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A MATHEMATICAL MODEL FOR ASSESSING TARGET VULNERABILITY RESEARCH EFFORTS

Science Applications, Inc.
8400 Westpark Drive
McLean, Virginia 22102

31 October 1978

Final Report for Period 3 April 1978—31 October 1978

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The methodology developed in this study is intended to provide a research engineer with a systematic approach for evaluating the merits and orientation of a target vulnerability research program.

The methodology emphasizes consideration of fundamental parameters included in the weapon effects-target interaction descriptive process and the individual relative significance of these parameters in a targeting scheme. The

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20. ABSTRACT (Continued)

methodology employs a decision tree format for evaluating proposed work. The decision tree concept is used as a format for qualitative systematic review of basic experimental planning and design concepts. The components of the tree address such areas as problem definition, research objectives, physical characteristics of proposed experiments, and prior thinking as to how experimental results will be used to evaluate program objectives.

PREFACE

This report represents the draft final report, under Contract DNA001-78-C-0213 sponsored by Defense Nuclear Agency (DNA). The objectives were to develop a methodology for assessing priorities and merits of a target vulnerability research program, and demonstrate application of this methodology to a problem agreed upon by DNA.

This study was sponsored by the Strategic Structures Division of DNA with Dr. Kent Goering and Capt. Mike Moore, USA, serving as Technical Monitors; their support and comments are gratefully acknowledged.

A special appreciation is extended to Dr. John E. Cockayne of SAI. His willingness to devote countless hours discussing experimental planning considerations provided invaluable assistance toward orienting the content of this study.

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1. INTRODUCTION

A fundamental concern of target vulnerability (nuclear) research is the necessity to plan and conduct programs under economic and other constraints. The economic factor demands judicious planning to ensure a program is designed to maximize the data's information. Since funding may preclude total problem resolution, care must also be exercised to ensure research efforts are oriented toward weapon effect and target response parameters most critical for reliable vulnerability prediction. In addition to limiting data quantity, the research budget may also influence the technical reliability of an experimental format. For example, the desire to maximize data, for a given level of funding, often necessitates reliance on a structural scale model, or component, to infer response and failure characteristics of a composite structure. But without a benchmark to provide a measure of similitude, a biased error could be introduced if the test data is arbitrarily assumed to be correlated in a one-to-one manner with the full scale composite structure. Of course, the funding constraint also requires consideration of inherently random phenomena that might be characteristic of the test structure and experimental environment. If these properties are capable of inducing large variations in measured data, a vulnerability confidence interval may be excessively large or unattainable for a given level of funding.

While the economic constraint might dictate the format and extensiveness of a program, the technical concern for similitude of weapon effect and structural response relates directly to the informative value of the data. With the possible exception of early program experimental excursions, empirical data not characteristic of a nuclear effect-target interaction is of marginal value to a vulnerability engineer, and of no value to the targeting community. Obviously, care must be taken to ensure a program is designed to simulate information resembling that one would expect to observe in an actual nuclear environment. If the level of funding and/or international treaties prohibit duplication of the desired phenomena, techniques must be available for converting measured data to a nuclear environment.

Perhaps the greatest constraint placed on a research engineer is the initial absence of adequate information needed to formulate a clear and decisive research program. Early phases of these programs may often be designed using subjective reasoning which may or may not prove to be valid. When programs are initiated in a technology void of data, one should proceed cautiously and be prepared to recognize inconsistencies between data and assumptions, as soon as possible. Accordingly, a research planner should be somewhat conservative in commiting funds, early in a program, toward potentially high risk experiments.

1.1 OBJECTIVES

The objectives of this study are to: (1) provide a systematic procedure for evaluating the merits and orientation of a target vulnerability research program, and (2) demonstrate application of this procedure to a problem of interest to DNA.

Merits of a target vulnerability research program, in the context of this study, are defined in terms of the value of reducing uncertainties and the likelihood of achieving the desired objectives. Throughout this study, unless noted otherwise, uncertainty will refer to ignorance, or limited understanding, of the solution to a given problem. Of course, this does not necessarily imply that the research community cannot resolve the issue(s) but only that available information precludes an objective inference as to the solution. The likelihood of success, while maintaining in spirit its connotation in a statistical sense, refers to the chance of a successful outcome given an appreciation for satisfying basic concepts in experimental planning and design. Problems to be addressed in this area include careful consideration of the physical characteristics of a proposed experiment and prior thinking as to how the experimental results will be used to evaluate program objectives.

The orientation of a research program refers to addressing the most important problems as determined by appropriate measures. Considering the user of this research it seems appropriate to use a measure of effectiveness applicable to a targeting (operational) context in order to evaluate what results are desireable from a vulnerability research program.

With respect to the methodology itself, an objective of this work was to devise a straightforward approach, simple in design and usage. This objective is intended to be consistent with the very nature of target vulnerability estimates, and their subsequent use in targeting scenarios. Quite simply, there are basic questions common to resolving all target vulnerability estimates, the absolute precision of which is neither necessary nor possible. In many instances, a small sample of data may be adequate for predicting target damage without concern for significance of residual error. To further refine the data can be merely an academic exercise, especially in view of the subjective reasoning usually (and, often necessarily) employed to arrive at a hardness estimate, and targeting factors exterior to the charter of a research program.

While the methodology itself is deliberately simple, some of the input may be difficult to obtain or not readily available. Both of these problems, again, are characteristic of target vulnerability. For example, a previous DNA study[1] demonstrated the rigorous analysis necessary to maximize the probability of realizing a successful data collection program. Alternatively, situations may arise where such analysis is not applicable, requiring qualified subjective estimates to supplement voids in empirical data and target intelligence. It should also be anticipated that some vulnerability problems may appear indeterminate with respect to existing test data and theoretical analysis. Although the quantification techniques presented with this methodology will be of little help initially, the logic supporting the process is expected to prevail in view of the basic parameters common to most targeting problems.

1.2 SCOPE

The methodology is an ordered sequence of steps to guide a research engineer toward formulating a decision as to whether research is jsutified and evaluating options to achieve the research objectives. Section 2 is an overview of the value of vulnerability research and what research must do to support the user of these efforts. Section 3 outlines some of the basic targeting mathematics, discusses the fundamental input to a targeting methodology, and demonstrates the significance of these parameters in a targeting context. Sections 4 and 5 describe the methodology and are interjected with simple examples demonstrating specific concepts and the use of the contents from Section 3.

Partial application of the methodology to a specific problem is presented in Section 6. Included in this section is a targeting evaluation based on an interpretation of information currently available from a specific research program. Also included in this section is an approach for recommending a vulnerability value to the targeting community based on this interpretation of reduced data. Because of time limitations application of the methodology presented in Section 5 was not sufficiently completed for presentation in this document.

2. VALUE OF VULNERABILITY RESEARCH

The ultimate reason for supporting vulnerability research is, of course, to provide the targeting community with the necessary information required to plan effective allocation of weapon resources. In a target rich environment, realization of this goal requires vulnerability estimates to be reasonably accurate and consistent with target damage objectives. However, the vulnerability estimate, while being a necessary prerequisite for realizing targeting objectives, does not in itself constitute a sufficient operational measure. The research community must also provide a targeter with a means to transform units of target hardness (e.g., psi) to units of range, for a given weapon system, as well as provide additional information which may allow for flexibility in choice of alternative weapon systems and height of burst (HOB) options. While "true" target hardness and supporting information are abstract mathematical concepts, it is most desirable for the customer if residual uncertainty could be reduced to a level of little consequence.

2.1 OBJECTIVES OF A VULNERABILITY RESEARCH PROGRAM

If a vulnerability research program is to be of value to the targeting community, two issues basic to all targeting problems must be resolved.

- Identify the dominant weapon effect damage mechanism (e.g., blast, shock, crater).
- Quantify the minimum level of effect necessary to ensure <u>at least</u> a specified level of damage.

With the possible exception of conventional aboveground structures, the dominant effect should not arbitrarily be assumed, nor the importance of this first task discounted. If the wrong mechanism is chosen as the continuous measure to predict the binary result (fail/no fail), a serious biased error could be introduced into a targeting methodology. For example, many experiments are conducted in a HE (high explosive) environment. While overpressure impulse may be an adequate measure in the test environment for predicting target failure, it may not be the dominant damage mechanism. When the data is mapped to a nuclear environment a serious biased error could be introduced if the HE-to-nuclear equivalence relation for the damage mechanism differs from that for blast. Hence, equivalent blast measurements in the nuclear environment may not correlate with target damage as it did in the experimental environment.

The second task is often the one most difficult to accomplish. In fact, between research budget constraints and scatter in measured test data, the true target hardness can never be completely resolved. Even with unlimited funding the data scatter phenomenon, characteristic of the experimental environment and human involvement, cannot be completely eliminated. As such, there will always be some uncertainty associated with the estimated average level of effect required to damage the target. However, depending on the estimated level of target hardness and weapon system parameters, uncertainty about the estimated value may be of slight consequence to the targeting community.

For a vulnerability research program to be of any operational value to the customer, analysis must also establish a range-to-effect relationship for the damage mechanism. Without this information a targeter has no quantitative means of estimating a probability of target damage. To enhance weapon system flexibility, a research effort should also determine if target response is dependent on loading parameters other than peak effect (e.g., duration), and the dependence of these parametric values on size of weapon yield. Figure 2.1 summarizes the measures required to support the mechanics of a targeting methodology.

