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SYSTEMS VULNERABILITY AND LETHALITY IN THE DEVELOPMENT PHASE

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Vulnerability is a subject that has been of interest to the Army for some time. Early investigations to quantify the effects of weapons damage on targets were begun shortly after World War I.

At this time, 1925, interest in the effectiveness of various antiaircraft weapons became active. Tests were performed in which 3-inch antiaircraft shell, caliber .30 and caliber .50 machine gun bullets were fired against aircraft with running engines to determine the relative effectiveness of such weapons against aircraft targets. The damage was carefully studied and analyzed in terms of the shots fired. On the basis of these and other firing tests for evaluating a number of different antiaircraft guns, it was recommended that a 90-mm weapon be adopted because of its superior over-all effectiveness.

The effectiveness of antitank weapons also was investigated. In 1925-1928, caliber .30 and caliber .50 AP bullets, 37-mm AP shot, and 57-mm AP shot were fired against obsolete Renault tanks; the results showed that this tank was vulnerable only to the 57-mm shot. Many other tests were conducted to determine the armor-piercing capabilities of different bullets and shot.

It was not until the end of World War II, however, that a major program was initiated for the systematic study of the vulnerability of Army weapon systems. In July 1945 the Office, Chief of Ordnance directed that investigations be initiated to determine the optimum caliber for aircraft weapons. This work was the forerunner of the comprehensive vulnerability programs conducted by the Ballistic Research Laboratory (BRL).

Within the next few years the program was expanded to include the vulnerability of armored vehicles, personnel, as well as a wide range of other targets. Figure 1 is a list of target categories of concern to the Army and the various damage mechanisms currently considered in the BRL vulnerability program.

TARGET CATEGORIES	DAMAGE MECHANISMS
Aircraft	
Anti-A/C Artillery	
Armored Vehicles	
Assault Guns	
Buildings	
Communications Equipment	Blast
Field Artillery	Penetration
Field Fortifications	Flame & Incendiary
Land Transportation	Radiation
Missile Systems	Chemical
Personnel	Laser
Power Generation Facilities	High Power Microwave
Radar Installation	Particle Beam
Rockets & Launchers	Non-Nuclear EMP
Supply Depots & Dumps	
Support Vehicles	

Figure 1. Scope of BRL Vulnerability Program

As stated in Army Materiel Command (AMC) Regulation 70-53 "Non-Nuclear Vulnerability and Vulnerability Reduction" dated 16 June 1971, vulnerability is a quantitative measure of the susceptibility of a target structure or material to a given damage mechanism - it is the characteristic of a target which describes its sensitivity to combat damage mechanisms. For example, vulnerability of an aircraft is the effect of damage on the aircraft from a given attacking weapon or agent-(12.7-mm API projectile for example) or group of such threats (23-mm HEI projectile, SA-7 missile with blast/fragmentation warhead, etc). Each of the individual components in the aircraft has a level, or degree, or amount of vulnerability; and each component's vulnerability contributes in some measure to the overall vulnerability of the aircraft. Some components contribute more than others. The critical components on an aircraft are those components which, if damaged or destroyed, would lead to an aircraft kill. The systematic description, delineation and quantification of the vulnerability of the individual critical components and of the total target vulnerability is known as a vulnerability assessment. Certain elements of a vulnerability assessment are common to all analyses, regardless of the threat considered. Figure 2 is a simplified logic diagram for a typical vulnerability assessment. The elements of such an assessment are: (1) definition of the problem; (2) an assembly of the physical and functional descriptions of the target; (3) a description of the specific threats the target will encounter and their associated damage mechanisms (penetration, fire, etc); (4) preparation of the target description; (5) identification of the critical components and determination of the target's damage-caused failure modes for the selected kill

