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Historical Perspectives on Vulnerability/Lethality Analysis

by J. Terrence Klopcic
and Harry L. Reed
EDITORS

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Historical Perspectives on Vulnerability/Lethality Analysis

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Abstract

Commencing in the early 1990s, Mr. James O'Bryon of the Office of the Secretary of Defense (OSD), Operational Testing and Evaluation (OT&E), charged the Vulnerability/Lethality Division (VLD) of what is now the U.S. Army Research Laboratory (ARL) to capture in a hard-bound book the art/science of vulnerability and lethality (V/L) analysis. This work has since expanded into the publication of a series of volumes, each dedicated to a particular portion of the V/L community—ground mobile targets, hardened fixed targets, aircraft, etc.

As a first step in this mammoth effort, a number of articles were commissioned to be gathered from some of the giants in the history of V/L analysis. These articles gave a foundation from which the writing of the first of the series commenced and are collected in this report with the hope that future generations of V/L analysts will find in them inspiration for their own accomplishments.

Preface

One morning in June of 1990, I found myself sitting in a conference room in La Jolla, CA, waiting to brief the JASONs, a group of approximately 60 leading academics from across the nation who consult annually on a myriad of defense-related issues. Mr. Dick Vitali, Acting Director of the U.S. Army Laboratory Command (LABCOM), had requested a review of the U.S. Army Ballistic Research Laboratory (BRL) vulnerability/lethality (V/L) program by the JASONs. Such an examination was timely as it had been barely 5 years since the inception of the Live Fire legislation. A number of weapon platforms had been tested, and significant variances had been observed between test and model outcomes. Many practices and strategies were due a reexamination. As I awaited my opportunity to brief the committee, Mr. Art Stein was presenting material, some of it gathered as much as 50 years ago. As I listened to the presentation, I was as much struck by the human and historical elements as the quality and breadth of the technical message. I decided right then that it was important to bring Art Stein and his message to BRL, particularly for the younger people to experience.

In the fall of 1992, BRL was reformed and merged into the U.S. Army Research Laboratory (ARL). To celebrate the many contributions made in the field of V/L, we invited Art Stein, Dave Hardison, and a host of senior analysts back to the lab to review our recent accomplishments and to have them discuss key activities of the past. This volume reproduces a number of those presentations from "Vulnerability Day."

A separate project initiated by Mr. James F. O'Bryon, Director, Live Fire Testing, Office of the Secretary of Defense, has focused on the development of a V/L Handbook. Early on, we expected to present a number of articles discussing early vulnerability history. As that document has evolved in other directions, it seemed valuable and prudent to make these hitherto-unpublished manuscripts available to the community at large.

Particular thanks goes to Dr. J. Terrence Klopcic and Mr. Harry L. Reed, Jr., for bringing these historical threads to these pages.

PAUL H. DEITZ, Technical Director
U.S. Army Materiel Systems Analysis Activity
(formerly Chief of ARL's Vulnerability/Lethality
Division, October 1990 to November 1997)

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Table of Contents

Page

Preface ... iii

1. Introduction ... 1

2. Development of the Ship Design Vulnerability Analysis Process
Robert K. Barr ... 3

3. On the History of Vulnerability/Lethality Analysis
Roland G. Bernier ... 12

4. Reflections Related to Assessment of the Vulnerability of Armored Combat Vehicles and the Lethality of Antiarmor Munitions: The Last Two-Thirds of the First Fifteen Years [A Meandering Tale of Unverified Remembrances of an Aged Analyst, Once of BRL]
Davidson C. Hardison ... 20

5. Two Turning Points and a Continuing Improvement
Richard E. Kinsler ... 36

6. Milestones in Modeling the Vulnerability of Military Personnel to Fragmenting Munitions
William J. Sacco and Wayne S. Copes ... 42

7. Excerpts on Vulnerability
Joseph Sperrazza ... 55

8. Historical Vignette on Vulnerability/Lethality Analysis
Arthur Stein ... 76

9. Changes in Vulnerability/Lethality Analysis Over the Years
Stewart W. Turner ... 121

10. The Best and Worst of Times
Lawrence G. Ullyatt ... 128

Distribution List ... 137

Report Documentation Page ... 153

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1. Introduction

Commencing in the early 1990s, Mr. James O'Bryon of the Office of the Secretary of Defense (OSD), Operational Testing and Evaluation (OT&E), charged the Vulnerability/Lethality Division (VLD) of what is now the U.S. Army Research Laboratory (ARL)* to capture in a hard-bound book the art/science of vulnerability and lethality (V/L) analysis. This work has since expanded into the publication of a series of volumes, each dedicated to a particular portion of the V/L community—ground mobile targets, hardened fixed targets, aircraft, etc.

As a first step in this mammoth effort, a number of articles were commissioned to be gathered from some of the giants in the history of V/L analysis. These articles gave a foundation from which the writing of the first of the series commenced. In addition, the editors of this report were drawn to a chapter in a report written by Dr. Joseph Sperrazza and compiled by Mr. Alvin Hoffman.†

It was noted that these historical articles were irreplaceable treasures in themselves. These writings include anecdotes, lessons learned, and rules of thumb derived from experiences that will never again be available to the V/L community. Admittedly, many of the anecdotes have been overcome by events, the lessons made inapplicable by changes in the field, and the rules replaced by sophisticated algorithms supported by computing power that was incomprehensible at the time the rules were formulated. However, as has been so often remarked, "You don't know where you're going if you don't know where you've been."

For this reason, we have assembled the writings of nine individuals (given in alphabetical order) into this report. Except for that by David Hardison, these vignettes were obtained from the authors by TASC under Subtask 5, Contract No. MDA 908-88-G-9056 (J6360-411). Hardison's reflections

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* The U.S. Army Ballistic Research Laboratory was deactivated on 30 September 1992 and subsequently became a part of the U.S. Army Research Laboratory (ARL) on 1 October 1992.

† Sperrazza, J., and A. J. Hoffman. "An Historical Perspective on Weapons Performance." U.S. Army Materiel Systems Analysis Activity, Aberdeen Proving Ground, MD, June 1997.

were recorded in the Proceedings of Vulnerability Day, which was held on 25 September 1992, at the U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground (APG), MD.

Care has been taken to limit editorial alteration so that the writings retain as much of their original tone as possible.

Hopefully, future generations of V/L analysts will find in these articles inspiration for their own accomplishments.

2. Development of the Ship Design Vulnerability Analysis Process

by Robert K. Barr

The development of a ship design vulnerability analysis process has endured varying elements of resistance from within the ship design community. This resistance has had the effect of retarding development of a single focus analysis process and resulted in a lack of adequate organization relative to the many diverse modeling capabilities which support ship design analysis. The impact of the resistance has been the increased attention regarding design test and evaluation of ship acquisition by the Office of the Secretary of Defense (OSD) and Congress. This attention has effectively increased OSD's oversight of the ship design community's vulnerability assessment capabilities.

March 3, 1983, was a unique period to initiate my first tour in the Pentagon. Based on my 32 yr of experience in damage control, engineering, and operations, I had been asked to accept a position as the Chemical Warfare Defense and Ship Survivability Officer with the Office of Deputy CNO for Surface Warfare. The primary focus of that office was to support research and development leading to acquisition of personnel defense equipment and detection tools for chemical agents. A secondary responsibility was the management of a seven-ship class survivability improvement backfit program. This program supported vulnerability reduction primarily for "cheap kill" fragmentation protection and fire spread. The seven ship classes included cruisers, destroyers, and major amphibious units totaling 47 ships. This effort was the culmination of several years of accidents and incidents which had received congressional attention regarding major unit readiness reductions in what some considered should have had less devastating and fiscally costly results. This was also the period the results of the British Falkland Islands campaign was impacting the U.S. Navy's ship design community. The Falkland's issue was ship loss due to firespread, including personnel injuries and deaths from Exocet missiles and their unexpended fuel burn within the impacted ship. It became obvious to me there were more questions regarding the focus and needed improvements in the ship survivability design arena than there were answers. This conclusion was soon confirmed in April and May 1983 by two separate directives to me calling for CNBO Executive Board (CEB) reviews of the Passive Fire Safety (Protection) Program for Ship Design and the entire Ship Survivability Program.

There were no formal programs for either passive fire protection or ship survivability, which meant programs must be established in order to comply with CEB requirements. The programs were established and presented to the CEB in December 1983 and February 1984, respectively, and each was approved with some additional direction on the overall ship survivability program. That direction was to plan and implement a survivability backfit program to correct all existing ship design deficiencies within a 2-yr period. A related objective of the overall ship survivability program was to establish a military worth assessment process to analyze the value of any given survivability improvement toward warfighting capability. An additional outcome of the CEB involved the adequacy and intent of the U.S. Navy's policy statement regarding Public Law 95-485 titled Navy Shipbuilding Policy. At that time, the Navy's 1979 directive simply restated the 1978 Public Law, but lacked direction or responsibility for implementation. It was concluded the directive lacked viable meaning regarding the Navy's intent. Interestingly enough, these three key elements, coming out of the CEB's of fiscal year 1984, continue to play a major role relative to the need or design analysis in support of fiscally sound vulnerability reduction.

The proposal to program the two-year implementation of correction of existing survivability design deficiencies came from the Chief of the Material Command. The program planning effort to comply with the CEB direction took 1 yr to complete and only included those ships that would have 10 yr remaining service life following the alteration installation. The planning included the man-day work load involved, the number of repair yards available, and the operating schedule for each ship. When completed, the projected cost for the entire program was $5.8 billion, and the implementation schedule exceeded 5 yr. It became obvious that Navy's budget would support implementation of only the highest priority alterations that provided proven payoff value based on experience. The paramount conclusion reached from the program analysis was that any survivability alteration to an operating ship design has a cost ratio of 5:1 over implementation in the original construction cost. The affordability issue is a turning point relative to providing an analysis of early implementation of survivability into original ship design.

The idea for a miliary worth assessment was a CEB survivability program recommendation that grew out of the Naval Sea Systems Command. This idea was intended to utilize the combined analysis capability of cost and vulnerability assessment computers to determine the most viable survivability improvements toward maintenance of material readiness supporting warfighting capability. The objective was to evaluate a baseline ship design and several improvements over that baseline to identify the most cost-effective means to reduce readiness vulnerability over a range of one, two, or three weapon impacts. The assessment analysis would actually evaluate the baseline ship and two to three complete ship designs with increasing survivability improvements to establish a dollar cost curve relative to the number of hits absorbed while maintaining an acceptable degree of warfighting capability.

The military worth study effort to develop an analysis program was carried out by the Center for Naval Analysis (CNA) in 1984 under the direction of a CNO Flag Officer Review Board. CNA utilized an existing ship design, the DD 993, with several potential improvements in survivability. The analyst took advantage of the U.S. Navy's ship vulnerability model and the Naval Sea System Command's new ship design cost analysis computer in combination with CNA's computer to develop and prove a military worth program for analysis of the value of vulnerability reduction efforts. The Flag Board was progressively briefed during the development, and upon completion of the study effort approved the concept. DCNO Surface Ships directed and funded development of the assessment process within the Systems Command in fiscal year 1985. While the CNO/CNA effort was a turning point supporting vulnerability reduction analysis and proving the capability, the ship design communities' resistance to this effort was sufficient that the Systems Command did not expend the funds to develop and implement the program.

In view of the CNO level criticism regarding the Navy's shipbuilding policy directive supporting Public Law 95-485, I initiated action to rewrite the directive to support implementation direction and assign specific responsibilities. The initial action occurred in July 1984. That action involved the ship design community including experts in vulnerability reduction from Naval Sea Systems Command. A consensus on implementation needs and responsibilities proved very difficult because of concerns over everything from classification to details regarding potential for variances on survivability design specifications. Following development of several strawman drafts of the instruction to meet the concerns of the participants, it became obvious the survivability and ship design communities were not going to reach an agreeable conclusion in support of any policy. In the meantime, other more detailed directives were being developed to support passive fire protection, shock hardening, and damage control and firefighting. Unfortunately, the products of these directives would not be subject to any overall assessment process or implementation policy. In 1987, I determined the CNO policy statement on survivability was essential and required a new approach. The approach involved developing a CNO level policy with responsibility, levels of survivability performance by ship class, and identification of specified weapons effects requiring design consideration for vulnerability reduction. This directive was signed and implemented in September 1988 as OPNAVINST 9070.1 titled Survivability Policy for Surface Ships of the U.S. Navy. While the directive was reviewed and approved by the Naval Sea Systems Command, prior to implementation, and requires that command provide the focus for comprehensive development, assessment, and implementation of Surface Ship Survivability, to date, no NAVSEA directive has been implemented to meet that responsibility. Although no implementation directive has been developed at the NAVSEA level, the OPNAV 9070.1 Instruction has been utilized to provide the basis for quantification of the vulnerability analysis in ship design.

The increased emphasis on vulnerability reduction in ship design over the past 10 yr has resulted in some positive attempts to improve the analysis capability. The military worth study of 1984 did result in an attempt to utilize the SVM, previously used as a ship design tool, to take on an increased vulnerability analysis role. This effort was further aided by the development of the fast ship vulnerability model (Fast SVM) to reduce the analysis time. In the latter 1980s, the development of a computer support shipboard survivability management approach, titled the Integrated Survivability Management System (SMS), also supported the analysis capability. The ISMS development led to a refinement of the Fast SVM to improve real-time system analysis that resulted in a program suitable for PC operation. That program is now known as the Battle Damage Estimator

(BDE). The BDE takes weapon impact information produced by the FSVM and relates it to component, system, and mission impact in both a documented listing and pictorial display relating to failed capabilities within their proper location in the profiled hull form. The BDE is rapidly nearing adequate detail and sophistication to support a true vulnerability analysis of a particular design as it relates to primary damage. The BDE has preliminary inputs supporting some secondary damage spread effects currently related to fire spread, crew casualties, and directly related flooding. With continued effort the BDE has the potential to support the damage analysis necessary to accommodate the needs of vulnerability analysis. The military worth analysis approach would still require fiscal analysis to adequately assess the true warfighting value of vulnerability reduction.

In September 1990, the U.S. Navy co-sponsored a technical workshop with the American Defense Preparedness Association (ADPA) Combat Survivability Division, Ship Section. The theme of the workshop was Survivability Assessment Methodologies, with emphasis on ship vulnerability reduction and damage recoverability. The following were the workshop objectives:

(1) Examine current assessment methodologies and techniques,

(2) Evaluate how well vulnerability and damage recoverability are addressed in the ship and system design process, and

(3) Identify proposed improvements that can and should be made in assessment methods and tools.

The 2-day workshop result drew five principal conclusions as follows:

(1) There is no formal, documented assessment process which provides quantifiable, recognized, and accepted assessments of survivability during the ship design process.

(2) The requirements for the Cost and Operational Effectiveness Analysis (COEA) (DOD INST 5000.2) place increased emphasis on the need for organizational guidance and policy for

survivability assessment; however, there is a lack of an organized procedural structure and survivability assessment policy with the Navy to guide the Navy technical community.

(3) Computer methods and programs are nonstandard and inadequate to provide the needed assessment tools for total ship survivability. This inadequacy is further burdened by the inability to establish data linkages between the various assessment programs.

(4) Total ship survivability assessment requires consideration of the full spectrum of features involving both susceptibility and vulnerability in order to converge to a balanced survivability design. Current assessment procedures, techniques, and tools do not fully provide the integration required to achieve that objective.

(5) Mechanisms need to be improved to encourage and afford greater opportunity for communication and interface among members of the survivability community.

During the workshop, awareness of the forthcoming DOD INST 5000.2 governing "Defense Acquisition Management Policies and Procedures" resulted in increasing emphasis on the assessment process, particularly relative to the Cost and Operational Effectiveness Analysis (COEA). Following the workshop in February, OSD published the 5000 series of acquisition directives. The implementation of these new acquisitions resulted in two additional activities. The first was that NAVSEA asked for formalization of the Navy/ADPA Survivability Assessment Methodology Report. Since I had participated in the workshop, I was tasked to finalize the report. I completed that report in June 1992 with the following recommendations submitted to NAVSEA:

(1) Methodology and Process: Develop a directive and implement a formal survivability assessment process that will identify design vulnerability relative to specified threats to support a determination of the ability to meet operational requirements.

(2) Survivability Policy: Establish an organizational structure and guiding survivability assessment requirements policy.

(3) Computers and Assessment Programs: Provide standards and guidance for computer to computer data transfer communication requirements necessary to improve assessment efficiency.

(4) Assessment Requirements: Continue to develop more effective, fully integrated assessment tools and processes that will enable the assessment of the total ship design over the full spectrum of survivability.

(5) Organizational Interface and Communications: Develop an effective means of conducting COEA for total ship survivability.

I am not aware of any NAVSEA activity that would result in implementing those recommendations to date.

The second activity following promulgation of the DOD INST 5000.2 was OSD's LFT&E Office asking me to support the LFT&E effort through the Institute for Defense Analyses (IDA). This involved development of a program to conduct an LFT&E process in support of ship design analysis. That participation resulted in development of a process that is believed to be the most equitable approach to assessment methodology to achieve LFT&E requirements, short of firing a live weapon at a ship. The LFT&E Assessment process consists of four elements:

(1) Component, systems, and full-scale ship tests conducted under research and development program as design specification proof of technology tests.

(2) Surrogate tests to evaluate design to include armor proof, full-, and sub-scale ship section tests.

(3) Damage scenario-based engineering analysis of specific weapons impacts.

(4) Demonstrating the ability of a full-up ship and crew to combat simulated damage from threat weapons and continue to fight.

The results of the four component tests are combined to form an LFT&E of the total system. To date, this system appears to be the most executable approach to achieving the LFT&E objectives and supporting the ship design community's needs. The SVM/BDE computer-supported analysis would be utilized in appropriate areas of all four components.

Biographical Sketch

CPT Barr is from West Palm Beach, FL, where he enlisted in the U.S. Navy, March 1951. His enlisted service includes tours at the Recruit Training Center, San Diego, CA, Damage Control Training Center, Treasure Island, San Francisco, CA, USS PRAIRIE (AD-15); Instructor Duty at Camp Elliott Retraining Command, San Diego, CA, and USS GRAPPLE (ARS-7), where Captain Barr served as a Chief Damage Controlman until commissioned a Limited Duty Officer in October 1961.

Upon completing the LDO course at the Officer Candidate School, Newport, RI, in 1962, CPT Barr was assigned to USS CABILDO (LSD-16) as Damage Control Assistant and Ballasting Officer. During the tour in CABILDO, he augmented to unrestricted line, then was assigned to CIC Training School at NAS, Glynco, GA, prior to proceeding to USS WALLER (DD-466) as Operations Officer in July 1965. In March 1967, CPT Barr took command of USS ROCKVILLE (EPCER-851), an underwater research ship, homeported at Little Creek, VA. In June 1968, he reported to the Fleet Training Center, Norfolk, VA, where he served as Director of Navigation and Leadership Training School until October 1970, at which time he attended the Naval Gunfire Support School, followed by an assignment with the 3rd Marine Division, Okinawa, Japan, as the Staff Naval Gunfire Officer.

In April 1972, CPT Barr was assigned to the Naval Safety Center's Surface Ship Directorate as Destroyer Safety Program Analyst and Head of the Safety Information Division. He served as Executive Office, USS HALEAKALA (AE-25) in the Pacific Fleet from January 1975 until October 1976. He was then assigned to the Atlantic Fleet Weapons Training Facility where he served as the Live Ordnance Air to Ground and Ship Gunfire Range Office at Vieques Island, Puerto Rico, from December 1976 to July 1978. In November 1978, he took command of USS PLYMOUTH ROCK (LSD-29) where he served as Commanding Officer until December 1980. He served as Executive Officer of the USS SAIPAN from February 1981 to January 1983. He was then assigned to DCNO Surface Warfare in the Pentagon as Head of the Ship Safety and Survivability Office from March 1983 to January 1990. Following his February 1990 retirement, CPT Barr established the consultant service, Ship Survivability Technologies, and has continued to provide support to improve ship design vulnerability reduction efforts.

CPT Barr attended Palm Beach High School prior to entering the Navy and while in service attended Old Dominion University at Norfolk, VA.

His awards include the Legion of Merit, Meritorious Service Medal with Bronze Star, Navy Commendation Medal with Bronze Star, Navy Achievement Medal with Bronze Star, Meritorious Unit Citation, the Battle Efficiency E, Good Conduct Medal with two Bronze Stars, National Defense Medal with one Bronze Star, Korean Service Medal, Armed Forces Expeditionary Medal with second award, Humanitarian Service Medal with Bronze Star, Republic of Korea Presidential Unit Citation, and the United Nations Service Medal.

CPT Barr is married to the former Ina Kathryn Coché of Alexandria, VA.

3. On the History of Vulnerability/Lethality Analysis

by Roland G. Bernier

Vulnerability and lethality are opposite aspects of the interaction between military targets and the munitions designed to defeat them. Modern analysis originated in the mid-1940s. It evolved as a process of definition and quantification in ever-increasing detail. A necessary starting point is clear definition of target defeat (i.e., kill or damage). Many such levels of degradation in function and/or mission have been defined and standardized to suit various target-munition encounters—for example, K, A, B, and C kills for aircraft; K, F, and M kills for tanks; among others. Some standard *kills* were defined as time-dependent, others as mission-peculiar, and still others to quantify repair time. In general, most V/L analyses presume detection and hit of the target.

Historically, the study and application of V/L principles appear to have lagged behind the design and development of military materiel by one or two decades. Aircraft and armored vehicles were introduced in the 1920s, but systematic V/L analysis and application were not considered seriously until the 1940s. Similarly, the helicopter was deployed in Korea in the early 1950s, vulnerability was analyzed seriously in the late '50s and early '60s for Vietnam, and vulnerability reduction became an influential design factor in the new helicopters for the 1970s. Vulnerability reduction is now a requirement in the early design of all military materiel. Concurrently the design of lethality into new munitions has become increasingly more formalized and sophisticated.

Formal V/L analysis essentially started with the Optimum Caliber Program at APG in the mid-'40s. When World War II ended, the (new) Department of the Air Force found itself with hundreds of *war-weary* aircraft. Many of these (fighters and bombers) were flown to APG. Funds and personnel were provided for the dual purposes of analyzing vulnerability and developing aircraft (and antiaircraft) munitions. Selected sections/components of the aircraft were penetrated by selected bullets, shell, and/or shell fragments, and the damage was described and assessed by aircraft specialists. Standard damage categories (i.e., KK, K, A, B, C, D, E) were defined for the assessment methodology. Firings were conducted against running engines, aircraft structures, and cockpits, actual and/or simulated. Against fuel, air-stream was simulated by means of an operating *slave ship*. These aircraft firings were complemented by more controlled test firings against components such as fuel cells, flight controls, and hydraulics and against materials such as metal alloys, armor, transparencies, etc.

Early V/L development of databases and methodology (in the 1940s) originated with aircraft targets and antiaircraft munitions. But parallel developments soon appeared for other military material and munitions (e.g., armored tanks, trucks, ships, as well as nonmilitary targets, buildings, bridges, etc.). Increasingly sophisticated V/L analysis even included personnel (at least males).

Fundamentally, methodology consists of combining size factors (i.e., measured presented areas and empirically determined probability factors for various components, projectiles [threats], and defined kills of interest). The basic unit of V/L was (and continues to be) *vulnerable area* (A_v), simply defined as the product of presented area (A_p) and kill (damage) probability (P_k). In general, total P_k may be the product of various constituent P_k factors (e.g., probability of penetration, probability of leak, probability of ignition, probability of fire propagation, probability of a functional or mission kill, et al.). A large variety of such P_ks have now been accumulated in computerized data banks for various combinations of components, mechanical/physical systems, attacking munitions, and desired forms of damage/kill. When suitable P_ks are not already available, they are derived from firings against materials, components, subsystems, systems, mock-ups, whole targets, static and/or dynamic, engineering analyses, and even from combat damage data when it is available.

Component and/or total presented areas are either measured or calculated one way or another from blueprints, photographs, models, projections, computerized target descriptions, and even from actual hardware (when practical). Probably the first models to be used (early 1940s) were the black plastic models originally designed for WW II aircraft identification training. In the mid-'40s (and later), elaborate wood (balsa) and plastic models with color-coded components and systems were designed and built specifically for V/L analysis. These were photographed from various angles; 35-mm slides were then projected on a ground glass screen for actual measurements of desired component areas. With the advent of the computer age, the whole process has been mechanized. Computerized target descriptions became possible to account for masking of components by other invulnerable and/or vulnerable components and/or structure. Note that vulnerable areas and presented areas are usually additive. Historically, the evolution of V/L analysis was driven by the development of ordnance materiel—sometimes new targets, sometimes new threats, and sometimes both. Near the end of WW II, the proximity (VT) fuze was a most important development for antiaircraft and other artillery because it greatly increased probability of hit. Such shell were developed in sizes from 180 mm down to 40 mm and considered (but found impractical) down to 20 mm. While direct hits were capable of immediate kills, usually kills were achieved from single and/or multiple hits by small fragments down to one gram or even less. Such extremes in threats required vastly different analyses, both for input damage data and for methodology.

Structure represents the largest component of aircraft, and many other targets, but structural members are generally not vulnerable to nonexplosive shell, bullets, and fragments. Monocoque and semi-monocoque structures are employed in modern aircraft and some other targets which are vulnerable to internal blast from shell larger than 20 mm. A notable exception was the B-17 Flying Fortress structure, which was *geodetic*. Early damage tests included a WW II German high-capacity 30 mm. Most small rocket warheads are capable of structure kills by internal blast. Conversely, external blast structure kills require much larger warheads generally from guided missiles. Other components/systems subject to kill/damage by penetration include fuel, propulsion, controls, armament, and personnel; all of which are possible to defeat by bullets and/or fragments, sometimes very small in size/weight.