GENERAL	SPECIFIC
Target	
dominant damage mechanism	blast, shock, crater
target hardness (failure) level	magnitude of weapon effect required to achieve at least a specified damage level
correlation between target response and dynamic loading parameters	dependency between target response and dynamic loading parameters in addition to peak effect
Weapon Effect	
range-to-effect	range = f(peak effect, yield, HOB/DOB)
yield scaling relationship	dependency between dynamic loading parameters and magnitude of yield)
Uncertainty Estimate	a statistical, or subjective, estimate of error with regard to critical parameters

Figure 2.1 Target and Weapon Effect Information Required for Operational Applications

3. TARGETING MATHEMATICS OF THE METHODOLOGY

Since the principle customer of a vulnerability research program is the targeting community, it seems appropriate to evaluate the merits and orientation of these programs in a targeting context. If identified uncertainties are a significant factor in planning a weapon allocation scheme, the research community may be justified in committing funds to alleviate the problem(s). Alternatively, if residual error does not influence weapon allocation and damage assessment predictions, efforts to reduce this error would appear to be of no value to the customer.

The following paragraphs outline the mathematics of a target damage predictive scheme and its dependency on parameters that may be addressed by the research community. Much of the mathematics is quite elementary, yet of sufficient substance to provide the research analyst with a quantitative appreciation for the value of reducing uncertainty. This chapter is intended to provide the research analyst with an awareness of those factors critical to providing the customer with a useful product.

3.1 TARGETING VOCABULARY

As much of the methodology presented in the following pages is applied in a targeting context, a brief explanation of the basic targeting concepts are presented in the following pages.

DISTANCE DAMAGE FUNCTION - a mathematical model used to predict the probability of achieving at least a specified level of damage as a function of ground range between the target and weapon placement. The Defense Intelligence Agency[2] suggests using the so-called log normal function, characterized by two parameters (R_{50}, σ_d). The first parameter provides an estimate of the target (nuclear) hardness, in terms of ground range. The subscripted value indicates the expected probability of achieving at least the specified damage objective at this ground range. The second parameter is a dimensionless measure intended to describe shot-to-shot random variations in target resistance and the free-field damage effect. The spirit of interpretation of a damage probability (for a given range, r_0, denoted by $P_d(r_0)$), as used by the targeting community, is in the classic sense of probability theory. That is, although observations from event-to-event appear uncorrelated, over a long sequence of repeated events the relative frequency of damaged targets will tend toward the damage probability. Figure 3.1, depicts a distance damage function model.

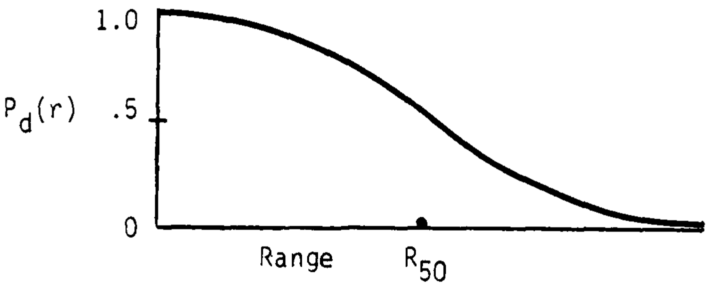

Figure 3.1 Distance Damage Function

<u>PROBABILITY OF KILL</u> - the average probability of achieving at least a specified level of target damage when shot-to-shot weapon placement varies in a random fashion about the designated aimpoint (DGZ). The average probability of kill (denote by, P_k) is obtained by integrating the distance damage function over the weapon placement distribution function. While the type of placement distribution function may depend on the weapon delivery system and mode of attack, the function most commonly employed for strategic systems is a circular Guassian distribution (single parameter, denoted by CEP). The parametric (CEP) value defines the radius of a circle, centered at the designated ground zero (DGZ), within which weapon placement is expected to occur with probability 0.5. Figure 3.2 depicts a common format for presenting P_k values as a function of normalized (w.r.t., CEP) target hardness, in terms of ground range, and offset aimpoint distance from the target.

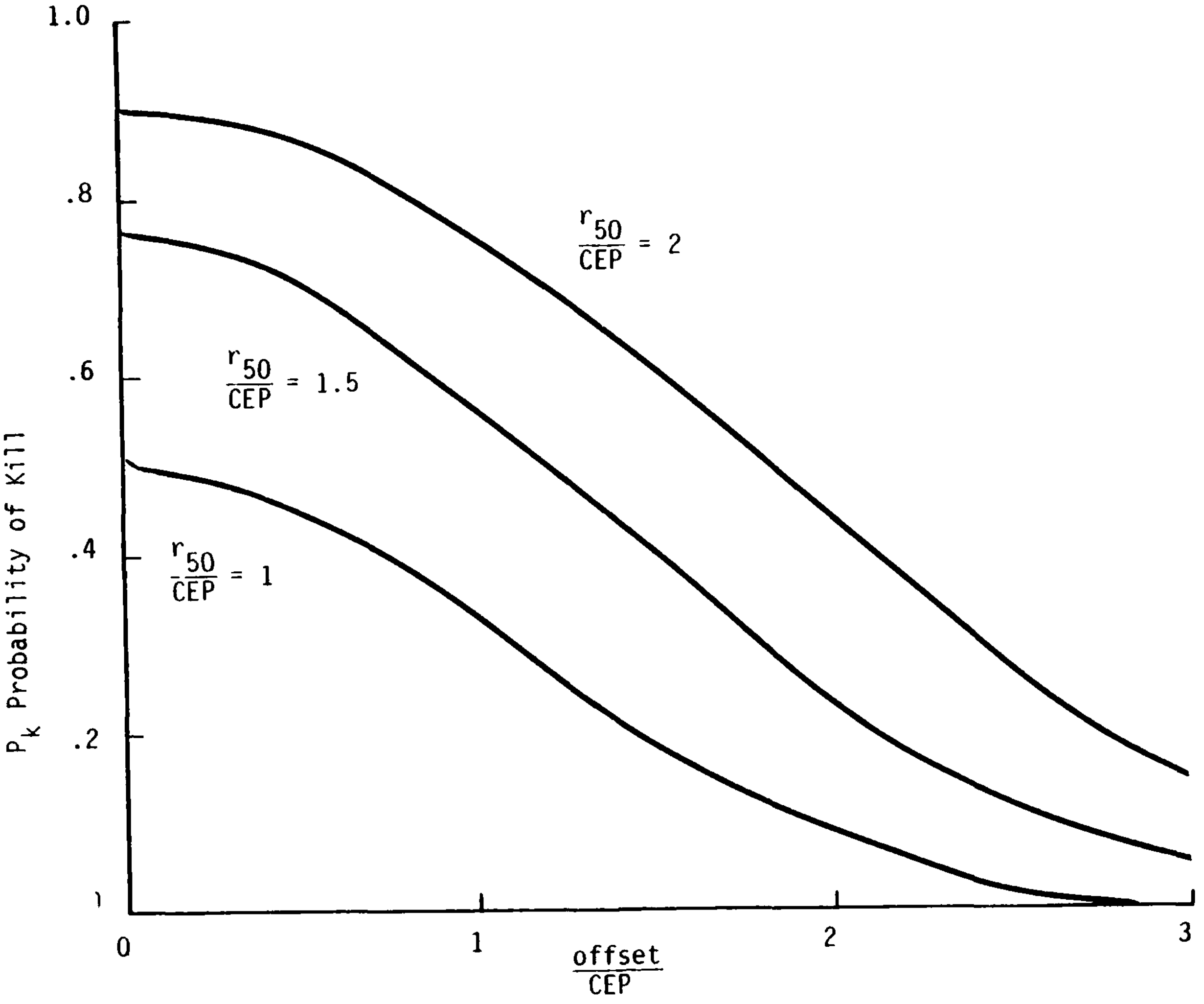

Figure 3.2 Probability of Kill to Point Targets as a Function of Aim Point Offset

PROBABILITY OF ARRIVAL - (denote by, POA) - the probability that a weapon system will survive a pre-launch attack, and function according to specified design from launch to arrival at the target location (reliability), and penetrate enemy defenses.

DAMAGE EXPECTANCY - (denote by, DE) - by definition,

$$DE = POA * P_k$$

COMPOUNDED DAMAGE EXPECTANCY - given independently targeted weapon systems, the probability that at least one weapon will achieve at least the specified level of target damage when n weapons are employed against the same target.

$$DE_n = 1 - \prod_{i=1}^{n} (1 - DE_i), \qquad \text{where}$$

$$DE_i = POA_i * P_{ki}.$$

$$DE_n = 1 - (1 - DE)^n, \text{ if}$$

$$DE = DE_i, \text{ (for } i=1, \ldots n).$$

Figure 3.3 graphically depicts compounded damage expectancy as a function of n.

3.2 SIMPLIFIED APPROACH FOR CALCULATING PROBABILITY OF KILL

As noted on a previous page, probability of kill, P_k, values are determined by integrating a distance damage function over the region of possible weapon placement. The log normal damage function model, currently recommended by DIA, does not lend itself to a closed form solution of this integration procedure. Since this property is desirable for simplifying appreciation of uncertainties in a targeting context a uniform damage function model is used throughout this study.

