, by downsizing or eliminating some facilities, others can increase in capabilities. Perhaps a national vulnerability test center could be created that would serve all Services, with significantly more capabilities than currently exist at any one facility today, at a cost below that in effect today.

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6 Conclusions and Recommendations

Conclusions

After reviewing the vulnerability assessment methodologies, evaluating the cost, effectiveness, and deficiencies of these methodologies, and reviewing the Live Fire Test (LFT) law and the Department of Defense (DoD) Live Fire Test & Evaluation (LFT&E) program, the committee has come to the following conclusions.

- *Conclusions Regarding the Live Fire Test Law & the DoD LFT&E Programs*

1. **The committee believes that the requirements in the Live Fire Test law have been interpreted in several ways and that these different interpretations have caused confusion and tension in the Live Fire Test programs. Nevertheless, the committee believes that the law is a valuable contribution to vulnerability assessment and to the design of survivable aircraft. Furthermore, it is satisfactory in its present form because of the waiver process.** The committee believes that verification of vulnerability by live fire testing is necessary and that this law ensures that verification.

2. **The committee believes that the 1987 congressional Live Fire Test law mandates live fire testing of full-scale, full-up aircraft, including on-board ordnance, unless a waiver is granted by the Secretary of Defense.** Therefore, any LFT&E program that has not received a waiver must conduct full-scale, full-up tests. This law was written because of Congress's belief that the Services were reluctant to fully test the vulnerability of their systems as they were being developed. The program that evoked the law was the Army's Bradley Armored Fighting Vehicle (AFV). The AFVs were being purchased before their vulnerability was fully known. Because of Congress's concern that a similar situation may exist for systems other than armored vehicles, it made the law applicable to all covered systems, including aircraft. According to the fiscal year (FY) 1988–1989 DoD Authorization Act Conference report, "The conferees intend that the Secretary of Defense implement this section (2366) in a manner which encourages the conduct of full-up vulnerability and lethality tests under realistic combat conditions, first at the sub-scale level as sub-scale systems are developed, and later at the full-scale level mandated in the legislation" (U.S. Congress, 1988).

3. **The committee believes that the 1988 Live Fire Test & Evaluation Guidelines and the 1989 Live Fire Test & Evaluation Planning Guide are not consistent with its interpretation of the LFT law.** The Navy and the Air Force have interpreted the 1988 LFT&E Guidelines to imply that full-scale, full-up tests are not required. Furthermore, the LFT&E policies presented to the committee do not consider such tests to be cost-effective, particularly if on-board ordnance is included. Consequently, neither Service has developed LFT&E programs that contain full-scale, full-up Live Fire Tests. However, both Services strongly support the conduct of sub-scale inert and full-up tests throughout the development process. The Army policy on LFT&E supports

a "building-block" approach consisting of component testing through full-scale, full-up system testing that satisfies the Live Fire Test law. The Army also strongly supports subscale testing. The emphasis of its LFT&E program is on sub-scale testing, with limited full-scale, full-up testing to confirm the results obtained from the sub-scale testing. However, the Army LFT&E program for the RAH-66 did not contain firm plans for testing a full-scale, full-up helicopter; the full-scale testing was going to be conducted only if the sub-scale test results showed it to be necessary.

4. **Because all three Services believe that an LFT&E program plan that contains only sub-scale testing is in compliance with the law as interpreted by the Office of the Secretary of Defense (OSD) 1988 LFT&E Guidelines, no waivers have been requested.** The OSD Live Fire Test Office has been unable to convince them that an LFT&E program that does not contain full-scale, full-up tests is not in compliance with the law. This conflict in interpretation is exacerbated by the fact that all of the current Service aircraft acquisition programs were under way at the time the law was written. Furthermore, the 1987 law made no provisions for funding these tests. It is difficult to make a major change, such as that required by the LFT law, in the middle of a test and evaluation (T&E) program without additional funding and schedule delays.

5. **The committee believes that a waiver is required to omit the full-scale, full-up tests.** Congress recognized that there may be weapon systems for which a full-scale, full-up test program is unreasonably expensive and impractical when it wrote the LFT law. Therefore, it included a provision for the Secretary of Defense to grant a waiver from such tests, provided a plan for alternatives to realistic vulnerability testing is prepared.

6. **The committee believes that there are aircraft for which a full-scale, full-up test program is unreasonably expensive and impractical, and that there are aircraft for which a full-scale, full-up test program is neither unreasonably expensive nor impractical.** Thus, there are programs for which a waiver is justified and programs for which a waiver is not justified. The committee also believes that in order to make the waiver process a viable alternative LFT path, the waiver process must be formalized. This formal process must contain a procedure that can identify when the full-scale, full-up tests are unreasonably expensive and impractical, and when they are not. This formal procedure would remove the threat of a stigma being associated with a waiver.

7. **The committee believes there should be no stigma attached to a waiver because the waiver is an acceptable alternative LFT&E path.** Apparently, the Services are opposed to requesting a waiver for any program because of the apprehension that their program will suffer in some manner as a result of the waiver. They believe that a stigma will be associated with such a request. The Committee holds the opinion that the waiver is an acceptable alternate LFT&E path. The waiver is accepted by Congress as reasonable when the full-scale, full-up tests are certified by the Secretary of Defense to be unreasonably expensive and impractical, and an alternative plan for realistic vulnerability testing is proposed. No approval by Congress is necessary if the certification is given before the system enters full-scale engineering development.

8. **A serious problem in both the analyses and the Joint Live Fire Testing (JLF) of aircraft has been the omission of on-board ordnance as a critical component.** It may be one of the largest contributors to vulnerability, particularly for aircraft that carry the ordnance internally. Alternatively, on-board ordnance may reduce the aircraft's vulnerability by shielding critical components. Analysis and testing must be conducted both with and without on-board ordnance in order to properly account for this materiel.

9. **The stated intent of the full-scale, full-up tests mandated by the Live Fire Test law is to aid in design by providing information on any weaknesses sufficiently early in the design process to allow the weaknesses to be corrected.** However, the Services and industry believe that the full-scale LFTs are conducted too late in the development cycle to have any impact on the design. The committee believes that if no major vulnerabilities are discovered in the full-scale tests, this information is of great value to the acquisition decision makers, and if a major vulnerability is discovered, it should be corrected. Other arguments against the full-scale, full-up tests are the facts that full-scale tests may be conducted on a nonrepresentative target and consume money that could be used for more of the earlier sub-scale tests. Counterarguments are that there is much to be learned from testing full-scale targets similar to the complete system and that sufficient funds need to be programmed for vulnerability testing. Vulnerability testing is an important T&E task in the acquisition process that has been significantly underfunded in the past. The committee believes there is a place for full-scale testing somewhere in the life of the aircraft. For those aircraft in which full-scale, full-up testing is unreasonably expensive and impractical during the full-scale development phase, later full-up tests on production aircraft that are no longer operational, such as done in the JLF program, can impact any subsequent modifications of the aircraft, as well as future aircraft designs.

10. **The implied intent of the Live Fire Test law is to force the consideration of vulnerability during the design process.** In the programs the committee examined, evidence of early considerations of vulnerability was obvious. Thus, even though full-scale live fire tests had not been planned or conducted, the law has had beneficial effects. The committee believes that additional motivation to consider vulnerability in the design can be obtained by placing realistic design

requirements on the maximum amount of vulnerability allowed at program inception. This requirement on the design, coupled with appropriate live fire testing and the Live Fire Test law, would better meet the intent of the LFT law and good DoD design practice.