The aircraft appeared as a military target during WW I primarily because of its fuel tanks. In the 1920s came self-sealing tanks (e.g., the German Heinkel) and all the major U.S. rubber manufacturers. These were effective against the inert bullets—0.30 cal. and 0.50 cal., ball and armor piercing. Shortly thereafter, incendiary (and armor-piercing-incendiary [API]) bullets were developed. Such machine gun bullets included incendiary mix in the nose, and functioned (flashed) upon impact. Sensitivity depends upon striking velocity, the thickness of material impacted, and the obliquity of strike. For safe handling, sensitivity had to be compromised. For V/L analysis, data on probability of function (i.e., sensitivity data) had to be developed parametrically by empirical firings. However, ultimate sensitivity required a fuze, which in turn required projectiles at least as large as 20 mm. The high-explosive-incendiary (HEI) shell is commonly used today in 20- to 40-mm aircraft and antiaircraft cannon. While these shell kill primarily through fuel fire, their blast and fragmentation are also effective against personnel, controls, engines, and small structures (e.g., helicopter rotor blades).

The earliest fuel tanks for aircraft and other vehicles were sheet metal—aluminum alloy or thin steel—very prone to rupture and leakage from projectile perforations. Self-sealing cells have reduced this hazard, but metal and nonsealing bladders continue to be employed in many applications (e.g. trucks, aircraft external tanks, et al.). Some fuel fire kills can result from ullage (vaporspace) explosions, but in general fuel fires do not ignite inside or outside the tanks. Ignition and fire propagation normally occur in voids between the fuel cell wall and the external skin/structure. Hence, external tanks and *integral* tanks, even nonsealing bladder or metal tanks, are not prone to kill by fire. And, in some designs fire prevention has been achieved by filling voids and spaces with lightweight plastic foams.

Fuel type also affects fire vulnerability; diesel and kerosene (JP-1) are less flammable than gasoline and the wide-cut jet fuels (JP-3 and JP-4). Experiments have demonstrated that fires still occur at high altitudes (i.e., over 50,000 ft), but such fires appear less damaging.

Fuel lines/hoses of all types also pose fire problems, especially high-pressure lines. Conversely, suction fuel systems/components are not prone to leak (or fire) from projectile damage (i.e., penetration, perforation or even severance). Hydraulic fluid poses another fire hazard, especially when under high pressures; however, nonflammable hydraulic fluid is available. Lubricating oil is combustible, but usually it is not readily ignitable by projectile sparks and flashes; fuel-oil coolers are a notable exception.

Fuel kills are also possible without fire or explosions (e.g., fuel depletion), which can be avoided by design (e.g., multiple redundant tanks and/or feeds). Also, completely full tanks are prone to *hydrodynamic ram* damage, which can cause tank rupture and sometimes even structural kill.

Fuel fires are readily ignited by single HEI shell at any striking velocity and by single API and INC bullets at sufficient striking velocities. Ignition by inert steel fragments is also possible at very high striking velocities. Bullets and shell are launched at velocities of 1,000 to 3,000 fps, but shell warhead fragments are launched at 2,000 to 10,000 fps. At striking velocities of 5,000 fps or more on aluminum alloy, vaporific flashes can occur, sufficient for fuel ignition, and sometimes even sufficient to delaminate some types of structure materials like honeycombs. To achieve hypervelocities experimentally, controlled fragmentation shell were designed as well as hypervelocity two-stage light-gas (helium) launchers.

While kills by fire and other means can be achieved by single shot/fragment strikes, most kills during WW II and before probably resulted from compounding multiple hits, where one hit caused leakage, and ignition occurred from another hit(s) or from an on-board ignition source.

Analysis of accident and combat damage revealed that crash fires were the most frequent cause of personnel fatalities, especially for helicopters. This led to the development of crashworthy fuel systems including structures, tank material, hoses and fittings, which were applied for Vietnam and to all new helicopters since. Note that fuel fire experimental analysis occurred in the late 1940s and the 1950s; applications of fire prevention concepts began in the 1960s and have continued since. Instantaneous fire detectors and lightweight fire suppressors and extinguishers continue to be developed and applied.

By far, fuel represents the largest source of fire/explosion and loss, but other systems/materials can also contribute, such as on-board munitions and, in particular, the explosives and propellants in machine gun and cannon magazines, rocket, and missile warheads, not to mention logistic loads in transport ground and air vehicles.

The evolution of V/L analysis also covered many dynamic systems and components, especially reciprocating and turbojet engines and their accessory shafts, gear boxes, gears, bearings, pumps, et al. In general the heavy reciprocating air-cooled engines were found much tougher than their contemporary liquid-cooled engines and the modern turbo jet engines. The supply of WW II aircraft and trucks provided targets for dynamic controlled damage studies and firing tests against reciprocating engines. A major finding was their resistance to oil-starvation. Oil-starvation tests were also conducted on helicopter transmissions. In general, bearings were found more vulnerable than gears. The reciprocating engine testing was conducted during the late 1940s; transmission and other oil-starvation testing came later in the 1950s.

Turbo machinery vulnerability testing involved both large turbojets and small turboshaft helicopter engines. Static and dynamic testing was conducted against centrifugal and axial compressors and turbines with shrouded and unshrouded blading. Combustor testing involved hole size effects on thrust. Prototype engines were made available for damage tests, and such testing continues as sacrificial engines become available. Firing ranges and test vehicles continue to be improved.

Perhaps the most critical components/system involved controls—especially flight controls on air vehicles. These involved mechanical, hydraulic, and electrical systems and their small components (e.g., cables, pulleys, bell-cranks, push-pull rods, torque tubes, as well as hydraulic lines, pumps, and accumulators and also electronic components as technology progressed from the 1930s to the present).

Detailed wound ballistic and human engineering data has been incorporated into V/L analysis of air and ground vehicles since the 1940s as the state-of-the-art advanced.

V/L analysis also influenced the development of armor of all types from quilted nylon body armor through heavy protection against large armor-piercing projectiles including antitank shaped-charge penetrators. Early concepts involved titanium alloys as well as USMC Doron—a loosely bonded fiberglass laminate in the 1930s. Before modern lightweight armor became available, tipping plates and over arrangements were improvised in H-21 cockpits and other aircraft to protect against 0.30-cal. and 7.62-mm bullets in Vietnam in the early 1960s. The development of ceramic-faced composites was initiated by the need for lightweight armor. Aluminum oxide, boron carbide, and other ceramic tiles were bonded to Doron or nylon fiber-reinforced plastics for armor against small caliber armor-piercing and API bullets on seats, and critical components. Modern technology provided Kevlar to replace fiberglass and nylon for ultralightweight armor protection.

While modern technology frequently served to reduce vulnerability, more often it tended to increase vulnerability by decreasing weight and/or increasing performance and sophistication. As a result, continual improvement of V/L analysis has been required to keep pace with ordnance evolution.

Biographical Sketch

Roland Bernier received his B.S. from St. Michael's College, Winooski Park, VT, in January 1945. Additional courses were also completed at The Johns Hopkins University (1945–1948) and the Ballistic Institute (University of Delaware) (1948–1949).

From January 1945 until 1979, he was employed at BRL, APG, MD. Since 1948, he pioneered research and development in lethality and vulnerability, vulnerability reduction, and survivability. These efforts involved experimental testing and early development of methodology including actual applications to aircraft design. Since retirement from the BRL (1979), he has functioned as a technical consultant to various DA and DOD agencies directly, as well as to supporting industries, such as the SURVICE Engineering Company (Aberdeen, MD). Early research concerned aircraft fuel fires, hypervelocity impact, test facility development, and related testing.

In the 1950s and 1960s, his primary effort was dedicated to support the integration of survivability into current and future Army aircraft. Career progress included Chief of the Experimental Test Section of the Aircraft Weapons and Vulnerability Branch 1964–1970, to Chief of the Vulnerability Reduction Branch 1970–1976, to Chief of the Aerial Targets Branch 1976–1979 (retirement). Local recognition included the Robert H. Kent Award (1973) and membership in the BRL Fellows. In 1966 and again in 1979, the BRL Vulnerability Team received the Department of the Army Research and Development Award for Technical Achievement.

Within DA, Bernier was consulted by numerous agencies and Project Managers and served on the Source Selection Boards for LOH, HLH, DIVAD, et al., including UTTAS and AAH, which culminated in the Black Hawk and Apache helicopters. Similar service was also provided to the

USAF and USN (e.g., AMST). At the tri-Service level, in 1971 he assisted in the formation of the Joint Technical Coordinating Group for Aircraft Survivability (JTCG/AS), where he served as the AMC alternate Principal Member for numerous years.

Internationally, he contributed to AGARD, NATO, and TTCP working groups in survivability.

In 1962, he participated in an ARPA team to South Vietnam, actually installing crew armor in deployed helicopters and other aircraft. Subsequently, he organized the collection of combat damage and casualty data. Documentation and analysis of such data formed the basis for the introduction and justification of vulnerability reduction features in the design of new aircraft.

Throughout the years, the expertise of the BRL team was thoroughly utilized and appreciated by DOD agencies and industry. In testimony, no less than 40 letters of commendation/appreciation were received from the project managers (e.g., Aircraft Survivability [PMASE]), professional societies (e.g., MORS, SAE), major aircraft companies, and their supporting hardware manufacturers. Among these were the Sikorsky Division of United Technology; the Vertol Division of Boeing Aircraft Co.; Textron Bell Helicopter; McDonnell A/C Co. (including the MH designers, Hughes Tool Co.); Lockheed (Georgia); General Electric (Lynn Mass. Aircraft Engine Division), General Dynamics (Fort Worth); Goodyear Aerospace; FMC Corporation; and the Denver Research Institute, among others. Not least are appreciation letters from the Deputy Under Secretary of the Army for Operations Research, and the Presidential Science Advisory Committee (PSAC).

Mr. Bernier passed away in December 1996.

4. Reflections Related to Assessment of the Vulnerability of Armored Combat Vehicles and the Lethality of Antiarmor Munitions: The Last Two-Thirds of the First Fifteen Years [A Meandering Tale of Unverified Remembrances of an Aged Analyst, Once of BRL]

by Davidson C. Hardison

Thank you for the kind introduction. And thank you even more for the invitation to be here among friends of so many years. After all, I have been "retired" for 8 yr now. It is nice to be permitted to participate in occasions such as today.

The truth is that, in retirement, I have absolutely no pressing calls on my time. Therefore, I am free to take part in activities, such as those of today, any time I please. My remarks today are in the form of a tale. Its title is "Reflections Related to Assessment of the Vulnerability of Armored Combat Vehicles and the Lethality of Antiarmor Munitions: The Last Two-Thirds of the First 15 yr." Its subtitle is "A Meandering Tale of Unverified Remembrances of an Aged Analyst, Once of BRL." Its filename is "BRL9.25.92."

To my mind, BRL armored vehicle vulnerability/lethality work spans some 45 yr, more or less. My tale concerns program years 5–15, or, using a different calendar, 1954–1964. I tell you at the outset that the sequential ordering of my remembrances have not been verified by document review. Let a historian do that. For me, the marvel of the aged brain is that it recalls that, not that it occasionally loses track of when. And besides, in retirement, one is free to put on his shoes and then his socks, in just that order, if he wishes to do so!

My tale is one of activities and persons, myself included. In Biblical terms, it begins about 40 yr and 40 days ago when I first arrived at the BRL in August 1952 as the Korean War was approaching its end. As the Chief of the Ordnance Engineering Laboratory, Herb Weiss was busy publishing at least one technical report every month, and expanding his workforce. As one among numerous others, my application for employment had been accepted.

Full of energy, enthusiasm, apprehension, and expectations, I was met by Dick Peterson, Floyd Hill, Jerry Zeller, Andy Benvenuto, Bill Gholston, Al Vincent, Gene Williams, Sid Wise, George Scott, and a couple of others who welcomed me and told me that I would be working in the Combat Analysis Section of the Tank Branch.

To that moment, I had never seen a tank. But, soon, I was supposed to know of their tactical employment, gunnery procedures, fire control, accuracy, rate of fire, armament, logistic support, and vulnerability.

Dick Peterson, Chief of the Combat Analysis Section, was my first boss. He, and his boss, Floyd Hill, were brainy men who were already keenly interested in tank tactical operations. This resulted in my first assignment being to retrieve and digest all of the After-Action reports of tank battalions used in NW Europe during WW II. The months I spent examining and analyzing those primary source documents were among the most informative of my extended sojourn in the wilderness of operations analysis. To this day, I find my fundamental operational instincts driven more than makes sense by what I mined from those war records.

But soon Floyd had become impatient with the pace of Dick Peterson and Andy Benvenuto in publishing the results of their analysis of line-of-sight data taken from topo maps. So I was tasked to help rewrite their report and get it out. Clearly the role of an editor, and not much more. I still remember my surprise that Floyd decreed that I, in his words, "the principal writer," would be listed as a coauthor. Thus my first major lesson learned with the Army was that credit bestowed and credit due do not always match even closely. Later, as I received several awards, I saw that they rarely do.

And then came Project Stalk—a large field experiment in which over 13,000 main rounds were fired at 5 different target ranges by 25 tank crews using 11 different tank, fire control, armament systems. Floyd Hill had had a strange notion that, in tank battles, the ability to achieve quick kills might be good. So he decided to get some experimental facts. In the Stalk trials, boxes of data were gathered regarding firing times, and whether hits occurred.

My attempts to understand the meaning of the Project Stalk data were immensely interesting—mostly because what had happened in the range firings was not, especially as regards accuracy, even close to pretest expectations. Yet the test facts remained. Indeed, no targets were hit after the shooting stopped. Determining why the misses had been so frequent, and so unrespecting of the claims of system advocates, proved to be fun indeed.

Processing the Stalk data was manual and quite time consuming. It was so slow that one had ample time to ponder underlying causes. To me, it is unclear whether comparable thought would have occurred had the fast data processing machines of later years been available; I think not.

The point in relating these tangential ditties is to explain that I was not involved in the vulnerability activities of the Tank Branch my first 3 yr at BRL, and that the tank vulnerability work had started a couple of years prior to my arrival. So the first one-third of the first 15 yr of BRL work on the vulnerability of armored vehicles was over before I became acquainted in detail with what was being done. Therefore, my focus on the later two-thirds of the first 15 yr.

By 1954, Floyd Hill, with his unquenchable thirst for theory-free empirical data, had D&PS do a sizable number of trials in which tank-fired AP, APC, HVAP, HEAT, and HEP projectiles were used to attack M4, M5, M24, M26, T29, M46, and T34 tanks. Jack Shanley and Ernest Kirkpatrick had done hundreds of static firings of HEAT shells against stacks of steel and other armors. Over in TBL, Joe Regan had made scores of static shots of HEAT shells into armor arrays backed by Celotex panels to collect behind-armor fragments, but the data were much too precious to be inspected and used by mere mortal analyst.

Elsewhere on campus, Mort Sultanoff made fast photographs, Julie Simon made x-rays, and Lou Zernow advanced Nobel schemes—even his smaller ideas were dynamite. Off campus, Charlie Salter at OTAC saw enormous promise in fused silica, Don Kennedy extolled aluminum liners, Perlmutter at RARDE designed successful APDS projectiles, Picatinny fretted over production tolerances, and (not yet at BRL) Bob Eichelberger, as always thereafter, lamented the absence of adequate theory and then proceeded to improve it.

Meanwhile Gene Williams, Bill Gholston, Dan O'Neill, and Al Vincent struggled mightily, but with at most limited success, to make sense of the results of the vulnerability firings that Floyd Hill had commissioned.

What these persons had to work with were blue, ink-besmudged, smelly, firing records. These, by and large, did a good job of documenting the materials used in the tests, the conditions of the tests, the observed physical damage to vehicle components, and the values of three metrics called "M," "F," and "K" as scored by persons experienced in tank operations and officially designated as "Damage Assessors."

At least in the cockles of my aged brain, it is now unclear precisely how the damage assessors determined the two-digit values of the M, F, and K metrics. Moreover, if memory is correct, it was equally unclear at a much earlier time. Whether they were unambiguously related to values in some Standard Damage Assessment List (SDAL) is not now recalled, but your historian surely can find out if he cares to do so.

So the M, F, and K metrics, and possibly an early SDAL, were in-place and hallowed before I became involved much in vulnerability matters. Exactly what they were supposed to mean was, to my mind, both ill-conceived and ill-defined, and so they have remained.

Meanwhile, folks such as Morgan Smith, Harry Kostiak, Jerry Dailey, Tom Coyle, Roland Bernier, Don Mower, Robbie, and others over in the Aircraft Vulnerability Branch reportedly were well along in understanding the vulnerability of flying machines, thanks in no small measure to the work begun mostly by Art Stein during the late '40s and early '50s. Hopefully, Art will later share some memories of his pioneering efforts. And Joe Sperrazzo had already overseen his definitive work in the field of wound ballistics. No more 58 ft-lb; hereafter wound ballisticians would worship

$MV^{3/2}$, and incredible polynomials, and personnel casualty predictions thereafter would be time-tagged and mission-dependent.

It was fascinating back then to sit, to pretend to be thinking, and to watch the tank vulnerability analysts work over the large blueprints of a tank spread to, and beyond, full coverage of a drafting table. Much of their time was spent in trying to figure out what the tank was really like at some particular point of interest—what was the armor thickness, armor obliquity, and into what compartment might residual jet, or projectile fragments, or spall, impinge. The conversations were endless, priceless, and costly. An uninvolved listener sometimes had unasked questions regarding the ultimate accuracy of the process which he viewed to be mostly S&P. Here S&P is used not as the abbreviation for Standard and Poor of financial matters, but as the short name of the Stare and Ponder tank vulnerability assessment method that was used in the early–mid 1950s.

The major issues of substance were the vulnerability of the just-developed M41, M48, and T43 tanks, and the lethality of our AP, APC, and HEAT projectiles when used to attack the T34, T54, and JSIII tanks. On the other side, there was the vulnerability of Soviet tanks, and the lethality of their 100- and 122-mm projectiles against our tanks.

The emphasis definitely was more on "getting the numbers," that is the M, F, and K "kill probabilities," than on practical measures to increase the survivability of our tanks or on feasible means to increase the lethality of our antiarmor munitions. Perhaps these early steps toward improvements in measuring the capabilities of existing things had to come first, but then, even as much later, it seemed wrong to allow it to be the principal objective. Surely the goal had to be increased survivability and increased lethality of our stuff, not just improved measurements of the capabilities of existing systems conceived by others. Some, I not included, were bothered about a potential conflict if one tried to be both impartial assessor and improvement instigator. Others, I included, judged good materiel to be paramount and found the concerns about conflicts of interests to be both revealing and insulting.

Notice that I just used the words "kill probabilities," not the more correct ones of "average loss of function." That was deliberate to illustrate the point that, even in the early days, there was sloppy thinking as what the metrics really were and that, even then, the metrics were applied in largely inapplicable ways.

Up to this time, and perhaps we are now up to about 1955, there was essentially no use of computers in the study of vulnerability of armored vehicles. The calculations, to the extent the assessments were not subjective, were all manual; the tools were blue print, slide rule, pencil, columnar pad, and desk calculator.

In fact, there was no accepted systematic scheme for generalizing the results of the firing records, and no methodical way for applying their implications to other rounds or other targets. At least in retrospect, in seems that the usual practice had two steps: (1) infer the fraction of the presented area of the target that would be perforated by a particular round under selected attack conditions and, (2) somehow or other, mostly the method of S&P mentioned earlier, estimate the consequence of damage to exterior and interior components. For convenience in making the estimates, the interior components were grouped into several more or less homogeneous "compartments" such as fuel, ammunition, engine, crew compartment, etc. Yes, those were the halcyon days when tanks, not tank armor programs, were compartmented!

By about this time, the Vulnerability Section had let a contract with AAI, Inc., to fabricate wire-frame and exterior iconic models of the M47, M48, T43, and JSIII tanks at a scale of about 1:12. These physical models were conceived to be helpful, when used as a matched pair of wire-frame and exterior view, for visualization of the components that would be insulted from particular attacks. AAI did its work fine, and the models were delivered, so far as I recall, on schedule. But analysts soon found them to be not helpful at all. I believe that the models were never once used. They remained as curios for years—one more idea that had earlier seemed promising but that turned out to be not worthwhile. And they had been constructed for four target vehicles when one would have been sufficient to reveal their lack of worth.

Meanwhile, the folks in the Aircraft Vulnerability Branch were justly exhibiting pride that they knew all that was to be known about the vulnerability of flying machines, and apparently of other aspects of air warfare as well. Their prewar estimates of the exchange rates between F-86 and MIG-15 in air-to-air combat were reportedly shown in the Korean War to be unbelievably exact. So the early work of Stein, Weiss, Smith, et al. had already paid off, even if it was a little hard to figure out just how.

And by this time, Kirkpatrick and Shanley were in the glass business in a really big way. It had turned out that, within limits here of interest, the unit price of custom melts of glass was very close to the reciprocal of the amount purchased. So Kirkpatrick had ordered tons of glass blocks of multiple sizes and shapes—he just could not resist the bargain.

Most of these glass blocks eventually wound up in surplus stores. There they saturated the bookend market east of the Mississippi River for years. But, before they could be declared surplus, these glass blocks had to be properly accounted, stored, and protected.

The glass blocks had been delivered in cardboard cartons of, say, 6 cubic feet each with metal bands surrounding the packages in two planes. This packaging in cardboard cartons eased the handling of the blocks but, exposed to the elements on Spesutia Island, it was not long before the metal bands began to rust, and the cardboard boxes lost their look of freshness. Moreover, it was not easy to mow between the stacked boxes so unsightly grass prospered—altogether a most untidy range.

Nothing would do but that these cartons of glass be stored properly in transport containers, those ubiquitous 8 × 8 × 10 ft metal boxes. Of course, these metal containers also rusted. So, to ensure their longevity, they all were given several coats of paint—paint outside of metal containers outside of metal bands outside of cardboard boxes outside of blocks of glass, the only impervious material present. It would have made more sense to build a glass igloo containing the metal boxes containing the bands around cardboard boxes in which the cans of paint might have been stored. But what made sense did not matter; what looked good did! Point: don't believe old timers when they tell you that things were sensible in the "good old days." Truth is, there was nonsense then just as now and, at least arguably, in comparable amounts.

As regards tank perforability by KE projectiles, the five pieces of information treated as essential were target armor thickness, armor obliquity, a ballistic limit vs. T/D curve for the projectile type, projectile diameter, and projectile velocity at impact. But, even then, it did seem that projectiles made of hard dense materials, such as tungsten carbide, did quite well, and that long projectiles such as the fin-stabilized "Arrow," on occasion, did better than comparable diameter short projectiles of the same material, especially on the rare occasions when they happened to hit with small yaw. So already, the potential advantages, and delivery challenges, of high L/D KE rounds were apparent, even if the measures were crude. For HEAT, only three data were needed: armor thickness, armor obliquity, and Pen vs. Standoff. If one but understood the application of these, and could almost read a drawing, she, albeit mis-titled, was a journeyman vulnerability analyst.

For KE projectiles, the main focus was on perforability, and with considerable justification. Up until that time, with the low L/D steel projectiles impacting at modest velocities, it had required a large diameter shot to perforate the thickest armors on tanks. If perforation occurred, the level of behind-armor damage was so impressive that precision of measurement was comparatively unimportant, or so it was believed. But for HEAT, a similar argument did not hold, and behind-armor damage was at issue from the outset. Moreover, exterior components, not themselves much hurt by small HEAT shells, often resulted in the HEAT warheads being several feet from the main armor when warhead detonation occurred. Understandably, improved penetration at long standoff (i.e., precisely where the poor quality shaped charges then in service were deficient) clearly was an important need, but one not reflected in official Requirements of the time.

By 1956 or so, Floyd Hill and Ernest Kirkpatrick and Jack Shanley and Gene Williams and other early beacons had repaired to enriched callings elsewhere. Gerry Zeller was by now a section chief, and his main challenge was to "make sense out of the Firing Records" and "figure out how to make vulnerability assessments." Gerry was not quick, or slick, or clever, or—to my knowledge—ever very wrong. He was intuitive, plodding, careful, peerless with a French curve, patient to a fault, possessed of excellent analytical instincts, and a master of approximations. He always first imagined the way output data ought to relate broadly to input data, and then he looked for evidence supporting or contradicting his intuition. He perhaps too highly respected first moments; he always recognized, but often set aside, the implications of higher ones.

Gerry tried, with validity that others having insights different from his have later questioned, to roughly correlate average behind-armor damage to exit hole diameter for both KE and HEAT rounds, depending on which compartments the perforating rounds insulted. His scatter diagrams showed enormous scatter, but he thought he saw patterns. He saved as grossly predictive the trends he thought he saw, and set aside the unaccounted residuals. By so doing, he both advanced the then current practices and left ample room for later persons having more advanced adding machines to improve the accounting. But be not deceived: what you do now, though better, is what he did before you.

While speaking of Gerry Zeller's work, let me next recall a few details of the birth of the Tripartite Standard Tank Targets, later, the NATO Standard Tank Targets. Gerry and I, with our colleagues Bill Snarr of Canada and Ronnie Shepherd of England, had learned the power of international means to accomplish matters that we would have been unable to pull off unilaterally at home. By the mid–late '50s it had become plain that tank and antitank munitions, being designed to meet "requirements," at minimum cost, were not what they should have been, and in ways that were fixable but only if the "requirements" were more meaningfully stated. But then, as later, "requirements" were not our responsibility. So the basic challenge was somehow to arrogate de facto control in the absence of responsibility and authority. The solution was to have the co-conspirators tasked by the Tripartite users to look at intelligence information and technical options open to thoughtful future vehicle designers to identify a standard set of testable range targets, the defeat of which would be taken as evidence of sufficiency of antitank munitions. That way, others would continue to state the requirements; we would just assist a little by telling them what they surely must have meant.

So, in the summer of 1956, or some other good year thereabouts, we repaired to Ottawa for the seance. Each of us came with initial views, and they were not close to being the same. For what I now recall as two solid weeks, the examinations continued. The discussions remain in my memory to this day as my best example of several serious persons trying very hard to get as close as possible to an admitted unknowable. But it was all for a proper end, and it paid off.