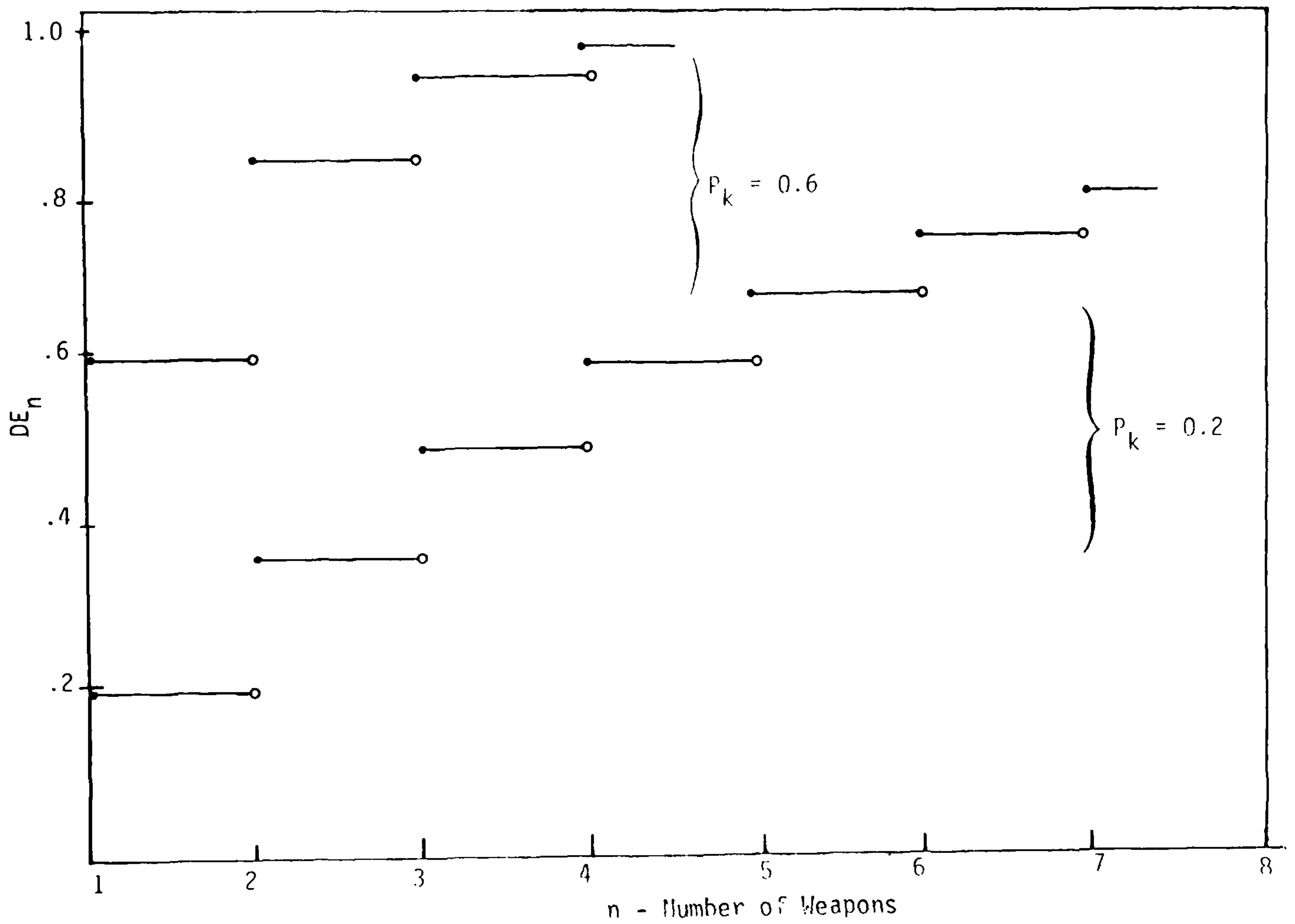

Figure 3.3. Compounded Damage Expectancy vs. Number of Weapons

In addition to enabling closed form expressions, this model is also attractive in the sense that the resultant P_k values are very close to those obtained using a log normal model. As such, the implication of weapon effect and target response uncertainties, measured in a targeting context, is about the same for either model. This precision in P_k values, between the two damage function models, is demonstrated in Figure 3.6.

The use of a uniform* distance damage function implies the absence, or negligible effect, of shot-to-shot random variation in target resistance and free-field weapon effect, i.e.,

$$P_d(r) = \begin{cases} 1, & 0 \leq r < r_o \\ 0, & r \geq r_o \end{cases} .$$

Thus, the probability of kill is simply the probability of the weapon (assuming detonation) landing within the "damage radius", r_o. Figure 3.4, depicts the differences between a uniform distance damage function and an alternative model that accounts for random error.

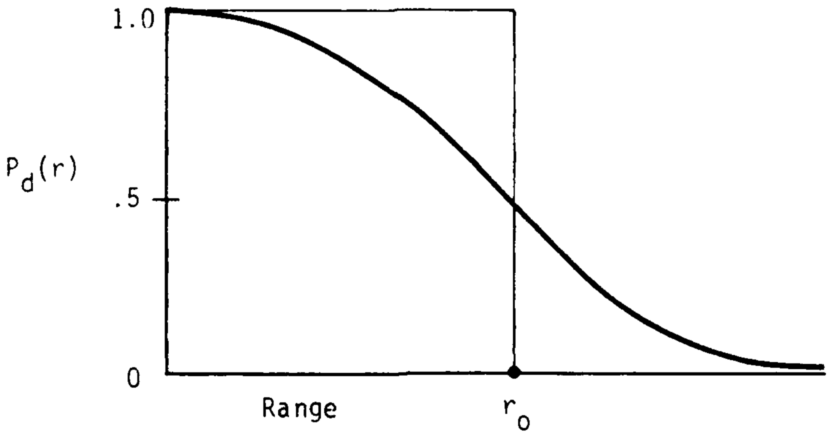

Figure 3.4 Uniform Damage Function vs. Damage Model with Random Error.

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*also referred to as a cookie cutter

Using a circular Gaussian distribution to model weapon placement error, a targeter would visualize the targeting scenario as depicted in Figure 3.5

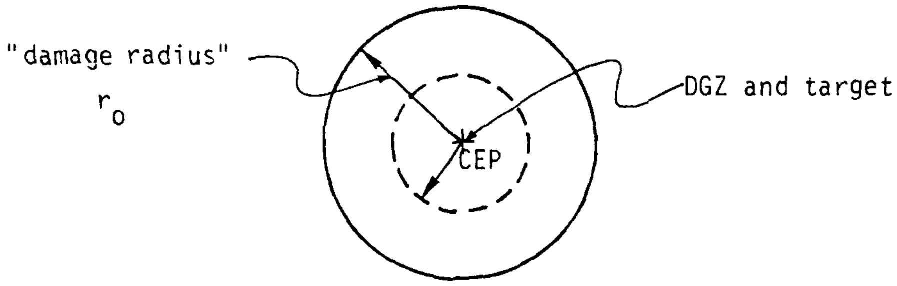


Figure 3.5 Point Target Representation

To calculate the probability of kill, P_k, the following integral is evaluated.

$$P_k\ (r_o,\ \text{CEP}) = \frac{1}{2\pi}\int_0^{2\pi}\int_0^{r_o} x\,\frac{\exp(-x^2/2\sigma^2)}{\sigma^2}\ dx\ d\theta$$

$$= 1 - \exp\ (-r_o^2/2\sigma^2)$$

$$= 1 - \exp\ (-\ell n(2)\ r_o^2/\text{CEP}^2), \qquad (1)$$

because $\sigma^2 = \text{CEP}^2/2\ell n(2)$.