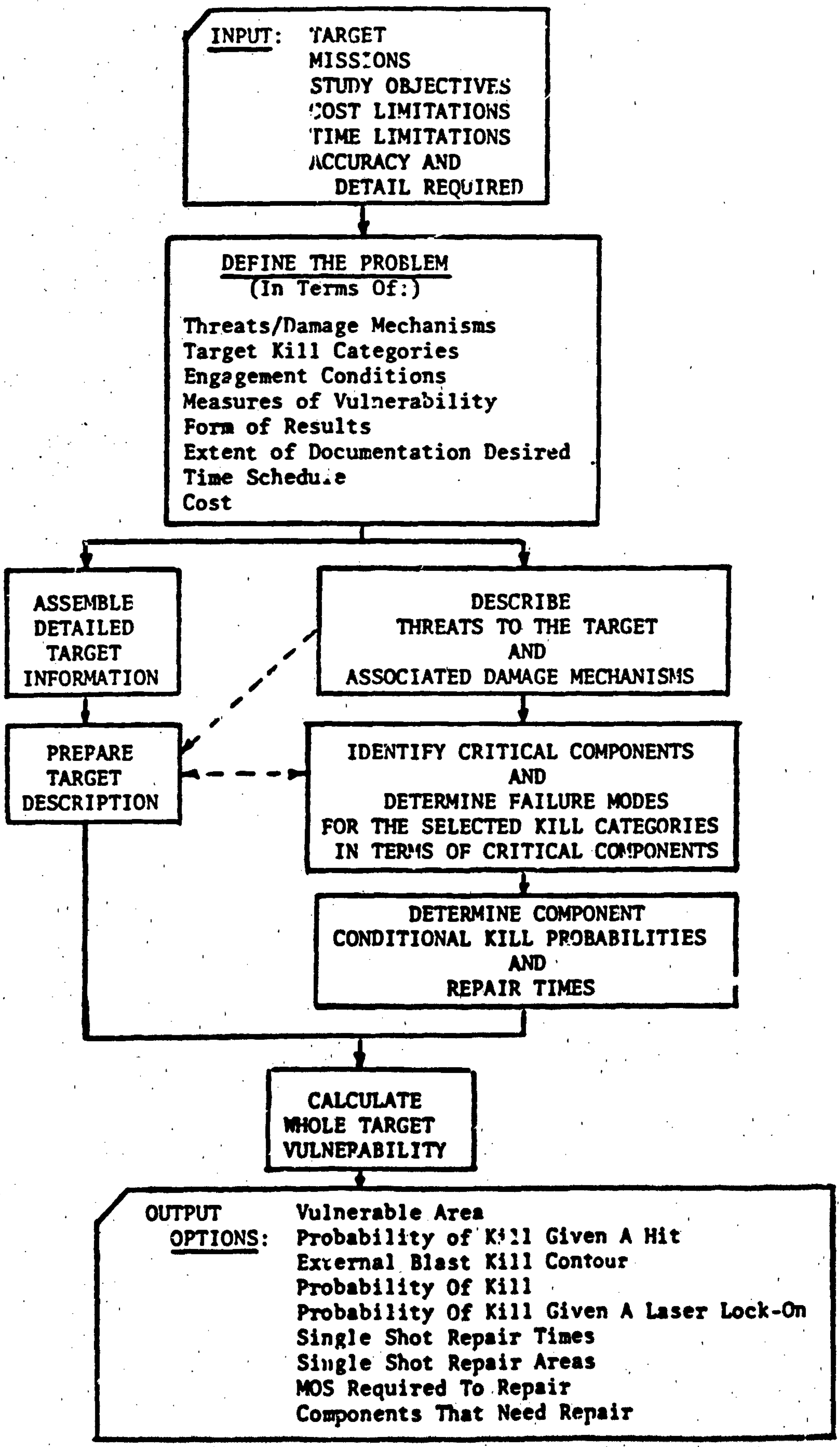

Figure 2. Typical Vulnerability Assessment Logic Diagram

categories in terms of the critical components; (6) determination of the conditional probabilities of kill for each critical component and the single shot expected repair times for damaged components; and (7) computation of the vulnerability measures for the whole target based upon the selected threat.

The first step, or element, of the vulnerability assessment involves definition of the problem. Timely and careful definition of the problem is absolutely essential for a successful study. The basic specifications for the study are provided to the vulnerability analyst by the user of the results of the study who initiates the study. Some users of vulnerability information:

Army Materiel Systems Analysis Activity
Concepts Analysis Agency
Materiel Development Commands: AMCCOM, AVSCOM, ERADCOM, MERADCOM, MICOM, TACOM, etc.
Operational Test and Evaluation Agency
Program Managers: Advanced Attack Helicopter, M1, etc.
Training and Doctrine Command Centers, Schools, Commands and Activities
U.S. Army Nuclear and Chemical Agency
U.S. Air Force, Navy and Marines
Allied Foreign Governments