After the fortnight of discussion, we finally reached agreements, only to discover that no one had been designated the note-taker, and that the many turns in the serpentine path of logic were not easily reconstructed. In much fatigue, and some despair, Ronnie Shepherd suggested the report be very short, that it say "We thought long and hard about the assigned task and concluded that: (1) . . ." And so we did. Perhaps nothing speeded acceptance of the proposed targets more than the paucity of documentation of the rationale of their derivation, another example of "The Law of Sausages: Consumers Who Observe Production No Longer Are Consumers." Was it not Henry Ford, who when found at the site of an early auto accident with a young lady, not his wife, refused to comment, saying only "Never apologize, never explain"?

If there is anyone here who has not heard of these early Standard Tank Targets, he probably is in the wrong meeting. They were important drivers in the design of Western world antitank munitions for at least two decades—too long, of course, but with substantial benefits for years.

After only a decade of work in the tank vulnerability business, it had become reasonably clear at BRL that one really needed to describe each potential target vehicle in such a manner that the description could be used routinely whatever the attacking projectile. The person most responsible for doing just that was Dick Hoyt. Dick was quick, slick, clever, and to my personal knowledge, sometimes very wrong. He had a frontiersman's way of thinking not then found often, now rare indeed; a willingness to fell a forest one tree at a time. His proposed approach was to select a particular impact point and attack direction and then to describe the shotline all the way through the vehicle, noting the compartments traversed and defining all the stuff that would be encountered by, say, a nondeflected jet of great length.

A critic quickly pointed out that vehicles are far from homogeneous. If other impact points and/or attack direction be selected, the shot-line materials almost certainly would be different. Dick agreed, and asked how many samples would suffice (i.e., what grid size would make one comfortable).

Thinking that the effort involved would dissuade him from such a labor-intensive approach, it took about 10 s for one to suggest a cell size of 4 in, with one point to be selected uniformly at random within each cell. Dick's response was to calculate that, for seven directions of attack, there would be about 20,000 cells involved, that an industrious analyst should be able to characterize an average of about 30 cells per hour or 330 per working day. So one should be able to describe a target vehicle in a mere 2 mo of uninterrupted work.

And then, by golly, he did just that! Others checked cells selected at random and confirmed his data. The data files of these 20,000 or so cells per vehicle immediately suggested use of ORDVAC as the bookkeeper. Moreover, comparatively simple algorithms were written to combine the armor penetrating characteristics of attacking projectiles, the target description, and the results of Zeller's behind-armor damage correlations. Howard Ege, surely more than anyone else, was responsible for this computer application, and for perfecting the ability to generate enormous stacks of printouts showing what the computer said would happen if a particular round were to hit a particular target at a particular location under defined conditions. And, of course, integration over these specific points was an almost trivial computer task, given the distributions to be used to weight them. So, to Howard Ege, more than to others, belongs the credit for introduction of the relentless discipline intrinsic to the algorithms of the computer-based methods used, with many major improvements to be sure, until today.

Howard also, with some not-so-subtle prodding, came up with an innovative scheme of using the three-color alpha-numeric printers then available to construct a slightly distorted color graphic showing the vulnerability of a vehicle depending on strike location for attack conditions fixed. Essentially, the scheme exploited the fact that line spacing on the printer was, or could be made, close to the width of two print characters. For each cell, the average functional loss, correct to two places, was printed in a color depending on its magnitude, at a position on the page corresponding to its location on the vehicle. What resulted was a first-generation vulnerability color map. It was quite helpful for briefing analysis procedures and results, and even more so for data quality control. One simply could not find the errors in tabulated data; it was much easier to see them in pictures. Once Dick Hoyt had described one target tank, he knew quite precisely what it should cost to hire commercial firms to do as many others as we wished to pay for. As I recall, firms such as Denver Research Institute were happy to have the money—it was not much—and we were happy to have the tank description data in this highly usable form. I admit we were even happier to not have to do the knuckle work. Altogether, a good deal for all parties.

Dick Hoyt went on in later years to introduce the use of combinations of standard geometric shapes to represent the armor and interior components of armored vehicles. That process clearly is in the lineage of current methods, but it will not here be discussed.

By this time, vulnerability questions were spreading from tanks to other armored vehicles such as APCs and SP howitzers. In particular, the very small shaped-charge bomblets such as those later carried in cluster shells and munitions were a hot topic. Fortunately, a tall, gangly, fast-thinking, slow-talking young man from Mississippi named Bob Kirby had returned to BRL after completion of an active-duty sabbatical in the Army. As I recall matters, it fell to Bob, more than to others, to do the testing, adapt the analysis methods, and analyze the lethality of these small bomblets and to estimate the vulnerability of targets to attacks by them. His work, for example, was the first to show what happens when the tiny jets from small shaped charges and massive pistons of tank-sized diesel engines attack each other.

In the end, Picatinny chose bomblet sizes that probably were other than best. Whether that be correct or not correct, they had advice from the antipersonnel lethal area technicians of Abe Golub's Artillery Branch of BRL. But, what the hey, as the lawyers say, you win some and you lose some, but you get paid for all of them. And, what is more, in our business, you sometimes even get to know when you are right. Ample rewards, I would say—who could ask for more!

As BRL armored vehicle vulnerability numbers and BRL antiarmor lethality numbers became available in increasing quantities in the Ordnance Corps, and in the Army more generally, they stimulated endless questions, mostly from advocates of a particular pet rock, as to whether the "ivory towered scientists" at BRL were even close to right. That was as it should have been. After all, persons were threatening to make serious system development decisions based on our numbers, when elsewhere others were making quite different vulnerability/lethality assessments.

For example, at about this time of 1957–58, the French were selling all who would buy them antitank missiles carrying HEAT warheads of about 100-mm diameter, and claiming assured defeat of known and projected tanks. We were favoring Shillelagh-sized warheads and saying that their considerably larger warhead would prove better suited to defeat of future tanks. Englishmen felt certain the only prudent thing to do was to carry 60 lb of HE as did the Australian Malkara and English Orange William antitank missiles. Incidentally, neither of Her Majesty's missiles entered field service, but it was not because they were found too small!

It was in that context of controversy that I, as now seems to have been my habit, exceeded my authority and at a meeting in London proposed live-fire tests that later became known as the Tripartite Trials at CARDE. The trials were Tripartite alright, but the U.S. did provide the test warheads, the target vehicles, the mechanics to repair target vehicles, most of the vulnerability analyst, and the strawman test plan and the strawman evaluation plan, both of which were implemented with minor improvements. Canada provided the real estate and range support, and the UK sent a couple of keen analysts, one of whom was Lynn Jones, who later made many contributions to the UK, NATO, and even to U.S. defense efforts.

These trials proved to be important but, to my mind, not for the reasons many persons later seemed to think. They did yield much data, but, in perspective, they added little to what was known at BRL before them. Contrary to what Chicken Little briefers have crowed, they most certainly were not the first and only "live-fire test" prior to Chicken Little. What the CARDE trials did do was to force BRL to expose in detail its armored vehicle vulnerability approach, warts and all, for others to inspect, to question, and to suggest improvements. And they resulted in comparisons of test results with forecasts of them made prior to the shots. So, importantly, they moved the BRL approach from a fairly closeted laboratory scheme to a far-from-perfect, but broadly understood, method used widely in Tripartite circles. Thus, from the CARDE trials, the BRL vulnerability program gained some valuable data, gained some slight improvements in methodology, and gained major increases in credibility—as much or more, I judged, as one gets from most tests.

At some point in this tale it would have helped to talk of the efforts to find practical means of defeating shaped-charge jets, of the work to assess the benefits of spall liners, and of the attempts to build composite-armor hulls and turrets for the ill-fated T95 tank whose development was terminated in 1958 because of serious problems in design of the hull, chassis, suspension, track, fire-control, engine, transmission, gun, and ammunition. But those stories, along with the saga of MBT-70, the beginning of TOW and Dragon and Sheridan, can best await another day when questions of classification no longer arise.

Besides, this tale has already meandered for too long. I hope that I have minded, or reminded, you of some of the activities, and a few of the lasting accomplishments, of the last two-thirds of the first 15 yr of BRL's armored vehicle lethality/vulnerability work. Subsequent to the time of this tale, there have been two additional 15-yr periods during which others have advanced the art and, perhaps even more, the art-work of vulnerability analysis. Persons more familiar with the contributors and their contributions must spin those yarns at later gatherings.

In closing, I want to return to a point made near the beginning—that credit bestowed and credit due do not always match. When I reflected back on the early years, I thought first on what was done and then next on who did it. I concluded it proper to emphasize the contributions of five particular individuals whose work proved to matter. Let me again mention them and what, to my mind, they did:

- Floyd Hill, who, possessing a never-ending conviction in the value of theory-free empirical data, caused the initial firings that generated the data that begged to be explained.

- Gerry Zeller, who succeeded in interpreting the firing data in terms of more-or-less predictable interaction of a projectile having measurable terminal ballistic properties with a vehicle having describable target properties.

- Dick Hoyt, who had an inability to recognize that the amount of work involved in preparation of detailed descriptions of tanks as targets was prohibitive, and who was both able and willing to do just that, thus demonstrating a workable way to describe tanks as targets and, as important, that preparation of target descriptions was mainly a matter of commitment, not principle.

- Howard Ege, who achieved the lasting discipline and production potential resulting from putting the target description data on the computer and marrying to it projectile terminal ballistics, to include the results of the target damage work done by Zeller.

- Bob Kirby, for extending the vulnerability assessment envelop to include armored targets other than tanks and munitions other than antitank munitions.

So far as I know, not one of these five persons ever received any special recognition from OSD, OSA, HQDA, AMC, the Director, BRL, or their Laboratory Chief. If they did, fine. If not, it was a mistake. For, according to the remembrances of this Aged Analyst, once of BRL, each of us, in no small way, is indebted to each of them for what they did. To be sure, others were there then, and still others have followed. In many cases, their work was good also. But, it is best thought of as "the same as," or as "refinements of," or "different from" that of these five persons of the later two-thirds of the first 15 yr. Therefore, without hesitation, we—their contemporary or follow-on coworkers who knew them best—should now share a sustained applause that loudly acclaims that they have our unsurpassed accolade: superior craftsmen.

I now lead it, and, if you agree with my assessment, I invite you to join.

Biographical Sketch

Mr. David C. Hardison received a B.A. in Mathematics from the Atlantic Christian College in 1949, an M.A. in Mathematics from Duke University in 1951, and an M.S. in International Affairs from the George Washington University in 1972. He also received a diploma from the National War College in 1972.

From 1952 to 1964, he worked as a weapon system analysis in BRL, including a tour as the Chief of the Armored Systems Branch. He served as Scientific Advisor to the Commanding General of the U.S. Army Combat Developments Command from 1964 to 1972, and from 1973 to 1975 as an Analysis Advisor to the Deputy Chief of Staff, U.S. Army.

In 1975, he became the Deputy Under Secretary of the Army for Operations Research, and in 1980, he moved to the Department of Defense as the Deputy Under Secretary of Defense, Tactical Warfare Programs. He returned to the Army as Director of the U.S. Army Concepts Analysis Agency, and retired from that position in 1984. Since then he has been a defense consultant.

Mr. Hardison's areas of interest include tactical warfare systems, military operations research, and systems analysis.

5. Two Turning Points and a Continuing Improvement

by Richard E. Kinsler

In the mid-1960s, it became apparent that North Vietnam was supporting the war in the South by moving large quantities of war materiel south along the Ho Chi Minh trail. Since the bulk of this war materiel was moved by trucks, the study of the vulnerability of trucks became a priority throughout the DOD. As a result of this priority, the *Science* of vulnerability estimation for surface targets progressed rapidly from manual methods, through the early target description techniques and *Parallel-Ray* analyses of single-fragment impacts, to the early Combinatorial Geometry target descriptions and *Point-Burst* analytical techniques, all of which are the direct ancestors of the techniques used today.

BRL was able to obtain approximately 300 medium weight class cargo trucks simply by paying for their transportation to Aberdeen. Shortly after the arrival of this *motor pool* of trucks, we obtained some 400 new and rebuilt engines for the trucks, again for the cost of transportation. The fact that the trucks were being phased out of the inventory had no effect on their value as targets for study. As it turned out, these older trucks were of the same design generation as the Soviet trucks which were being targeted along the Ho Chi Minh trail. A maintenance shop was established in what is now the main BRL conference room in building 300, and recent graduates from the mechanics course in the Ordnance School were used to staff the shop until they received their assignments.

One of the early uses of the trucks was to attempt to understand the different ways that trucks lost the capability of powered movement, and the types of damage that resulted in the loss of this capability. Analysis, supported by tests, quickly revealed that the ignition system, the lubrication system, and the cooling system were the three systems which most often resulted in complete loss of powered movement (mobility) of the truck as a result of impact by a small caliber projectile or a fragment of *reasonable* (e.g., about 1,000 grains or less) size. Tests also demonstrated that the time required for a truck to become nonfunctional was repeatable, given loss of the ignition system (immediate loss), or complete loss of the engine lubricant (about 10–15 min), or complete loss of engine coolant (about 25–30 min). Heavier power train components (e.g., steering components, gear trains, axles, etc.) tended to fail immediately after damage, or they did not fail within a meaningful length of time. Based on these test data, the kill criteria for trucks were established as the time elapsed between the onset of damage and the complete loss of powered movement. The criteria were defined as:

Kill Level	Elapsed Time (min)
A	0–5
B	0–20
C	0–40

- Establishing these kill criteria based on the measured response of the target to a specific class of damage (e.g., lower engine damage resulting from complete loss of lubricant) as opposed to a specific type of damage (e.g., a hole in the oil pan) was a turning point in the field of vulnerability analysis. For the first time, a kill criterion had been established for surface targets which was founded on an observed, repeatable phenomenon. Easily observed and readily understood loss of function (powered movement) was the result of physical processes acting because damage had been sustained by the truck. As a result of defining the kill criteria for trucks in this manner, the probability of kill calculated in the analysis of trucks was a true probability that the truck lost all powered movement, rather than suffered some undefined reduction of capability.

While we, at BRL, were developing kill criteria having some rational basis, and trying to establish a rationale for criticality analyses, Falcon Research and Development Company of Denver, CO, was under contract to the Naval Weapons Center (NWC) at China Lake, CA, to develop a computerized target description of the ZIL-157 truck and to conduct a single-fragment vulnerability analysis of the truck. BRL and NWC joined forces to conduct a series of analyses of the truck. The BRL kill criteria were proposed and accepted for use in the study. The NWC contribution to the study was to be the target description and the analysis program, whose output was to be the vulnerable area of the truck, based on an array of single fragment mass-velocity combinations. The BRL contribution was to be the results of the criticality analysis, a set of $P_{k/h}$s for each of the critical components and *validation* of the analytic results, based on our experience from having examined a lot of fragment-induced damage on trucks.

At that time, a few experimentally derived $P_{k/h}$s existed; however, $P_{k/h}$s for each critical component did not exist. Neither time nor resources were available to determine $P_{k/h}$s experimentally. Therefore, it became necessary to devise some analytical method of developing *consistent* and defensible $P_{k/h}$s for all critical components of the truck. Over the next several months, the basic concept of performing a miniature vulnerability analysis of each critical component, examining each of the six cardinal faces of the component from several obliquities, and using established engineering techniques (modified by test observation) to estimate the size and placement of the hole required to render the component nonfunctional was established and reduced to practice. For the first two targets, the ZIL-157 truck and the KrAZ-214 truck, the $P_{k/h}$s were calculated by hand. Only later did we feel that we had enough time to develop and de-bug a computer program to do the arithmetic, thus freeing analysts from the mechanical calculators of the day and moving them into the computer age.

- Establishment of a method of developing $P_{k/h}$s analytically is seen as the second turning point described in this vignette. Since components are designed by engineers who are trained in the application of natural laws, it seems to make eminent good sense to have other engineers "reverse engineer" a component to predict the level of damage required to render the component nonfunctional and ratio sensitive areas to presented areas to develop a probability of kill. Developing the component $P_{k/h}$s in this manner produces a $P_{k/h}$ which is a true probability that the component will cease to function, rather than some measure of component degradation short of complete loss of function. One of the criticisms leveled at the method is that only perforation of the component is considered. This criticism is not entirely warranted; however, it is true that consideration of other damage mechanisms is somewhat subjective and heavily dependent on the background and expense of the analyst. It remains for current analysts to expand the method to include other damage mechanisms such as shock, structural deformation, crack propagation, etc. Perforation of components is the primary kill mechanism observed in full-scale test programs when a damaged target is examined. When other damage mechanisms have been observed, damaged components typically had also sustained killing damage from fragment perforation.

Results of the criticality analysis and the $P_{k/h}$s were forwarded to Falcon in Denver. This began the second most interesting phase of the study. Falcon would run the analysis on the large computers at NWC and air express the resulting case of computer print-out to the Baltimore-Washington International Airport. We would meet the plane, claim our case of computer print-out, bring it back to BRL, and spend the next day or so studying the results. There would then be a 2- or 3-hour telephone conversation with the analyst at NWC. Modifications would be made, the analysis re-run, and another case of print-out air expressed east. After about three of these cycles, all decided that the analytical results did not differ too badly from what had been observed in full-scale testing. The results were then summarized and forwarded for use in the end game analysis.

Only later, when some of the analyses were run at BRL, did we begin to develop a true appreciation of the magnitude of a single truck analysis. The first analyses that were run on the computers at BRL were run either at night, or over a weekend, because one single run required the complete attention of either the BRLESC I or BRLESC II computer, and all of the operational tape drives (for both machines) for somewhere between 8 and 10 hr. Initially, the typical analysis would run to about 95% completion and then drop off of the computer because of tape parity errors. Naturally, this typically occurred just before the print cycle began, resulting in the loss of all data. (All available tape drives were being used to store input data, and none was available to store output.) Later, as disk drives were developed and BRL began to obtain them, we were able to write to disk and save the first part of the run.

- The third point implied in this vignette is more of a relentless progression around a spiral curve which begins slowly, but whose radius is ever decreasing, resulting in an ever-sharper curve. It is the ever-faster increase in the raw computing power and capability of computers.

In the mid-1960s, a component-level analysis of a not-very-complex truck to a single fragment impact was completed only by utilizing the entire computational power of the largest computers available (on either the East or the West Coast) for a period of 8–10 hr. The large matrices necessary for the conduct of the analysis were kept in volatile memory because they were always changing and it was not practicable to work with them if they were on tape. As mentioned above, it was not unusual to lose 6 or 7 hr of computational effort because of tape parity errors. It was the late 1960s and early 1970s before computers had progressed to the point where it was practicable to begin conducting complete point-burst analyses of a truck from all azimuth-elevation combinations in a single run, although single burst points and limited azimuth-elevation combinations had been calculated as the analysis program was developed and compared with full-scale test results.

The three turning points identified herein are considered premiere in the science of vulnerability analysis because they were basically *the tip of the arrow* in the sense that they were some of the initial work done as the field was just being established and was in the process of rapid development. Although the kill criteria established for trucks in the 1960s were based on observed test results, it is probably time for the community to re-examine the criteria. Truck design has changed over the last 25–30 yr, as has the additive packages used in lubricants and coolants. It seems reasonable to assume that these changes have had some effect on the elapsed time required for a truck to lose the capacity for powered movement after the onset of the damage.

The basic method of analytically developing a probability of kill, given a hit for a critical component, has not changed over the last 25–30 yr. True, there have been a number of generations of the "$P_{k/h}$ Program," but each of these generations has added capability to the computer code, without altering the basic premise of developing a probability of kill by developing some type of ratio of component-sensitive area to component presented area. The current efforts to develop the $P_{cd/h}$ GEN methodology with its associated database, and somehow assign a *level of confidence* to the $P_{k/h}$s plus incorporate *rules of thumb* for use by analysts, are long overdue. This effort is a giant step in providing a basis for consistency among all analysts. It is also seen as an outstanding method of immediately disseminating useful test results to a target audience.

The march of progress of computers is known to all, but is probably best appreciated by those who remember *the bad old days* when computers were young and did not nearly have the abilities of even laptop computers today. Conversations with analysts who conducted analyses on those early computers or who worked to develop the current methods of target description should result in many interesting *war stories.*

Biographical Sketch

Mr. Kinsler spent the majority of his professional life as a vulnerability analyst in the Surface Targets Branch of the Vulnerability/Lethality Division of the BRL. He has written or co-written more than 70 technical reports covering most phases of vulnerability analysis, ranging from the unconventional attack of conventional targets through the more conventional vulnerability analyses conducted today.

His practical experience ranges from the design and conduct of large full-scale test programs through smaller hands-on studies in demolitions research. He also has extensive experience in the exploitation of foreign materiel.

6. Milestones in Modeling the Vulnerability of Military Personnel to Fragmenting Munitions

William J. Sacco and Wayne S. Copes

This is a short chronicle of milestones in modeling the vulnerability of military personnel to fragmenting munitions.

6.1 Milestone 1: Current Incapacitation Criteria. Currently used criteria for estimating the probability of incapacitation from a single fragment wound were published in 1965. The probability of incapacitating a soldier given a *hit* by a fragment is modeled as a function of body region, an infantryman's tactical role (attack, defense, supply, or reserve) and the time after wounding (30 s, 5 min, 12 hr).

These criteria are based on a complex set of experiments, assessments by physicians and experienced combat soldiers, and analyses of the effects of four steel fragments: the 0.85-grain steel sphere, and the 2.1-, 16-, and 225-grain steel cubes. The original wound ballistics assessments of these fragments were conducted during the period 1954–1960 (references 1, 2, 3, 4, and 5).

Criteria development began with fragment firings into animals and excised animal organs. The resulting data were the basis for relationships between the mass and impact velocity of a fragment and its velocity retardation and the hole size created in various organs.

Wound Classes (see Table 1 for examples) were established to define the degree of damage to anatomic structures. Pertinent wound classes vary with the mass and striking velocity of the fragment being evaluated. For example, the 0.85-grain steel sphere may, for any impact velocity, be incapable of producing the severe skull fragmentation or depressed skull fracture of wound class B_2.

Table 1. Example Wound Classes

Wound Class	Description
B_2	Skull; severe fragmentation or depressed fracture
B_7V_2	Bone; with concurrent cardiovascular wound
B_7V_1	Bone; with concurrent cardiovascular wound
H_1	Hand; any wound at this velocity
K_2	Ureter, Urethra, and Urinary Bladder; puncture wound with leakage
N_7V_7	Nerve; with concurrent cardiovascular damage
P_7	Lung; puncture with small blood loss

Solider incapacitation was related to limb functioning. Table 2 lists 16 combinations of limb disabilities or deficits, called Functional Groups. Deficits were described as either loss of fine muscular coordination (F) or total loss of function (T). Table 2 also gives the percent incapacitation for each tactical role by Functional Group. For example, injuries in Functional Group I cause no disability in any tactical role. Injuries in Functional Group XV cause a 100% disability to soldiers in the assault role, but only a 50% incapacitation to soldiers in the defensive role.

That difference occurs because the functioning of the legs required for soldiers in the assault is not required for soldiers in the defense. Estimates of percent disability for Functional Groups were made by physicians and experienced combat personnel. Wound Classes were assigned to Functional Groups by physicians. The assignment of a Wound Class to a Functional Group may differ with the post-wounding time of the assessment (Table 3). For example, lung puncture with small blood loss (P_7) results in no disability 30 s after injury (Functional Group I), but by 30 min it results in substantial disability (Functional Group X).

The process of estimating the incapacitating effects for particular fragments began after the Wound Classes pertinent to the four basic fragments were identified and assigned to functional groups at various post-wounding times. Fragment striking velocities of 1,000, 3,000, and 5,000 ft/sec were assumed. The *projection* process for deriving those estimates was laborious,

Table 2. Incapacitational Functional Groups and Percent Disability by Tactical Role

Each Arm	Each Leg	Functional Groups	Assault	Defense	Reserve	Supply
N,N	N,N	I	0	0	0	0
N,N	N,F	II	50	25	75	25
N,N	F,F	III	75	25	100	50
N,N	N,T	IV	100	50	100	100
N,N	T,T	V	100	50	100	100
N,F	N,N	VI	50	25	75	25
F,F	N,N	VII	75	50	100	50
N,T	N,N	VIII	75	75	100	75
T,T	N,N	IX	100	100	100	100
F,F	F,F	X	75	75	100	75
F,F	F,T	XI	100	75	100	100
F,F	T,T	XII	100	75	100	100
F,T	F,F	XIII	100	100	100	100
T,T	T,T	XIV	100	100	100	100
N,N	F,T	XV	100	50	100	100
N,F	F,F	XVI	75	50	100	75

Notes: N - No effect.
F - Loss of fine muscular coordination.
T - Total loss of extremity function.
(Note - No attempt is made to differentiate between the right and left limbs.)

requiring several man-months of effort. Cross sections of the human anatomy were used (reference 6). They detail the anatomic structures of a male, 69 in tall, weighing 155 lb, in 108 horizontal cross sections. Figure 1 is an example of a computerized cross section. The projection process for assessing one fragment mass, at one striking velocity, for one tactical role and post-wounding time is summarized below:

Table 3. Effect of Post-Wounding Time on Assignment of Functional Group

Wound Class	Description	30 sec	5 min	30 min	12 hr	24 hr	5 days
B_2	Skull; severe fragmentation or depressed fracture	XIV	XIV	XIV	XIV	XIV	XIV
$B_?V_2$	Bone; with concurrent cardiovascular wound	VI	X	XIV	XIII	XIII	XIII
$B_?V_1$	Bone; with concurrent cardiovascular damage	IV	XV	XI	XI	XI	XI
H_1	Hand: any wound at this velocity	VI	VI	VI	VI	VI	VI
K_2	Ureter, Urethra, and Urinary Bladder; puncture wound with leakage	I	I	I	X	XIV	XIV
$N_?V_?$	Nerve; with concurrent cardiovascular damage	VI	X	XIV	X	X	VI
P_7	Lung; puncture with small blood loss	I	III	X	X	X	XIV

(1) Using hole size and retardation data derived from animal tests, wound tracks are projected onto cross section for fragment impacts occurring from the front of the body (0° azimuth). The wound track specifies the damage to each anatomic structure the fragment contacts.

(2) For each wound track, the functional group associated with the **most serious Wound Class** and its percent disability (0, 25, 50, 75, or 100%) are identified and recorded.