For example, if r_o = 1000 ft, and CEP = 900 ft, then

$$P_k\ (1000,\ 900) = 1 - \exp(-\ell n(2)\ (1000/900)^2)$$

$$\cong\ 0.58.$$

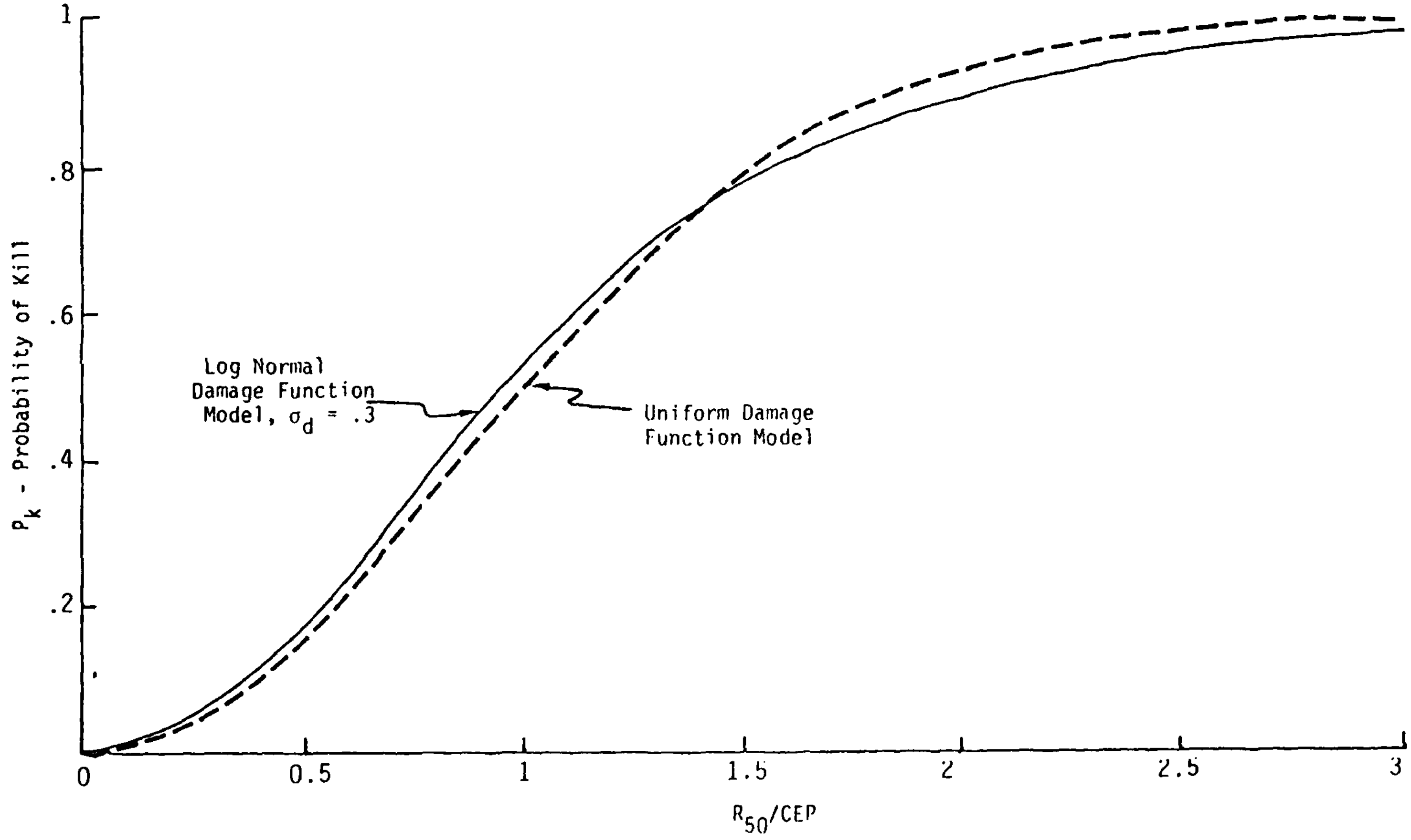


Figure 3.6. Comparison of Damage Predictions, Log Normal vs. Uniform Models

3.3 QUANTIFYING TARGETING UNCERTAINTIES FOR TARGETING PURPOSES

The significance of random error attributable to weapon effect and target response is usually of minimal concern to targeting applications. The small implication of this error in a targeting context is caused by the dominating influence of random error inherent to weapon placement. This cause, and subsequent effect, is similar to what would result when three statistically independent random variables are combined in a linear fashion. That is, if the variance of one variable is considerably larger than both of the other two, the variance of the resultant random variable will be approximately that of the largest input variance. In this situation a uniform damage function provides an adequate means with which to assess the impact of non-random error in an operational context, as well as providing the visual and calculational benefits gained from closed form solutions.

While random error attributable to effect-response interaction tends to be operationally insignificant, this is not necessarily true with non-random error which may be introduced through a statistically small data base or a biased estimator.

Both of these problems are of concern to vulnerability research and assessments. For example, the centrality of a target response random error distribution may be statistically bounded by a confidence interval, or it may only be tentatively bounded by two or three observations. In either case, there is some uncertainty (non-random) as to whether or not a selected value is in fact the true centrality value. If the estimate is wrong, it will always be wrong. This type of error will never average out,as does random error, over a long sequence of events.

The biased error can occur for example if target response is correlated with a weapon effect that is not the cause of damage. If the measured effect does not scale with weapon yield, as does the actual damage mechanism, a biased error will be introduced when small yield experimental results are extended to an operational yield.

Depicted in Figure 3.5 was the "damage radius" r_0, the centrality value of the effect-response random error distribution. This is the primary measure the targeting community requires and should be part of the end product of a vulnerability research effort. The following paragraphs examine the potential sources of uncertainty in this measure and how these component uncertainties influence this measure.

The value of r_0 (damage radius) is determined by the target hardness, measured in terms of the dominant damage mechanism (e.g., blast), and the range-to-effect relationship for this damage mechanism using inputs of yield and HOB. Many of these weapon produced effect (denote by e) environments tend to change in intensity, with respect to range, in a power law fashion. That is, if the measured intensity at some range, r_0, if e_0, then in a neighborhood of e_0 ($|e - e_0| < \delta$), the relationship,

$$\frac{r}{r_0} = \left(\frac{e_0}{e}\right)^{1/\gamma} , \qquad (2)$$

holds for some value γ. For example, using Brode's equation[3] to estimate peak surface overpressure (for a surface burst) for a given range and yield, one could calculate values of γ, as presented in Table 3.1.

Table 3.1. Effect (P_{SO}) - Range Power Law Relationship.

Peak Surface Overpressure (P_{SO})	γ (Calculated)
<< 1 (acoustic limit)	$\geq$ 1.0
1 - 10	∿ 1.7
10 - 100	∿ 2.2
100 - 1000	∿ 2.7
> 1000 (hydrodynamic limit)	$\leq$ 3

Now, let I_0 be the average of two measured effect (P_{SO}) values, one causing structural damage (550 psi), the other causing no damage (450 psi). Given I_0 = 500 psi, and the bounding values, one could use equation 2 to estimate uncertainty in range (r) as a function of uncertainty in target hardness (I).

$$r_0 \text{ (500 psi, yield)} \star \left(\frac{500}{550}\right)^{1/2.7} \leq r(\text{ft})$$

$$\leq r_0 \text{ (500 psi, yield)} \star \left(\frac{500}{450}\right)^{1/2.7} .$$

Given a yield of 1 KT, Brode's equation (surface burst) suggests r_0 (500 psi, 1 KT) = 197 ft. Hence, the uncertainty in range, attributable to uncertainty in target hardness, may be expressed as

$$190 \leq r(\text{ft}) \leq 205.$$

An alternative approach for estimating the spread in range is to calculate Δr with respect to I. Using equation 2, it follows that,

$$r = r_0 \left(\frac{I_0}{I}\right)^{1/\gamma}$$

$$\ell n \; r = \ell n \; r_0 + \frac{1}{\gamma} \ell n \left(\frac{I_0}{I}\right)$$

$$\frac{\Delta r}{r} \cong - \frac{1}{\gamma} \frac{\Delta I}{I} . \tag{3}$$

Evaluating equation 3, for I near I_0, then

$$\frac{\Delta r}{r_0} \cong \begin{cases} \frac{1}{\gamma}\left(\frac{I_0 - I}{I_0}\right) & \text{for } I < I_0 \\ -\frac{1}{\gamma}\left(\frac{I - I_0}{I_0}\right) & \text{for } I > I_0 \end{cases} .$$

Using the previous example, one could perform the range evaluation by,

$$-\frac{1}{\gamma}\frac{\Delta I}{I_0} \leq \frac{\Delta r}{r_0} \leq \frac{1}{\gamma}\frac{\Delta I}{I_0}$$

$$197 - \frac{197}{2.7}\left(\frac{550 - 500}{500}\right) \leq r \leq 197 + \frac{197}{2.7}\left(\frac{500 - 450}{500}\right)$$

$$190 \leq r \leq 205.$$

It is worth noting from the relationship, $\frac{\Delta r}{r_0} = \frac{1}{\gamma}\frac{\Delta I}{I_0}$, that the uncertainty in range is influenced by both uncertainty in target hardness and the parametric value for γ. Hence, in a targeting context, a large uncertainty in hardness may or may not be significant as determined by the value of γ, which has a multiplying effect.

Equation 2 can be further expanded if one wishes to consider other weapon yields. That is, implicit to equation 2 is a base yield, say w_0 (KT). If one wishes to estimate r for a yield other than w_0, one could use the equation

$$r = r_0 \, (I_0, w_0) * \left(\frac{I_0}{I}\right)^{1/\gamma} * \left(\frac{w}{w_0}\right)^{1/\beta_0} , \qquad (4)$$

where the value of β_0 is a function of the type of effect e, and possibly the magnitude of the yield and e_0^4 . Now, assume the parametric values (r_0, β_0, w_0) are averaged values, based on 2 or 3 samplings, used to estimate the true unknown values (ζ, β, ω). Then, the true (unknown) value for r (range) is

$$r = \zeta\left(\frac{I_0}{I}\right)^{1/\gamma}\left(\frac{W}{\omega}\right)^{1/\beta} \quad . \tag{5}$$

It would now be useful to assess the uncertainty in r, not only from uncertainty in target hardness but also range-to-effect (ζ), base yield (ω), and the yield power law parameter (β). Again, using r as the desired measure, one obtains from equation 5,

$$\ell n\ r = \ell n\ \zeta + \frac{1}{\gamma}\ \ell n\left(\frac{I_0}{I}\right) + \frac{1}{\beta}\ \ell n\left(\frac{W}{\omega}\right)$$

$$\frac{\Delta r}{r} = \frac{\Delta\zeta}{\zeta} - \frac{1}{\gamma}\ \frac{\Delta I}{I} - \frac{1}{\beta}\ \ell n\left(\frac{W}{\omega}\right)\frac{\Delta\beta}{\beta} - \frac{1}{\beta}\frac{\Delta\omega}{\omega} \quad . \tag{6}$$

Evaluating this equation near the parametric values (I_0, r_0, β_0, w_0), one obtains,

$$\frac{\Delta r}{r} = \frac{\Delta\zeta}{r_0} - \frac{1}{\gamma}\frac{\Delta I}{I_0} - \frac{1}{\beta_0}\frac{\Delta\omega}{w_0} - \frac{1}{\beta_0}\ \ell n\ \left(\frac{W}{w_0}\right)\frac{\Delta\beta}{\beta_c} \quad . \tag{7}$$

Since each of the parametric values (I_0, r_0, β_0, w_0) are averages of the respective observations, each of the terms ($\Delta\zeta$, ΔI, $\Delta\omega$, $\Delta\beta$) can assume both positive and negative values. If there is insufficient information with which to test for some functional dependency, then the "normalized" maximum uncertainty in range can be estimated by

$$\frac{\Delta r}{r} = \left|\frac{\Delta\zeta}{r_0}\right| + \left|\frac{1}{\gamma}\ \frac{\Delta I}{I_0}\right| + \left|\frac{1}{\beta_0}\ \frac{\Delta\omega}{w_0}\right| + \left|\frac{1}{\beta_0}\ \ell n\left(\frac{W}{w_0}\right)\frac{\Delta\beta}{\beta_0}\right| \quad . \tag{8}$$

To facilitate ease in presenting these expressions, the notation $\overline{\Delta}(\bullet)$ will be used throughout the remainder of this report to denote maximum uncertainty. Accordingly, equation 8 may be rewritten as,

$$\overline{\Delta}r = \overline{\Delta}\zeta + \frac{1}{\gamma}\overline{\Delta}I + \frac{1}{\beta_o}\overline{\Delta}\omega + \frac{1}{\beta_o}\ln\left(\frac{w}{w_o}\right)\overline{\Delta}\beta \quad . \qquad (9)$$

To demonstrate use of this equation, consider the following hypothetical case presented in Table 3.2.