The user must designate the target (aircraft, tank, etc) and threats to the target. The mission or missions of the target to be evaluated must be described as well as the objectives of the study. In addition to being highly dependent on the objective and use of the study results, the scope of a vulnerability assessment is also dependent on time available versus the time required to perform the assessment, study cost and the levels of accuracy and detail desired for the study. These factors must be carefully considered and specified at the very outset of the vulnerability study. Complete understanding and agreement must be achieved on the following between the user and the vulnerability analyst at this first step of the vulnerability assessment:

target
threats/damage mechanisms
target kill categories
engagement conditions
level of accuracy and detail
measures of vulnerability
form of results
extent of documentation desired
time schedule
cost

As much of the target's physical and functional description as possible must be gathered on each of its systems, subsystems and components. Sources of this information include the manufacturer, operator, intelligence agencies, operational and maintenance manuals, perspective drawings, schematics, scaled three-view drawings, detailed inboard profiles, cross-section drawings, and field

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examination. The descriptive material gathered should include information on configuration, dimensions, materials of construction and location of all systems, subsystems and components to include armor and/or components used to shield critical components. Complete descriptions of how the components, subsystems and systems function (including redundancies) and how they relate to the overall operation of the target under study must be obtained.

Because of the diverse terminal effects of the various damage mechanisms each vulnerability assessemnt is usually made considering either a specific threat or a specific damage mechanism. Threats and damage mechanisms typically considered (listed in figure 1) are: a non-explosive penetrating projectile, fragment, or shaped charge, the fragments and blast from internally or externally detonating high explosive projectile or missile warheads, flame and incendiary devices, radiation, chemical, laser, high power microwave, particle beam and non-nuclear EMP.

After as much information on the target as possible is assembled, a target description is prepared for analysis. The form and exact content of this description depends upon the study specifications concerning level of accuracy and detail desired, vulnerability measures, time available for the study and cost as well as the degree to which the needed target information is available. Consequently, the target description may range in form and sophistication from simple sketches to schematics to detailed inboard profiles to completely computerized geometric models that faithfully represent the actual target down to the smallest details (see figure 3, computer description of a tank).

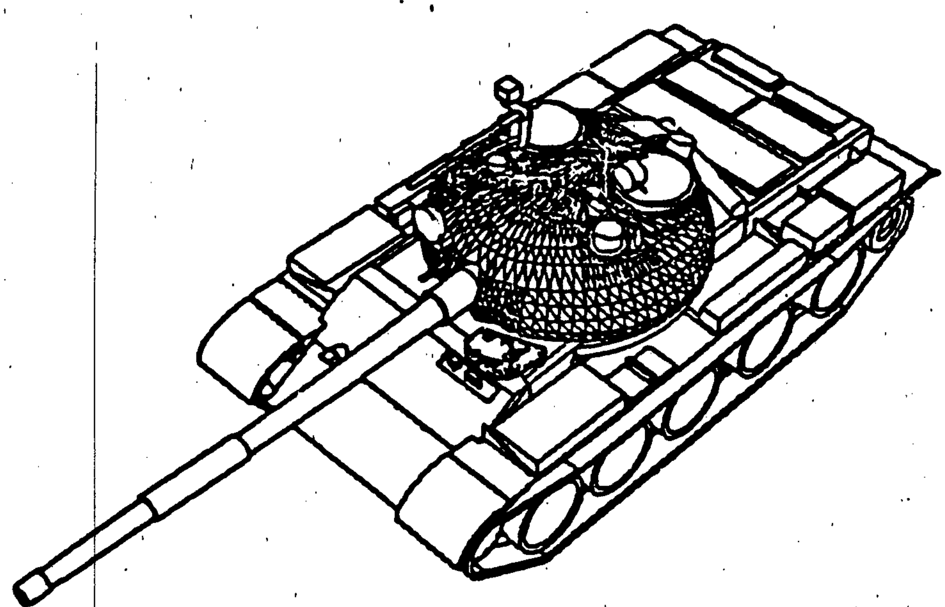

Figure 3. Computer Description of a Tank.

Information from all prior steps in the vulnerability assessment process is used to identify critical components and determine target failure modes for the selected kill categories in terms of the critical components. Generally, each of the targets in the categories of prime interest to the Army (see list in Figure 1) are associated with a distinct set of kill categories or kill criteria. These kill categories express the results obtained when the target is attacked. Several examples are listed in Figure 4. Other kill criteria relate to cost inflicted in terms of time to repair or replace.