11. **The lack of a definition of the specific threat munitions to be used in design and in Live Fire Testing has resulted in considerable controversy regarding which threat weapons to use in the Services' LFT programs.** Even the cursory review of threats posed to the systems examined by the committee leads to the conclusion that the design threats are probably not the only threats likely to be encountered in combat. Furthermore, other threats likely to be encountered in combat may be more lethal than the design threats. This is particularly true for the C-17, and possibly the RAH-66. Nevertheless, the acquisition process must include a threat projection and a design threat selection as an integral feature; it is both necessary and feasible. Without it there is no real discipline in the development process, and the testing process is free to test against whatever threat it chooses, relevant or not relevant. The ambiguity in the phrase "munitions likely to be encountered in combat" makes it possible to put a system in an unfavorable position based on Live Fire Tests against threats for which the system was not designed.[1] The committee believes that the design threat selected for some systems is not the major threat likely to be encountered when these systems are fielded. The design threat must be projected forward in time in order to prevent the system capabilities from falling behind the threat capabilities. There will be an understandable reluctance on the part of the intelligence community to make such a projection, but it can, and must, be done. Furthermore, the design threat must be reviewed at each milestone or other major decision point.

12. **Apparent separation of the oversight of vulnerability analysis from the oversight of live fire testing, both of which are part of the T&E process, has created a situation that is detrimental to the overall OSD vulnerability program.** The committee is concerned that the apparent organizational separation of OSD review of vulnerability analyses and Live Fire Testing that currently exists could substantially impede a coordinated program to determine vulnerability policy, facility requirements, and model and data base development. The problem with the separation of the two oversight responsibilities is that there can be undue emphasis placed on one or the other methodologies. By making one office responsible for both, a proper sense of perspective and a synergistic, long-term development program can be achieved. Furthermore, the committee believes that oversight to the analysis/modeling methodology is a T&E issue. The committee believes that the separation may be a major contributor of the current problem. By combining the oversight of the two methodologies, the proper emphasis can be given to each methodology. The committee believes that in the future DoD environment of prototypes and deferred production, overall vulnerability reduction in the design can best be served by the integration of analyses and supporting live fire tests.

- *Conclusions Regarding the Vulnerability Assessment Methodologies*

13. **Based upon its review of the two methodologies, the committee concludes that both vulnerability analysis and live fire testing, including the mandated Live Fire Testing, are essential in a mix peculiar to each aircraft development program.** The committee believes that a primary application for these methodologies should be to aid in the design of aircraft throughout the development process. The proper design and validation of the vulnerability of an aircraft require a well-planned application of both methodologies, including analyses, sub-scale testing, and full-scale testing. The importance of early sub-scale testing to the design cannot be overemphasized. The analytical and testing aspects of vulnerability design and assessment must be not conducted independently. A consistent oversight of the entire process is required. In general, analysis/modeling is all that is available in the very early design stages, whereas confirming sub-scale testing is essential in the middle and later design stages. The sub-scale tests also provide information for the data bases that support the analysis/modeling efforts. Full-scale testing, because it occurs late in the development cycle, is used to discover any weaknesses of the total and integrated design.

14. **The committee believes that both methodologies need to be improved and that these improvements should be mutually beneficial.** There appears to be a sufficient start of a modeling capability and weapons effects and materials data base to warrant an increased dependence on analysis/modeling for future vulnerability assessments as an aid in design. However, the committee also believes that the current analytical methodology and supporting data bases are not yet sufficiently robust, correct, precise, representative, and interactive to permit a total dependence on this methodology. Much work needs to be accomplished in the model development and in the accumulation of weapons effects and material $P_{k/h}$ data bases. Consequently, live fire testing in the future should be oriented toward verifying the improved modeling procedures, extending the data base of weapons effects and material responses, and validating proposed design features and equipment for reducing vulnerability. The analysis/modeling methodology requires additional support to continue the development of models that account for all of the phenomena and damage effects observed in live fire tests and in combat. In particular, additional realistic sub-scale testing, both inert and full-up,

[1]The Army's DIVAD gun system was a victim of this practice. It met the documented target requirements but failed against nondocumented targets.

is necessary in order to continue the development of the $P_{k/h}$ data base needed for improved models. This requires the development or improvement of test facilities that can perform such tests.

- *Conclusions Regarding the Vulnerability Programs for Aircraft*

15. **The vulnerability of currently fielded U.S. aircraft will become more important in the future.** Under present funding expectations, current aircraft are going to remain in the inventory for many more years. These aircraft are going to require product improvements because of the anticipated improvements in the weapons available to the Third World. One of these product improvements should be in the area of vulnerability reduction. No formal process currently exists to focus routinely on changes in the vulnerability of U.S. aircraft caused by the increase in weapon lethality. Such a routine vulnerability reduction review should be established. Vulnerability reduction as a means of achieving survivability enhancement is particularly important for existing aircraft that cannot take advantage of the new stealth technology.

16. **There is insufficient attention given to the requirement to design for vulnerability.** DoD Instruction (DoDI) 5000.2 includes survivability as a critical system characteristic and requires that survivability objectives be defined initially at Milestone I and finally at Milestone II. However, no specific reference to vulnerability is made in DoDI 5000.2. Vulnerability requirements should be identified as part of the survivability characteristics and incorporated in development contracts.

17. **The collection of actual combat data on the vulnerability of U.S. aircraft is not given proper emphasis.** Peacetime live fire testing, as well as computer-based modeling, would benefit greatly from a comparison with actual combat data. However, the procedures required to collect the proper data are not in place. In briefings provided to the committee, a list of lessons learned from the attempts to collect combat survivability data during Desert Storm, including the following: (1) existing official reporting systems were not adequate for capturing survivability data; (2) valuable records were destroyed because of established retention limits; (3) data questionnaires could not be completed adequately by field personnel on their own, (4) permission for data collectors to enter the theater was strongly resisted; and (5) arrangements to support the data collectors were not in place and were worked out with great difficulty for the few collection teams that did deploy.

- *Conclusions Regarding the Vulnerability Infrastructure*

18. **The process of designing and testing for vulnerability is extremely complex and would benefit from continuous input and oversight from a broad range of experts in the vulnerability community.** It is important that cooperation be established among the Services and between the Services and the Live Fire Test Office. The Joint Technical Coordinating Group on Aircraft Survivability (JTCG/AS) is an organization that has fostered this type of teamwork and inter-Service cooperation. However, it would be useful to have a standing board of vulnerability experts annually review the programs and plans with the Director, Test and Evaluation.

19. **The vulnerability community of the future most likely will become smaller in both the number of programs and the size of the infrastructure.** The committee recognizes the fact that the Department of Defense is going to reduce the size, funding, and number of aircraft programs, both new and product improvements. There most likely will be a corresponding drawdown in the related vulnerability assessment activities, both in analyses/modeling and in testing. The committee believes that this drawdown should be carried out very carefully to ensure that essential vulnerability assessment personnel, capabilities, and facilities are not lost in the process.

Recommendations

Based upon the results of the committee's study and the conclusions given above, the committee makes the following recommendations:

- *Recommendations Regarding the DoD Live Fire Test & Evaluation Program*

1. **The committee recommends that the Director, Test and Evaluation, issue Guidelines that replace the 1988 Live Fire Test & Evaluation Guidelines and that more clearly conform with the requirements for the full-scale, full-up tests mandated by the Live Fire Test law.** The binding force of the existing 1988 LFT&E Guidelines is unclear to the committee and to the Services, and should be replaced with a directive whose force is understood. The recommended directive should completely define the procedures and requirements for planning and conducting the Live Fire Test and Evaluation program for both sub-scale and full-scale tests. The directive should require the conduct of vulnerability tests under realistic combat conditions, first at the sub-scale level as sub-scale systems are developed, and later at the full-scale level mandated in the legislation. In addition, the directive should contain a formal process for requesting a waiver and the requirements for developing the alternatives to the realistic survivability testing of the full-scale, full-up system.