(3) The procedures described in 1 and 2 are repeated for fragment impact azimuths in 60° increments around the body.

(4) The procedures above are repeated for each of the 108 anatomic cross sections.

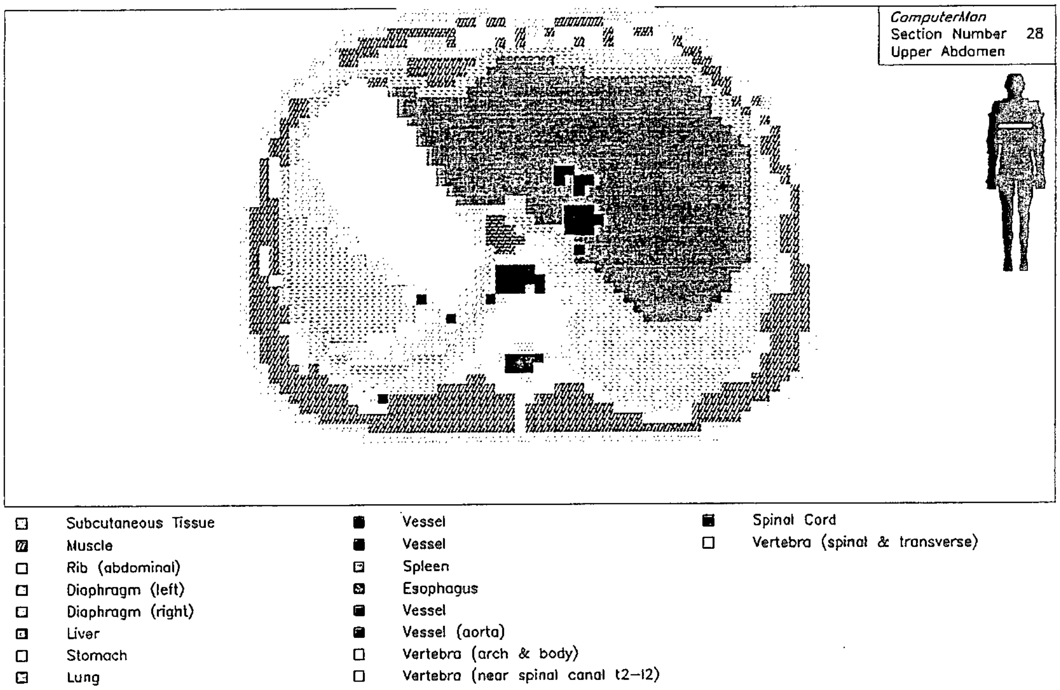

Figure 1. ComputerMan Cross Section.

(5) The *probability of incapacitation* (for the specified fragment mass, striking velocity, tactical role, and post-wounding time) is the ratio of the weighted sum of the body areas vulnerable to 0, 25, 50, 75, and 100% incapacitation to the total body area over all projection azimuths. (Note that the resulting ratio is actually an expected percent incapacitation, not a probability of incapacitation.)

Steps 1–5 are repeated for each fragment mass and striking velocity combination for a particular tactical role and post-wounding time. Regression analyses were performed to relate incapacitation probabilities for a function of mass and velocity.

The methodology used to derive the estimates considered only the effect of the single most incapacitating injury on each wound track assessed, thereby disregarding the individual or synergistic effects of other injuries on that track.

6.2 Milestone 2: Current Serious and Lethal Injury Criteria. In the late 1960s, the need for improved helmets and body armor for ground troops was widely acknowledged. Items such as the M1 helmet and Standard B ballistic nylon vest have been in the U.S. inventory largely unchanged since their introduction 15–25 yr earlier. The methodology used to estimate the protection afforded by such items is an adaptation of that used for the effectiveness evaluation of fragmenting munitions (references 7 and 8). However, the incapacitation criteria used in munitions evaluations were deemed inappropriate for the evaluation of protective items intended to enhance soldier survivability. Efforts were undertaken to develop criteria for predicting the probability of sustaining *serious* or lethal injury from fragment wounds, which had historically been the most frequent cause of death and injury to U.S. troops. The resulting wound criteria were published in 1969 (reference 9). Definitions of *serious* and *lethal* wounds given in reference 9 are:

- Serious: "probably result in hospitalization (e.g., wounds to the cranial, pleural, and peritoneal cavities; larger muscle wounds; and vascular, nerve, and skeletal damage)."

- Lethal: "probably result in death (e.g., injuries to the head, larger vessels, lungs, central nervous system, and abdominal organs)."

6.3 Milestone 3: ComputerMan Simulation of Incapacitation. ComputerMan was developed at the Chemical Systems Laboratory (CSL) (now Chemical Research and Development Command) (reference10) and refined at the BRL (references 11 and 12). The initial objective of ComputerMan was to reduce the time and cost of the projection process (see Milestone 1).

The ComputerMan contains a representation of the human male described in Milestone 1. A grid of 5-mm × 5-mm squares (*cells*) was overlaid on each cross section. The most vital tissue that occupied the cell was assigned to the cell.

Random projectile trajectories or *shot lines* can be simulated by scanning the cross section, or single trajectories can be projected by specifying the coordinates for the point of entrance and for one other point along the shot line. Thus, a user may make production projection runs which include standardized body components (head and neck, thorax, abdomen, pelvis, upper limbs, and/or lower limbs), individual or groups of horizontal cross sections.

In addition to satisfactorily duplicating the manual projection procedures, verified by comparing incapacitation values generated by both methodologies, the ComputerMan provided these additional advantages:

- Reduction in time for each ballistic evaluation from several man-months to less than one man-day, with commensurate cost savings.
- Computation of variable azimuth and evaluation wound tracks not previously feasible.
- Computations for variable personnel postures.

6.4 Milestone 4: ComputerMan Applications and Extensions. Soon after its development in the late 1970s, the CRL ComputerMan was applied to a (1) fixed-wing and rotary-wing pilot incapacitation assessment, and a (2) maxillofacial fragment injury study for the U.S. Army Dental Command.

6.4.1 BRL Extension to ComputerMan. During the 1980s BRL (now part of the ARL) made many enhancements and modifications to ComputerMan (reference 11). The program can be operated in several modes: point burst, grid shot, and single shot. In all modes, the user may select:

- Protective clothing to be worn by the soldier.
- Projectile speed, shape, mass, and density.
- The level of output detail.
- The position of the soldier (e.g., standing, sitting, crouching, and prone).

6.4.2 ComputerMan Multiple Wound Methodology. A penetrating injury often involves multiple organs. In estimating incapacitation, the CRL ComputerMan considered only the most severe injury along the wound track. A version of the ComputerMan incapacitation model (reference 12) accounts for all injuries along the wound track by establishing rules for combining limb dysfunctions, increasing the number of functional groups, and bounding incapacitation computations. The bounding is necessitated by the ambiguity associated with combining the limb states F (loss of fine muscular coordination) and F; the ambiguity is whether multiple Fs (arising from different injuries) result in an F or a T (loss of total muscular coordination). The ComputerMan model can assign an F to compute a *minimum effect* or a T to compute a *maximum effect.*

In reference 12, it is shown that the most severe wound method underestimates incapacitation relative to the multiple wound method and that the discrepancy between the two predictions is greater as multiple hits are considered.

6.5 Milestone 5: New Directions. The Live Fire Test Program (LFTP) of OSD is sponsoring the refinement of models for prediction of serious, lethal, and incapacitation effects of injury caused by combat injury mechanisms. The work is motivated by the importance of these injury mechanisms in combat, the limitations of current criteria, and the availability of contemporary data from trauma and strength/endurance databases.

6.5.1 Motivational Detail. The LFTP, mandated by Congress in 1987, sponsors realistic testing of major U.S. conventional weapons systems and platforms emphasizing assessment of crew casualty vulnerability.

Most weapons platforms require personnel operators who can be categorized into five groups: exposed crews (dismounted infantry, airbase support personnel); armor crews; aircraft crews; naval crews; and tactical vehicle crews.

Combat incidents and Live Fire Testing of such systems as the Bradley Fighting Vehicle have shown that crew casualties substantially affect system performance. The incapacitation assessment for each crew member is based on infantry models, as there are no incapacitation models for other military specialties and combat roles. Moreover, crew lethalities are not assessed. A more complete and accurate assessment would predict crew incapacitation levels (specific to the military specialty and role) and survival rate.

Injury databases from trauma centers and strength/endurance databases from exercise science center and health clubs provide an opportunity to refine modeling predictions of incapacitation and survival/death outcomes. Indeed, many of the cited combat injury mechanisms also occur in civilian life. Injuries from assaults, guns, burns, explosions, industrial accidents, and motor vehicle collisions abound and are well documented. Trauma databases contain many single and some multiple mechanism events with thorough descriptions of injuries, treatments, and outcomes. The strength endurance databases may provide validity checks for the many assessments required to extend incapacitation models to many military specialties/combat roles.

Recognizing the critical need to improve and standardize crew casualty assessments among services and the opportunity offered by the contemporary databases, the Live Fire Test Office has sponsored research to utilize contemporary data and methods to validate/update incapacitation, serious and lethal injury criteria for fragments.

6.5.2 Current Research.

- Incapacitation

The research needed to accomplish validate/update incapacitation by fragments has been characterized by three interfaces:

(1) Insult-injury: A fragment results in injury to the military person. Consideration of such insults begin with their effect on the person. The attenuating effects of protective equipment are not considered. To quantify the casualty process, it will be necessary to develop, adopt,

or modify an existing injury taxonomy, sufficiently robust to accommodate all military fragment injuries.

(2) Injury-degradation of elemental capabilities: Injuries may result in the degradation of a military person's element capabilities (i.e., the fundamental descriptors of his/her ability to perform military duties). Here again, specification of those elemental capabilities is required. It is anticipated that they will include physical, sensor, and cognitive capabilities.

(3) Degradation of operational capabilities: The ultimate objective of the process is to be able to consistently estimate the effect of any injury(ies) on the ability to perform specific military duties. The elemental capabilities defined in the second interface must, therefore, be capable of being translated into the operational capabilities required by specific military jobs.

The stated goal is to complete the revised process by 1997.

- Lethality A review of the current serious/lethal wound criteria found:

(1) Inadequate documentation,

(2) The broadness (and resultant limitations) of the definition of serious injury,

(3) The presumption that only the most serious injury on a wound track is needed to assess human response, and

(4) The inability to account for increases in survival probabilities from medical and logistical advances.

An objective of the current research is to use contemporary data and methods (e.g., severity scoring systems) to validate/update serious and lethal injury criteria for fragments.

The new serious/lethal criteria are based on patient data from the American College of Surgeons Major Trauma Outcome Study (MTOS) (reference 13). The MTOS database contains demographic, cause of injury, injury severity, and outcome data on contemporary trauma patients, most treated in U.S. trauma centers. The modeling process consists of the following steps:

(1) Derive relationships between contemporary measures, of injury severity [Abbreviated Injury Scale, Injury Scale, Injury Severity Score (ISS) and Anatomic Profile (AP)] (references 14, 15, and 16) and survival probability using MTOS data.

(2) Collaborate with AIS developers and ARL personnel to enable ComputerMan to generate AIS codes for each injury along a wound track.

(3) Use ComputerMan to generate wound tracks and associated values of measures of injury severity for the standard fragment mass/velocity combinations, by body region and the entire body.

(4) Estimate the resulting probability of survival using the relationships described in (1) above.

The stated goal is to complete the research by December 1994.

6.6 References

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Biographical Sketches

Bill Sacco has more than two decades of experience in medical research and databasing. He graduated from the California State Teachers College in 1951 with a B.A. in Mathematics. He received an M.Ed. from Loyola College (Baltimore) in 1960 and a Ph.D. in Applied Mathematics from the University of Delaware in 1969. From 1953 to 1980, Dr. Sacco was employed by the

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7. Excerpts on Vulnerability

by Joseph Sperrazza

7.1 Evolution of Kill (Damage) Criteria. A "kill" definition is a general statement of the effect desired. "Kill criteria" specify either target degradation performance or damage that will produce a kill. They are influenced by many factors. Usually defined separately for each target class (tank, missile, truck), it is not unusual for a given kill type to apply to several difference target classes. Damage criteria also may be defined with respect to particular tactical situations or with respect to a major target function (mobility, firepower). In addition, damage criteria may be defined with respect to a single, specific mission; for a class of missions; or averaged over all missions. Damage criteria may also be defined with respect to certain classes of weapons, a given level of kill of a target being acceptable for a weapon for which the target is a secondary target, but not acceptable for a weapon for which the target is primary. Also, since not all attacks will be completely and immediately successful, it is often desirable to provide quantitative evaluation of partial and/or delayed kills. Hence, it is not unusual to specify damage which ranges from a desirable outcome (an immediate, complete kill) to the least acceptable which still has military significance. In many cases, the maximum performance degradation of a target does not occur until some interval of time after suffering the damage. Hence, a set of kill criteria often is expressed as a combination of the desired performance degradation and the time after attack within which this degradation must occur. These time criteria must be consistent with both the tactical requirements and the behavior of the particular target subsequent to application of the damage mechanism.

To be complete, damage should be related to the overall burden inflicted on the enemy by the attacker. For example, for a tank target, complete destruction not only prevents accomplishment of its mission, but also costs the enemy one easily counted unit of its military power. However, with many targets the situation is more complex because the damage inflicted may be repaired or the

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Note: The references in this section have retained the original numbers given them in the AMSAA report.

target is regenerated in some way. For example, a damaged truck may be repaired or rebuilt. Hence, a complete set of kill criteria should specify not only the desired result (whether immediate or delayed) in terms of target performance degradation, but also the expense to the enemy in terms of target repair or replacement time and/or cost.

Six target classes are described in the paragraphs that follow:

1. Personnel
2. Armored Vehicles
3. Transport Vehicles
4. Artillery
5. Air Defense Systems
6. Tactical Missiles (with and without launcher).

7.1.1 Personnel. At very early stages in man's history, the first aggressive weapons were simple tools and hunting devices. As time progressed, hand-to-hand fighting was carried out with axes or maces of stone, bronze, and iron heads. Later, they were replaced with the more wieldy sword. Bows and arrows demonstrated their efficacy against troops, especially protected by body armor, at the Battle of Crecy in 1346. In the 14th century, the use of firearms and explosives became more prevalent in war, and they dominate in today's world.

Several decades prior to World War I, attempts were made to quantify the casualty producing effects of weapons. Unfortunately, the word casualty has had almost as many meanings as there have been authors of the numerous publications dealing with the subject. The word criterion usually has to do with the mathematical function (equation or law) of the most suitable combination of the physical characteristics (parameters) of a penetrator, such as its mass, shape, density, and velocity with which to relate a casualty.

One of the oldest and probably the simplest criterion (from a doctrine due to the German Army, reference 23) and one that has been used extensively by analysts, is that a penetrator would kill (the meaning of casualty in this case) if its kinetic energy equals or exceeds 8 m-kg (58 ft-lbs). It would not kill if its energy were less. In the book "Ordnance and Gunnery" (reference 24), criteria for several types of wounding are given, based on the ability of a missile to penetrate into pine wood. For example, if the penetration is 7.9 mm (0.31 inches), then only a slight contusion of the skin is said to result; on the other hand, if the penetration is 16 mm (0.63 inches), the resulting wound is said to be "dangerous." A "very dangerous" wound is said to result if the penetration is 30 mm (1.18 inches). In Missile Casualty Report No. 15 (reference 25), Lamport suggests that a casualty-producing wound should be assessed in terms of days lost from full service.

In 1945, McMillen and Gregg (reference 26) of Princeton concerned themselves with discovering the minimum energy required to produce an "incapacitating wound." They mention that there was a growing tendency to discount the 8-m-kg rule as being the proper minimum. Asserting that wounds can produce various degrees of severity, they decided to consider only "fatal" or "severe" wounds. They suggested that such wounds would be caused when a missile penetrated into and struck certain "vulnerable" regions of the body with a residual, critical velocity of not less than 75 m/s. They defined these regions as being all the vital organs, eyes, nerves, and blood vessels having a diameter greater than 0.25 cm and tissues of cavities such as the peritoneal, pleural, pericardial, vertebral canal, and cranial. All the rest of the body (including muscle, fat, tendons, bones, etc.) was considered to offer protection to the vulnerable regions.

Using penetration and retardation data obtained with steel balls of 1.6, 3.2, and 6.4 mm in diameter (approximately 0.02, 0.14, and 1.1 grams, respectively) fired through human skin, cat muscle, and beef bone, estimates were made (reference 27) of what parts of the total vulnerable region of a human male body (using drawings of anatomical cross-sections in reference 28) could be penetrated and impacted with at least the required residual critical velocity. There existed no sharp demarcation at the 8-m-kg energy level. Furthermore, significant values of vulnerable areas were evident for energies much smaller than 8 m-kg. Because of their postulate that certain parts of the body are invulnerable, then as mass and velocity of the missile increase without limit, vulnerable area (for any particular missile trajectory) approached a limit less than the total presented area of the body for that direction. Thus, for example, if a missile strikes the anterior aspect, the ratio of the maximum vulnerable area to the total presented area is 0.43.

Post World War II experiments carried out at the Army Chemical Center contradicted the existence of such large invulnerable regions as proposed by McMillen and Gregg. Penetrators (even quite small ones of the order of 0.02 grams) can penetrate deeply at high striking velocities and can cause damage to the vulnerable parts such as blood vessels, nerves, etc.

Recognizing the necessity of having a quantitative casualty criterion for evaluation of antipersonnel weapons, T. E. Sterne in March 1951 (reference 29) reanalyzed McMillen and Gregg's data. He expresses $P_{K/H}$ (that a wound is either fatal or severe) as a function of mv/A, where m is weight of the penetrator, v is its striking velocity, and A its average cross-sectional area. He chose mv/A because it related to penetration.[*] He fitted three straight lines to the data and arrived at the following provisional casualty criteria for fatal or severe wounds:

$$P_{K/H} = 0 \qquad \text{for } mv/A \le 0.48$$
$$P_{K/H} = 0.48\,(mv/A - 0.48) \qquad 0.48 \le mv/A \le 1.22$$
$$P_{K/H} = 0.36 \qquad mv/A \ge 1.22$$

where the units of mv/A are in 10^5 gm/cm-s.

In May 1951, Sterne (reference 31) reinterpreted some of the penetration data used by McMillen and Gregg and reformulated some of the penetration laws. He discarded their concept that a vulnerable region should be struck at a critical velocity of not less than 75 m/s and decided in favor of a critical energy of 2.5 × 10 ergs.[†] He established a dependence on $P_{K/H}$ on m and v somewhat different from what appeared in reference 29.

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[*] Note: In addition, Gurney suggests in reference 30 on the basis of hydrodynamical considerations, that mv^3 (or equivalently $m^{1/3v}$ or mv/A, ignoring shape factor) should be a suitable parameter for wounding since he thought it should relate to the diameter of the temporary cavity.

[†] Equivalent to causing a 2.0-cm^3 temporary cavity in tissue according to some work done by Harvey and Butler in 1945.

In November 1951, reference 32 by T. E. Sterne was published. The note summarized the results of experiments carried out by the Biophysics Division, Army Chemical Center, in which three newly proposed types of hand grenades were tested against goats. The grenades consisted of spheres of pentolite explosive on whose surface were attached (pasted on) preformed steel fragments. The total weights of the grenades ranged from 340 to 410 grams; the weights of individual fragments* were 0.04, 0.14, and 0.28 grams with initial velocities of 2,380, 1,680, and 1,490 m/s, respectively. Each grenade was detonated at the geometric center of an array of several goats placed side on to the burst at distances of 1.5, 3.0, and 4.5 m (some goats were placed at 18 m, but so few hits and of such minor nature were obtained that the results were ignored in the study).

Each goat was autopsied after each experiment, each wound track mapped out, and each wound assessed on the basis of what level of incapacitation a man would experience had he been subjected to an equivalent wound. Three categories of incapacitation were considered: incapacitation within five seconds ("K" casualty); incapacitation within five minutes ("A" casualty); and fatal or severe wounding ("B" casualty). From these basic data, Sterne inferred estimates of $P_{K/H}$ associated with each combination of fragment weight and fragment velocity (taking into account loss in velocity of a fragment due to air drag). He plotted these probabilities as a function of mv/A for the three levels of incapacitation. Confidence limits (established from statistical theory) were included in the plots. The results did not take into account differences in amount of protective tissue offered by the human body as compared to goat targets. (Details of the test are contained in reference 33.)

In reference 34, Sterne pooled the data of reference 32 together with newly acquired data of the Army Chemical Center with two more types of grenades tested against a similar array of goats. One of the grenades consisted of 950 1.5-mm steel spheres (0.017 grams) in a matrix of aluminum, surrounding a pentolite sphere; the initial fragment velocity was about 1,440 m/s. The other grenade

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* The number per grenade was:

Fragment Weight	No.
0.04 grams	2,000
0.14 grams	1,100
0.28 grams	750

consisted of 350 rectangular steel fragments of initial dimensions of 2.4 × 2.4 × 1.4 mm (0.06 grams) pasted on the spherical pentolite; the initial fragment velocity was 1,360 m/s. Only the fatal or severe wounding category was considered. The best estimate of $P_{K/H}$ as given by the number of incapacitating wounds divided by the number of hits, was plotted vs. mv/A. It was obvious from this plot that the curves of reference 29 fell seriously below an average curve that could be passed through the datum points.

In May 1952, a formal agreement on wound ballistics was promulgated and agreed upon by the Chemical Corps, Ordnance Corps, and Medical Services in which the Biophysics Division of the Army Chemical Center, Chemical Corps, was to experimentally determine incapacitation effects of wounds caused by fragments, bullets, etc., on men. While awaiting acquisition of wound ballistic data under this program, the Ballistic Research Laboratories (BRL) issued a memorandum on 4 January 1955, recommending tentative standard wounding criteria for nonstabilized fragments as follows:

". . . a. That for the present time, the curve of [reference 29] be used by persons computing lethal areas for both small and large fragments.

b. That the curves of [reference 32] be used as limited standards until further notice for incapacitation within five seconds or within five minutes.

c. That the '8-meter-kilogram' rule be used on a very limited basis, if at all, and then with the understanding that it tends to underestimate the lethality of small fragments.

d. That, whenever investigations or evaluations of lethality are conducted, the conducting agency explicitly state which of the above criteria are being used. . ."

As a result of the 1952 agreement, the Army Chemical Center initially carried out a comprehensive series of experiments with "chunky" shaped (spheres/cubes) steel fragments. The BRL was responsible for analyzing the data and for generating new casualty criteria.

The essentials of the program were as follows. Retardation laws for a fragment under consideration were established by experimentation with various layers of an American soldier's winter uniform, combat boots, and helmets; goat tissue such as skin, muscle, liver, lung, etc.; and goat bones such as ribs and sternum. Special guns were used to project the fragments singly; standard velocity measuring techniques were used to measure the entering and exiting velocity of a fragment.

Goats were subjected to single fragment hits upon selected regions. Gross clinical observations were made at regular time intervals until time of death or sacrifice. X-ray pictures were sometimes taken to observe wounds and to locate the fragment. Each goat was dissected, a careful mapping of the wound track made, and the pathology of the wound described. Medical doctors studied the effect of each wound on the ability of the goat to function and then estimated how similar wounds would affect the ability of a soldier to function.

Next, hypothetical wound tracks were traced through horizontal anatomical cross-sections of a standing human male. Six directions, at 60° intervals, were considered for each cross-section (for as many as 100 cross-sections) starting with the anterior direction. A sufficient number of tracks were considered for each direction so that there was complete overlapping between tracks when size of the fragment was taken into account. From the retardation laws established previously, and a knowledge of the impact velocity, inferences were made of the residual velocity of the fragment along the track.

The wounds were categorized into functional (or disability) groups that related to the behavior of the extremities (arms and legs).* Thus, disability was expressed in terms of usefulness of the arms and legs. An extremity need not necessarily be hit to become disabled since a hit on certain parts of the spinal column, for example, could render all extremities inoperable.

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* The principal medical assessor for the first series of tests used 10 such groups; medical assessors for subsequent series expanded them into 16.

Some basic concepts were introduced in the definition of casualty. The assessments considered the ability of a soldier to perform diverse prescribed duties. Four tactical situations were included: assault, defense, supply, and reserve. The ability to see, hear, think, and communicate were considered as a fundamental necessity in all of the situations; loss of these abilities is assumed to be incapacitating. General descriptions of the duties are contained in reference 35.

Time after wounding is a critical parameter. Seven discrete times after wounding were considered which ranged from 1/2 minute to 5 days. A wound could fall in different disability groups depending on the time after wounding. The disability groups were assigned percentages which were associated with the degree of effectiveness with which a soldier could perform his duties as a result of the wounding.

A comprehensive analysis of these latter data led the BRL to publish in 1956, Report No. 996 (reference 36) by Allen and Sperrazza, which announced that the conditional probability $P_{K/H}$ that a random hit by a steel fragment would incapacitate a helmeted infantry soldier could be expressed by the relation.

$$P_{K/H} = 1 - e^{-a(mv^{\beta} - b)^{\eta}}$$

where m is weight of the fragment, v is striking velocity, e is the base of the natural logarithm, and a, b, η, and β are constants determined from the experimental data. The best value of β was found to be 3/2. The law implies a much stronger dependence of wounding on striking velocity rather than weight of the penetrator. It was suggested at that time that the relation be applied for evaluating effectiveness of antipersonnel weapons.

Since 1974 the Swedish Government has carried out a series of wound ballistic experiments, primarily with bullets. Their studies were concerned primarily with the formations and growth of temporary cavities. A survey of the work is contained in reference 37. Moreover, the Swedish Government has sponsored a series of symposia on wound ballistics, and their proceedings appear as Supplementa (reference 38) to the Acta Chirurgica Scandinavia. The proceedings also contain a comprehensive description of investigations carried out by other countries.

Although in war, bullets are second to fragments in terms of casualty production, the literature is replete with descriptions and characteristics of different bullets and their projectors, i.e., handguns, rifles, and machine guns. The wounding potential of bullets is more difficult to forecast because they spin. Reference 37 gives a comprehensive portrayal of bullet/target interaction.