Table 3.2. Hypothetical Uncertainty Problem.

Parameter	Estimated Value	Error in Estimate	$\overline{\Delta}$
r_o - range-to-effect	500 ft	± 10%	.10
I_o - target hardness (psi)	80 psi	± 15%	.15
γ - power scaling parameter	2.2	—	—
w_o - base yield	2 KT	± 5%	.05
w - desired yield	100 KT	—	—
β - yield scaling parameter	3	± 5%	.05

Using the $\overline{\Delta}$ values in Table 3.2, and equation 9, one obtains

$$\overline{\Delta}r = \underbrace{(0.1)}_{\text{range}} + \underbrace{\left(\frac{0.15}{2.2}\right)}_{\text{hardness}} + \underbrace{\left(\frac{0.05}{3}\right)}_{\text{base yield}} + \underbrace{\left(\frac{\ln\left(\frac{100}{2}\right)}{3} * 0.05\right)}_{\beta\text{ - yield scaling}}$$

$$\overline{\Delta}r \cong (0.1) + (0.068) + (0.017) + (0.065)$$

$$\overline{\Delta}r \cong 0.25 \ .$$

The interpretation of this measure, $\overline{\Delta r}$, is that the estimate of r (range), at 100 KT, may be in error by as much as ± 25 percent. It may be interesting to note that even if the target hardness were known exactly (i.e., $\overline{\Delta I} = 0$), the $\overline{\Delta r}$ value would only be reduced to about 0.18.

As a check against using equation 9 to estimate maximum uncertainty in r, the data in Table 3.2 was inserted into Brode's equation (surface burst). The estimated values (r_0, I_0, γ, w_0, w, β_0) resulted in a range (100 KT) prediction of 1850 ft. The upper and lower bound ranges were 2375 ft and 1455 ft, respectively. Thus, the $\overline{\Delta r}$ values one would obtain directly from Brode's equation are +28 percent and -21 percent.

The uncertainty measure for range, $\overline{\Delta r}$, can be further expanded upon when one considers uncertainty in the parametric value for γ. To help illustrate the uncertainty measure development for this parameter, Figure 3.7 depicts a hypothetical set of existing test data. Given that the effect e "falls off" as $1/R^{\gamma}$, there exists a relationship, $e = (a/r^{\gamma})$, where the value of "a" is dependent on γ and a functionally dependent pair of values (r_m, e_m). The data in Figure 3.7 suggest that the range-to-effect relationship is adequately understood for values of effect between $0.1{*}e_m$ and $1.0{*}e_m$. However, for levels of effect greater than $1.0{*}\ e_m$, the limited data and its scatter suggest some uncertainty in the value of γ used to plot the estimated curve. Now, the value of "a" used to construct the estimate curve can be derived from $a = e_m {*} r_m$. Therefore, for values of effect between e_m and 5 e_m, the range-to-effect is estimated by

$$r = \left(\frac{e_m {*} r_m^{\ \gamma}}{e}\right)^{1/\gamma} , \qquad e_m \leq e \leq 5\ e_m .$$

To estimate the uncertainty in r, as a function of uncertainty in the value of γ, one may again calculate the $\overline{\Delta r}$ term, and evaluate at

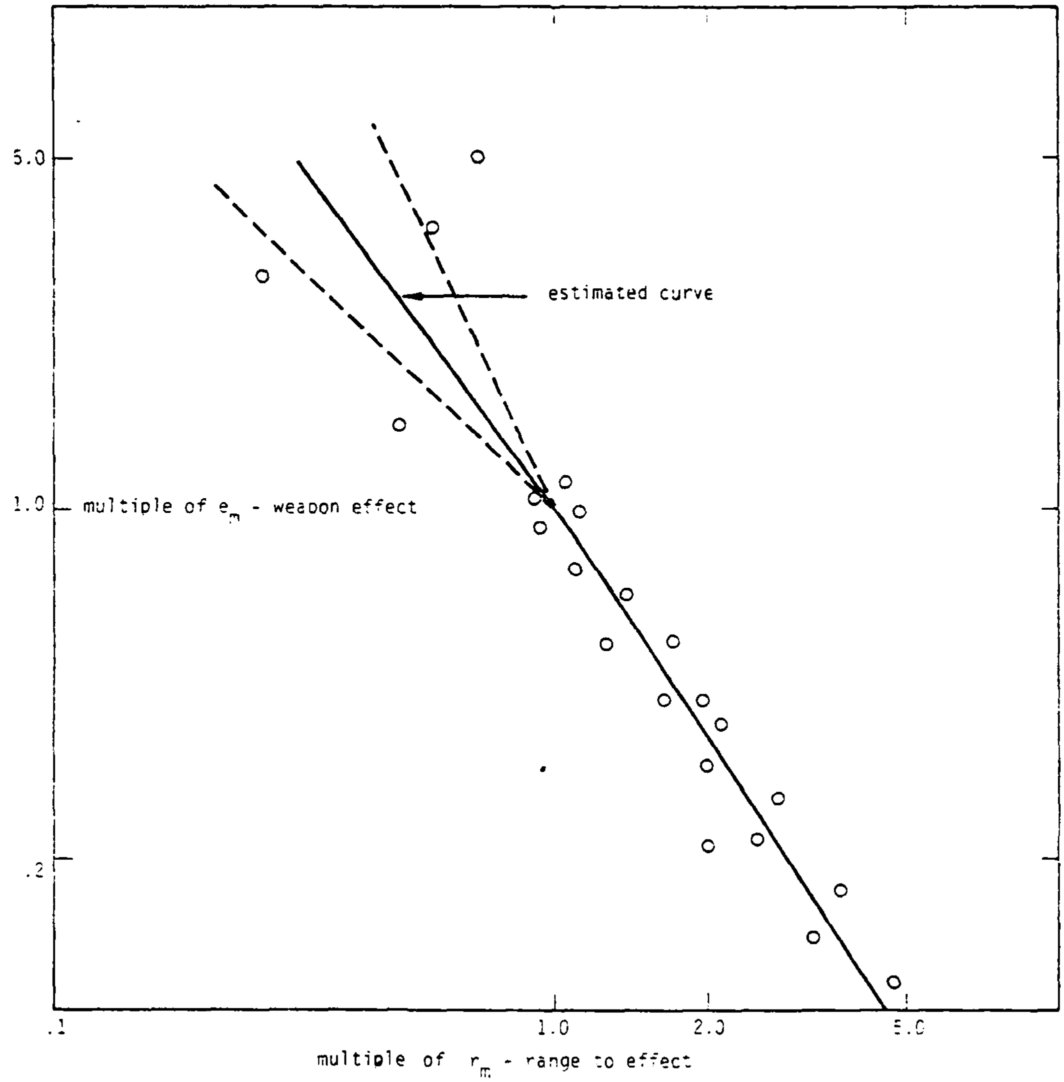


Figure 3.7. Hypothetical Test Data.

some value e, for $e_m \le e \le 5\ e_m$. The derivation of $\overline{\Delta}r$ is as follows

$$r = r_m * \left(\frac{e_m}{e}\right)^{1/\gamma}$$

$$\ell n\ r = \ell n\ (r_m) + \frac{1}{\gamma}\ \ell n\ \left(\frac{e_m}{e}\right)$$

$$\frac{\Delta r}{r} \cong \frac{-1}{\gamma}\ \ell n\ \left(\frac{e_m}{e}\right)\ \frac{\Delta\gamma}{\gamma} \quad . \qquad (10)$$

If, for example, $e = 3\ e_m$, $\gamma = 3$, and $\overline{\Delta}_\gamma = 0.1$, then

$$\overline{\Delta}r = \left| -0.37 * 0.1 \right|$$

$$\overline{\Delta}r \cong 0.04.$$

Using the relationship in equation 10, one may now rewrite the form of equation 9 to account for the $\overline{\Delta}_\gamma$ term and its coefficient. Thus, using I_0 as the estimate of the true e,

$$\overline{\Delta}r = \overline{\Delta}\zeta + \frac{1}{\gamma_0}\ \overline{\Delta}I + \frac{1}{\beta_0}\ \overline{\Delta}\omega + \frac{1}{\beta_0}\left|\ell n\ \left(\frac{w}{w_0}\right)\right|\overline{\Delta}\beta +$$

$$\frac{1}{\gamma_0}\left|\ell n\ \left(\frac{e_m}{I_0}\right)\right|\overline{\Delta}\gamma \quad . \qquad (11)$$

To continue the example presented in Table 3 2, with $\overline{\Delta}\gamma = 0.1$, and $e_m = 50$ psi, then

$$\overline{\Delta}r = 0.1 + \frac{0.15}{2.2} + \frac{0.05}{3} + \frac{\ell n(\frac{100}{2})}{3} * .05$$

$$+ \left|\frac{\ell n(\frac{50}{80})}{2.2}\right| * 0.1$$

$$\overline{\Delta}r \cong 0.27.$$

Although it may appear that equation 11 is counting the same error twice, with the $\overline{\Delta}\zeta$ and $\overline{\Delta}\gamma$ terms, this should not be construed as a problem. The value for e_m, as previously demonstrated, is interpreted to be the largest measured effect, less than e_o, at which sufficient data exists for adequately predicting the rate at which effect changes with range. Beyond this region, $e > e_m$, the data is so sparse an adequate measure of γ cannot be obtained. There appear to be several candidate values for γ, each with a scattering of data about it. Of course, as e_m approaches e_o the $\overline{\Delta}\gamma$ terms drop out of equation 11 since,

$$\lim_{e_m \to e_o} \left(\ln \frac{e_m}{e_o} \right) = 0.$$

Before carrying these expressions through to a targeting context, it is worth noting a very important problem not yet addressed. This has to do with the question of nuclear equivalence relations and dominant damage mechanism. With respect to the latter issue, it is interesting to note that this problem would be of no concern if the targeting community used weapons with a yield equivalent to that used in a research program. For this situation, all that is necessary is some continuous measure of weapon effect that can be correlated with target failure. Obviously, it makes no difference whether the selected secondary measure (e.g., peak surface overpressure) is the cause of damage or not, since in fact it can be adequately used to predict target failure. For example, in a particular test environment the level of nuclear radiation measured at a steel frame structure exposed to blast loading may be a very good measure for predicting structural failure, even though this effect, by itself, does not influence structural response. Given the range-to-effect relationship for the radiation phenomenon, the targeting community could construct a targeting scenario with this measure provided their weapon yield size was that of the research program. However, since most target research programs use weapon yields at least several orders of magnitude removed from operational yields, one must ensure that the measured effect is also the primary cause of target damage or be fortunate enough to select a measure that scales with yield as does the damage mechanism.