2. **The committee recommends that the Director, Test and Evaluation, formalize the waiver process by developing a risk-benefit assessment methodology that can be used uniformly to determine whether a full-scale, full-up test program for any particular aircraft is "unreasonably expensive and impractical." The methodology must also be applicable to the evaluation of the alternate Live Fire Test program for the sub-scale targets.** The process for

requesting a waiver, described in the DoD directive recommended above, should include a risk-benefit assessment methodology that quantifies the benefits associated with full-scale, full-up Live Fire Tests and the risks associated with waiving these tests. Such a methodology should give emphasis to early testing and, where possible, consider the desirability of Live Fire Testing of full-scale development prototypes and structural test models. Once the benefits and risks have been quantified, a decision can be made as to whether the full-scale, full-up tests are unreasonably expensive and impractical. The committee strongly believes that such a methodology is essential to the process of requesting a waiver.

3. **The committee recommends that the Secretary of Defense take measures to ensure (a) that the LFT&E Guidelines are properly enforced by requiring either that covered systems be subjected to full-scale, full-up testing or that a waiver be obtained; (b) that any waiver be fully justified; (c) that the waiver process be uniformly applied; and (d) that no stigma be attached to the use of the waiver process.** The committee believes that requesting a waiver is a legitimate procedure that must not adversely affect the program. The granting of a waiver does not eliminate all requirements for Live Fire Testing; an acceptable alternative realistic vulnerability assessment program must still be conducted. Furthermore, the availability of the risk-benefit methodology in recommendation will remove the arbitrary basis for granting a waiver currently in place and replace it with a logically based procedure used for other large-scale projects in which risk is involved.

4. **The committee recommends, for the full-scale, full-up Live Fire Tests, that the specific "likely to be encountered" munitions referred to in the Live Fire Test law be the weapon(s) specified in the requirements documentation for the system, projected forward to the time when the system is to be fielded. Furthermore, the threat should be reviewed and updated periodically at the milestone decision points to ensure that the specified design weapon(s) is representative of the major "likely to be encountered" threat(s) to the system.** There has been considerable disagreement on what "weapons likely to be encountered in combat" means and what weapons should be used for system design and in the Live Fire Tests. The design weapon(s) specified in the requirements documentation must be the best estimate of the primary threat, projected forward to the time the system is to be fielded. Selecting threats for the design that are less lethal than others likely to be encountered is unacceptable. Furthermore, this design threat must be the threat used to satisfy the system tests mandated by the Live Fire Test law. Without this linkage between a realistic design threat and the test threat, the test agency can arbitrarily select threats that may not meet the user's requirement for the system and that may jeopardize the future of the program. For the component and subsystem tests conducted during the design phase, the committee encourages the use of threats more lethal than the design threat when appropriate.

5. **The committee recommends that the Director, Test and Evaluation, expand the charter of the Live Fire Test and Evaluation program from its current oversight of those tests that are part of the congressionally mandated LFT program to include oversight of vulnerability assessment.** This new OSD program, known perhaps as the Vulnerability Test and Evaluation program, would have broad oversight of the evaluation of the vulnerability of the system design throughout the lifecycle of the system and would be the Services' advocate for the recommended integrated vulnerability evaluations at OSD milestone reviews. These evaluations would be accomplished using both analyses and live fire testing, including all of the Live Fire Testing mandated by the LFT law.

- *Recommendations Regarding the Vulnerability Assessment Methodologies*

6. **The committee recommends that both the analysis community and the live fire testing community routinely include on-board ordnance in their assessments.** A waiver to allow full-scale Live Fire Tests without on-board ordnance should be granted only after an examination of the results from alternate live fire tests of sub-scale components and their integration into analyses of the full-up aircraft carrying such ordnance.

7. **The committee recommends that the Secretary of Defense direct the multi-Service coordinated development and authorization for use of improved analytical vulnerability assessment models that are applicable to all military aircraft.** The committee believes it is inevitable that the emphasis given to, and reliance on, the models will increase in the future as budget limitations force greater reliance on prototyping. Consequently, it is imperative that the models be improved. The current JTCG/AS-approved models could form the basis for the new models. The 1987 General Accounting Office (GAO) study on Live Fire Testing provides many suggestions on how to improve these models.

8. **The committee recommends that a long-term live fire test program be funded in which realistic components, subsystems, and systems are specifically tested to develop a data base to support the analytical models.** The committee believes that improvements in the analyses/ models recommended above can be achieved only when properly supported by live fire testing programs and phenomenological investigations, and the committee is concerned that the present OSD Live Fire Test priorities do not adequately support this data base improvement. The funding for these tests should be provided by the Director, Test and Evaluation.

9. **The committee recommends that the Secretary of**

Defense (a) establish a program to examine the combat data collected from Desert Storm for "lessons learned" regarding the susceptibility and vulnerability of U.S. and allied aircraft; and (b) develop formal, institutionalized procedures for collecting data in future conflicts, for ensuring that the data collectors have access to the theater, and for permanently storing the data. The combat survivability data collection program should reflect the importance of collecting and preserving the data and should be coordinated among the three Services through a joint agency, such as the JTCG/AS.

- *Recommendations Regarding the Vulnerability Programs for Aircraft*

10. **Because of the expected service life extension of currently fielded U.S. military aircraft, the committee recommends that the Under Secretary of Defense, Acquisition establish a formal vulnerability assessment and reduction program for these aircraft.** This program should require that all product improvement or upgrade programs to existing aircraft include vulnerability reduction as a major goal of the program.

11. **The committee recommends (a) that a vulnerability assessment program be an integral part of every aircraft acquisition program; (b) that vulnerability assessment and evaluation be a specific item examined at each formal milestone review; and (c) that adequate funds be appropriated to the program.** The specific distribution of the funds between analysis/modeling and live fire testing for each program should be proposed by the individual Service, with OSD review and acceptance.

12. **The committee recommends that aircraft programs that become "prototype" programs, such as the RAH-66,** *not* be excluded from live fire testing. The RAH-66 COMANCHE helicopter has recently been changed to a "prototype" program. The committee is concerned that the RAH-66 might be developed as a prototype without adequate consideration or testing of its vulnerability. If the decision is made at a later date to go into production with the prototype, it will be too late to correct any design weaknesses.

13. **The committee recommends that specific vulnerability requirements on the design be a part of the survivability objectives defined at Milestones I and II.** These vulnerability requirements should be identified as part of the survivability characteristics and incorporated in the aircraft development contracts.

- *Recommendations Regarding the Vulnerability Infra structure*

14. **The committee recommends that the Director, Test and Evaluation, establish a permanent Senior Vulnerability Assessment Board comprised of senior Services' technical leaders, high-level OSD officials, and nationally recognized experts from industry and academia.** This board would be advisory to the Director, Test and Evaluation, and chartered to review annually the proposed vulnerability assessment and budgets of DoD and to review the vulnerability assessment programs on specific aircraft programs as the need arises. This board would be similar to the boards already formed for conduct of coordinated 6.1, 6.2, and 6.3a Tech Base programs in the DoD. The committee believes that such a board would provide the Services with a "before-the-fact" input into the establishment of vulnerability policy and would lead to a better acceptance of this policy.

15. **The committee recommends that studies be conducted to determine if the existing Army, Navy, and Air Force vulnerability analysis community, test facilities, and infrastructure can be reduced proportionally to the expected overall infrastructure reduction within DoD.** Project Reliance, the existing senior joint Services' R&D cooperation group, should be charged with conducting the studies of how best to accomplish a meaningful infrastructure reduction. As a part of this consolidation study, mechanisms for accommodating unique Service needs in consolidated testing facilities must be developed in order to allow multi-Service acceptance of data derived from singularly designated facilities. The committee believes that this drawdown should be carried out very carefully to ensure that essential vulnerability assessment personnel, capabilities, and facilities are not lost in the process.