Tank Target	Helicopter
Catastrophic	Attrition
Mobility	Forced Landing
Firepower	Mission Abort

Figure 4. Typical Kill Categories

It is usual in a study to specify a set of kill criteria or categories which range from the most desirable result (or complete success) to the least acceptable result which still has military significance.

Note that in many cases the maximum performance degradation of a target does not occur until some interval of time after application of a damaging agent. Hence, the set of kill criteria usually are expressed as a combination of the desired performance degradation and the time after attack within which this degradation must occur. As an oversimplified illustration, the set of kill criteria for a locomotive might range from "K-Kill" (most desired): immediate derailment, overturning and explosion, to a "D-Kill" (least acceptable): locomotive becomes incapable of movement within 60 minutes. These time criteria must be consistent with both the tactical requirements and the behavior of the particular target subsequent to application of the damaging agent.

As mentioned earlier, a critical component is any component which, if damaged or destroyed, would lead to a target kill, that is, a definable target kill level. In other words, a critical component is one that is essential to the functioning of a system and if the component performance is sufficiently degraded or if the component is rendered inoperative by combat damage, a target kill in same category will result. A component may be a critical component because it provides an essential function, such as thrust (engine), or lift (rotor blade), or control (rudder), or it may be a critical component because its mode of failure leads to the failure of a critical component that does provide an essential function. For example, a fuel tank in a wing can be perforated by a fragment, causing a fuel leak and eventual fuel depletion from that tank, with no substantial affect on the continued operation of the aircraft. In this situation, the wing fuel tank is not a critical component. On the other hand, the fragment impact and penetration of the tank could cause ignition of the fuel vapor in the ullage, with a subsequent fire or explosion and loss of first the wing and then the aircraft. In this event, the wing tank is definitely a critical component.

The first step in a critical component analysis is to identify the performance and mission critical functions the target must perform in order to operate and to accomplish its mission. The second step is to identify the major systems and subsystems that perform these essential functions. Next a failure mode and effects analysis and/or fault tree analysis to identify the relationship between each possible type of individual component or subsystem failure mode and performance of the essential functions. The fourth step in this element of vulnerability analysis consists of relating component or subsystem failure modes to combat-caused damage. Additional sources of input for this critical component identification and failure modes element of the vulnerability assessment process include dynamic tests of components, subsystems and systems, target accident records and prior combat damage data as well as engineering judgement and experience.

Once the critical components for a given target have been identified and the target failure modes have been resolved, component conditional kill probabilities and repair times must be determined. The capacity of a given threat to inflict a level of damage on a given critical component to satisfy the damage criteria for the component is determined in terms of conditional probability of kill ($P_{k/h}$) given a hit on the component by the threat. $P_{k/h}$ is defined as the probability of achieving a preselected damage level by application of a threat-caused damage mechanism to a materiel target or any of its components. Damage criteria for a given critical component (subsystem or system) are the levels of damage required for a pre-established degradation of the performance of the component (e.g., amount of material that must be removed from a drive shaft for failure, requirements for failure of a structural member, amount of damage required to incapacitate a system of gears, minimum diameter of hole in a fuel tank or line for engine starvation within a specified time period, etc.).

Consider, for example, a small fragment hitting the wheel of a truck. What is the likelihood that it can degrade the performance of the truck? Figure 5 shows that up to a velocity of 1200 feet/second there is no damage. As velocity increases for hits from any direction, the probability of damage or "kill" increases until, at slightly over 4000 feet/second, this fragment reaches its maximum potential for damage of the wheel or tire. These $P_{k/h}$'s are evaluated for several directions of attack on the component since, in most instances, the component's resistance to damage varies with direction of attack: some directions are "softer" than others. Analytical procedures exist for obtaining these conditional kill probabilities on many targets and components. The major results of this task are the specification of numerical values for the kill criteria (categories) for each critical component for each threat considered and, if needed by the user of the vulnerability output, the single shot repair on replacement times for all damaged components.

Input information for this task is obtained from weapons firing tests of target components, subsystems and systems, development tests, shop repair manuals, mechanics, manufacturers, accident records, combat damage data and engineering judgement and experience.