A similar concern exists for establishing the proper HE to nuclear equivalence relation. While this relationship has been empirically derived for many of the weapon effect parameters, the equivalence values are dependent on the parameter of interest. As with the damage mechanism concern previously discussed, one must ensure that the measured effect is the damage mechanism before test data is extended to predict target damage in an operational environment.

To illustrate these two potential problems, consider again the data in Table 3.2. Assume the 2 KT weapon is of an HE source and we wish to extend the test data to a 100 KT nuclear environment. Using a 2-to-1 equivalence relation for blast, and cube root scaling, the estimated lethal range in a 100 KT environment would be $r_0\left(\frac{100}{2*2}\right)^{1/3}$, where r_0 is the range-to-effect for 80 psi from a 2 KT HE explosive source. If, in fact, blast was not responsible for structural damage, and the true damage effect has a 1-to-1 correlation between an HE and nuclear charge, and a yield scaling parameter of 0.35, then the range to effect would be $r_0\left(\frac{100}{2}\right)^{0.35}$, at 100 KT nuclear. In terms of an operational context, the implication of this error is that the targeting community would underestimate the lethal radius of the target by about 33 percent.

3.4 PLACING UNCERTAINTIES IN A TARGETING CONTEXT

The input to equation 11 includes most of the factors which might be addressed in a target vulnerability research program. This expression can be used to determine the value of conducting research, orienting continued efforts, or determining when further efforts would be of marginal value. However, to appreciate the significance of an estimator, such as $\overline{\Delta}r$, from the customer's point of view the term should be evaluated in an operational context. Before this procedure is demonstrated, a relationship will be shown allowing for simplification later on. Equation 1 may be rewritten as

$$1 - P_k = \exp(-\ell n(2)\ r^2/CEP^2). \qquad (12)$$

Taking the natural log of both sides, one obtains

$$\ell n\ (1 - P_k) = -\ell n(2) * \left(\frac{r}{CEP}\right)^2, \quad \text{for } P_k < 1$$

or equivalently,

$$\frac{\ell n\left(\frac{1}{1-P_k}\right)}{\ell n(2)} = \left(\frac{r}{CEP}\right)^2 \qquad (13)$$

The operational measure to follow will be in the same form as the vulnerability uncertainty measure, i.e., $\overline{\Delta}P_k$. The magnitude of this measure is dependent on a P_k value, and parameters $\overline{\Delta}_r$ and $\overline{\Delta}_{CEP}$. The measure of uncertainty in an estimated CEP value ($\overline{\Delta}_{CEP}$) is provided for insertion into a research error budget. Of course, if one wishes to exclude this parameter, or any other term, their respective $\overline{\Delta}$ value need only be set equal to zero. Now, consider the expression

$$P_k = 1 - \exp(-\ell n(2)\ r^2/C^2) \qquad C = CEP.$$

If either of the estimated values for r (lethal range) and c have some non-random uncertainty associated with them, one can estimate the operational impact of this error as follows.

$$\ell n\ (1-P_k) = -\ell n(2)\ \left(\frac{r}{C}\right)^2$$

$$-\ \frac{\Delta P_k}{1-P_k} \cong -\ell n(2)\ \left[\frac{2r}{C^2}\ \Delta r\ -\ \frac{2r^2}{C^2}\ \frac{\Delta C}{C}\right]$$

$$-\frac{\Delta P_k}{1-P_k} \cong -2\,\ell n(2)\left(\frac{r}{C}\right)^2\left(\frac{\Delta r}{r} - \frac{\Delta C}{C}\right)$$

$$-\Delta P_k \cong (1-P_k)\ 2\ \ell n\ (1-P_k)\left(\frac{\Delta r}{r} - \frac{\Delta C}{C}\right) .$$

Dividing both sides by P_k $(P_k \neq 0)$, and using the notation for maximum error, one obtains

$$\bar{\Delta} P_k = 2\left(\frac{1-P_k}{P_k}\right)\ell n\left(\frac{1}{1-P_k}\right)\left(\bar{\Delta} r + \bar{\Delta}_C\right) ,$$

where $\bar{\Delta}_r$ is evaluated from equation 11, i.e.,

$$\bar{\Delta}_r = \bar{\Delta}\zeta + \frac{1}{\gamma_0}\bar{\Delta} I + \frac{1}{\beta_0}\ \bar{\Delta}\omega + \frac{\left|\ell n\left(\frac{W}{W_0}\right)\right|}{\beta_0}\bar{\Delta}\beta + \frac{\left|\ell n\left(\frac{e_m}{I_0}\right)\right|}{\gamma_0}\bar{\Delta}\gamma . \qquad (14)$$

To demonstrate application and interpretation of this model consider the following hypothetical problem. After conducting two structural tests in a 1 KT air blast equivalent HE environment, the estimated target hardness has been bounded between 300 psi and 700 psi, peak surface overpressure (P_{SO}). The high explosive blast environment is estimated equivalent to that from a 2 KT nuclear weapon, with an error of ± 10 percent. Table 3.3 tabulates this information, plus additional observations.

Given the information in this table, equation 14 can be used to calculate $\bar{\Delta}_r$.

$$\bar{\Delta}_r = \underset{\text{range}}{\underline{0.1}} + \underset{\text{hardness}}{\underline{\frac{0.4}{2.7}}} + \underset{\text{base yield}}{\underline{\frac{0.1}{3}}} + \underset{\text{yield scaling}}{\underline{\frac{0.02}{3}\left|\ell n\left(\frac{100}{2}\right)\right|}} + \underset{\text{range scaling}}{\underline{\frac{0.05}{2.7}\left|\ell n\left(\frac{300}{500}\right)\right|}}$$

$$\bar{\Delta}_r \cong 0.32.$$

Table 3.3. Hypothetical Test Program Results

Parameter	Estimated Value	Error in Estimate	$\overline{\Delta}$
I_o target hardness (P_{SO})	500 psi	± 40%	0.4
w_o - base yield (nuclear)	2 KT	± 10% Uncertainty in HE Nuclear	0.1
r_o (500 psi, 2 KT)	250 ft	± 10% all existing test data	0.1
e_m	300 psi	---	---
γ - range scaling	2.7	± 5%	0.05
β - yield scaling	3	± 2%	0.02
w - operation yield (nuclear)	100 KT	---	---
CEP	915 ft	± 5%	0.05

Then,

$$\overline{\Delta}P_k \cong 2\left(\frac{1-P_k}{P_k}\right) \ell n \left(\frac{1}{1-P_k}\right) \quad (.05 + 0.32) \qquad (15)$$

Equation 15 is plotted in Figure 3.8 for values of P_k between 0 and 1.

Given the CEP of our 100 KT operational system, then P_k (500 psi, CEP) = 0.5, one can enter Figure 3.8, at $P_k = 0.5$, and see that $\overline{\Delta}P_k \cong 0.51$. From this measure one could determine that the existing uncertainties are of such magnitude as to cause a P_k value of 0.5 to be in error by as much as ± 51 percent, i.e., $0.24 \leq P_k \leq 0.76$. If this spread in values is unacceptable to the customer, one could go back to the $\overline{\Delta}_r$ term and assess which aspect of the problem requires additional work. In this example it appears that further structural testing would offer the greatest potential for reducing the $\overline{\Delta}_r$ value. For example, if an additional test found no measurable damage at 500 psi, we could now bound target hardness between 500 psi and 700 psi, and reenter equation 14, with $I_0 = 600$ psi and $\overline{\Delta}I = 0.17$. Now, $\overline{\Delta}_r = 0.23$, and the P_k (600 psi, CEP) value drops to about 0.46 for the given weapon system. Referring again to Figure 3.8, the new $\overline{\Delta}P_k$ curve suggests that remaining uncertainties could cause a P_k value of 0.46 to be in error by as much as ± 41 percent. At this point it now appears that further effort concentrating solely on target hardness may be of little value since the range-to-effect uncertainty is now the dominant term.