The Future

The committee recommends to the Secretary of Defense that the broad issue of how to both design and test for vulnerability in an austere future be studied. Present concepts of analyses and live fire testing for vulnerability may not be adequate in a future of reduced budgets, fewer fielded aircraft, fewer program starts, smaller procurement numbers, and more "storage on the shelf" of technology capabilities with less time to react to emergencies. When such a study has been completed and an effective process has been developed for vulnerability design and validation, OSD should consult with Congress regarding revisions to the LFT law that reflect this new process.

Reference

- U.S. Congress, 1988. FY88–89 DoD Authorization Act Conference Report, Live-Fire Testing (Sec. 802).

APPENDIXES

A The Live Fire Test Legislation

FY87 DoD Authorization Act

SEC. 910. TESTING OF CERTAIN WEAPON SYSTEMS AND MUNITIONS

(a) Survivability and Lethality Testing and Operational Testing.

—(1) Chapter 139 of title 10, United States Code, is amended by adding after section 2365 (as added by section 909) the following new section:

2366. Major systems and munitions programs: survivability and lethality testing; operational testing

"(a) Requirements—The Secretary of Defense shall provide that—

"(1) a covered system may not proceed beyond low-rate initial production until realistic survivability testing of the system is completed in accordance with this section;

"(2) a major munition program or a missile program may not proceed beyond low-rate initial production until realistic lethality testing of the program is completed in accordance with this section; and

"(3) a major defense acquisition program may not proceed beyond low-rate initial production until initial operational test and evaluation of the program is completed in accordance with this section,

"(b) Test Guidelines—

"(1) Survivability and lethality tests required under subsection (a) shall be carried out sufficiently early in the development phase of the system or program to allow any design deficiency demonstrated by the testing to be corrected in the design of the system, munition, or missile before proceeding beyond low-rate initial production.

"(2) In the case of a major defense acquisition program, no person employed by the contractor for the system being tested may be involved in the conduct of the operational test and evaluation required under subsection (a).

"(3) The costs of all tests required under that subsection shall be paid from funds available for the system being tested.

"(c) Waiver Authority—The Secretary of Defense may waive the application of the survivability and lethality tests of this section to a covered system, munitions program, or missile program if the Secretary, before the system enters full-scale engineering development, certifies to Congress that live-fire testing of such system or program would be unreasonably expensive and impractical,

"(d) Waiver in Time of War or Mobilization—In time of war or mobilization, the President may suspend the operation of any provision of this section,

"(e) Definitions—In this section:

"(1) The term 'covered system' means a vehicle, weapon platform, or conventional weapon system—

"(A) that includes features designed to provide some degree of protection to users in combat; and

"(B) that is a major system within the meaningof that term in section 2303(5) of this title

"(2) The term 'major munitions program' means—

"(A) a munition program for which more than 1,000,000 rounds are planned to be acquired; or

"(B) a conventional munitions program that is a major system within the meaning of that term in section 2302(5) of this title.

"(3) The term 'major defense acquisition program' means—

"(A) a conventional weapons system that is a major system within the meaning of that term in section 2302(5) of this title; and

"(B) is designed for use in combat.

"(4) The term 'realistic survivability testing' means, in the case of a covered system, testing for vulnerability and survivability of the system in combat by firing munitions likely to be encountered in combat (or munitions with a capability similar to such munitions) at the system, configured for combat, with the primary emphasis on testing vulnerability with respect to potential user casualties and taking into equal consideration the operational requirements and combat performance of the system.

"(5) The term 'realistic lethality testing' means, in the case of a major munitions program or a missile program, testing for lethality by firing the munition or missile concerned at appropriate targets configured for combat.

"(6) The term 'configured for combat,' with respect to a weapon system, platform, or vehicle, means loaded or equipped with all dangerous materials (including all flammables and explosives) that would normally be on board in combat.

"(7) The term 'operational test and evaluation' has the meaning given that term in section 138(a)(2)(A) of this title."

—(2) The table of sections at the beginning of such chapter is amended by adding after the item relating to section 2365 (as added by section 909) the following new item:

"2366. Major systems and munitions programs: survivability and lethality testing; operational testing."

(b) Effective Date—Section 2366 of title 10, United States Code (as added by subsection (a)), shall apply with respect to any decision to proceed with a program beyond low-rate initial production that is made—

(1) after May 31, 1987, in the case of a decision referred to in subsection (a)(1) or (a)(2) of such section; or

(2) after the date of the enactment of this Act, in the case of a decision referred to in subsection (a)(3) of such section.

(c) Time for Submission of Annual Report of Director (OT&E)—Subsection (g)(1) of section 138 of such title [as redesignated by section 101 (a) of the Goldwater-Nichols Department of Defense Reorganization Act of 1986 (Public Law 99-433)] is amended by striking out "January 15"in the second sentence and all that follows through 'is prepared' and inserting in lieu thereof "10 days after the transmission of the budget for the next fiscal year under section 1105 of title 31."

FY88–89 DoD Authorization Act

SEC. 802 SURVIVABILITY AND LETHALITY TESTING OF MAJOR SYSTEMS

(a) Inclusion of Significant Product Improvement Programs—

The following material is section 2366 of title 10, United States Code, as amended by this section. The changes are in italic.

2366. Major systems and munitions programs: survivability and lethality testing; operational testing

"(a) Requirements—

"*(1)* The Secretary of Defense shall provide that—

"*(A)* a covered system may not proceed beyond low-rate initial production until realistic survivability testing of the system is completed in accordance with this section;

"*(B)* a major munition program or a missile program may not proceed beyond low-rate initial production until realistic lethality testing of the program is completed in accordance with this section; and

"*(C)* a major defense acquisition program may not proceed beyond low-rate initial production until initial operational test and evaluation of the program is completed in accordance with this section.

"(2) The Secretary of Defense shall provide that a covered product improvement program may not proceed beyond low-rate initial production until—

"(A) in the case of a product improvement to a covered system, realistic survivability testing is completed in accordance with this section; and

"(B) in the case of a product improvement to a major munitions program or a missile program, realistic lethality testing is completed in accordance with this section

"(b) Test Guidelines—

"(1) Survivability and lethality tests required under subsection (a) shall be carried out sufficiently early in the development phase of the system or program *(including a covered product improvement program)* to allow any design deficiency demonstrated by the testing to be corrected in the design of the system, munition, or missile *(or in the product modification or upgrade to the system, munition, or missile)* before proceeding beyond low-rate initial production.

"(2) In the case of a major defense acquisition program, no person employed by the contractor for the system being tested may be involved in the conduct of the operational test and evaluation required under subsection (a). *The limitation in the preceding sentence does not apply to the extent that the Secretary of Defense plans for persons employed by that contractor to be involved in the operation, maintenance, and support to the system being tested when the system is deployed in combat.*

"(3) The costs of all tests required under that subsection shall be paid from funds available for the system being tested.

"(c) Waiver Authority—

"*(1)* The Secretary of Defense may waive the application of the survivability and lethality tests of this section to a covered system, munitions program, *missile program, or covered product improvement program* if the Secretary, before the system enters full-scale engineering development, certifies to Congress that live-fire testing of such system or program would be unreasonably expensive and impractical. *The Secretary shall include with any such certification a report explaining how the Secretary plans to evaluate the survivability or the lethality of the system or program and assessing possible alternatives to realistic survivability testing of the system or program.*

"*(2)* In time of war or mobilization, the President may suspend the operation of any provision of this section.

"(d) Reporting to Congress—At the conclusion of survivability or lethality testing under subsection (a), the Secretary of Defense shall submit a report on the testing to the defense committees of congress (as defined in section 2362(e)(3) of this title).