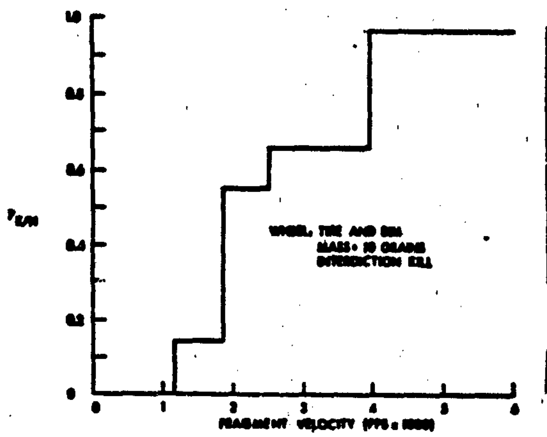

Figure 5. Kill Probability Function

Once the target description preparation, identification of critical components, determination of failure modes for the selected kill categories, and derivation of component conditional kill probabilities and repair times have been completed, the whole target vulnerability can be assessed. This assessment is accomplished analytically with appropriate methodology. The extensive calculation requirements generally lead to computerized whole target vulnerability models. Models exist for the wide range of target categories and damage mechanisms of interest to the Army (see Figure 1). Because of the diverse nature of the hostile environment in combat, the measures of vulnerability of a target vary with the type of threat encountered. For example, if a hit on an aircraft must occur in order for a threat to be effective, such as small arms projectiles and contact fuzed high explosive warheads, one measure of vulnerability is $P_{K/H}$, the conditional probability of an aircraft kill given a random hit on the aircraft. Another measure of vulnerability to impacting damage mechanisms is A_V, the aircraft's vulnerable area. This is a theoretical, non-unique area presented to the threat which if hit by a damage mechanism would result in a kill. In contrast, when damage is caused by the effects of a nearby high explosive warhead detonation, the vulnerability may be expressed in the form of a $P_{K/D}$ (probability of kill given a detonation) envelope or kill probability contour about the aircraft, on which a specified detonation will result in a certain probability of kill. If only the blast from the exploding warhead is considered, the envelope represents the vulnerability to external blast.

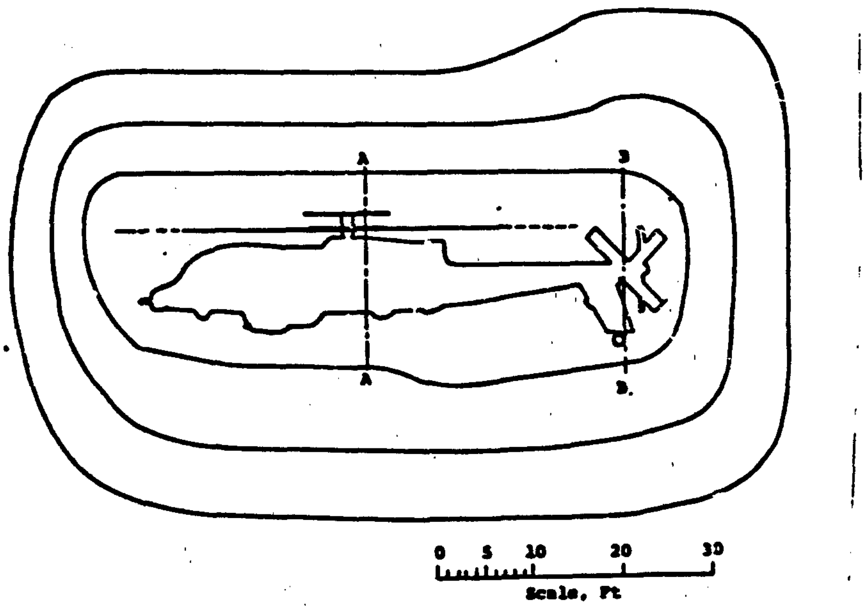

Figure 6. Attrition Kill External Blast Contours of a Helicopter for Three Warhead Explosive Charge Weights - side profile.

Figure 6 is an illustration of these blast kill envelopes for a selected helicopter. The innermost contour corresponds to the lowest explosive charge weight evaluated for this helicopter. Laser vulnerability can be measured by the probability of a kill, given a laser lock on the target for a specified time. For the mission available kill category, which is utilized to assess logistics burden and target down time, two single shot measures of repair time for the damaged target are used: minimum expected elapsed time required to repair the damage and minimum expected time in man-hours required to repair the damage. In addition to these repair time measures, a single shot repair area associated with a specified repair time interval is used.