The stability factor of a bullet should exceed 1.3 to 1.5 to assure reasonable behavior in flight. In muscle tissue, or its simulants, bullets of low stability can tumble quickly, making it difficult to accurately estimate wound track dimensions. To compound the problem are the many different types of bullets available both commercially and militarily.

In spite of the many parameters associated with bullets, analyses of experimental data of the Army Chemical Center show that estimates of bullet incapacitations follow the same general law as for fragments. In particular, wounding potential is a function of $mv^{3/2}$, where m is bullet weight and v is striking velocity.

Because of this strong functional dependence on velocity, the U.S. Armed Forces were able to markedly reduce bore size of their military rifles from the previous North Atlantic Treaty Organization (NATO) standard of 7.62 mm to 5.56 mm. Concurrent with this smaller bore are significant reductions in total weight of rifle and weight of each round, but with a significant increase in muzzle velocity.

Penetrating fragments and bullets can produce quite different wound tracks. In personnel targets, bullets of low stability can tumble. On the other hand, fragments generally produce straight wound tracks. Although high velocity penetrations are accompanied by significant lateral translation of tissue and large temporary cavities, ensuing incapacitations relate primarily to the size and depth of the permanent cavities (reference 39). This latter reference also reports that energy spent in forming a temporary cavity usually can be absorbed with little residual damage, especially for the more elastic tissues of the body. However, relatively inelastic tissue can suffer damage due to temporary cavitation. The permanent cavity is characterized by destroyed, crushed tissue/components.

Finally it should be recognized that in an environment of optimized fragmentation projectiles, e.g., grenades or bomblets, delivered either by surface weapons or aircraft, a soldier can experience multiple fragment wounds. In such situations, synergism can occur. By that it is meant that although any one wound may not be sufficient to cause a significant level of incapacitation, the combination of two or more of relatively minor wounds can be quite incapacitating. Mathematically synergism can be expressed as

$$x = \sum_{i=1}^{i=m} a_i x_i$$

where x is the total level of incapacitation, x_i = incapacitation associated with each wound, and a_i are coefficients determined experimentally. Because of the enormous amount of work required to develop casualty data even for just two simultaneous wounds and because weapons designers prefer a conservative answer to the effectivity of a system, each fragment hit is considered to be independent of any other. Thus, total incapacitation is found from

$$\begin{aligned} P_K &= 1 - (1 - P_{K/H_1})(1 - P_{K/H_2})\ldots(1 - P_{K/H_n}) \\ &= 1 - \prod_{i=1}^{n} (1 - P_{K/H_i}) \end{aligned}$$

where P_{K/H_i} is the incapacitation associated with each fragment.

Vulnerability of personnel to air blast depends primarily on its intensity (peak over pressure) and duration. Biomechanical criteria consider the following elements (reference 40):

Blast Loading:

This is a key parameter. Actual pressure-time histories must be determined spatially on anatomical components.

Biophysical Interaction:

Required is a detailed understanding of the transfer of blast loadings to each biological component and dissipation of the energy within the component.

Biological Response:

Identification, quanitification, and monitoring are required of the biological response to the blast loading. Generally, animal species are studied experimentally; extrapolations are made to humans.

Biomedical Tasks:

Evaluations must be made of degraded task performances arising from the incapacitating effects of blast.

Hazards Assessment:

Biomedical criteria for assessing hazards involves learning levels of blast that are "safe," those that result in degraded performance, and those associated with low, intermediate, and high levels of lethality.

Blast effects on humans are separated into three phases (reference 41 and reference 42), namely;

(a) Primary blast - Injuries related with peak over pressure.
(b) Secondary blast - Injuries caused by penetrating and nonpenetrating fragments.
(c) Tertiary blast - Injury resulting from translation of the body.

For the most part, injuries suffered from primary blast are those which result in loss and crushing of internal organs, nervous system, and lungs. Injuries suffered by secondary blast are those produced by fragments while tertiary blast effects are similar to those of total body impact with other objects.

7.1.2 Armored Vehicles. Tanks are emphasized because of their importance on the battlefield. Threats capable of defeating tanks are land mines, shaped-charge warheads, or armor-piercing kinetic energy rounds. Some results of extensive firings against tanks with such ordnance were summarized by Zeller (reference 43). Major components are:

1. Ammunition
2. Crew compartment/crew
3. Engine compartment
4. Fuel compartment/fuel
5. Gun tube
6. Running gear and suspension
7. Fire control

A further subdivision of the running gear and suspension is:

1. Track front
2. Track edge
3. Hubs
4. Wheels
5. Others including rollers, shock absorbers, etc.

Primary kill categories are mobility, M, firepower, F, and K for loss of the entire tank. We shall illustrate defeat criteria for a tank as they relate to military function.

A medium tank is a heavily armored, track-laying vehicle equipped with a large caliber, high velocity gun. The vehicle is designed to defeat and destroy enemy armored forces with a combination of battlefield mobility and firepower. It is designed to be invulnerable to many types of weapons which are capable of defeating "softer" (i.e., less well armored) targets. For a tank to perform at full potential, it must remain mobile and it must be capable of employing its firepower effectively. Defeat criteria are keyed to loss of mobility or loss of firepower. A catastrophic kill is also included as it denies economic repair of battle damage. A tank is said to have sustained a K-kill when the damage is immediate and massive and is not economically repairable. Such damage is typically the result of ignition of the basic load of main gun ammunition with resultant fire and explosion, or the ignition of onboard fuel.

A tank is said to have sustained an M-kill when damage prevents the tank from executing controlled movement and the damage is not repairable by the crew on the battlefield. A tank may suffer an M-kill because of a broken track or damage to the power train. Additionally, a mobility kill may be achieved if the driver is incapable of controlling the movement of the tank because of damage to its controls. Wounding or killing the driver alone does not constitute an M-kill because other crew members can drive.

An F-kill is achieved when damage prevents the crew from delivering aimed fire from the main gun on a target and the damage is not repairable by the crew on the battlefield. Damage to the gun itself (to include its elevating and traversing systems), fire control, and crew will contribute to a firepower kill. Again, once a K-kill is achieved, the conditions for an F-kill are satisfied.

An M-kill or F-kill is achieved when *either* a mobility or firepower kill is achieved. Defeat of any components which result in loss of mobility or firepower results in an M-kill or F-kill. Obviously, achieving a K-kill satisfies the M-kill or F-kill criterion.

7.1.3 Transport Vehicles. In addition to armored vehicles as targets, there are those military vehicles which are unarmored and used to transport supplies, military equipment, or personnel and for towing guns, trailers, etc., on or off paved highways (reference 44). This type of vehicle received little or no attention prior to the Vietnam conflict.

As an example, the Soviet truck ZIL-130G represents a "family" of vehicles which use many common components such as engine, chassis, cab, and drive trains. Therefore, analytical values derived for the ZIL-130G are applicable to many components of numerous other trucks in the "family." See reference 45 by Kruse and Brizzolara. Additionally, Kinsler and Wilson (reference 46) summarize damage criteria for transport vehicles.

The primary function of transport vehicles is moving materiel and troops. If a truck is incapable of controlled movement, it obviously cannot fulfill its mission. Thus, the defeat criteria for a truck are keyed to loss of mobility or to the time required to repair the truck once it is damaged.

A truck is said to have sustained a K-kill when damage is immediate and massive, and the truck is fit only for salvage. Such damage is caused usually by ignition of the onboard fuel which develops into an uncontrollable fire, or severe damage caused through violent reaction of the cargo.

To achieve an M-kill, sufficient damage must be done to a component so that the truck will become incapable of controlled movement within one of the following time categories:

Kill Level	Time to Failure, min
A	≤ 5
B	≤ 20
C	≤ 40

Once an A-kill is achieved, the B-kill and C-kill levels are satisfied. Similarly, once a B-kill is achieved, the C-kill level is satisfied. However, killing two or more B-kill components will not result in the truck sustaining an A-kill.

The interdiction kill (I-kill) criterion measures the success of an attack in terms of both (1) loss of function, and (2) the time required to make repair. Interdiction kill may be used to measure the success of an attack directed against trucks either in or behind the battle area where no immediate ground follow up is planned. For a component to be capable of sustaining interdiction kill damage, the component must be of such a nature that, if damaged, its loss would either cause the truck to stop or materially detract from the efficiency of operation of the truck.

Once it has been determined that a component is capable of sustaining I-kill damage, it remains to determine the amount of time required to repair the component. Two types of repairs are considered: (1) expedient repair, and (2) thorough repair. Expedient repairs are made only on those components that are absolutely necessary for the continued operation of the truck. When an expedient repair is made, it is done as rapidly as possible without necessarily attempting to return the component to its original condition. Thorough repairs are made on all components that contribute significantly to the performance, safety, and to some extent, the efficiency of the truck. Thorough and expedient repairs for components differ in the following respects:

1. Thorough repair means either the damaged component is replaced or undergoes complete, extensive repair work (usually done in a shop).

2. Expedient repair involves the quickest (either field or shop) type of repair to a component which returns the truck to an operating condition.

In some cases, expedient and thorough repairs for a component are the same. For example, in the case of the coil, the most expedient repair is replacement which also happens to be a thorough repair. Both expedient and thorough repair times are quantitatively classified in terms of the amount of time required to make the repair. The assignment of repair times is based on the following assumptions:

1. Sufficient personnel, parts, tools, and equipment are immediately available to perform the repairs.

2. No time is allowed for transport of repair items to the damaged vehicle, or vice versa.

3. The repairs required are immediately apparent (i.e., no time is lost in the diagnosis).

The repair times are subdivided into the following classes:

$\leq$ 0.5 man-hour
$\leq$ 1.5 man-hours
$\leq$ 8.0 man-hours

7.1.4 Artillery (Towed and Self Propelled). This weapon system consists of elements such as guns (including its fire control), prime movers for towing ammunition and propellants, as well as the crew. The goal is to impose at least a firepower kill (F-kill). A catastrophic kill implies the artillery system is damaged beyond repair. The system experiences an F-kill when it suffers damage sufficient to preclude accurate fire and this damage cannot be repaired in the field. Also assessed is the ability to relocate to another site. Mobility of the prime movers (trucks and weapon carriers) and the crew determines the effect to which this is possible.

7.1.5 Air Defense Systems. Defeat criteria for gun air defense systems are similar to those for artillery; i.e., firepower or catastrophic kill. Anti-air (AA) sites are similar to artillery sites except they include components such as radar, vans, power generators, and interconnecting power lines. Criteria considered are firepower and catastrophic kills.

7.1.6 Tactical Missiles. Missile targets include: surface-to-surface, air-to-surface, air-to-air, and surface-to-air. Missiles exist in several configurations. We consider tactical missiles and restrict our comments to surface-to-air missiles.

A typical surface-to-air missile (SAM) site consists of several missile launchers, radar vans, revetments, and bunkers for storage of missiles which are not in the ready configuration (reference 44). The function of this target is to detect and track attacking aircraft, and then launch and guide the missiles to kill those aircraft. A target of this type represents highly sophisticated and advanced equipment. It can suffer damage either to the command and control system, or the missiles themselves and their launchers. These elements of the site are considered as specific targets, and damage to various systems or subsystems by threats such as blast or fragmentation are considered in detail in assessing their vulnerability.

7.2 Relationships of Kill Criteria to Damage/Degradation. Kill types, damage level, and kill criteria for the preceding six targets are considered using a consistent set of definitions and terminology. Table 7* shows these comparisons. This is not a straightforward task. Vulnerability definitions, methodology, and terminology for each target class, in the past, generally were developed in relative isolation from each other and by different groups of analysts. Thus, while the fundamental concepts may be the same across all target groups, the terminology, the divisions and subdivisions of the problem, and definitions are often somewhat at variance.

Note that the kill definitions for tanks in Table 7* include proposed new definitions for M-kills and F-kills and two proposed new kill types, T1 and T2. These proposals were made jointly by Ballistics Research Laboratory (BRL), Aberdeen Proving Ground, and Armament Division (AD), Eglin Air Force Base, personnel during a joint project to develop a new Standard Damage Assessment List (SDAL) for tanks under Project Chicken Little (reference 47). Reference 48 describes the philosophy underlying the SDAL, and presents the final outcome of the updated SDAL in the form used by vulnerability analysts. The reader is referred to reference 48 for detailed information on the organization, administration, and implementation of the effort to update the SDAL and for details on the voluminous raw data that were recorded. A large body of data was recorded in an attempt to capture the thought processes of the generators of the SDAL. This was done to provide an audit trail for future investigators and to provide data for the construction of a knowledge base to be used in an exploratory effort to develop an expert system which could possibly be used to modify or supplement the SDAL.

The original SDAL, prepared in 1959 (reference 49), was based on World War II tactics and equipment, and was geared to relatively simple analysis tools and techniques. Modern equipment,

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* Not included in this report.

tactics, and analysis tools are markedly different from those of the World War II era. It was judged appropriate to update the SDAL to reflect these changes.

The SDAL cites the degradation in tank combat utility, given the loss of any specific one of the select group of tank components and/or subsystems that appears on the list. In keeping with past practice, the meaning of "combat utility" is the capability of a tank to perform close combat mission, i.e., the task or role assigned to and performed by an individual tank during the conduct of a combat engagement. Further discussion of kill definitions and criteria may be found in references 36, 43, 36, and 50 through 53.

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Biographical Sketch

The following biography includes excerpts from the information assembled on the occasion of his receiving the Department of Defense Distinguished Civilian Service Award.

A native of New York City, Dr. Sperrazza began his career in civilian service to the U.S. Army in 1941 as an engineer in the Arms and Ammunition Division of the Development and Proof Services Laboratory at Aberdeen Proving Ground, advancing to chief of testing for all armaments. After WW II, he joined the Terminal Ballistics Laboratory of the Ballistic Research Laboratories (BRL) where he advanced from Branch Chief to Associate Technical Director. During this time, he made outstanding contributions in the fields of systems analysis, wound ballistics, penetration mechanics, air blast, small arms, and weapons effects.

In 1969–1970, Dr. Sperrazza took the Weapon Systems Laboratory of BRL and formed the Army Materiel Systems Analysis Activity (AMSAA), which immediately became the analysis center of the U.S. Army and the right hand of the Commander of the Army Materiel Command. Under the guidance of Dr. Sperrazza, this outstanding organization evolved to include such programs as air defense and aircraft survivability analysis, evaluations of armored systems, communications and *electronics, helicopter armament studies, and evaluation of infantry and support weapons. AMSAA's logistics documentations, mobility analysis, reliability and maintainability research, systems engineering, and tactical operations studies have supported every aspect of U.S. Army operations.*

In addition, Dr. Sperrazza founded and served as the first chairman of the Joint (Army, Navy, and Air Force) Technical Coordinating Group on Munitions Effectiveness. As a scientist, he established the personnel casualty criteria in most wide-spread use today, first as an analyst in the 1950s, and then again as a participant in Vietnam in the late 1960s-early 1970s.

His nomination for the Department of Defense Distinguished Civilian Service Award concludes:

> "Joseph Sperrazza is a deeply dedicated, impulsive public servant who exhibits the drive of youth, set challenging goals, acts swiftly, is sleepless and restless. Although a creator of destructive weapons, he is a constructive advocate of international good-will and world peace. He is very compassionate and exercises his influence to preserve the dignity of the individual.
>
> Dr. Sperrazza is recognized as a meticulous and exacting scientist. Blessed with inventive genius extraordinary, he has a restless curiosity with a driving persistency which never admits the possibility of defeat. He, with the inspired aid of his associates, has produced an enviable record of creative achievements which have contributed materially to the strength of the military posture of the nation. His active, analytical mind, tempered by sturdy common sense, has an insatiable appetite for broad, in-depth investigations that stimulate pertinent productive research. Dr. Sperrazza displays zeal and enthusiasm that permeate into additional fields of scientific endeavors and human interest and enrich each of those with whom he has contact."

Dr. Sperrazza passed away in June 1998.

8. Historical Vignette on Vulnerability/Lethality Analysis

by Arthur Stein

See also Stein's Addendum on German experience in World War (WW) II as extracted from the North Atlantic Treaty Organization (NATO) Conference Report "Operational Research in Practice," 1958 (reference 13).

The presentation here of personal experiences and viewpoints regarding the development of vulnerability/lethality analysis, including landmarks in the development of vulnerability science, requires great discipline since it could become quite voluminous. I have chosen, therefore, to emphasize the WW II period and the subsequent years up to the Korean War. This is a period experienced by only a few currently active vulnerability/lethality analysts. I expect the subsequent periods to be well covered by others.

At the outset, however, my personal listing of *landmark* events in the development of vulnerability science includes:

(1) The experiences, data, and lessons of wartime—WW II, Korean War, War in Southeast Asia, the Arab-Israeli Wars and the Gulf War (references 14, 9–13, 80, 102, 106–110, 133, 134).

(2) The development of the shaped charge and Miznay-Schardin devices, including the excellent work done by many U.S. and foreign ballisticians too numerous to mention here (references 106–108, 118).

(3) The initiation and conduct of the first (and to date the largest) systematic testing and analysis of threat weapon lethality against aircraft and of aircraft vulnerability at the

Ballistic Research Laboratory (BRL), starting in late 1945 (references 14, 21–38, 43, 46–55, 58–60, 67, 68, 76–99, 129).

(4) The antiarmor program started at BRL in about 1950, initially to have been modeled after the antiair program (references 106, 109–116, 133, 134).

(5) The work on wound ballistics by Kokinakis and Sperrazza (e.g., reference 57).

(6) The establishment of the Joint Technical Coordinating Groups for Munitions Effectiveness (JTCG/ME-1965) and Aircraft Survivability (JTCG/AS-1971). These groups were established through the foresight and efforts of Dr. Joseph Sperrazza, Dale Atkinson, Jerry Reed, CDR Moose Johnson, and Frank McCourt and others. Although the charter was signed in 1971, it was not until the following year that Richard Ledesma from OT&E made funds available through the Test and Evaluation for Aircraft Survivability (TEAS) program. The continued success of the JTCG groups has required strong support from a succession of very many persons. It is noteworthy that, largely through the efforts of Dale Atkinson, the JTCG/AS served not only as a support and publishing body, but also did much to foster a greater and more free interchange of information between government and industry (reference 4).

(7) The investigations (and validations of predictions) of aerodynamic damage to aircraft, such as predictions of the increase in damage-induced drag due to wing damage insufficient to cause direct structural kills. Unfortunately, this topic has not received the attention it deserves (references 59–75).

(8) The development, use, and assessment of active and special armors. Although the shaped charge was thought by some to have spelled the "end of the tank" on the battlefield because of the antitank capability conferred on the foot soldier, this was clearly no longer the case (references 106–108, 120–123, 129).

(9) The availability of increasingly more powerful computers for vulnerability model development and for finite element codes in terminal ballistics. Thus far, however, there exists also an increasing need for test data because of the very rapid changes in armor and aircraft materials and configurations, and in weapon technology. This need has not been met adequately (references 4, 117, 118, 120–129, 131).

(10) The Joint Live Fire Test Program and in particular those of its tests designed to shed light on damage phenomenology (references 124, 129, 131).

(11) The Live Fire Test legislation and the ensuing dialogues and motivations for vulnerability and casualty reductions. It is instructive to examine the significant increase in vulnerability related activity within the services and industry since the passing of this legislation (references 119–132). To no small degree this has been due to the efforts of James O'Bryon.

(12) The stimulation of self-evaluation and of reawakening of vulnerability data needs, in-house within the Army and later by the series of National Academy of Science, National Research Council (NRC) reports (references 117, 118, 120–124, 128–132).

(13) The serious attention being given to the development of suitable objective cost-benefit procedures to apply to requests for waiver from full-up, system-level Live Fire Testing. When this objective, stemming from one of the NRC recommendations, is achieved, it will be a landmark development (references 103, 104, 124).

The list of references attached includes reports on the subject with which I am familiar. There are undoubtedly others covering the period. It is an extensive list since they contain contents of current value and may be otherwise *lost* in antiquity.

8.1 Armor Vulnerability in WW II. The potential of tank armor and of aircraft was first fully exploited in WW II. "From the beginning of World War II, it was clear the tank was a dominant weapon on the battlefield; means to stop it became a critical challenge to every combatant force. Tanks themselves, antitank guns, shoulder-fired rocket launchers, and mines all were pressed into service in this role." (See article by BG Philip A. Bolte (USA, Ret.) in reference 108.)

GEN Bolte observed that all armies learned that tanks needed infantry support but that infantry needed an armored vehicle with top protection. The United States never fielded an adequate antitank gun, and "units often abandoned those they had. On the other hand, the Soviets and the Germans both adopted powerful antiaircraft guns to antitank use with considerable success." "The most successful shoulder-fired antitank rocket launcher was probably that of the Germans" (reference 108). Donald Kennedy in his publication on the history of the shaped charge observed that the 2.36 inch MSA3 HEAT rocket *Bazooka* resulted from adding a rocket motor to the M9A1 2.36 inch rifle grenade, which had "woefully inadequate range and accuracy" (reference 107). "The Bazooka became the most widely employed antiarmor weapon used by the United States Armed Forces in World War II. It was generally believed by the American public to be an invincible weapon and powerful killer of armor, a theme portrayed in many of the World War II movies." Kennedy goes on to note that, "as much of a morale booster as it may have been, the Bazooka also had its shortcomings. In the Sicilian campaign, the U.S. Army's LTG James Gavin was to later observe that the Bazooka lacked penetration capability and that his troops were literally being crushed into the earth by German tanks they were unable to defeat." "It is possible that the problem was not in the lack of penetration of the shaped charge, but the failure of the fuzes to initiate the warhead quickly enough. The improved 3.5 inch Super-Bazooka was introduced hurriedly into the Korean War after continued use of the 2.36 inch Bazooka showed it to be inadequate for defeat of the Russian armor employed by the North Korean Army." "U.S. Army combat teams were reporting being overrun by the Soviet T34-85 tanks. Similar problems were reported by Navy and Air Force pilots who complained that 5 inch HVAR rockets were bouncing off of the North Korean tanks. In response to an urgent wire from the Chief of Naval Operations to the Naval Ordnance Test Station (NOTS) to do something about the latter problem, NOTS developed a totally new warhead and fuze system and delivered the first 1,000 rounds to Korea in less than 20 days!"

In my opinion the problem was not that the Bazooka had not been tested against armor but that it indeed was the excessively long delay before the warhead functioned, and hence it had the wrong standoff and perhaps even damaged the cone before functioning. Would not that have been found out in testing? Not if the tests were static warhead tests rather than dynamic tests of the fired system. There are still many testers who believe that static tests of shaped charge warheads are preferable since then you could hit where you want to and the remaining velocity should not add any significant increase in effects. The demonstration of appropriate fuze time-to-function under realistic dynamic conditions is critical, however, as was shown by this early combat example.

It is instructive as well to consider other observations by GEN Bolte in his chapter in reference 108. "By the time the U.S. entered the war, it had developed an armored doctrine and an armored force. On the other hand, it had fallen short in the development and manufacture of new war equipment, including tanks and the means to defeat them." "During the war, combat vehicles, including tanks and armored infantry carriers, were improved, but emphasis was placed primarily on quantity once the U.S. joined the war. Antiarmor means generally fell short of requirements throughout the war." "Infantry was equipped with antitank cannons, generally of a caliber too small to be effective against enemy tanks, and with a short-range, shoulder-fired rocket launcher." (GEN Bolte described the Bazooka as "an effective antitank weapon, but required the soldier to be within 100 yards of his target to have a reasonable probability of hitting a tank.")

"The United States produced 88,410 tanks during World War II. By 1945, U.S. tank production consisted of M24 light tanks, M4 medium tanks, and M26 heavy tanks. The workhorse of the Army was the M4 tank." "The M24 Chaffee was a good light tank, as was its predecessor, the M5. The problem with light tanks in Western Europe, though, was that they could not stand up to German medium tanks, the bulk of the German armored force." "The M4 Sherman was, by the standards of its day, a well-designed tank that could hold its own with German medium tanks. By the end of the war, it had been equipped in the M4A3E8 version with a respectable 76 mm gun. Nevertheless, the 76 mm gun still left it in trouble against German Panther and Tiger heavy tanks." "The 1941 M6 heavy tank was not acceptable, the Armored Force considering it too heavy, undergunned, poorly shaped and requiring changes in transmission; only 40 were produced. By the time the M26

Pershing, a heavy tank in its day, entered the battlefield, it was too late in the war to have much impact. Only 20 saw action."

"The armored infantry carrier by the end of the war was the half-track, a lightly armored body on a truck chassis. It did not provide overhead cover, making the infantry particularly vulnerable to artillery fire, nor did it have near the off-road mobility of the tanks it was to accompany." "Towed infantry guns were often discarded by using units, who learned quickly that they were generally inadequate against German tanks. Self-propelled antitank guns, known as tank destroyers, were far more effective. By the end of the war, the standard such weapon was the M36, mounting a 90-mm gun on a medium tank chassis. About 1,700 of these were manufactured or converted from earlier models." "Antitank mines were effective in defensive operations, but required time-consuming hand emplacement. Both antitank mines and antipersonnel mines were developed and produced in the United States and were available in large numbers by the end of the war. Nevertheless, by this time most U.S. operations were offensive in nature, and there was no great requirement for mines of any type."[*] "Fighter-bombers were used effectively in an antiarmor role, particularly in Northwest Europe. By the summer of 1944, air-ground coordination had matured to a high degree of effectiveness, German airpower was on the move, and the mobile nature of the war resulted in many German formations being caught on the move. Such aircraft as the P47 were armed with eight 0.50 caliber machine guns and often used 500 pound bombs against tanks. On December 18, 1944, . . . , P-47s had destroyed more than 126 armored vehicles and trucks, dropping their bombs on 30 tanks."

In general, one can only conclude from this account that our armor/antiarmor ordnance during WW II suffered by virtue of inadequate testing against their projected future threats, those expected to be operational during the system's operational life. One can only conjecture how much more effective our armor/antiarmor forces would have been and how many casualties would have been avoided if today's V/L methodologies, including Live Fire Testing, had been in place.