"(e) Definitions—In this section:

"(1) The term 'covered system' means a vehicle, weapon platform, or conventional weapon system—

"(A) that includes features designed to provide some degree of protection to users in combat; and

"(B) that is a major system within the meaning of that term in section 2303(5) of this title

"(2) The term 'major munitions program' means—

"(A) a munition program for which more than 1,000,000 rounds are planned to be acquired; or

"(B) a conventional munitions program that is a major system within the meaning of that term in section 2302(5) of this title.

"(3) The term 'major defense acquisition program' means—

"(A) a conventional weapons system that is a major system within the meaning of that term in section 2302(5) of this title; and

"(B) is designed for use in combat.

"(4) The term 'realistic survivability testing' means, in the case of a covered system *(or a covered product improvement program for a covered system),* testing for vulnerability of the system in combat by firing munitions likely to be encountered in combat (or munitions with a capability similar to such munitions) at the system, configured for combat, with the primary emphasis on testing vulnerability with respect to potential user casualties and taking into equal consideration the *susceptibility to attack* and combat performance of the system.

"(5) The term 'realistic lethality testing' means, in the case of a major munitions program or a missile program *(or a covered product improvement program for such a program),* testing for lethality by firing the munition or missile concerned at appropriate targets configured for combat.

"(6) The term 'configured for combat,' with respect to a weapon system, platform, or vehicle, means loaded or equipped with all dangerous materials (including all flammables and explosives) that would normally be on board in combat.

"(7) The term 'operational test and evaluation' has the meaning given that term in section 138(a)(2)(A) of this title."

"(8) The term 'covered product improvement program' means a program under which—

"(A) a modification or upgrade will be made to a covered system which (as determined by the Secretary of Defense) is likely to affect significantly the survivability of such system; or

"(B) a modification or upgrade will be made to a major munitions program or a missile program which (as determined by the Secretary of Defense) is likely to affect significantly the lethality of the munition or missile produced under the program.

—(2) The table of sections at the beginning of such chapter is amended by adding after the item relating to section 2365 (as added by section 909) the following new item: "2366. Major systems and munitions programs: survivability and lethality testing; operational testing."

(b) Effective Date—Section 2366 of title 10, United States Code (as added by subsection (a)), shall apply with respect to any decision to proceed with a program beyond low-rate initial production that is made—

(1) after May 31, 1987, in the case of a decision referred to in subsection (a)(1) or (a)(2) of such section; or

(2) after the date of the enactment of this Act, in the case of a decision referred to in subsection (a)(3) of such section.

(c) Time for Submission of Annual Report of Director (OT&E)—Subsection (g)(l) of section 138 of such title [as redesignated by section 101 (a) of the Goldwater-Nichols Department of Defense Reorganization Act of 1986 (Public Law 99-433)] is amended by striking out "January 15" in the second sentence and all that follows through 'is prepared' and inserting in lieu thereof "10 days after the transmission of the budget for the next fiscal year under section 1105 of title 31."

B The General Accounting Office Study: Live Fire Testing; Evaluating DoD'S Programs

The General Accounting Office (GAO) study was conducted at the request of the Chairman, Seapower Subcommittee, House Armed Services Committee. The purpose of this study was to answer four questions: (1) What is the status of each system originally scheduled for live fire testing under the JLF program? (2) What has been the methodological quality of the test and evaluation process? (3) What are the advantages and limitations of full-up live fire testing, and how do other methods complement full-up testing? (4) How can live fire testing be improved? Of interest here are questions 2, 3, and 4. The conclusions presented by GAO for each of these three questions for the aircraft portion of its study are given below. The abbreviations DTPS and V/L stand for detailed test plans and vulnerability/lethality, respectively.

What Has Been the Methodological Quality of the Test and Evaluation Process?	
AIRCRAFT SPECIFIC Overall Planning	• In general, JLF/Aircraft planning has been well organized and thorough. • JLF/Aircraft established a formal process to designate test priorities; however, test priorities were actually driven by more pragmatic concerns (target availability and the need to ensure tri-service cooperation). • The principal constraint on realism is the inability to simulate flight conditions on the ground. Airflow is used to simulate airspeed but the coverage area is small, and other environmental factors affecting fire are not simulated at all.
Setting Test Objectives	• In FY85 and FY86 DTPS, JLF/Aircraft specified objectives congruent with the version of the program objectives they had established. These were generally feasible, with the exception of objectives related to determining probabilities.

Test Planning	• JLF/Aircraft test designs are generally congruent with test objectives, efficient with respect to conserving targets, and realistic given their limited objectives. • Some DTPS specified target requirements which exceeded the availability of those targets. • Testers are highly sensitive to test efficiency from an engineering standpoint, i.e., designing tests to conserve targets and prevent testing effects. • DTPS omit key information (e.g., data analysis plans) and are inconsistent in selection of threat velocities.
Implementation	• To the limited extent we could observe them, departures from test plans have generally been reasonable.
Analysis and Results	• Only one draft report has been completed—the F100 engine steady state fuel ingestion test. This report omitted key information, overstated the generalizability of results, and presented a highly questionable mode. Recommendations were congruent with results and sensitive to the likelihood of user acceptance.
GENERAL LFT ISSUES Conflict over Objectives	• The JLF charter did not define live fire testing well enough to give test designers a clear direction. • There have been several conflicting versions of the objectives of JLF and live fire testing in general. This appears to have in part resulted from the decision to task the JTCG's to implement JLF. • The conflict over objectives reflects underlying differences between the interests of proponents of full-up testing and those of modelers, resulting in largely incompatible approaches.
Availability of Targets	• The principal constraint faced by all JLF test officials is a lack of targets. This is in part a result of inadequate planning; there is no assigned responsibility to provide targets and related support to JLF. Consequently, test officials have had to spend a substantial portion of their time "selling" the program to skeptical service components. • The systems and components that JLF does receive are frequently in poor condition, yet JLF provided no funds for restoration. • JLF has been further hindered by competing governmental and non-governmental interests and negative attitudes toward destructive testing.
Statistical Validity	• In general, the sample sizes of JLF and related live fire testing have not been sufficient to produce statistically reliable results. This would be a problem even if the number of targets listed in the test plans could be obtained. • The statistical input to JLF has been minimal and had little effect, and the few applications of statistical analysis to live fire test data thus far are highly questionable. Several efforts are underway to make live fire tests more statistically interpretable. • As a substitute for statistical analysis, engineering judgment—which is heavily relied upon through the V/L process—has little scientific validity, being subject to individual and collective biases. • The most common form of vulnerability/lethality indicator—probability of kill given a hit $P_{K/H}$ has not been demonstrated to be reliable or valid.

Shot Selection	• Controversy over shot selection is to some degree a conflict between sampling efficiency and the desire to avoid bias at all costs. • Random sampling from combat distributions is a reasonable way to preclude intentional or inadvertent bias in shot selection. However, sampling from a uniform distribution avoids tester bias *and* biases in the combat data. • The shot selection problem will not be resolved by technical solutions alone. An interim solution might be to designate that some proportion of shots be selected judgmentally and others randomly, but ultimately, it appears impossible to agree on how to select live fire shots without first deciding on test objectives.
Human Effects	• JLF plans do not provide an adequate treatment of human effects. • The claims of some JLF officials that personnel vulnerability is well known are overstated. • Given the current state of the art, it is unlikely that JLF will produce precise estimates of casualties.
Incentive Structure	• DoD's incentive structure is not entirely conducive to realistic live fire testing.
COMPARISON PROGRAMS Past Programs	• The state of the art of live fire testing has improved since prior live fire testing programs, but some potentially solvable problems raised earlier have not been solved. For example, little progress has been made in the empirical validation of V/L estimates ($P_{K/H}$s)
SUMMARY CONCLUSION	• There is little completed testing on which to base a methodology evaluation. However, it is apparent that the technical capability to do full-up testing is not well developed. This is partly due to the historically low emphasis on live fire testing in the U.S.