At the completion of a target vulnerability assessment the results are provided to the user in the form specified at the problem definition step: computer listing, report, graphical format, computer tape, etc. These results will be in terms of one or more of the agreed upon measures of vulnerability:

- Vulnerable area
- Probability of kill given a hit
- Probability of kill given a laser lock-on
- Probability of kill
- External blast kill contour
- Single shot repair times and repair areas

Components that require repair/replacement
Military occupational specialties (MOS) needed to perform the repairs

Vulnerability and investigations to reduce velnerability interface with every stage in the life cycle of materiel. Figure 7 basically shows the normal Army materiel life cycle as defined under current procedures for materiel acquisition. Of course it is quite simplified, but it does show the various phases from requirement to disposal and salvage.

The first step is preparation of the ROC (Required Operational Capability). This is the ideal stage for vulnerability input and considerations to reduce materiel vulnerability. At this stage the Vulnerability/Lethality Division of the Ballistic Research Laboratory helps establish realistic requirements. Sometimes new analytical studies are conducted to provide guidance on specific problems. More frequently, however, the inputs are based on previous experience. Vulnerability reduction principles are introduced to the initial requirements working group, new vulnerability reduction technology is exposed. Alternative concepts are evaluated and assistance is provided in preparation of the specifications.

During Concept Formulation quick, approximate vulnerability analyses are performed in support of the task force, trade-off studies, and source selections. Normally, the objective of these early analytical studies is to examine a relatively large number of candidate designs, and to filter out those which show the most promise of meeting the conflicting requirements posed by the user. Because of the very short time available for such studies, the large number of candidate designs which must be considered and the fluidity of the design details, these analytical studies conducted in this early phase of the development cycle are often "quick-and-dirty" with many approximations. Less sophistication in target descriptions and other inputs is needed to conduct the studies. A major function of the vulnerability community here is its assistance provided in finalizing the technical data package.

Next is Validation. In this phase the vulnerability analyses tend to be quick, because the time available is still short. The analysis can be somewhat more sophisticated at this stage because the design features are beginning to firm up. The questions to answer are whether or not the prototypes meet the requirements and whether additional guidance can be given for design purposes and thus allow maximum munition effectiveness or system survivability. During this phase vulnerability support is provided to review contractor proposals, evaluate trade-offs, review technical risks, evaluate final concepts, assist in contractor selection and to improve systems and components.

By the time Engineering Development is reached, the most rigorous, sophisticated vulnerability assessments can be performed. This is done in support of design studies and system evaluations. Time to conduct these rigorous assessments is adequate and the design is fully fixed. All elements are accounted for and data can be provided for complete systems evaluation. Vulnerability testing is conducted for engineering development and to determine if components, subsystems and system meet the vulnerability specifications. Engineering change proposals (ECP) are reviewed for vulnerability impacts and guidance in vulnerability/lethality considerations is provided to the program manager.

Vulnerability interface with the Developmental Testing (DT) and Operational Testing (OT) phase takes the form of advice, as appropriate, on how to remedy vulnerability or lethality related deficiencies found by TECOM (U.S. Army Test and Evaluation Command) and vulnerability/lethality input data to meet the needs of the operational testing performed by OTEA (Operational Test and Evaluation Agency). In addition, these DT/OT tests in many cases provide an excellent source of hard input data which is utilized for improvement and substantiation of vulnerability models and analytical procedures.

During production, deployment and operational use of a materiel item product improvements are made that require vulnerability input. Experience gained in combat may necessitate "fixes" to reduce vulnerability. Also, battlefield damage surveys may be conducted. Valuable combat data may be obtained from these surveys which help validate vulnerability assessment methodology. In addition, careful study of this data may yield the direction for further hardening the system for increased battlefield survivability.

The last phase in the materiel life cycle is phase-out and salvage. Such salvage or surplus materiel is very valuable as target materiel. By conducting full scale weapons firing tests against this materiel, necessary basic data can be obtained for input to analytical models and to substantiate the vulnerability assessment methodology.