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[*] It is a fact, however, that mines accounted for 20% of Allied tank losses in WW II. Mines were the greatest cause of tank casualties in Korea (38.1%).

GEN Bolte continued in his chapter to discuss armor/antiarmor activities subsequent to WW II and up to the present. I believe his account would be very helpful to others contributing to this publication.

8.2 Aircraft Vulnerability in WW II. Professor Robert Ball in his book on *The Fundamentals of Aircraft Combat Survivability and Design* (reference 4) provides an excellent description of many of the WW II aircraft together with a summary of much of their survivability enhancement features. What follows should be considered supplementary to his account and also a partial reflection of what was found in the BRL program conducted on some WW II aircraft tested subsequent to WW II.

With respect to the B-17 and its heavy losses in WW II, this *workhorse* bomber had a history of change during the war to make it more survivable. One was the ability to fly at high altitude (26,000 ft). I recall that the provision in new bombing tables at BRL for flight altitudes above 20,000 ft was considered to be highly classified. The history of fires was such that 80% of all aircraft were estimated to have gone down in flames. As Professor Ball correctly accounts, fires in the B-17 were not due only to the fuel system but in engine nacelles and simultaneous damage to oxygen and hydraulic systems (although hydraulics were vulnerable to fire even without the simultaneous damage to oxygen systems). The ruggedness of the B-17 structure was vividly illustrated by a famous picture receiving wide press of a B-17 returning to its base in England. One saw an empennage following the forward cockpit and fuselage with much sky between the two. The aircraft was distinguished by relatively large dry bays. Pure incendiary shell (not APIs) with their larger flash duration times and flash lengths were particularly effective in starting fuel tank fires. The incendiary shell bodies would core the self-sealing fuel tanks, effectively defeating their self-sealing features. The importance of the ability to fire rearward, particularly through the later addition of a tail turret, was noted by Herbert Weiss at BRL when he compared German fighter debriefings with camera film (reference 12). Earlier during the war these compared quite well. Pilots would claim they opened fire at, say, 800 m and pulled away at, say, 200 m. Later, for B-17s with tail turrets, they would still make similar claims, but now the film would indicate they may have opened fire at about 3,000 m and pulled away at about, say, 2,000 m. These findings were in part compounded by the fact that, due to attrition, later German fighter pilots were less experienced.

During the war the VIII Bomber Command had an Operations Research Section which specifically addressed battle damage and means for reduction of bomber losses (reference 11). After the war BRL was provided with B-17 3-view profile drawings on which were spotted impact points for hits on returning aircraft by fragments and bullets. These had been used by the VIII Bomber Command to associate areas of low hit density with high vulnerability and were used by BRL to confirm its findings in its postwar vulnerability program. As a final note of possible interest on the B-17, it is recalled that the Douglas Aircraft group, which became the RAND Corporation in 1948, had been tasked to determine the best flying formation to bring heavy bomber defensive fire against attacking interceptors. They used model bombers with light emitters at gun positions and shields (stops) to prevent fratricide. Many such models were positioned by simple supports into candidate formations. These were positioned within a sphere lined with brightness detectors. Since luminosity varied as the square of the distance, as did density of fire, they had a workable analog system to give directly related readings of density of coverage for many interceptor attack positions.

The post-war BRL vulnerability program included the Air Force's three principal fighters—the liquid-cooled P-38s and P-51s and the air-cooled P-47s. These were fired upon at Aberdeen Proving Ground (APG) with full loads of fuel and hydraulics under pressure and engines running. The findings completely verified the combat experience. We thought of the liquid-cooled aircraft as each having two circulatory systems around the engine, viz., oil and coolant. A hole in either was at least an engine attrition kill; if one hit the engine presented area, it was difficult not to record such a kill. Moreover, the 100% ethylene glycol coolant was flammable.

The P-47 fighter was the least vulnerable aircraft employed as a target at Aberdeen. The R-2800 Double Wasp engine had a $P_{k/h}$ of only 0.05 for a caliber 0.50 API hit. It could operate and pull required thrust with many of its cylinders out. One-quarter-pound blocks of TNT were used in off-line tests to destroy individual cylinders in various firing sequences, but no criticalities were observed. The large engine masked the large fuselage fuel tank located between it and the cockpit and below the cockpit, as well as a smaller auxiliary fuel tank to its rear. In its air-to-ground attack role when it was attacked from the front, the only vulnerable areas of any consequence were the top of the pilot's head (about 1/2 sq. ft. of *K kill*) and the oil cooler inlets located beneath the engine (about 1/2 sq. ft. for a *B kill*). As with essentially all reciprocating engines, oil starvation resulted in engine seizure in a time very close to 15 min. The twin-engine B-26 medium bomber and the F6F Navy fighter also used the R-2800 engine.

It is interesting to note that almost all U.S. WW II combat aircraft had features added to reduce vulnerability after combat experience. This was done even if it meant some weight increase and loss in some performance. Self-sealing fuel tanks, armor plate in and about cockpits and often around oil tanks and oil coolers, were common. Structures were rugged and could absorb many hits. The history of the Japanese Zero presented in Professor Ball's book (reference 4, Appendix A) is of particular interest. The early Zeros were acclaimed for their range and maneuverability but were vulnerable. As the war progressed, their advantage over early Navy and Marine aircraft was negated. Modifications were made to make the Zero less vulnerable; these included self-sealing fuselage and wing tanks. What is not generally known, however, is that these tanks were placed within aluminum box-like containers for support, without backing board or spacers as in U.S. designs. As a result, when hit by a caliber 0.50 projectile, the hole in the box would have petaling which extended into the otherwise well-built and competitive self-sealing fuel tank, so that the hole could not seal itself. The added weight in this instance was for naught. This is a good example of a case wherein live firing into the entire assembly rather than the self-sealing tank component alone would have revealed the mistake.

The analysis of WW II air combat records by Herbert Weiss contains much information of value, particularly regarding attack tactics and accuracy of fire by German fighters (reference 12). However, insofar as vulnerability is concerned, we see again the greater vulnerability of the liquid-cooled engine (Messerschmitt 109) when compared with the radial air-cooled engine (Focke-Wulf 190).

From the German perspective, a most interesting paper is a post-war account of methods and problems of air defense over Germany in WW II, including the extent of application of operational research methods by the German side during the war (reference 13). A summary of remarks made by leading WW II German scientists is presented in an Addendum herein.

Before the U.S. entry into WW II the primary British operational research activity included many investigations of problems related to air combat and air defense, but a small fraction of this was related to aircraft vulnerability. References 1–3 are a small sample of this work. In the U.S., there were a few studies on lethality of antiaircraft guns, primarily at BRL by Robert H. Kent, again with little related to aircraft vulnerability (references 5–9).

With the U.S. entry into the war, the staff at BRL was greatly expanded, but most attention was devoted to the principal function of the laboratory (i.e., to the basic tasks of exterior, interior, intermediate, and terminal ballistics and the provision of artillery firing tables and of bombing tables). As the war progressed, however, the requirements increased for research directly applicable to problems received from our combat forces. These included work related to the breaching of concrete structures and bunkers, personnel incapacitation, fuze function (e.g., as in a jungle environment), and the reduction of ground and aircraft gun fire dispersion and of bombing dispersion, including best bombing patterns.

The development of the piezoelectric blast gauge in 1943 enabled the acceleration of the study of blast phenomena. There developed an extensive program to determine the destructiveness of various shell and bombs and the basic nature of blast waves. Since most testing was on the ground, Dr. R. G. Sachs developed scaling laws to estimate blast wave effects at attitude using standard atmosphere values for temperature and pressure and using ground level data on peak pressure and impulse. To get the same peak pressure at 60,000 ft as at sea level, one would require about 80% more explosive.

With respect to the matter of aircraft vulnerability, there was little work performed at BRL during the war. The limited effort on lethality of antiair weapons continued (e.g., reference 10), but the basic ballistic work on fragmentation and blast contributed greatly to the post-war program. Similarly, the work on penetration of thin plates was useful in the post-war studies of L/V of air systems. Elsewhere in the U.S. there were a number of relevant specialized activities. Aircraft designers employed self-sealing fuel tanks and typically built rugged aircraft structures (reference 4). Acceptance tests of aircraft ammunition were conducted by the testing organization (Development and Proof Services) at APG. Most significant for the post-war aircraft weapons and vulnerability program was a Navy-supported effort at the New Mexico School of Mining and Technology (then located in Albuquerque). A significant program was conducted on 5-in/38 and 3-in/50 VT-fuzed naval antiaircraft shell against aircraft suspended from towers to obtain fuze burst patterns. Due to the foresight of the Naval and university individuals involved, the damages by fragments hitting the aircraft were carefully traced and recorded and the implication for aircraft vulnerability were assessed. In so doing, they developed the first listing of various damage categories. Their experience proved most helpful in the planning of the major post-war program at BRL.

8.3 The Aircraft Lethality/Vulnerability Program at BRL, 1945–1951. The first and probably largest systematic investigation of the lethality of antiair munitions and of the vulnerability of aircraft was started in the latter part of 1945. Of the various efforts discussed here, it was this program with which I was most personally involved, up until I left BRL at the end of 1951.

The way the program was started is of interest. Briefly, in July 1945 the Chief of Ordnance sent a letter to COL Carr, Chief of the testing agency (Development and Proof Services [D&PS]) at APG, MD, directing that tests be conducted to determine the optimum caliber for aircraft weapons. The letter noted that there resided at Phillips Field at APG about 30 miscellaneous WW II "war-weary" aircraft and specified about 15–20 specific types of ammunition which should be fired at the aircraft. In addition, each type was to be fired so as to obtain several different striking velocities and from several different aspect angles. The aircraft were to be fully loaded with fuel and with all systems operating.

COL Carr assembled a small group in D&PS to deal with the matter. With Floyd Watts as the lead, the group contained a number of engineers, including Joseph Sperrazza, whom many of you know and who was an Ordnance Engineer in D&PS at the time. There was concern about the ability to conduct all the tests without losing the aircraft before the tests could be completed. After discussions with COL Carr and Mr. Watts, Joe asked me to consider a statistical design for the tests. At the time I was a staff sergeant on a ballistic team stationed at APG, awaiting orders to proceed overseas to calibrate the muzzle velocities of field artillery, so we were not very busy. (I had previously worked for BRL from 1941 until 1944, when I went into service with the Army.) After a long day and the best assumptions I could make respecting the expected variability of results and the number of hits we might expect to get per aircraft before we lost it by firing into the fuel tanks, I wrote a memorandum which concluded that if one wanted answers for each condition within 10%, more than 4,000 aircraft were required, but that if answers within 20% were acceptable, then 1,200 aircraft would suffice. This presentation was forwarded to the Chief of Ordnance who was somewhat shocked, to say the least. There was a conference call to APG to which COL Leslie Simon, Director of BRL, was invited. COL Simon backed up the analysis and to everybody's surprise, the request for 1,200 aircraft was approved (additional detail is provided in reference 129).

It did not take long before the responsibility for directing the program was transferred to BRL, with the tests to be conducted by D&PS. The many targets which would be available would enable phenomenological and well-instrumented investigations so that results could be used to predict damage by new munition types against new types of aircraft. In particular, they would enable continuation of the blast and fragmentation work which BRL had been investigating. I was transferred to BRL, and it was not long before Dr. Sperrazza went to BRL to specialize in blast investigations with Dr. James Sarmousakis, Wilfred Baker, and others. The vulnerability community is indebted to the leaders in the Office of the Chief of Ordnance, the U.S. Air Force, BRL, and in D&PS, for their foresight in supporting this program. Much of the work was supported by the Air Force out of Wright-Patterson Air Force Base. The original optimum caliber program was supplemented in March 1946 by a project to determine the optimum characteristics for aircraft and antiaircraft weapons. One year later a project was established specifically to determine the vulnerability of combat aircraft to ordnance weapons. The results were to be used for the design of aircraft, to reduce their vulnerability, and also for the design of more lethal weapon systems. Later, the weapons effectiveness studies were expanded to include all types of weapons and the vulnerability of armor and other targets. Initially these programs were to be modeled after the aircraft programs, but later they look on a character of their own.

8.3.1 Description of the General Program. How was this program, the most extensive of its kind in the world, conducted (reference 14)? The 1,200 aircraft which were received, some brand new and still in crates, consisted of essentially all types of WW II Air Force and Navy combat aircraft. In addition there were conducted a large number of off-line tests. Most of the work was for use of the Air Force, a much lesser amount for the Navy. First, procedures had to be developed for measuring the vulnerability of various aircraft components to different types of antiair weapons. Second, these procedures were used in experimental and test work to obtain the detailed data. Hypotheses developed during the course of the program were tested using additional firings. Then, on the basis of the findings, design changes were recommended to improve aircraft passive defense; these were made available to the Air Force, Navy, and to aircraft designers. In addition, the results were used as inputs to weapons effectiveness studies, particularly by BRL itself but also to new emerging government and industry operations research groups. Although WW II obsolete aircraft were used to obtain data, the major objective was the formulation of design principles and predicted capabilities of sufficient universality that they could be applied to combat aircraft generally, especially to aircraft still in the design stage. Recommendations for passive defense of specific aircraft were regarded as secondary.

This process was illustrated on the occasion of a visit in about 1948 by an Air Force committee of three asked to determine whether the $2 million being provided yearly to BRL by the Air Force was being well spent. (Parenthetically, it is noted that the vulnerability program realized an additional $1–2 million per year from a scrap dealer who was on APG to dispose of aircraft carcasses. The committee consisted of COL Charles Lindberg, GEN James Doolittle, and a Navy Admiral whose name I do not recall. COL Lindberg, in particular, was most perceptive in his questions. He asked the key question - "How can shooting at obsolete aircraft help in the future?" My answer, in brief, was as follows.

It may be said that we view a new aircraft as a collection of numbers of differently colored bricks, representing the different major components. A small aircraft may have 100 blue bricks, 300 red bricks, and so on. A larger aircraft may have 800 blue bricks, and 500 red bricks. If white bricks represented the pilot then the two would have the same number. These then represented the component presented areas from which we obtained its vulnerable areas. A new aircraft will have its own set of presented and vulnerable areas for the components. However, if our phenomenological studies (for example, of fuel ignition) showed a dependence on skin thickness for fuze or incendiary projectile function and on dry bay shotline length for fuel ignition following a function, then we would modify the numbers appropriately. Thus the aircraft were to us primarily convenient collections of components and assemblies for obtaining basic physical data. When a new, previously untested type of component existed on the new aircraft, then we went to the chief engineer in the company which developed the component. For example, the first time we had to estimate the vulnerability of an axial flow jet engine we had not yet tested one. However, from observation of thousands of impacts of different types of bullets, shell, and fragments we had a good idea of what physical damage (hole sizes and shapes) would occur to the various parts. Thus we would start at the front of the engine and ask the designer what a pinhole in a particular part would do to the engine function. He might say it would have negligible effect. We would then proceed to larger and larger holes until he was very sure of a serious malfunction resulting. We then systematically proceeded, front to rear, doing the same bounding process on effect of holes on function. While only a start, nevertheless we would aggressively seek out engines from damaged aircraft to use as targets to buttress this type of estimate with information on foreign material ingestion, cascading of compressor blade damage and forms of synergistic damage. Fortunately, the committee supported the program and the Air Force support continued.

Different types of range facilities were employed. At times there were eight ranges used simultaneously. Gunfire ranges enabled firings at targets from extremely short ranges to ranges up to 3,000 yards in order to obtain different striking velocities. The longer ranges and aiming plots at short ranges also helped to insure random hits on components where we wanted that (else, as we found, gunners had learned how to kill an engine just before lunch or quitting time). The principal tests for fragments were conducted in areas where we statically detonated cylindrical controlled fragmentation test shell. Nine types of such shell were designed, fabricated, and tested by the Terminal Ballistic Laboratory, primarily by Messrs. Tolch and Shaw, to yield three different fragment masses, each at three different initial velocities (reference 58). One of these would be detonated in an arena which might have two aircraft with all systems operational and engines running off the fuel in their fuel tanks. Also in the arena were other targets such as self-sealing fuel tanks preceded by burster plates, penetration plates of different thickness of different type aluminum, mannequins, aircraft sections, and the like. Many such targets enabled better instrumentation than did the integral aircraft.

Damage categories established for damage assessment were for purposes additional to that of damage description. They were used to describe the impact of the damage to the aircraft tested for empirical purposes and also for use in effectiveness studies for new designs or contested foreign aircraft. We were responsible for the KK, K, A, B, C, and E categories, borrowing some of them from those used at the New Mexico School of Mining and Technology, previously described. During later years I was disappointed to see how long that simplified set of kill categories, except for category E, the time required for control to be lost, persisted.

We had damage assessors who were pilots or flight engineers assigned to us by the Air Force or Navy. We obtained detailed descriptions of the damage and also independent assessments from each of a group assigned to a test to get some concept of the variability of the subjective assessment. In our view, the observed damage for the defined tactical conditions would either have been a kill or no kill; it wasn't probabilistic. Nevertheless we could be introducing a large error and missing useful information if we insisted that they assign a one or a zero when in fact they were not sure. Therefore, we permitted the use of fractional numbers to reflect how they leaned. They could assess as an 80% kill, which meant that they were fairly sure it was a kill, but it might not be. The underlying assumption for the fractional kill assessments was that the expectation over many such assessments would be the expected number of kills one would have had if indeed some all-knowing person had used ones and zeros.

The concept of vulnerable area was used for comparisons and analytical purposes; this had proved to be useful and has continued to this day.

Close working relationships existed between vulnerability analysts and terminal ballisticians, the effectiveness analysts, and all the range testing personnel. It is noteworthy that the analysts were in control of the tests, attended almost all the tests for which they were responsible, and gained expert damage subject matter knowledge. To facilitate this process, individuals were assigned aircraft component responsibilities which meant that they kept abreast of information on the components or systems assigned to them and maintained all the informational files on these systems. For example, Roland Bernier was responsible for fuel systems, Jim Robinson was responsible for power plant systems, and so on. Morgan Smith planned and supervised all the aircraft vulnerability field testing on behalf of BRL. The fact that these experts could readily recognize the sure "zeros" in damage effects facilitated greater efficiencies in vulnerable area estimation. An exception to the foregoing was the conduct of blast tests, for which others in the Terminal Ballistic Laboratory were responsible, such as Joe Sperrazza and Bill Baker.

Use was made of contractors for support. The Cornell Aeronautical Laboratory supplemented BRL's work in investigations of fuel tank inerting. Cornell Lab also performed aerodynamic damage studies, as did Biot and Arnold, noted aeronautical engineers. The Ballistic Laboratory at the Johns Hopkins University (JHU) had a continuing contract to collect, organize, and evaluate the thousands of fragment impact damage data resulting from the controlled augmentation tests. Their Project Thor was responsible for the penetration data and equations which were so widely used and misused later. JHU also could hire high school students to build *vulnerability model airplanes* for use in presented area and masking calculations, whereas the civil service could not. These were both solid models and also clear plastic models with colored components.

It should be understood that high-speed computers were not available to the program during the early years. The first computer, the ENIAC, was fully occupied with other BRL problems of high priority, once it was installed. Presented areas and masking were estimated by use of three-view profile and subsystem drawings and descriptions in Aircraft Erection and Maintenance Manuals and by use of the aforementioned *vulnerability model airplanes*. These, coupled with photographs and the knowledge of the analysts respecting the many *zeros* and areas of rare vulnerability, enabled rapid estimations of vulnerable areas for any aspects of interest. The computers were not missed.

An example of the quick response possible from the vulnerability group was a phoned urgent request to BRL from an Air Force colonel at Eglin Air Force Base who needed an estimate of the relative losses for the different types of Air Force ground attack aircraft in Korea. At that time there were both old reciprocating aircraft in Korea (e.g., P-47) and newer jet aircraft (e.g., F-80, F-84). In all there were about a half-dozen aircraft types involved. The request which had been made of him by his superiors was urgent, and he needed information in about two days. A small group of about five analysts met this need by working out the relative vulnerable areas via frontal attack by ground AAA fire. The P-47 with which we were highly familiar was taken as the norm. Then the relative presented areas of the other aircraft were obtained, compared with the P-47. Adjustments to the $P_{k/h}$ for the components were made for differences in components or geometry (for example, masking and distances along shotline from skin to fuel tank). Then the results were all normalized to the P-47 and adjusted for attack exposure time. While crude, the quick response was necessary and made (reference 81).

The success of this program, in my opinion, resulted not only from a strong work ethic, individual motivation, and support and encouragement by BRL and the Office of the Chief of Ordnance. It resulted too because it could be a well-integrated and funded program with investigators free to pursue areas of concern. There was complete freedom from outside interests (such as program managers) for support. As a result when requests for specific information were made they could be responded to on the basis of the information collected by that date in the program. In very few instances did a request result in a new test program. To encourage the exchange of phenomenological information and coordination, BRL initiated the holding of conferences on aircraft vulnerability, including tripartite conferences with the United Kingdom. These included working conferences at which representatives of a number of U.S. Government and of U.S. companies were present as well (e.g., references 77, 47). Five such working conferences were held from 1948 to 1956. There also were ad hoc conferences on either general aircraft vulnerability or on some specific problem and combined conferences held every 18 months alternating in England to the United States. Throughout the BRL program and the conference interactions, emphasis was on physical and functional damage data and predictions. The bookkeeping required to obtain $P_{k/h}$s was largely incidental and of lower priority.

The following references are to some BRL publications during the 6 yr following the start of the aircraft vulnerability program and include a number of the effectiveness analyses, primarily by

Herbert Weiss, which made direct use of the developed vulnerability data, combining it and susceptibility analyses (references 21–59, 67, 68, 76–99). There are undoubtedly others which I do not have.

8.3.2 Off-Line Tests and Investigations.

8.3.2.1 Tests. As noted earlier, the basic vulnerability program was supplemented by many major off-line tests, experiments, and investigations. It is suggested that those interested consult the references cited which may include work done by other installations besides BRL.

- Blast Damage - Although basic to the aircraft vulnerability program, it may be useful to have these references cited separately (references 24–38).
- Aerodynamic Damage - This area has been sadly neglected in recent vulnerability analyses. It includes the effect of damage-induced drag and damage-induced flutter (references 59–75). It is of interest that the theoretical predictions of damage-induced drag were very closely validated in subsequent wind tunnel tests (references 72–75).
- Fuel Tank Inerting - Fuel tank inerting was practiced during WW II particularly by the Russians who, in view of the use of gasoline and the cold temperature environment, used the exhaust gas from generators brought next to parked aircraft (references 4, 46, 78).
- Vaporific Damage, Incendiaries, Tests of Pyrophoric Fragments (references 44, 47, 49, 76, 77, 79); also much work by the Navy at NOTS, China Lake.
- Vulnerability of Bombs and Other Ordnance (references 50–53).
- New Structures - Geodetic and full-monocoque structures were tested. The geodetic structure was either a Stirling or Halifax Bomber crated and sent to BRL from England. The full-monocoque structure was that of the D-558 Skystreak (references 33, 34, 37).

- Effects of New Materials - Metalite, glass, and phenolic materials (references 54, 55). Fires at High Altitude (reference 45). Spray ignition by incendiary bullets was tested in the Aberdeen Stratosphere Chamber at a simulated altitude of 65,000 ft, resulting in a transparent, pulsating orange flame. This raises the question of heat transfer by fire as a function of altitude.

- Oil Starvation of Engines - Engines were run with the oil flow cut-off. The engines seized usually in about 15 min (references 76–79).

- Ricochet of Bullets and Shell off Aircraft Wings - As wings of aircraft become thinner, the fraction of ricochets increases. It is a significant number for some directions of fire and should not be neglected (references 22, 23, 77, 79).

- First Test Firings Against Jet Engines - The first firings were against the first U.S. jet engine, the centrifugal-flow I40 engine in the P-59 aircraft. Because of the plenum chamber, this engine was relatively tolerant of foreign material ingestion. The firings against an axial flow TG-180 engine were also the first for that type of engine, more typical of follow-on engines. Various off-line tests were conducted. Thermocouple bridges around tailpipe holes enabled characterization of the heat profile and assessment of possible empennage damage. In a series of *David and Goliath* tests, a tethered man about 20 yd in front of a jet intake used a slingshot to toss ball bearings of increasing diameter into the intake. After each shot, the rotor and stator damage was inspected. The axial flow engine didn't suffer catastrophic damage with cascading damage to successive stages until the diameter of the ball-bearing was 1 1/2 times the clearance between stators and rotor.

- B-36 Blast Tests and Hydrodynamic Damage to Wing Structure - When a B-36 had an accident and went into the lake at Fort Worth, a team from BRL consisting of Sperrazza, Baker, and Stein went down to conduct blast tests using undamaged wings retrieved from the lake. The large fuel tanks were filled to various levels with water, and increasingly large blocks of TNT were detonated within the water until hydrodynamic structural kills were obtained on the wing structure (references 33, 37, 38).

- Duration of Fragment Sparks for Steel and Pyrophloric Fragments, Incendiary Flash Duration, Time Delays for Sprays From Holed Self-Sealing Fuel Tank - It was observed that steel fragment sparks were too short in duration to cause any fire with self-sealing fuel tanks. An exception exists for very high striking velocities (above 5,000 ft) when a vaporific effect may be obtained due to burning of minute particles of aluminum spall. The flash duration and path length was so much greater for straight incendiary as against armor-piercing incendiary projectiles that it causes one to question whether or not we should not today conduct comparative tests of the two types and get the overall lethality of each to modern aircraft (references 43, 44).

- Effect of Loss of Fractions of Propeller Blades - Sequentially more and more of a P-47 propeller blade was removed to determine when unbalance would kill the engine.

- Fuel System Fire and Explosions - Much attention was paid to off-line investigations of this major source of vulnerability, including the fact that the Bureau of Mines Temperature/Pressure charts on fuel vapor-air explosions are sensitive to the nature of their ignition source, so different than incendiary ignition sources (references 39–49).

- Nonspherical Blast Contours Around Moving Charges - Dr. Sperrazza devised the means for obtaining blast measurements around moving bare charges. This work enabled more accurate predictions of the characteristics of the nonspherical blast contours in air.