What Are the Advantages and Limitations of Full-up Live Fire Testing? (Both Land and Air Targets)	
ADVANTAGES OF LIVE FIRE TESTING	• As the only method providing direct visual observation of the damage caused by a weapon/target interaction under realistic combat conditions, full-up live fire testing offers a unique advantage over all other methods of V/L assessment. • The descriptions of directly observable damage that full-up testing provides are regarded as highly beneficial by users. • Full-up testing has already demonstrated some value by producing several "surprises," i.e., results that were not predicted, and might not have been detected by other methods of testing or analysis.
LIMITATIONS OF LIVE FIRE TESTING High Cost	• The primary limitation of full-up, full-scale live fire testing is cost. On a per shot basis, it is considerably more expensive than inert or subscale testing, primarily due to the high cost and limited availability of targets. Testing and restoration costs are also higher, as are their associated time requirements. Nonetheless, live fire testing costs are a very small percentage of total program costs.
Limited Information	• Full-up testing potentially yields less information about damage mechanisms per shot than inert or subscale testing, primarily because catastrophic kills destroy the target and its components, along with much of the instrumentation used to record the damage. However, not all full-up shots result in catastrophic kills; such shots potentially yield more interpretable information than equivalent inert shots.
Limited Generalizability	• Full-up live fire test results typically are less easily generalized beyond the specific test conditions than inert or subscale testing. Full-up testing brings a larger number of variables into play that potentially affect outcomes, yet because full-up testing destroys targets, a smaller proportion of relevant test conditions can be examined.
Limited Redesign Opportunities	• The impact of live fire testing of developed systems is limited by "frozen" designs which are prohibitively expensive to change. For this reason, test officials see the main benefit of JLF and related programs as reducing vulnerability of future systems through lessons learned. This is not to suggest, however, that important V/L modifications are never feasible.

How Do Other Methods Complement Full-up Testing? (Both Land and Air Targets)	
Subscale Testing	• Subscale tests can support larger sample sizes than full-scale tests (whether full-up or inert), and are useful in bounding effects and providing input to models. Certain types of subscale testing are also useful for developing generic characterization of munitions effects. • Subscale tests can provide only indirect evidence of synergistic effects on realistic targets, which must be inferred through an unproven analytical process (modeling). Therefore, subscale testing can supplement full-up, full-scale testing but not substitute for it.
Inert Testing	• Inert testing of full-scale targets is superior to full-up testing in characterizing mechanical damage to individual components and in conserving both components and targets. • Catastrophic damage cannot be observed directly from shots on inert targets, and the standard method for inferring a K-kill underestimates its true likelihood. Like subscale tests, inert tests can provide only indirect evidence of effects on realistic (i.e., full-up) targets, inferred through models acknowledged to be weak on combustibles. Therefore, inert testing can supplement full-up, full-scale testing but not substitute for it.
Combat Data	• Analysis of combat data, if available, has several advantages over V/L testing: it provides greater realism, includes information above the level of vulnerability and lethality (e.g., aggregated survivability measures), and is considerably less expensive. • Combat data provide less scientific control than testing, are limited to munitions and systems that have been employed in combat, and offer no direct view of the damage process or the conditions of firing. Like subscale and inert testing, combat data can supplement full-up, full-scale testing but not substitute for it.
Modeling	• V/L models support the design and interpretation of live fire tests, and are potentially useful in extrapolating beyond test results. A unique advantage of models over testing is their applicability to systems not yet built. • Models are widely used in V/L assessment generally, but play a more central role in the design and interpretation of armor tests than in aircraft tests. • It does not appear that models have as yet played as great a role in the design of live fire tests as some statements by the modelers would indicate. • Current vulnerability models share numerous limitations; specifically, fire, explosion, multiple hits, ricochets, synergistic effects, and human effects are not yet well modeled. • Many of the most important mechanisms for producing casualties are poorly modeled, if at all. Without specific efforts to bring these casualty mechanisms into the modeling process, V/L models can be expected to be of limited utility in predicting casualty reduction. • Currently used V/L models are inadequately validated.

	• A large part of the modeling and model revision process is closed to outside analysis, including weapon designers. This has led to claims that modelers ignore or misspecify important V/L mechanisms, or that they are accountable only to their own community.• Claims that vulnerability models predict poorly are somewhat overstated, often referring to predictions from older models not expected to be used in live fire tests, and insufficient test or combat data to permit unqualified conclusions. Additionally, little attention has been paid to the different levels of accuracy required for different user's purposes.• The stochastic components introduced into vulnerability models after the Bradley Phase I tests provide an unknown level of protection from invalidation by test data.• There are no clearly specified mechanisms for using live fire test data to calibrate or revise models.

How Can Live Fire Testing Be Improved?	
TECHNICAL IMPROVEMENTS We suggest that DoD	1. Improve the estimation of human effects. Begin by replacing noninstrumented plywood mannequins with the instrumented anthropomorphic type. 2. Improve the reliability and validity of quantitative V/ L estimates. For example, interrater agreement studies could determine the magnitude of the reliability problem, and provide insights into reducing it. 3. Expand efforts to improve statistical validity, and establish guidelines for the statistical interpretation of small-sample live fire test results. 4. Concentrate model improvements on currently weak areas vital to casualty estimation—fire and explosion and human effects. 5. Establish guidelines for how models can better support the design and interpretation of live fire tests. 6. Establish guidelines for how live fire test results can be used in the revision of models. 7. Allow outside analysis into the modeling and modeling revision process, and provide better documentation of the process for use by those analysts. 8. Accumulate comparisons of model predictions with live fire test results over multiple tests in order to assess improvements in models, and make results available to outside analysts; also redo predictions of earlier live fire shots after models have been revised in order to validate improvements. 9. Require that detailed test plans include shotlines, munitions, sample sizes, predictions, analysis plans, rationales for decisions, and other critical information to enable proper oversight. Keeping plans unclassified should not be a justification for omitting key information. 10. Develop, modify, or procure instrumentation to yield more information from catastrophic shots. 11. Improve methods for simulating in-flight conditions; specifically altitude, altitude history, maneuver load, and slosh.
GENERAL IMPROVEMENTS We suggest that DoD	1. Avoid requiring unrealistic or incompatible objectives in future live fire tests (e.g., combat realism *and* model validation). 2. Consider total program costs in considerations of target costs, including for example the concept of a percentage set-aside for live fire testing. 3. Determine whether the live fire testing infrastructure is adequate to implement the legislation, or has to be expanded. For example, only two facilities in the U.S. currently have high speed airflow capability. 4. Determine to the extent possible the cost of live fire testing of new systems, and the relative costs and benefits of different approaches to live fire testing. Currently, there are claims and counter-claims about the costs of full-up vs. subscale tests, but little data. 5. Promote awareness of the benefits to be obtained from destructive testing to top level military and civilian officials. 6. With the legislation as a foundation, continue to strengthen incentives that support realistic live fire testing.

Recommendations to the Secretary of Defense	
In addition to the improvements noted elsewhere, there is a need to resolve current conflicts about the purpose of live fire tests and to make clear that the objective of reducing vulnerability and increasing lethality of U.S. systems is the primary emphasis of testing. Accordingly, we recommend that the Secretary of Defense	1. Conduct full-up tests of developing systems, first at the subscale level as subscale systems are developed, and later at the full-scale level mandated in the legislation. This will minimize vulnerability "surprises" at the full-scale level, at which time design changes are more difficult and costly. 2. Establish guidelines on the role live fire testing will play in procurement. 3. Establish guidelines on the objectives and conduct of live fire testing of new systems, with particular attention to clarifying what is to be expected from the services. 4. Ensure that the primary users' priorities drive the objectives of live fire tests. Modelers are secondary users. 5. Recent live fire legislation requires the services to provide targets for testing new systems, but there is no similar requirement for the fielded systems in JLF, where lack of targets has impeded testing. Accordingly, we recommend that the Secretary of Defense provide more support to JLF for obtaining targets.