One of the vulnerability interfaces with DT/OT described earlier consists of the provision of system vulnerability information. This is particularly the case with Operational Test. An example of such systems vulnerability and lethality input to Operational Test was provided to OTEA for the AAH (Advanced Attack Helicopter) OT II. Of the 16 total issues addressed by the AAH OT II, two of these concerned issues on vulnerability/lethality. These were critical issues. A third issue concerned AH-64 combat damage repair. These three AAH OT II issues involving vulnerability, lethality and combat damage repair are:

*Issue 1. Is the AH-64's demonstrated effectiveness to defeat threat armored forces including air defenses consistent with those estimates of effectiveness which led to the decision to enter Full Scale Engineering Development (FSED)?

*Issue 14. What is the survivability of the AH-64 against threat weapons?

*Issue 11. What is the availability of the AH-64 in an operational environment?

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*Critical Issue

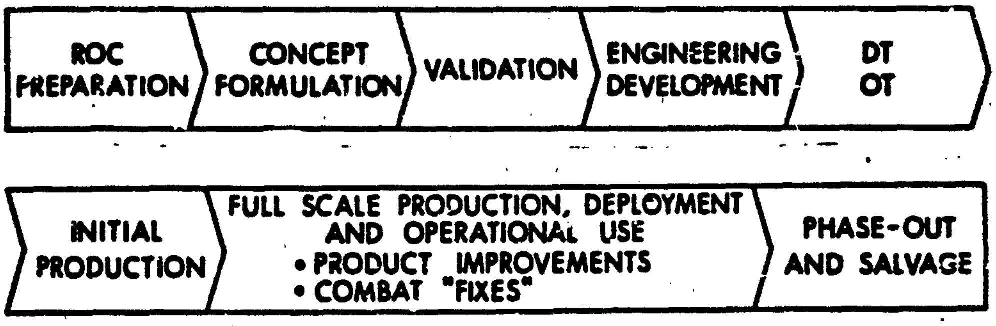

Figure 7. Life Cycle

The Vulnerability/Lethality Division of the Ballistic Research Laboratory provided the information specified by OTEA for use in resolving these issues in OT II. Figure 8 lists the weapon systems considered in AAH OT II. The firer/-target matrices are presented in Figures 9 and 10. These figures list the Blue targets and the threats to these targets and vice versa: Red targets and the Blue threats to these Red targets. Figure 9 lists the Blue weapons and the Red targets at which they were fired. Red weapons and their Blue targets are given in Fig. 10. Vulnerability assessments in terms of agreed upon measures of vulnerability were made for these combinations for a specified set of target kill categories and engagement conditions.

WEAPON SYSTEM	SURROGATE (ACTUAL)
M60A3	M60A1
M113/GLD	M113/GLD (Actual)
AH-1S (MC)	AH-1S (MC) (Actual)
AH-1/ATAFCS	AH-1/ATAFCS (Actual)
AH-64	AH-64 (Actual)
OH-58C	OH-58C (Actual)
T-72/125 mm	M60A1
*BMP/SA-7	M113/ADATS
**BMP/SA-7	M151/ADATS
***BMP/Sagger	M113/TOW
BTR-60	ADATS
ZSU-23-4	ADATS
SA-8	ADATS
SA-9	ADATS

*Two SA-7's were mounted in the BMP's and moved with the Threat Force Major body.
**Three SA-7's were mounted in jeeps with trailers or M706 wheeled carried and considered part of the notional flank unit.
***One Sagger was mounted in a BMP and moved with the Threat Force.

Figure 8. Weapon Systems Considered in AAH OT II

BLUE WEAPON	RED TARGETS						
	T-72	BMP (Sagger)	BMP (SA-7)	ZSU-23-4	SA-8	SA-9	BTR-60
M60/105 mm	X	X	X	X	X	X	X
HELLFIRE	X	X	X	X	X	X	X
TOW	X	X	X	X	X	X	X
Artillery 155 mm	X	X	X	X	X	X	X

FIGURE 9. BLUE WEAPON/RED TARGET MATRIX

RED WEAPON	BLUE TARGET					
	M60A3	M113/ GLD	AH-64	AH-1S(MC)	AH-1/ ATAFCS	OH-58C
T-72/125 mm	X	X	X	X	X	X
Sagger	X	X	X	X	X	X
ZSU-23-4	-	-	X	X	X	X
SA-7	-	-	X	X	X	X
SA-8	-	-	X	X	X	X
SA-9	-	-	X	X	X	X
Artillery 122 mm	X	X	X	X	X	X

X: CAN ENGAGE
-: CANNOT ENGAGE

FIGURE 10. RED WEAPON/BLUE TARGET MATRIX