8.3.2.2 Analyses. Although all estimates of vulnerability of particular aircraft, tested or predicted, involve analyses as do all effectiveness and trade-off analyses (references 10–14, 19–105), listed here are some examples with which analysts may not be familiar and which may have relevance today.

- Damage Growth Due to Impacts on Complex Components - A problem exists with the fact that damage to one part of a component may interact with damage to another part of the component to cause more functional damage than would be estimated if the two impacts were considered to be independent. This was observed with multiple randomly directed firings into the Twin-WASP R-2800 engine in the P47. Comparisons were made which provided the increase in vulnerability due to cumulative damage from 2 to over 20 impacts. Physically, the damage growth was considered to be analogous to the growth of bacteria in a jar of agar; the same general differential equations apply. The exponential growth equation for bacteria was then employed as the model for cumulative damage to the engine. The test data were fitted to that equation. This relationship then was used to predict cumulative damage to that component and verified in subsequent further tests (references 77, 79).

- Explosive Decompression of Cockpits - WW II aircraft went to altitudes requiring cabin pressurization, without pressurized suits. The question was at how large a hole would sufficient decompression occur to represent a kill. Preliminary estimates of this factor for a given cabin volume, hole size, and aircraft altitude were made for different cabin pressures; these were later found to be sufficiently accurate in a practical sense in test firings of 20-mm HE shell into pressurized cabins (references 77, 101).

- Fragmentation Damage to Aircraft Structure - As noted earlier, JHU assisted BRL in analyzing the damage caused by thousands of fragment impacts on many different airframes. It was found that the damage is negligible. As observed in BRL Report 751 by H. L. (Llew) Merritt, none of these impacts produced any "A" or "B" structural kills. It is possible that today's aircraft are not as robust in this regard as were the WW II aircraft, but it is not likely that the conclusion would be different. It is also possible that a high concentration of many fragments hitting a small area of a main structural member could cause a structural kill. However, this would imply either a direct hit or near miss by an explosive shell, and the blast or combined blast plus multiple impacts would probably be the overriding cause of damage.

8.3.2.3 Aids to Analysis.

- Nomograms and the Lotto Method - As noted earlier, computers were not available (indeed *computers* was the designation given to people operating Monroe or Marchandt calculating machines, as for bombing table preparation). Nomograms were developed, such as for penetration, ricochet, velocity loss, incendiary function, and velocity loss in liquid, which were most useful for vulnerability estimation. Fred King designed and had built the Lotto device, essentially a chemical test stand with graduated sliding arms at the ends of which were angular measures and movable slides. One end also had another graduated sliding arm. A model target aircraft with colored components was placed at the end of one arm. The other contained a missile or airburst projectile warhead at the desired attitude and distance from the target aircraft. The fragment side sprays could be swept out over the target and the distances from warhead to target components easily read. On a calculation form, these distances gave the density of fragments, their striking velocities on the components, and the appropriate component vulnerable areas. One could then go quickly to the next position within the warhead fuze delay range to get similar data. In this way, the expected number of kills (and hence probability of kill) on the aircraft could be determined quickly for a series of warhead burst positions along the warhead trajectory. No great skill was required to operate the device, and the operator could calculate about 200 airburst warhead position kill probabilities in a day. This method had excellent traceability as to causes of differences in Pk's.

- Utility of VT Fuzes on Airburst Projectiles of Different Sizes - At that time VT fuzes had one large forward lobe for target detection to initiate the airburst warhead. Thus, a warhead or shell which would otherwise hit the target on contact would instead be initiated airburst. The question was whether the airburst kills obtained with near misses would more than compensate for the kills lost by airburst prior to an impact. Advancing technology in miniaturization was making possible VT fuzes for projectiles as small as 30 mm. However, our analyses showed that unless the projectile was more than 75 mm in caliber, the contact fuze was more desirable. There were not enough fragments and little blast damage for the smaller shell or warheads. In this connection, there was great consternation in the U.S. at reports from our pilots in Korea that the 23-mm projectiles fired by the MIG-15 had VT fuzes on the basis of airbursts they saw in the vicinity of their aircraft. We didn't believe this and attributed the airbursts to the action of self-destruct fuzes, often used over one's own territory, which would detonate the shell after about 7–9 s time of flight. This latter explanation turned out to be correct.

8.3.2.4 Opportunities for Validation. Several opportunities for validation arose, from combat or misleading live-fire exercises against drones.

- MIG-15 vs. the F-86 in Korea - In a remarkable coordinated action, all the Services participated in the retrieval of the pieces of a MIG-15 in the waters off the Korean coast. We had no MIG-15 at that time, nor did we have its 23-mm gun and ammunition. The pieces of the aircraft were sent to the Cornell Aeronautical Laboratory, and its 23-mm weapon system and ammunition were sent to APG for analysis. I went to the Cornell Aeronautical Lab to examine the reconstituted MIG and to bring back information relevant to its vulnerability. (We assessed the small enclosed volume in the rear fuselage as being vulnerable to the blast of a shell as small as a 20-mm HE shell; the empennage would be lost. Six months later a Korean defector flew his MIG to South Korea. This aircraft had strong steel reinforcement to protect that area of the airplane.)

  We then assessed the probable ratio of losses of the MIG-15 vs. our F-86 in combat. To do this we assumed that almost all the losses of each aircraft in air-to-air combat would be due to detection by a higher formation of the formation of the enemy and a dive and fly-through of the enemy formation, with negligible losses in dog fights. We assumed that the MIGs would see the F-86 formation below 50% of the time, and similarly the F-86 would spot the MIG formation below 50% of the time. Discussions with combat personnel indicated the reasonableness of the assumptions. We then obtained the vulnerable areas of the MIG from the rear and above to the F-86 0.50 cal. projectiles and of the F-86 from the rear and above to the MIG-15 23-mm HEI projectiles. The MIG 23-mm gun at that time had a very low rate of fire, and our analysis of its projectile showed it to have relatively high drag and low muzzle velocity. As a result, we predicted a loss rate of eight MIG-15s to every F-86 (reference 80). At the end of the war, it turned out that this ratio was about 8.1 to 1, much closer than warranted by the errors which must have existed in our analysis, but nevertheless satisfying.

- F6F Drone - The USS Mississippi conducted a series of live firings with contact-fuzed 40-mm shell and 5 in/38 VT-fuzed airburst shell vs. F6F aircraft outfitted to be operated as drone targets. The object was to see which weapon system could best put a Kamikaze suicide aircraft out of its flight path so that it would miss its ship targets. We received a call from Dr. Charles Meyer, Chief of the Warheads Section at the Applied Physics Laboratory, who told us that the airburst 5 in/38 was much superior in the tests but he had concerns and wanted to know what we thought. We asked for a profile drawing of the drone installation. The drone equipment was located throughout the fuselage and had a large presented area. A fragment hit on the drone equipment could cause the aircraft to veer from its flight path. We did a cursory estimate of the F6F mission vulnerabilities to the two shell without the drone installation and concluded that, contrary to the test results, the 40-mm shell was clearly more lethal than the air burst 5-in shell. Dr. Meyer asked for suggestions as to what to do. We suggested that the vast bulk of the smaller side spray fragments from the 5-in shell be screened out by a protective covering of the drone equipment and rerun the test series and that 50 layers of nylon cloth should suffice. The Navy did this. F6F drone aircraft had the nylon cover installed at Johnsville, PA, and the test series was repeated. The results confirmed our analysis. The implication for later testing of ship defense against cruise missiles should be clear and also should be clear for tests against any surrogate targets which are not configured the same as the threats they represent.

8.3.2.5 Other Verifications. The combat experience in WW II confirmed the post-war analyses conducted at BRL, although except for the B-17 the combat data was late in coming. Certainly, the vulnerability problems of liquid-cooled engines and the low vulnerability of the P47 were confirmed. The German experience described in the Addendum was similar. So also was their confirmatory findings respecting the superiority of contact-fuzed AAA compared with their airburst weapons. Described earlier was the wind tunnel confirmation of predictions of aerodynamic damage. During a later time period, during the SEA conflict, there were further verifications of predictions. In particular, the work by Roland Bernier at helicopter bases in Vietnam served to reduce loss of helicopters and pilots.

8.3.2.6 Data Needs. The writer was privileged to participate in a JTCG/AS Component Vulnerability Workshop held 5–8 March 1991 at Wright-Patterson Air Force Base and organized by Gerald Bennett. A group of roughly 30 experienced aircraft vulnerability analysts participated. The results were sobering in that there are so many aircraft subsystems for which the required data is missing or obsolete. A few selected quotes follow:

- "Although the capabilities to get presented areas are good, the estimation of component damage is poor."
- "Not all things that happen are modeled (e.g., heat transfer at altitude to cause material failure during fires)."
- "Much remains to be done before one could have confidence in the prediction tools for aircraft vulnerability."
- "There is next to zero data base on internally stowed missiles."
- "Concepts for vulnerability reduction are often given up (*sweated out*) when coming down to production designs."

There are many other such findings, mostly specific data needs for the major aircraft subsystems and components.

It is suggested that a basic program to fill the needs should receive high priority within the government and vulnerability groups. This will not be possible so long as large efforts are diverted to concentrate on model structure and so long as the major support for vulnerability investigations are for specific projects (e.g., from PMs) and not phenomenological.

8.4 Armor Lethality/Vulnerability. In view of the direct experience with the armor program by other contributing to this publication, my account here is brief. Some of the armor references may be of interest since they represent the state of the art at the time the armor L/V program was initiated in the late 1940s (e.g., references 15–18, 106–111). Later references relate to data obtained in major armor and munition tests, the needs for more data, and the impact of the Live Fire Test legislation (references 112–123, 126–128, 131–134). The major message for armor as for aircraft is the need for phenomenological damage data on new munitions vs. new target configurations.

The post-war aircraft vulnerability program was expanded to include armor after the aircraft program was proceeding for several years. Although there was an active program in place for weapons such as the shaped charge and kinetic energy projectiles, the promise of the shaped charge to render the tank obsolete had encouraged intense work in that direction not only at BRL but at many other establishments (references 107, 108). Although the shaped charge was used in combat in WW II, it still had problems then and armor-piercing projectiles predominated. The first reports from BRL when the post-war program started related strongly to use of WW II data; much attention was given to tactics and the need to hit and kill with the first round, before the enemy could respond (references 110, 133, 134). Later, systematic investigation of tank vulnerability was continued with the CARDE tests in Canada; their results were utilized for tank vulnerability assessment for many years (references 112–116).

The Army reviewed values and shortcomings of its armored vehicle V/L in 1977 and made plans for updating its methodology and database (references 117-118). However, the rapid pace of development of new armors and antiarmor systems in the 1980s again resulted in perceived shortfalls, such as in the testing of the Bradley armored vehicle. This motivated Congress to pass its Live Fire Test legislation, mandating Live Fire Testing of full-up systems (reference 119). In another self-evaluation, BRL published an excellent account of the then-existing data needs and the measures required to meet these (reference 121). Later assessment of the practice and impact of the Live Fire Tests continue (references 121–123, 129, 131, 132). There would seem to be a consensus that the Live Fire Test program on armor has produced useful results.

8.5 References

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8.6 Addendum. (Extracted From NATO Conference Report "Operational Research in Practice," 1958 [reference 13]). A few citations of interest to survivability follow:

Professor Dr. Theodore Benecke (German)

1942

"The first large night raids of the RAF on cities like Cologne and Essen could take place. Air raids during daytime had been discontinued because of high casualties."

"Of the heavy AAA units, only about 25–30 percent were equipped with organic radar. At that time, the aircraft warning service had still to rely completely on the ground observer corps."

"The first daylight attacks of four-engined U.S. bombers of the 'Flying Fortress' and 'Liberator' type in 1942 caused new problems for the air defense, because these planes were heavily armed and strongly armored. Only a few raids, however, were made. Towards the end of 1942, individual RAF Mosquitoes started their sorties."

1943

"The spring of 1943 brought new tasks for the air defense of the Reich. With the first large-scale RAF night raids, which followed in quick succession on the Ruhr district, a new tactic was introduced. Pathfinder squadrons led the way and marked the target area, followed by a bomber stream executing a 30–40 min concentrated attack. This method permitted a quick penetration of the night-fighter area in the west, and only comparatively few night-fighters could make contact. Also the AAA could not do much against such a concentrated attack. The technique of a fire concentration of several 'ack-ack' batteries on one and the same target was useless with such a large number of attacking planes."

"The aircraft warning service at last received the information from the radar installations of the night-fighter control centers. When all these new measures began to function, the home air defenses were faced with quite new tasks due to the introduction of **tin-foil strips** (German cover-name: 'Doppel,' RAF cover-name: **'Window'**), for the jamming of radar equipment during the large air raids in July and August 1943. The night-fighter planes had now to be equipped with airborne radar, the frequency range of which was beyond the reach of tin foil strip interference. The AAA batteries were forced into providing fire barrages only, until the first interference-free airborne radar was available by the end of 1943."

"During the second half of 1943, the number of daylight attacks by the Americans increased. As long as the American bombers attacked without escort fighters, the German fighters were successful. And as long as the daylight attacks were made under clear weather conditions with good visibility, the AAA also succeeded."

"In connection with the description given and with reference to the purpose of this meeting, I now should like to put the following question:"

"Were there ways and means by which the home air defense of Germany could have been made more effective with the manpower and material than existing and employed?"

"I would like to answer 'Yes.'"

"The home air defense would have been made more effective, if the approach to **operational research and its application** had been a different one. It was a mistake to implement the operational planning for the AAA **without sufficient technical investigation and without statistical data on the effect of existing AA guns and shells in relation to the efficiency of the enemy air forces.**[*] 'Thumb judgment' was substituted. Mistakes were also made as regards planning of personnel and management of the AAA. The organizational structure of the AAA stationed within the Reich was, during the first war years, exactly the same as for the units stationed at the front. During all this time, young men fit to serve at the front line manned the guns of the AAA stationed within the Reich."

"Only when war events forced a change in Autumn 1943 were elderly men not fit for front-line service, labor-service personnel, employees of industrial plants and finally even women and youngsters made to serve with the AAA stationed in the homeland. If one had foreseen such a necessity early enough, and had acted upon it in a planned manner, the AAA Command would have been saved the constant uncertainty resulting from a continuous change of personnel, and one would have in time introduced the organization of a militia, which had been found quite suitable for AAA duties in other countries."

"**Successes were achieved, however, when methods based on thorough examination were applied, which today would be part of operational research.** I should like to mention two examples:"

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[*] Boldface emphasis added to highlight vulnerability/lethality items of specific interest.

"Dr. Gunter Voss, formally a branch chief of the Research Department within the Air Ministry of the Reich, undertook for the first time to apply mathematics in order to investigate the **factor of possible destruction of 'ack-ack' shells on airplanes.** His study is called *Betrachtungen iiber die mit schweren Flakgeschossen erreichbaren Zerstorungswahrscheinlichkeiten* (Analysis of the probability of destruction attainable by heavy anti-aircraft shells). In this study he showed that **the considerably reduced vulnerability of bombers against fragments of heavy 'ack-ack' shells, and the increasing size of such planes, made the use of high-explosive shells with contact fuses much more effective than the use of fragmentation shells with time fuses. As a result of this, the AAA was supplied towards the end of 1944 with shells fitted with contact fuses. Success was noticeable immediately. The number of shells used to bring down a plane was considerably reduced."**

Figures 1 and 2 are Figures 4 and 5 in the reference document.

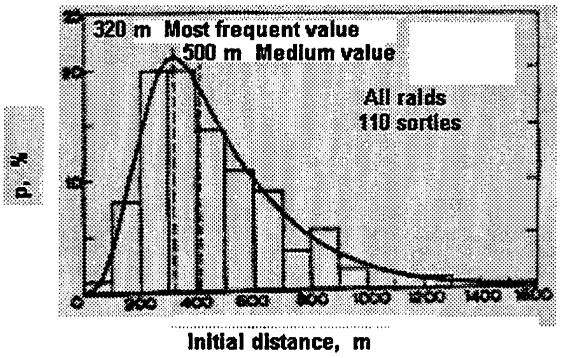

Figure 1. Evaluation of Distribution of Attacks in Relation to Distance.

"In another field of operation against enemy planes it was possible to improve results considerably, through minute evaluation of fighting techniques in use. Built-cameras in fighter planes provided every detail of a 'dog-fight' or an attack against a bomber, and thereby all maneuvers right up to the 'kill' could be closely examined. The study of these, and the resulting evaluation led up to improvements of weapons and gun-sights. These studies were made by Dr. Theodore Wilhelm Schmidt."

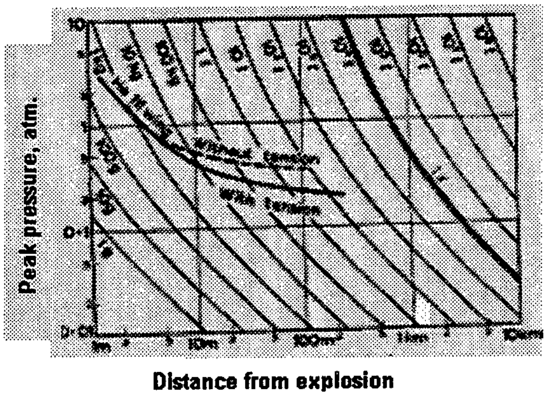

Figure 2. Distribution Curves for the Wing of a Heinkel 111 Bomber Show the Charge Needed for Destruction at a Given Distance.

Discussion. Th. W. Schmidt (Germany) said: "The combat film analysis presented by Dr. Benecke shows the effort made in Germany during World War II to obtain exact data on air combat as an essential basis for detailed studies on aircraft armament." "The first attempt from the German side to obtain motion pictures of air combat was made during the Spanish Civil War, but no cooperation could be obtained from the fighter pilots themselves. Objections which were made against a post-event evaluation of the air combat by civilian scientists were overcome only during World War II, when the German Air Force accepted film analyses as proof of a kill. Then we found we did not have enough cameras for installation. **The evaluation of nearly 1000 films of air combat provided sufficient data for statistical evaluation. This evaluation was never completed due to the grave situation in the years 1944/45; neither were the contemplated three dimensional models finished. Not until after the war was Dr. H. K. Weiss from Aberdeen able to conduct a statistical evaluation published as a BRL report. He first summarized the results of the German combat film analysis in concise form. The material for his report and also the film fortunately have been preserved through the post-war period by COL John J. Driscoll, U.S. Air Force, to whom I am greatly indebted."**

"In the field of simplified models for operational research I would like to mention one example, using a sphere for the complex-shaped aircraft, thus eliminating the influence of the angle under which the target was presented. Also, introducing the concept of the equivalent distance as the geometrical mean of the distances from opening to terminating the gunfire led to a simplified model for the hit probability in air combat in 1936 which was crude, but useful for answering quickly questions on the number of hits expected for different gun-sights or differently trained pilots. For more detailed answers to such questions a **photoelectric device** was constructed, but too late to be utilized fully as a mechanical model for air combat."

COL John J. Driscoll (USA) subsequently made the following written contribution to discussion: **"In the USAAF 8th Air Force during World War II, a statistical compilation was under way of the aircraft damage inflicted by the Luftwaffe upon the B-17 (Flying Fortress) and B-24 (Liberator) bombers. This study was purely a consolidation of hits by Flak fragments and aircraft gun projectiles. A few more specific but isolated analyses were made on their terminal ballistics effect of specific German aircraft gun projectiles in cases where the damage appeared unique and where identifiable fragments were involved. Comprehensive air-to-air combat film analyses were practically nonexistent. Furthermore, wartime data on such problems as optimum caliber were so inadequate that post-war analyses had to be made by means of extensive and expensive experimental trials. Similarly, although vulnerability data were available on some aircraft types, little specific guidance filtered up to the operational planners, and practically none to the aircraft designers. Consequently, combat data had little effect upon future operational requirements for new weapons, and negligible impact upon new aircraft specifications in the U.S."**

"On the other hand, despite a belated German appreciation of the potential on the combat film data, valuable directional guidance was ultimately received, particularly by the Luftwaffe's research and development program. Such an analytical approach produces data which, if properly digested and assimilated, are invaluable to all segments of a modern air force. **In the field of aircraft gun and projectile development great strides were made by the German Air Force, toward achieving a 'near-optimum' caliber, the 30-mm Schmidt's combat analysis data were correlated with the trends in the Luftwaffe's experimental fighter armament systems and gave highly accurate indications of the relative kill probabilities of the various weapons systems.** This technical guidance led to a rapid evolutionary development of the Luftwaffe's air defense interceptor forces. The fire-power build-up in the case of the Focke Wulf 190, for example, represents an order of magnitude increase between 1941 and 1945."

Figure 3 is Figure 3 in the reference report.

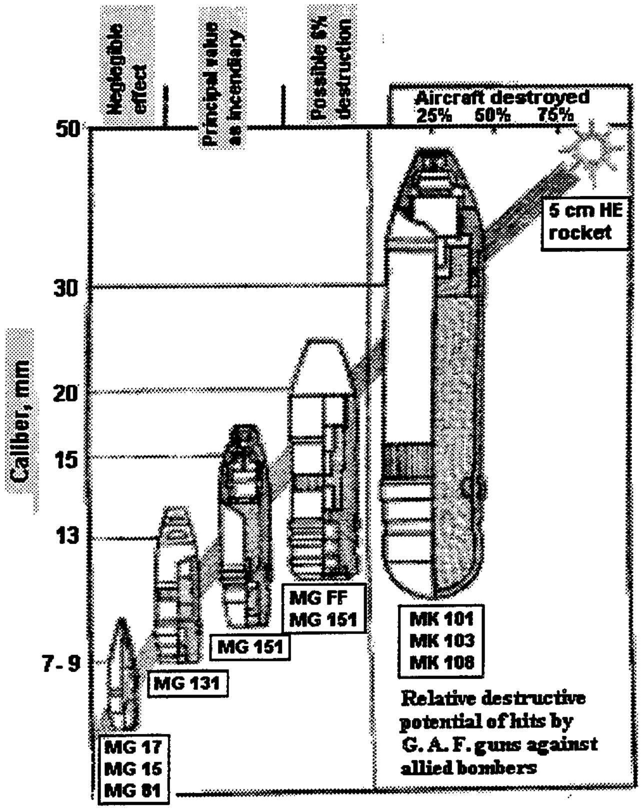

Figure 3.

"In the field of air combat weapons systems analysis, it should be noted that despite serious handicaps, Schmidt's analytical approach is generally recognized as the most advanced type. Schmidt's principal obstacles, listed below, could easily have been precluded:

1. The concept was not recognized until after 1941, resulting in a loss of three important years of air combat.

2. The shortage of gun cameras (even after appreciation of the concept) prevented the scale of coverage desired.

3. The analysis group was seriously understaffed and had available only improvised measuring equipment."

"In any post-war critique we have the distinct advantage of being able to perform a systems analysis of the World War II weapons with all the facts at hand, and with no need, therefore, to 'conjure up' important assumptions. **And in correlating Schmidt's wartime research with subsequent factual data, such as analyzed within the United States Strategic Bombing Survey studies, we are able to confirm the tremendous potential of such a combat analysis program. One is led to wonder as to what greater dividends might have been forthcoming to the Luftwaffe if their combat analyses had proceeded unhampered by the administrative obstacles. And closely correlated with vulnerability analyses of both friendly and enemy aircraft."**

"In reviewing the World War II studies of air combat data, one is impressed with the obvious dividends evolving from sound analyses of weapons effectiveness. Probably greater emphasis should have been given to correlating weapons effect with vulnerability studies of tactical targets: aircraft, armor, etc. In any event, it is evident that World War II operations analyses were generally conducted at a **sub-optimum level.** Drs. Benecke and Schmidt have both made this clear. Even within the Luftwaffe, where we found what is now recognized as the most advanced approach to air combat analysis, there was lack of early planning plus subsequent shortages of personnel and simple equipment. **In looking to the future, when the collection, analysis, and dissemination period might be a matter of days or weeks instead of years, the importance of these problems is amplified. The early establishment of a well founded and adequate program is essential."**

Biographical Sketch

Arthur Stein was a nationally recognized expert in military systems analysis with over 50 yr experience focusing on weapon system effects and factors affecting military system survivability.

He served in the military (1944–1946) and as a civilian at the BRL, APG, MD, from 1941 through 1951, except for 1 yr on a Ballistic Team. He was head of the Aircraft Weapons and Vulnerability Branch at the BRL (1946–1951); Director of the Ballistic Quality Control Program at the Ordnance Ammunition Command (1952–1955); Associate Director of the (multi-departmental) Applied Technology Group at Cornell Aeronautical Laboratory/Calspan Corporation (1955–1974); and Vice President of Falcon Research and Development Company, which was a leader in vulnerability analyses and computerized assessment models (1974–1983). After that time, he was an independent consultant.

He was a Research Staff Consultant to the Institute for Defense Analyses (IDA) with specific responsibilities in Live Fire Test and Evaluation. He was a Lecturer on Advanced Quality Control at the Universities of Chicago and Buffalo, President of the Military Operations Research Society (MORS), and Chairman of numerous programs and working groups/committees at MORS and the American Defense Preparedness Association (ADPA). He also served on a variety of "Blue Ribbon," Advisory, and Review Panels organized by DARCOM, DARPA, Picatinny Arsenal, NACA, NSIA/AMC, and the Research and Development Board Guided Missile Committee. In recent years he served on three National Academy of Sciences, National Research Council committees: the Board on Army Science and Technology (BAST) Panel on Energetic Materials (1984–1986), the Panel on Review of Army Vulnerability Assessment Methods (1986–1988), and the NAS NRC Air Force Studies Board Committee on Weapons Effects on Airborne Systems (1991–1992). Also from 1991 to 1992, he served as a member of the Fuel Systems Panel, Component Vulnerability (Pk/h) Workshop, Joint Technical Coordination Group/Aircraft Survivability. He was Guest Co-Editor of the Journal of Defense Research, Armor/Antiarmor Special Issue, *Vol. 20/No. 2, February 1991. Mr. Stein was also the author or co-author of over 100 publications.*

Mr. Stein passed away in June 1995.