References

U.S. General Accounting Office, 1987. Live Fire Testing, Evaluating DOD's Programs GAO/PEMD-87-17, Washington, D.C.: U.S. Government Printing Office.

C Board on Army Science and Technology Review of the Army's Assessment Methodology for Combat Vehicle Vulnerability to Anti-Armor Weapons

"During the combat-loaded, live-fire testing of the Bradley Fighting Vehicle System (BFVs) in 1986, differences of viewpoint arose among the Office of the Secretary of the Army, the Office of the Secretary of Defense, and the Congress regarding the role and conduct of live-ammunition firings and the interpretation of results in assessing the vulnerability of armored vehicles. To resolve these differences, the National Research Council's Board on Army Science and Technology was requested by Walter W.Hollis, Deputy Under Secretary of the Army (Operations Research), to examine and make recommendations concerning the Army's assessment of vulnerability of armored vehicles against anti-armor weapons. Accordingly, a Committee on the Review of Army Vulnerability Assessment Methods was formed to conduct the necessary studies" (NRC, 1989). The committee was tasked to conduct a review independently of the Army's in-house laboratories and contractors to (1) address issues that will help the Army define the objectives of its vulnerability assessment program, (2) define and analyze alternative ways to balance computation and live fire testing in reaching conclusions about vehicle vulnerability, (3) identify technical deficiencies where they exist, and (4) suggest alternatives for improvement as appropriate. The conclusions reached by the committee are given below (NRC, 1989).

1.	A clear distinction must be made between (a) live firings conducted against fully combat-loaded vehicles, and (b) live firings conducted against vehicle components, subsystems, and prototypes during the course of engineering design and development. The latter tests are intended to provide engineering information at minimum cost and expenditure of resources. Combat-loaded, live-fire tests are for a different purpose, namely, to provide an independent check on the general success of the design and development process with regard to the vulnerability of the vehicle to enemy fire with threat weapons likely to be encountered on the battlefield.
2.	The preparation of a ROC (Required Operational Capability) precedes the initiation of design and development of a new combat vehicle. All too often, the ROC underestimates the importance of emerging armor/anti-armor technologies. The result is that by the time the vehicle is ready to

	be fielded, the threat environment is more severe and perhaps even different in nature than that called for in the ROC. It is recommended that, as part of the design process, future designs allow for enhancement of ballistic protection during the vehicle's lifetime.
3.	It is important that vulnerability assessments of combat vehicles be as dependable as possible. Not only are they important in defining the hazards to crew and vehicle, they are essential in assessing vehicle survivability on the battlefield, as well as for many other important Army planning purposes. A complete description of the vulnerability of a vehicle is, however, a complex task. For each attacking weapon and warhead combination, the damage due to attack from all directions and at all ranges must be taken into account. To arrive at vulnerability assessments, therefore, the only recourse is to make use of mathematical models capable of being executed on a high-speed computer, so that the damage due to large numbers of attacks can be assembled. Such models must be supported by an adequate base of data obtained experimentally by firings against armor samples, components, and subsystems.
4.	Vulnerability models designed to at least two levels of comprehensiveness are required. For preliminary design purposes, a model is needed which provides relatively rapid estimates at an accuracy level sufficient to compare the relative advantages of competing concepts. At the opposite end of the spectrum, a more detailed model is needed for assessing the vulnerability of a design with best achievable accuracy. The committee has concluded that suitable models for addressing these needs are not currently available and further development is needed.
5.	The committee has reviewed the current BRL approach to more accurate model building. It is, in essence, based on the belief that better accuracy will result from models of increasing detail, i.e., models that incorporate the vehicle exterior and interior geometry in relatively minute detail and that trace behind-armor damage virtually fragment by fragment. It is the committee's opinion that such an approach is not justified because of the inability to forecast with precision the characteristics and performance of ever-evolving threat weapons, and because of the inherently stochastic nature of penetration and behind-armor damage mechanisms. The trend toward increasingly detailed models is not a productive direction and the committee suggests that BRL reconsider its current direction for model design. A lesser degree of detail, using an approach based on a more generic assessment of the vulnerability of major components, would still provide valid vulnerability estimates with reduced data requirements and shorter computational times.
6.	BRL is the Army's principal laboratory responsible for armor/anti-armor technology. Based on a review of the BRL data, encompassing unclassified as well as classified data, but not including sensitive compartmented information, it is evident that there is a significant lack of experimental information, particularly concerning the more sophisticated armor designs and anti-armor weapons represented representative of modern practice. A principal reason appears to be that in recent years the experimental work has tended to be conducted on an *ad hoc* basis for different development programs. The experimental research program that has been instituted to establish an integrated data base for use as a reference source for future designs and as a guide for formulating further research efforts has been neither coordinated nor comprehensive. The inadequacy of this experimental program is the largest single deficiency contributing to uncertainty in our current vulnerability estimates.
7.	One purpose of this study is to better define the role of live-fire tests against fully combat-loaded prototype vehicles. It is important, therefore, to carefully delineate what functions these tests fulfill and, equally important, what they do *not* add to the process of vulnerability assessment. Specifically, combat-loaded, live-fire tests do not contribute significantly to the assessment of vulnerability in a form needed to support subsequent survivability assessments and for other necessary Army uses. The quantity of data gathered by such tests is too limited in scope and depth to be statistically significant.
8.	Combat-loaded, live-fire tests will accomplish the following, provided the test series consists of randomly selected firings with shotlines selected by the procedure outlined in Chapter 5 or its equivalent:
	• During the interval between the start of the development and design process and the live-fire tests, the threat environment on the battlefield may have changed appreciably. Since the combat-loaded, live-fire tests are to be conducted with weapons constituting updated threat weapons, they provide some assessment of the vehicle performance with regard to vulnerability to weapons not incorporated in the ROC document. • The tests are conducted in an environment of high visibility within the Department of Defense,

	Congress, and, save for the limitations of classified data, the public at large. Knowing that the test results will be carefully observed during the approval process leading to large-scale production, the program manager and his staff will be motivated to ensure that adequate weight is given to vulnerability considerations throughout the design process. • The tests may uncover vulnerabilities that have not been anticipated and that represent design deficiencies. Experience to date has in fact shown that valuable information of this kind has emerged from combat-loaded tests. • The results of combat-loaded, live-fire tests should not by themselves be construed as a basis for approval or disapproval of the transition to full-scale production. Many additional factors must be taken into account in arriving at this decision.
9.	Combat-loaded, live-fire tests do not provide information of significant value for validating vulnerability models, although they may disclose vulnerabilities which have been overlooked in model formulations. The committee recommends that such tests should not be conducted with this purpose in mind.
10.	Experience to date with combat-loaded, live-fire tests has indicated that they do produce positive findings helpful in reducing vehicle vulnerability. Many of the findings, however, could have been anticipated by more careful engineering testing conducted earlier and with substantially lower expenditure of resources.
11.	To improve future design practices, and particularly to help less experienced designers without extensive "corporate" experience, the committee recommends preparation of a manual of good design practices for combat vehicles to reduce the vulnerability to penetrating rounds. Reflecting a compilation of sound design rules, as well as practices to be avoided, such a manual will help to prevent future mistakes that might result in increased vulnerability.