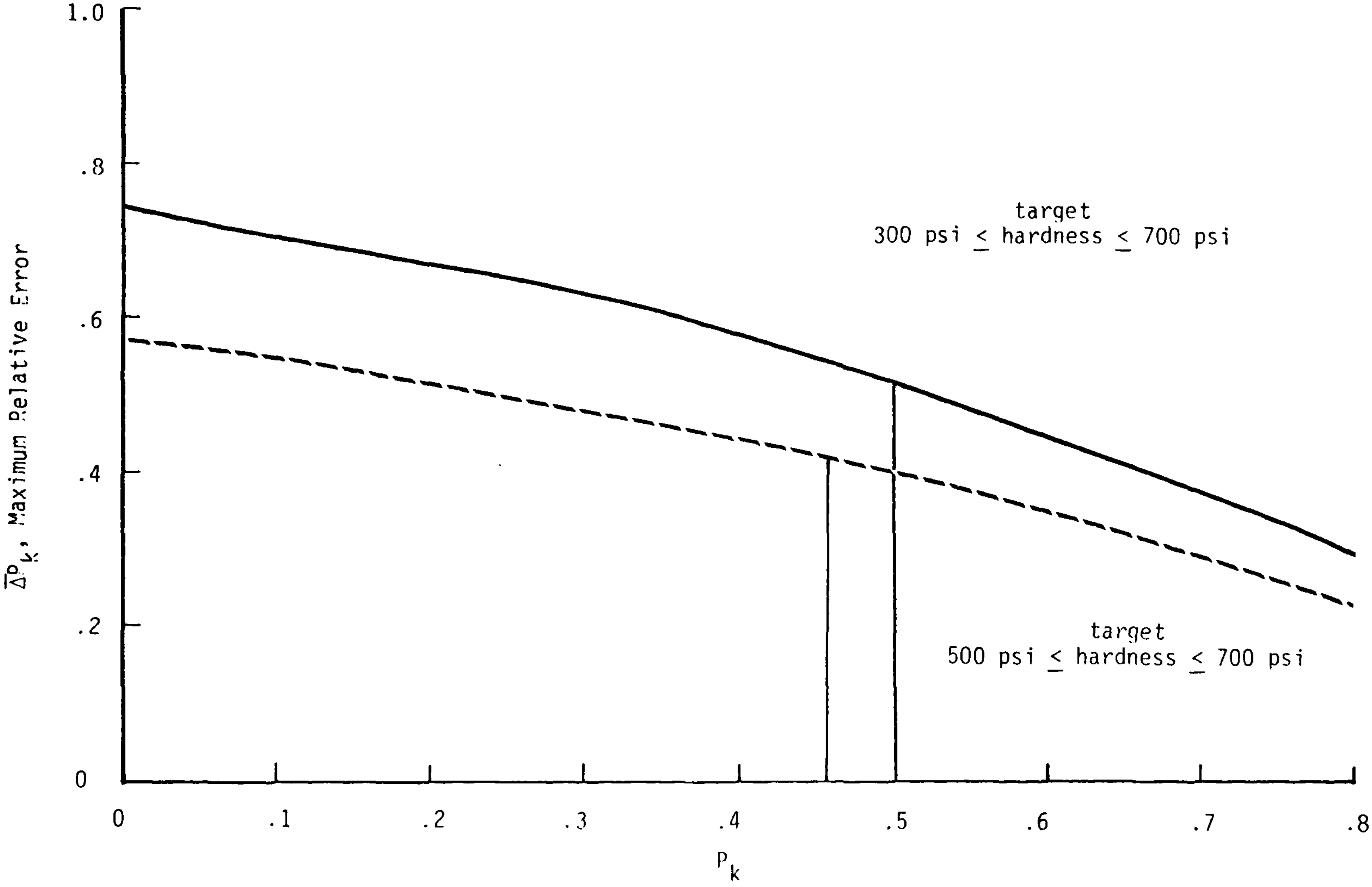


Figure 3.8. Operational Impact of Uncertainty in Targeting Parameters.

4. EVALUATING THE NEED FOR RESEARCH

This phase of the methodology is intended to be a guide for an analyst to follow to determine if a vulnerability research program is needed and which aspects of the problem should be addressed. Figure 4.1 is an overview of the steps in this phase of the methodology, each of which are addressed in the following paragraphs. Basically, the analyst is given certain information, and tools, with which to estimate target vulnerability. If a portion of this data is incomplete, or of inadequate resolution, the analyst will attempt to quantify the significance of this problem using the expressions in Section 3. Based upon the level of significance, measured in an operational context, the analyst should have some appreciation for the need of vulnerability research and which areas are in need of improvement.

4.1 ENGINEERING DESCRIPTION

The first step of the methodology is devoted to formulating an engineering description of the target using the information provided in the target data base. Essentially what is required is a sketch of the target, with dimensions and properties noted. Pertinent items include target geometry, construction materials and their properties, method of construction, and characteristics of the site geology. The last parameter is especially important for buried structures as the environment can significantly influence the mode and level of target response.

As is often the case with intelligence derived information, the data base may not contain all of the desired information. When such occasions arise the methodology suggests that the research engineer gain concurrence from the intelligence community as to a "best estimate" description. It is also suggested that each of these estimates be accompanied by a range of plausible alternative values for use in follow on analytic efforts or research program design. In addition, noted target-to-target parametric variations are also to be set aside

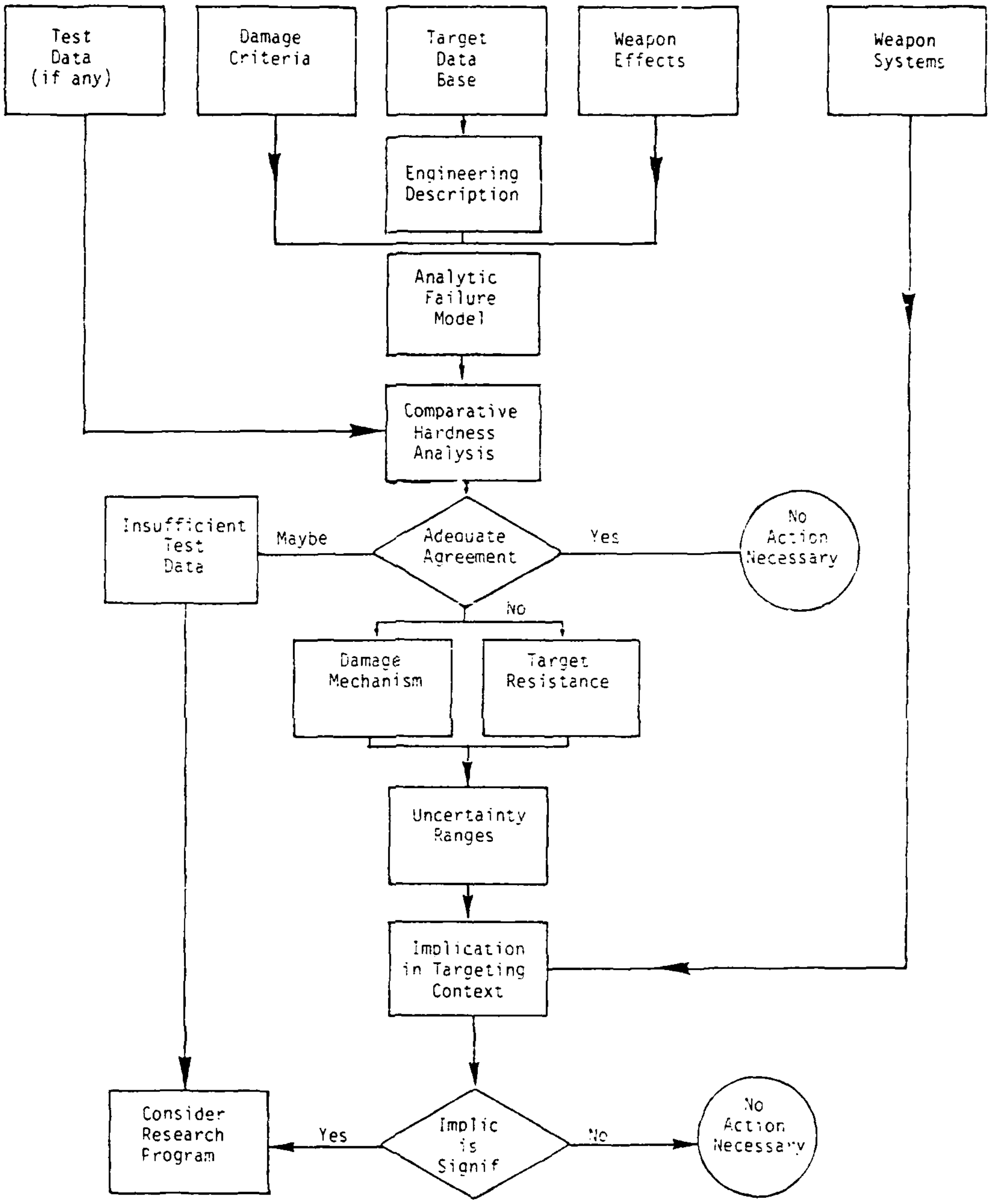


Figure 4.1. Sequence of Steps to Identify Significant Problems

with the intelligence related uncertainties. Although both of these factors may be important targeting considerations, the methodology stresses focusing attention on defining the vulnerability of a generic target configuration. With the successful completion of this task, the engineer should possess sufficient knowledge to estimate target resistance dependency on these factors.

Attention to detail of the transport media (site geology) may need to be as great as that of the structure itself. While this factor is usually not of serious concern with civilian targets, military strategic installations are often shielded against blast, by earth mounding or placement below ground. Properties of the media are needed to estimate weapon effect propagation and to determine if the surrounding media could act as an integral part of the structure in mode and level of response.

At the completion of this target descriptive task, the methodology suggests that the engineer use this information and the damage criteria, to conclude the engineering aspects of structural failure (e.g., mode of failure), the dominant damage mechanism, and a range of level of effect values within which the structure would be expected to fail. Although these (a priori) assumptions may prove invalid, this exercise does provide a tentative solution hypothesis for the engineer to support, or reject and reformulate, as he proceeds through the methodology. In addition, this mental exercise forces the engineer and his advisors to think through the entire vulnerability problem, possibly allowing for discovery of the ever elusive "intuitively obvious" aspects of the problem. Although this exercise may not describe the true state of nature, the only danger to forming premature conclusions lies in one's refusal to restructure his thoughts as conclusive contradictory evidence is obtained.