9. Changes in Vulnerability/Lethality Analysis Over the Years

Stewart W. Turner

When given the opportunity to write my personal perspective on Vulnerability and Lethality Analysis changes over the years, I felt compelled to highlight the results of two significant V/L analysis efforts in which I was closely involved. The first one deals with vulnerability reduction in U.S. aircraft and is a little known success story involving vulnerability analysis that needs to be told. The second one deals with a less successful effort to develop a joint lethality model called the Joint Service End Game Model and is instructive if future attempts are undertaken to develop a new joint service end-game model.

9.1 Vulnerability Reduction in U.S. Aircraft. Significant advances have been made in the reduction of aircraft vulnerability during the last 20 yr. Much of this work has been sponsored and/or directed by the JTCG/AS, which has been responsible for the publication of at least three major vulnerability documents and the development of numerous models during the period. I have had the privilege of being associated with the JTCG/AS for more than 10 of those years and can attest to the value of these contributions to vulnerability reduction in Air Force aircraft.

The quest for vulnerability reduction procedures had its genesis in the aftermath of the Vietnam War when the reasons for U.S. aircraft losses to hostile fire were examined in detail. During the Vietnam War more than 5,000 fixed wing and rotary wing aircraft from all services were lost due to hostile fire. The Air Force losses of fixed wing aircraft alone were more than 1,320 aircraft. This amounted to more than $20 billion total loss with more than $7 billion for losses of fixed wing aircraft by the Air Force. These large numbers provided the motivation to conduct the research, analysis, and testing needed to provide improved survivability for aircraft systems via vulnerability reduction and susceptibility reduction. It is well known that susceptibility reduction led to "stealth" aircraft such as the F-117. The discussion herein is limited, however, to only vulnerability reduction efforts.

Major improvements have been made in military aircraft survivability due to vulnerability reductions since the end of the Vietnam War. The F-100, the F-105, and the A-4 are examples of older aircraft that were easy to shoot down, and the evidence shows that many of these aircraft were shot down. The assessment of battle damage, the conduct of laboratory testing, and the development of penetration codes, component damage criteria, target models, and vulnerability models led to survivability enhancements in the later models of the F-4 and early models of the F-15 and F-14.

Continued efforts by the JTCG/AS in vulnerability modeling, in conjunction with parallel efforts by the JTCG/ME in lethality modeling, have resulted in significant improvements in the survivability of state-of-the-art aircraft such as the FA-18, C-17, F-22, and later models of the F-15. Examples exist which demonstrate the capability of the F-15 to continue flying after suffering massive structural and control damage. The very low U.S. aircraft loss rates during Desert Storm are testimony to this increased survivability.

The vulnerability reduction efforts of the JTCG/AS have been documented so that aircraft designers were able to use the analytical tools developed and incorporate the vulnerability reduction features into current aircraft designs. As a result, aircraft today are many times more survivable to hostile fire than comparable aircraft of 20 years ago.

The most recent JTCG/AS publication, "Design Guide for Reduction of Aircraft and Helicopter Vulnerability," is not yet released for general distribution. Nevertheless, the document has been distributed informally throughout the industry and has been used by aircraft designers. The document provides an update to two previous JTCG/AS documents on the subject of aircraft vulnerability reduction.

The document reflects changes in the state-of-the-art which have taken place since the earlier design documents were published. It contains all of the basic and fundamental information on military aircraft vulnerability design requirements and vulnerability reduction features. It provides valuable information and guidance to personnel concerned with the design and assessment of military aircraft and is directed at designers of aircraft and aircraft components to emphasize the importance of vulnerability reduction considerations at all stages of development. Ways are discussed by which inherent aircraft vulnerability may be reduced through configuration layout, component design, and/or the application of protection.

In my opinion, and with the exception of stealth, these efforts of the JTCG/AS have contributed greatly to the increased survivability of U.S. aircraft (including civil aircraft) and have completely changed the design practices of a major industry. This little publicized effort by the JTCG/AS should prove to be one of the most significant contributions to the U.S. aircraft industry this century and should result in major cost savings due to improved aircraft survivability through vulnerability reduction.

9.2 Joint Service End-Game Model (JSEM). During the '60s, '70s, and early '80s, each of the services used one or more different end-game models for assessing end-game lethality of air-to-air missile warheads. The Navy used MECA, the Air Force used both SHAZAM and SCAN, and the Army used AMEGS and LEGS. Several attempts to develop and/or adopt a common end-game model were totally unsuccessful during the above time period even though several million dollars were spent on an early attempt at a common model called REFMOD.

The advantages of a common model continued to be recognized by members of the JTCG/ME Anti-Air Working Group. Accordingly in 1986, one more attempt was made to develop a common JTCG/ME end-game lethality model to assess air-to-air missile effectiveness. With this attempt, however, the approach was changed to enhance the chance for acceptance by the service users.

The new model was to be called JSEM (Joint Service End-game Effectiveness Model) to clearly communicate its intended use and tri-service endorsement. The model was also to be a composite of the best features from each of the recognized models currently in use by the services. Finally, the model development was to be adequately funded to negate the need to rely on ad hoc groups as had always been done in the past.

A joint-service technical steering committee was established to set up guidelines and monitor the progress of the effort. The JTCG/ME contractor for JMEMs, Oklahoma State University (OSU), was given the task of coding the model in accordance with the specifications of the committee. The JTCG/ME spent several millions of dollars over eight years to develop and evaluate several versions of the JSEM model leading up to Version 2.2 that was completed in 1994. The lack of adequate, timely, funding caused the program to stretch out far longer than would be desired.

Tests in 1991 and 1992 confirmed that the JSEM consistently gave the same results as SHAZAM for cases involving fragment ray-tracing and, likewise, gave the same results as MECA for cases involving fragment density functions and ran 75% faster due to the use of "virtual memory" and other enhancements. Nevertheless, the model was not widely accepted by many of the service organizations for use in their end-game lethality analyses. Many service analysts stayed with their "old favorites" because the new JSEM gave the same answers by actual comparison, and, therefore, some analysts saw no reason to switch and increase their workload by learning a new model. Analysts at the NAWC, at OSU, and in the Anti-Air Working Group have, however, been using JSEM routinely.

This *Catch-22* situation was further exacerbated by the inability of the JTCG/ME, due to funding cutbacks, to put the model into SURVIAC, the ITCG model repository, for widespread distribution. Industry analysts were desirous of using the new JSEM, but without documentation and field support from SURVIAC, they were unable to use the model and so the customer base was reduced even further.

In reflecting on the reasons why such a situation could be allowed to happen when the JTCG/ME overtly took steps to gain wide acceptance of JSEM before investing many years and several million dollars in a model of little interest to many of the service analysts, a few observations come to mind. The observations should prove beneficial, particularly since the JTCG/ME is seriously considering investing heavily in another end-game model development effort called AJEM to be the "next joint service model":

1. Many of the key personnel within the government and at the contractor (OSU) left the project before JSEM was accepted as a joint service model. Without these "champions" to aggressively sell the model and provide answers to legitimate technical issues, little issues became major concerns which caused some people to lose interest in the model.

2. The development time was much too long to be compatible with the rapidly changing computer technology. In 1986 it was not conceivable that all of the penetration equations with point burst for each component could be incorporated into the basic framework of JSEM (i.e., incorporate a detailed FASTGEN model). Today, with 100-MHZ processors in desk top machines, this is possible. Thus, the "kid in the candy store syndrome" can easily lead to the justification for a newer model because JSEM looks obsolete.

3. Industry support, although present, was not actively sought at the onset of the development of the JSEM model. Today, industry participation in the Steering Committee would be beneficial in gaining wider support for a new model. Had industry been given the opportunity to participate, it is possible that industry could have provided the funds necessary to put JSEM into SURVIAC for earlier, wider distribution.

4. An evolutionary model is not as attractive as a revolutionary model. When the new product is in some ways very similar to the old models, analysts need to have some very compelling reasons to switch away from their old, familiar models. Some attractive advantage must be incorporated in the new model to ensure immediate acceptance by the analysis community.

5. The next attempt at a common air-to-air end-game model should begin with a detailed assessment of the problems with the previous attempts at a common model. Also, any new model should have the endorsement of OSD and the service representatives before work is begun. The community can ill-afford another unsuccessful attempt.

Biographical Sketch

Dr. Turner has been a leader for 33 yr in Air Force propulsion technology and the development and analysis of weapon systems. He is credited with many achievements in his career. During his early years, he was a pioneer in the development of the first segmented solid rocket motors, several types of thrust vector control, large nozzle technology, and maraging steel technology, all of which are in common use throughout the services and NASA today.

During the last 21 yr, Dr. Turner played a key role in the planning, analysis, and development of every Air Force tactical standoff weapon system developed at Eglin Air Force Base. He was selected to represent the Air Force in all matters pertaining to weapons systems analysis on several international missile development programs and is now an internationally recognized expert on weapon systems analysis in many countries including England and Germany.

Dr. Turner personally initiated and developed much of the analytical methodology used by the Air Force to procure all the tactical air-to-surface weapons for the War Reserve Material (WRM) stockpile, a $2 billion annual expenditure. In addition, he pioneered the development and implementation of the Air Force Attrition Database used throughout the Air Force for munitions planning and analysis and was recognized as the Air Force's expert on aircraft attrition for 15 yr.

Dr. Turner has extensive experience setting up and directing systems analysis organizations. He was selected by MG Eaglet to establish and direct the first composite analysis organization of more than 50 analysts at the Air Force Armament Division in 1984, and held the position as Director for 6 yr. During that time, he was involved in systems analysis to support major production decisions on all of the major Air Force weapon systems including AMRAAM, GBU-15, AGM-130, BLU-109, Combined Effects Munition, Hypervelocity Missile, Direct Attack Airfield Cluster Munition, DURANDAL GBU-24 A/B, GBU-27, GATOR, and several others, many of which were used successfully in Desert Storm.

Dr. Turner's expertise includes extensive experience in systems engineering and testing of weapons systems. He has served as Technical Director of Systems Engineering for nearly 2 yr at the Air Force Development Test Center, during which time he specialized in directing independent technical review teams to solve major systems engineering problems on Air Force weapon systems under development. He is credited with implementing several unique solutions to problems which significantly improved Air Force weapon systems currently in production.

Dr. Turner has a strong multidisciplinary technical background. His in-depth knowledge of aerospace engineering is enhanced by his demonstrated expertise in weapons systems analysis, aircraft and missile survivability, weapons testing, digital computer simulations, rocket and turbojet engine propulsion, Soviet threat characteristics, and target vulnerability. He is a fluent writer, an accomplished briefer, and an effective leader of technical review teams.

Dr. Turner has been a leader in the tri-service community, serving as Air Force Chairman of the Methodology Working Group for the Joint Technical Coordinating Group for Aircraft Survivability (JTCG/AS) and as Alternate Air Force representative to the Steering Committee for *the Joint Technical Coordination Group for Munitions Effectiveness (JTCG/ME) and as the Air Force representative to the Steering Committee for the JTCG Survivability/Vulnerability Information Analysis Center (SURVIAC). In addition, he has been a frequent technical consultant and active participant to the USAF Scientific Advisory Board and has contributed several papers which were incorporated in the final reports.*

Since his retirement from the Air Force in September '91, he has been actively involved as a Defense Systems Consultant in several different programs including the SMART Program and the Lethality/Vulnerability Master Plan for OSD, the JDAM 3, the C-17, and the AMRAAM programs for the Air Force, and an international missile program. He has also authored a major technical report for RAND entitled "The Effectiveness of Smart Weapons Against Selected Shelters in Iraq and Kuwait."

10. The Best and Worst of Times

by Lawrence G. Ullyatt

10.1 Denver Research Institute. As Charles Dickens so eloquently put it in the opening paragraphs of his famous novel, *Tale of Two Cities*, describing the state of affairs in France in the late 1700s, "This is the best of times and the worst of times." The words also describe the state of affairs in the world during the last 25–30 yr. During this period, the United States was busily improving its defensive posture in order to combat its potential enemy in the Soviet Union and the other Warsaw Pact nations. This was a time of great tension, a period during which we taught our children how to protect themselves from a nuclear attack by crawling under their desks and encouraging citizens to build fallout shelters in their back yards. The presence of the Berlin Wall was a constant reminder of the Iron Curtain and the resultant tension in the world. At the same time, the U.S. experienced periods of intense optimism and exhilaration such as the first lunar landings and, more recently, success in Desert Storm. We also experienced intense depression such as the assassinations of national leaders, the shuttle disaster, and the dissention caused by the Vietnam War. So it was in many respects the best of times and the worst of times in our country, all within the period of a few decades.

The attitudes and awareness of our own vulnerability during this time led Congress to allocate unprecedented amounts to the study of our human situation, a great deal of which went into the enhancement of our strategic strength (i.e., nuclear). Once everyone realized we had produced a stockpile of weapons that more or less maintained a very uneasy peace by allowing us to show we could destroy each other many times over, some of the funding eventually percolated down so it could be used to evaluate the level of our vulnerability to conventional weaponry. It was during this time that I became involved in the field of vulnerability assessment and saw a number of changes take place.

During this time the vulnerability "process" gained legitimacy and acceptance. Few really even knew what the word "vulnerability" meant up to this time. It was suddenly taken from the back room, where weapon system developers once gave it a certain amount of lip service, and moved to the board room, where companies had to include vulnerability reduction features from the preliminary design concept on up, not simply because it was the right thing to do, but because it was the law. Some of the changes were technological in nature while others were very much organizational. During the last 30 yr, a host of organizations have been formed to address the issues of vulnerability and survivability including the Joint Technical Coordinating Group for Aircraft Survivability, Joint Technical Coordinating Group for Munitions Effectiveness, Live Fire Test Office, and others. Organizations within each of the services have also been formed to evaluate the vulnerabilities of our own systems and improve their survivability. These include groups at the ARL (formerly BRL), Naval Weapons Center at China Lake, Naval Air Systems Command, and Wright-Patterson Air Force Base, just to mention a few. Survivability analysis and vulnerability reduction are now very big businesses in the military. I would like to share a few thoughts about the key changes that occurred over the last 30 yr that modified the way we think about vulnerability analysis.

10.2 Computerization of the Vulnerability Process. During the 1960s, a revolution in the way vulnerability analyses were being conducted took place. Up to that time, nearly all estimates were being performed by hand. Even though the first electronic computers were developed during WW II at the University of Pennsylvania for use in ballistics analyses at APG, they were not applied to a significant degree to the task of estimating the vulnerability of targets until much later. The first formal approach that was used to compute vulnerability was to create detailed engineering drawings of the targets on paper or Mylar and to trace the trajectory of the fragment or projectile through the target, recording the angle that the fragment intersected the first surface of the component, the distance it traveled through the component, and the angle at which it exited the component. This procedure was continued until the intersections and penetrations of all components along a given shotline were computed. Along with a set of equations used to estimate mass and velocity loss through various materials (the first of which were known as the Thor equations), the distance the fragment traveled and the hole size it created were estimated. This early approach was known as "hand shotlining," and it was very time-consuming. This process almost literally begged to be applied to the digital computer. It was very repetitious and involved rather trivial trigonometric calculations. To fully implement it on a computer, a three-dimensional model of the target was required. Up to this time, the computations were done on a set of orthogonal view drawings showing components from the front, sides, top, bottom, and rear. We must remember that computer-aided drafting, or CAD, had not yet been discovered. A procedure for modeling all components in three-dimensions had to be developed.

Two different schools of thought arose in the community, one that involved solid modeling of components and the other surface modeling. The former was adopted primarily by the U.S. Army and was known as Combinatorial Geometry or COMGEOM while the latter was known as the Shot Line Generator process or SHOTGEN. Along with a code that automated the Thor equations known as VAREA (which stands for Vulnerable Area technique) and later known as COVART (Computation of Vulnerable Area and Repair Times), these techniques would be employed for the next 20–30 yr. The evolution from the strictly hand processes to machine were not without their problems, however. When a mistake was made during the hand shotlining, it usually only affected the one shotline. Now with the digital computer performing hundreds or thousands of calculations, errors could easily be missed and the results could be incorrect by orders of magnitude. The process still relied heavily upon the use of draftsmen to prepare the models, of course, but now the computer programmer and computer analyst began to take more prominent roles. The tedious process of calculating the vulnerability of a target could now be accomplished in a fraction of the time it formerly required. Before the computer, it was not unheard of to take up to 2 yr to fully assess the vulnerability of a target. The development of the technique took place at just the right time because as a result of the Arab-Israeli conflicts in 1968 and 1973, the U.S. had an abundance of targets to analyze. We were now able to see how well our theoretical predictions held up with real hardware.

10.3 The CARDE Trials. The vulnerability analysis process has always relied upon the results of experiments to "fine tune" its procedures. Even with the original Thor equations that were totally empirically based, the process has been dependent upon the physical realities observed in tests. The first experiments I recall that had a significant effect on the way we assess vulnerability were the

CARDE trials, conducted in 1959. Named after the organization where the tests were conducted, the Canadian Armament Research and Development Establishment located in Valcartier, Quebec, this series of tests provided the tank analysts with a resource that up until that time was unavailable. From these experiments, the infamous Standard Damage Assessment List (or SDAL) was born; the SDAL was to be the basis of heavy and light vehicle vulnerability assessments for the next 25 yr. The SDAL is a listing of approximately 120 major systems and components which compose an armored fighting vehicle. It is an estimate of relative combat utility of a vehicle given the loss of the specified system or component. The original tests involved the firing of antitank rounds against a number of targets including the M47 and M48 tanks, and the compartment kill methodology developed at the BRL was tailored as a result of these experiments. The SDAL was gradually modified and updated over the years to reflect new systems that are employed in armored vehicles, but the transition has occurred very slowly in spite of the objections of its opponents. Whether the SDAL served us well over the years is subject to individual interpretation, but the fact of the matter is that it was a significant part of the history of surface target vulnerability analysis.

10.4 Joint Munitions Effectiveness Manuals. The Joint Chiefs of Staff requested the services to develop a joint manual to provide effectiveness information in 1963. In 1967, the Joint Technical Coordinating Group for Munitions Effectiveness prepared the first of the manuals for review by the Secretary of Defense. Thus, one cohesive organization, the JTCG/ME, responsible for the prediction of weapons effects on targets, was formed. Up to this time, each of the services estimated how well its munitions would damage or kill targets in which it was interested, but the techniques it used to compute these vulnerabilities were not consistent, and the results tended to make the munitions look good so the procurement would not be questioned. The JTCG/ME was formed to capitalize upon the vast quantity of data that was being generated and to standardize the process of weapon effectiveness assessment. The charter of the JTCG/ME was to include only weapons that were in production, not developmental systems. One of the reasons for this was to keep the JTCG/ME out of the political bickering that always tended to accompany the procurement of a new system. The major advantage of an organization such as the JTCG/ME is the unbiased position it takes with respect to the vulnerability process. It has published dozens of reports that describe in detail methods it considers to be viable in computing weapon effectiveness against various types of targets as diverse as armored vehicles, radars, buildings, bridges, aircraft, personnel, and many others. One extremely useful manual published by the group is the Air-to-Surface Target Vulnerability Manual, a compilation of over 4,000 pages of information related to the vulnerability of a myriad of targets. It constantly strives to improve the techniques it advocates by dedicating a portion of its budget each year to methodology enhancement. An organization like the JTCG/ME is valuable to the community because of what it provides, a nonpartisan "snapshot" of the vulnerability of various targets to different threats. So the JTCG/ME adds consistency and historical veracity to the vulnerability process.

10.5 The Live Fire Test Law and Role of Live Fire Testing. Another good check along the road to vulnerability assessment is the Live Fire Test Law. This law came about largely as a result of pressures on Congress due to the controversy surrounding the conduct of experiments on the Bradley Fighting Vehicle in 1986. In 1987, the Congress passed legislation mandating that all major weapon systems must prepare and execute a plan to perform full-up live fire tests prior to the approval to proceed beyond low rate initial production, or prepare an alternate plan and request a waiver. Over the years since the law has been in effect, there has been a tremendous amount of "political posturing," both by the services procuring the systems and by the contractors building them. As a result, several committees have been formed under the aegis of the National Research Council to fully study the issues involving the Live Fire Test Law with respect to the Army and Air Force. I was privileged to participate in these studies and to share my viewpoints with others in the field. Reports were published documenting our efforts, and the results were not without considerable controversy. I believe the major impact of these studies was to focus the community on the need (and now requirement) to consider live fire testing as an integral part of the entire vulnerability reduction/survivability enhancement process. Before the law, some testing was done to prove the viability of the system or components in defeating certain key threats, but the Live Fire Testing Law requires that the system be tested full-up with fuel, ammo, and simulated personnel on-board, if this is a typical scenario in which the system will be employed. A very effective organization was established to oversee and assist the services and industry to meet the requirements of the Live Fire Test Legislation, but this organization has undergone considerable change over the years. The legislation is still very much a requirement in the procurement process, so the DOD must maintain the strength and effectiveness of this important Live Fire Test Office. To date, the conduct of live fire testing has revealed many problems that have been able to be fixed prior to full-scale production. Proponents state that the amount of money saved has exceeded the cost of implementing the law, while opponents say we cannot afford the cost of live fire testing. The fact is the Live Fire Test legislation is with us at the present time, and we must comply with it. The result of this legislation is that a great deal of attention is being given to vulnerability reduction and survivability enhancement measures in all weapon systems falling under the requirements of the law, and this has been very positive. It means that lives will be saved and weapon systems spared in the long run. A side benefit of this legislation is that a large database of information related to the vulnerability of targets has been improved and this has further enhanced the accuracy of the methodologies that are employed.

10.6 International Cooperation. Some years ago, it became obvious to persons working within the vulnerability community that we could not afford to perform this work in a vacuum, either from the aspect of financing such work, or from the point that cooperation with our allies would bring about a synergism of thoughts and ideas, the result of which would be larger than the sum of the individual pieces. Organizations were formed to foster such cooperation, such as the Tripartite Technical Coordinating Panel (TTCP) involving the U.S. and Great Britain, and numerous other data exchange agreements between the U.S. and its allies. I have been privileged to be involved in many of these discussions over the years. One of the most recent efforts is to establish a mechanism for exchanging geometric target models between the U.S., France, Germany, and Great Britain. Although each country uses a different technique in building its models, it is possible to translate the descriptions from one format to another without sacrificing accuracy or fidelity. So something that was only a wish a few years ago will become a reality very soon. Joint studies using the same target model will now be possible, eliminating one source of difference in the results that has always plagued us. A number of nations are now adopting similar methods of describing targets, and this will bring about even closer ties in the future. Discussions are also underway to consider the possibility of conducting live fire testing in an international cooperative program. This will have the result of harmonizing the techniques we utilize in testing and learning more from each other and will allow us to understand each other better.

10.7 Summary—The Changing Face of Our Enemy. As a result of events in the former Soviet Union and in other former Warsaw Pact nations, the face of our enemy has radically changed. We have recently been involved in a major conflict with a nonsuperpower, Iraq, and still other nations threaten to involve the forces of the United States in local conflicts, such as in the former Yugoslavia, Somalia, North Korea, and others. Some of these countries may even be using our own weapons against us. China also remains a possible threat to the peace of the world. With the general attitudes in Congress in reducing the U.S. defense budget significantly over the next few years, we cannot forget that the threat is still very much present, but it has just changed from a concentrated threat, the Warsaw Pact, to a distributed threat, nearly all the nations that are not now our allies. Now we not only have to consider the weaponry and forces of the former Warsaw Pact, but we also need to be prepared for the possible threat these same weapons pose in the hands of smaller third world countries. This means more effort must be dedicated to the assessment and planning for countering these potential threats before they become a problem, not afterward. We must also remember that it takes over a decade to develop and field a new weapon system.

Surely the increased awareness in the community of the importance of vulnerability reduction and survivability enhancement is good, because it is the "right thing" to do. Survivability of our troops is vital, and survivability of our weapon systems is very important. It is encouraging to see that emphasis is being given to this area, but we must be aware of how these rapidly decreasing resources are being spent. It is important that adequate funding remain in the area of vulnerability/survivability assessment so that improvements in methodology, testing, and documentation can continue. The importance of modeling in simulating the real world will grow as weapon systems become more expensive and complex, and defense budgets decrease. Directly related to accurate modeling is the fundamental testing that forms a foundation for the models. We must continue to dedicate resources to those organizations working in this area so that the next 30 yr do not become the "worst of times" for our country's defensive posture.

Biographical Sketch

Mr. Lawrence G. Ullyatt began his career in the field of vulnerability assessment when he joined the Falcon Research and Development Company in Denver, CO, in the early 1970s. Prior to this time he worked as a flight test engineer at the Boeing Airplane Company in Seattle and as a test engineer at the General American Research Division in Niles, IL, where he conducted research into the simulation of underground explosion technologies for several years. In 1981, he moved from Falcon R&D to the Denver Research Institute, a part of the University of Denver, and, as Director of the Computational Dynamics Laboratory, is in charge of all vulnerability/survivability activities. Mr. Ullyatt has participated in a number of national and international data exchange efforts and has served on three committees under the National Research Council, National Academy of Sciences, studying vulnerability and live fire testing issues. He has written numerous technical reports on vulnerability analysis and has presented many papers on the subject.

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13. ABSTRACT ***(Maximum 200 words)***

Commencing in the early 1990s, Mr. James O'Bryon of the Office of the Secretary of Defense (OSD), Operational Testing and Evaluation (OT&E), charged the Vulnerability/Lethality Division (VLD) of what is now the U.S. Army Research Laboratory (ARL) to capture in a hard-bound book the art/science of vulnerability and lethality (V/L) analysis. This work has since expanded into the publication of a series of volumes, each dedicated to a particular portion of the V/L community—ground mobile targets, hardened fixed targets, aircraft, etc.

As a first step in this mammoth effort, a number of articles were commissioned to be gathered from some of the giants in the history of V/L analysis. These articles gave a foundation from which the writing of the first of the series commenced and are collected in this report with the hope that future generations of V/L analysts will find in them inspiration for their own accomplishments.

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