Reference

• National Research Council (NRC), Committee on a Review of Army Vulnerability Assessment Methods, 1989. Armored Combat Vehicle Vulnerability to Anti-Armor Weapons, A Review of the Army's Assessment Methodology, Board on Army Science and Technology, Commission on Engineering and Technical Systems, Washington, D.C.: National Academy Press.

D Preliminary Recommendations from the JTCG/AS $P_{k/h}$ Workshop

Preliminary Recommendations from the Fuel System Working Panel of the 1991 JTCG/AS $P_{k/h}$ Workshop:

- Develop the Ullage Explosion Model to calculate ullage vulnerability to explosions from API, HE, and fragment impacts.
- Reexamine the BRL Void Space Fire data to determine that the probabilities for fire due to fragments and 23-millimeter HE projectiles are consistent with other data.
- Modify the COVART model to handle the simultaneous analysis of thermal and mechanical damage to components.
- Determine how the BRL void space fire probabilities need to be modified for JP-5 and JP-8 fuel.
- Determine how the BRL void space fire probabilities will change from open to closed void spaces.
- Determine the probability of fire initiation due to "mixed functioning" of the incendiaries.
- Develop a methodology to determine the probability of fires due to secondary ignition sources.
- Develop data curves for the vulnerability of fuel system hardware components.
- Determine how the BRL void space fire probabilities will change if the "striker plate" consists of composite materials.
- Perform a test program to determine the probability of fire initiation due to a "mixed functioning" of the incendiaries.
- Determine if the burn characteristics of composite materials are sufficiently different to warrant a change in the BRL void space probability numbers.
- Determine how the altitude will affect the probability of fire initiation, the probability that fires will sustain, and the damage that might result from sustained fires.
- Determine and quantify the vulnerability of fuel system components due to directed energy weapons.

The following findings of the eight working panels are taken from a preliminary copy of a briefing being prepared to be given to the JTCG/AS Central Office and to OSD. This briefing material was furnished by Gerald Bennett, ASD/XRM, WPAFB.

Fuel System Panel

- Empirically based fuel/fire/explosion $P_{k/h}$ data exist that are
  1. more than 15 years old,
  2. for metallic structures only,
  3. for sea level only.
- No traceable fuel system hardware $P_{k/h}$ data exist.

Flight Controls and Hydraulics Panel

- Actuators
  1. Analyses are only on older (1950s) designs.
  2. Sparse test data do not match actuators analyzed.
  3. New designs and technologies have no analyses or tests.

- Hydraulic fluid reservoirs, and accumulators
  1. One set of experimentally validated fluid $P_{k/h}$ data exists.
  2. Other components have no documented test data or analyses.

- Cables, bellcranks, and mechanical components
  1. Analytic models and some $P_{k/h}$ data exist.
  2. Selective tests needed to validate analyses.

Crew Station Panel

• Traceable crew $P_{k/h}$ data are available for fragments and projectiles (toxic gases, overpressure, and burns not considered).
• JLF crew station tests will provide test data support.
• Ejection seat pyrotechnic $P_{k/h}$ data are not available.
• Cockpit controls and displays $P_{k/h}$ data are not available.
• Liquid oxygen (LOX) converter $P_{k/h}$ estimates are of low confidence.
• Windscreen/canopy $P_{k/h}$ data developed.
• For the on-board oxygen generating system (OBOGS), on-board inert gas generating system (OBIGGS), flat panel displays, there are no $P_{k/h}$ or test data.

Engines and Accessories Panel

• $P_{k/h}$ data have kept pace with new designs.
• Test data form important $P_{k/h}$ input.
• Large analysis data base exists on obsolete and current designs.
• Confidence level is high for older/current designs (exceptions: large engines, fan sections, and small unguided-aerial-vehicle engines).
• Fuel ingestion analytical technique is available.

Stores, Ammunition, and Flares Panel

- Bombs and missile warheads
  1. Results are design and threat specific.
  2. Analyses predict burn and prompt reaction thresholds.
  3. Intermediate zone requires added tests.

- Propellant and rocket motors
  1. Results are design and threat specific.
  2. Analyses predict burn and prompt reaction thresholds.
  3. Complex propellants require added tests.

• Flares, ammunition drums, and ammunition boxes: limited test data and $P_{k/h}$ estimates

Electrical and Avionics Panel

• Most work (test and analysis) dates from 1983 or before.
• Component design technologies date from the 1950s and 1960s.
• A large test base exists, but for ballistic resistance (V_{50}) development.
• More than 90% of the tests/analyses are for fragments.
• No $P_{k/h}$ estimates exist for many common components.
• Techniques are adequate for penetration related kill criteria.
• $P_{k/h}$ for some lethal mechanisms are only obtainable from tests.
• Avionics and electronics are flight critical for many new aircraft designs.

Structures, Landing Gear, and Armor Panel

- Structure
  1. Analysis/data are not easily mapped into vulnerability analyses.
  2. Models are largely for skin panels and simple structure.

- Landing gear
  1. Few test/analysis data exist (not flight critical).
  2. Some data are available for Army truck tires.

- Armor
  1. Data are experimentally derived, so confidence levels are high.
  2. Most data are for projectiles and current materials.

Helicopter Unique Components Panel

• Analysis techniques are valid for metal rotor blades.
• Component $P_{k/h}$ data are mostly for fragments and armor-piercing projectiles.
• Flight controls can use aircraft techniques and data.
• Tail boom structural analysis capability is poor.
• Little recent test/analysis has been done for $P_{k/h}$ development.
• Extensive tests are needed for failure at specified conditions.

ACRONYMS

AAA	anti-aircraft artillery
AFV	armored fighting vehicle
AP	armor-piercing projectile
API	armor-piercing projectile with incendiaries
BAST	Board on Army Science and Technology
BRL	Ballistic Research Laboratory
BRL-CAD	Ballistic Research Laboratory Computer-Aided Design program
COVART	Computation of Vulnerable Area and Repair Time
DDDR&E (T&E)/TWP	Deputy Director, Defense Research and Engineering (Test and Evaluation)/Tactical Warfare Programs
DEM/VAL	demonstration and validation
DoD	Department of Defense
DoDI	Department of Defense Instruction
DT	developmental tests
DT&E	development test and evaluation
EMD	engineering, manufacturing and development
FEBA	Forward Edge of the Battle Area
FMEA	Failure Mode and Effects Analysis
FTA	Fault Tree Analysis
FY	fiscal year
GAO	U.S. General Accounting Office
HE	high explosive
HEI	high explosive with incendiaries
HEIVAM	HEI Vulnerability Assessment Model
HEVART	High Explosive Vulnerable Area and Repair Time
IDA	Institute for Defense Analyses

IOT&E	initial operational test and evaluation
JLF	Joint Live Fire
JSEM	Joint Services Endgame Model
JTCG/AS	Joint Technical Coordinating Group on Aircraft Survivability
JTCG/ME	Joint Technical Coordinating Group for Munitions Effectiveness
LFT	Live Fire Test
LFT&E	Live Fire Test and Evaluation
LOX	liquid oxygen
LRIP	low-rate initial production
MECA	Modular Endgame Computer Assessment
N/A	not applicable
NRC	National Research Council
OBIGGS	on-board inert gas-generating system
OBOGS	on-board oxygen-generating system
ORD	Operational Requirements Document
OSD	Office of the Secretary of Defense
PM	Program Manager
SAM	surface-to-air-missile
SQuASH	Stochastic Qualitative Analysis of System Hierarchies
STAR	System Threat Assessment Report
SURVIAC	Survivability/Vulnerability Information and Analysis Center
T&E	test and evaluation
TBD	to be determined
TEC	Test and Evaluation Committee
TEMP	Test and Evaluation Master Plan
WPAFB	Wright-Patterson Air Force Base
WWII	World War II