4.2 ANALYTIC FAILURE MODEL

At the completion of the engineering descriptive process the methodology focuses attention on analytic tools to estimate target hardness. The objective of this step is to initiate efforts toward building an analytic failure model capable of reasonably simulating the target's dynamic response to applied loadings. The rationale for this effort is three-fold: 1) a tentative model can be used to plan the layout of a proposed experiment, 2) continuing research experiments may be unnecessary as model validity is established, and 3) a validated model can address the customer's concern for intelligence related uncertainties and noted target-to-target variations that could influence target hardness.

The mechanics of this step consist of exercising an analytic failure model representative of the engineering description, desired damage criteria, and dominant weapon effect damage mechanism. Although the theoretical concepts of the model should agree with the hypothesized engineering characteristics, it may be difficult, at best, to adequately simulate the structural dynamics. As data is made available, however, these deficiencies may be alleviated to a level of inconsequence. Of course, at this point in the methodology, the model predictions should be viewed at the same level of reliability as the hypothesized range of target hardness values.

One of the many problems with using an analytic failure model resides in the need to quantify the specified damage criteria. Since this criteria is usually expressed in a qualitative manner (e.g., roof collapse), one must be able to transform this description to an equivalent engineering parametric value (e.g., ductility, strain) for insertion into the analytic model. Additionally, one must ensure that the parametric value is in the context of the composite structure. An abundance of data is available to quantifying this parameter for certain homogeneous materials (e.g., steel), and possibly some basic structural component. However, if the mode and level of response of a composite structure differ significantly from that of an analytically modeled component, the model prediction may be an appreciably biased estimate of the composite structure hardness.

The second area of concern with these failure models entails adequate characterization of the applied loading function. One must ensure relative agreement with observed data and correct assumption for the dominant damage mechanism. Erroneous reasoning with respect to the latter concern can have as great an impact on a target damage prediction scheme as biased error in estimated target resistance.

The third area of concern evolves from the simplifying assumptions often used to model target resistance and response. Such assumptions often lead to a single degree of freedom model with a bilinear resistance function. While this type of model may be adequate for many types of structures, it does not necessarily have all-inclusive applicability.

4.3 EXISTING TEST DATA

Before continuing on to the comparative hardness analysis step, a few words are in order pertaining to the use of existing test data. The methodology places a heavy emphasis on this data, the importance of which cannot be overstated. Existing data may provide valuable insight into bounding target hardness, orienting a research effort, and identifying previous research approaches that failed to provide the desired information. However, depending on the target in question, relevant existing test data may not necessarily be from a nuclear environment, nor that of a composite structure. Some data may simply reflect binary failure/survival observations, without accompanying measurements from a correlated continuous parameter (e.g., strain, peak surface overpressure). Data may be from a scale model structure, or based on applied loading conditions unlike that of a nuclear weapon environment. The point being made here, of course, is that existing data may not completely resolve the immediate problems of interest. Data interpolation may be required, opinions inserted, and independent subjective uncertainty bounds prescribed. While this exercise may in fact raise more questions than it resolves, it seems illogical to ignore the abundance of data and engineering judgment possibly gained from previous efforts.

In the process of gathering this data, attention should be given to the weapon effects data base as well as measurements from structural tests. For example, one may note in equation 9, a 10 percent error in range-to-effect, for $P_{SO} > 1000$ psi, is equivalent to a 30 percent error in target hardness.

4.4 COMPARATIVE HARDNESS ASSESSMENT

The objective of this step is basically two-fold: 1) draw some conclusions between existing test data and the hypothesized results formulated in the engineering descriptive process, and 2) determine if there is a correlation between observed test results and predictions obtained with the analytic failure model.

First Objective: Test Data vs. Hypothesized Conclusions.

The intent of this effort is to determine if existing empirical data can lend support to the engineering hypotheses, or identify faults in need of revision. The data may be of sufficient quality to provide a quantitative measure to bound target hardness, or at least suggest the hypothesized hardness range is tending in the proper direction. For example, if a single observation noted "sure" survival at 100 psi, a hypothesized range of 300 psi - 500 psi may be reasonable. Of course, the target may in fact actually be about 1000 psi hard. However, the single observation at 100 psi does not contradict the tentative hypothesis. Conversely, if the test structure failed at 100 psi, one should not arbitrarily reject the hypotheses. Further investigation is required to assess physical similarities between the generic and test structure physical properties, the source and manner of loading, and similitude of test environment with that of a full scale nuclear environment. For example, if the sample data was a small scale structure, qualified reasoning may suggest biased error in modeling similitude (w.r.t., the generic target) could underestimate target hardness by a factor of at least 2 and possibly 4. In view of this large uncertainty in similitude, one may not even wish to consider the sample as representative of the generic structure.

The engineer may find this quantifying evaluation step difficult to perform for new or unusual structures. This will, most likely, usually tend to be true since previous research was probably not planned with the thought of what data might be needed 5 to 20 years later. However, the data may still be of value for a qualitative comparison. Relevant data may tend to support the assumed mode of target failure and point out visual discrepancies between small scale and full scale test results. This latter observation may be of significant value if the engineer decides to propose initiation of a structures research effort. One may also note large variations in target response, from previous tests, under comparable (possibly by yield scaling) loading conditions. This again is a valuable observation when considering proposed experiments. As stated earlier in this document, characteristics of a test environment including the structure may cause large variations in measured data.

Considering the type of information which could be gained in a qualitative review, the engineer may be prudent to view the process as a continuing learning phase of the methodology. Unless the data clearly demonstrates otherwise, the hypothesized conclusions should not be rejected based on these qualitative observations.

Second Objective: Analytic Model vs. Test Data

This phase of the comparative analysis is intended to be a quantitative exercise to begin model validation and check for deficiencies against measured structural and free-field effects data. A feature of this exercise, not available to the first objective, is the flexibility to revise model parameters to account for: 1) material property differences between the test and generic structure, and 2) differences between observed and desired level of damage. If structural data is not available, the forcing function may be checked against measured weapon effect data. Alternatively, data may be available to verify model response predictions for static loading conditions. Of course, if no structural or effect data is available, the theoretical model is only as good as the engineer's intuition for problem solution.

4.5 RESULTS OF COMPARATIVE HARDNESS ANALYSIS

The output from the comparative analysis, as depicted in Figure 4.1, will be one of three observations. One possibility is that the test data is of no value with respect to this particular target. Testing may never have been conducted on such a configuration, or the test environment was so far removed from a nuclear environment that it has no applicability. Basically, the analyst has no greater appreciation for solution of the problem than when he first hypothesized his results. The engineer may now want to consider proposed research for clarifying significant areas of concern.

The second possible conclusion is that the test data is of some value but cannot provide total problem resolution. If deficiencies are noted, necessary corrections to the analytic model should be made at this time for future planning purposes. It is expected that the analyst would not enter this block unless he now has some appreciation for the dominant damage mechanism, engineering characteristics of target failure, and a plausible range of target hardness values. That is, the engineer now possesses sufficient insight into the problem so that he can justify values inserted into equation 9.

The third alternative is that the test data was of sufficient detail to provide an adequate target hardness assessment and model validation. The network of events in Figure 4.1, suggest that no further action is now necessary. One must remember, however, that intelligence related uncertainties and noted target-to-target variations were set aside for future consideration. The analyst should now go back and ascertain if these variations are within the scope of applicability of the analytic failure model.

4.6 IMPLICATION IN A TARGETING CONTEXT

The final step in this phase of the methodology provides the engineer with a means to quantitatively evaluate the usefulness of existing test data to bound the hardness level of the target under consideration. Through the use of equation 9 or 11, the engineer has a simplified means to accomplish this task, as well as evaluate the combined significance of all noted uncertainties. With the aid of equation 15 and the curves such as depicted in Figure 3.6, the uncertainties may be easily evaluated in an operational context. An additional example is presented, in the following paragraphs, to demonstrate this exercise and introduce an additional uncertainty term not discussed in Section III.

The research community is considering conducting destructive experiments, at the request of the targeting community, on a structural steel frame building. Existing data is available for the weapon effect (drag loading) environment, as are some small scale (structural) test results from a controlled laboratory experiment. The small scale structural test data tended to demonstrate failure level similitude for various size structures, with engineering properties similar to the generic engineering descriptive target. The "best fit" predicted failure level suggest the target hardness to be about 32 psi (peak dynamic pressure), with about ± 10 percent uncertainty. However, the largest structure tested was only about 1/5 the size of the actual target. A group of engineers have suggested that this data might be extended to estimate target hardness, but have also expressed concern over the possibility of a biased error as large as 30 percent between the test and full scale environment. It is not certain at this time, however, whether the test results would tend to overestimate or underestimate hardness of the actual target. Free-field dynamic pressure measurements suggest about a ± 10 percent uncertainty in range-to-effect predictions in the domain of hardness for the test structures. Table 4.1 summarizes all given information.

Given this data and equation 14, one may calculate $\overline{\Delta}r$.

Parameter	Estimated Value	Error in Estimate	$\overline{\Delta}$
I_o target hardness (Q_y)	32 psi	± 10%	0.1
B_e - biased error in transformation	1	± 30%	0.3
w_o - base yield (HE) test environment	500 pounds	--	--
w_o - base yield (nuclear)	1000 pounds ($5 * 10^{-4}$ Kt)	± 10% Uncertainty in HE ~ Nuclear	0.1
w - operational yield (nuclear)	3 Kt	--	--
r_o (32 psi, 3 Kt)	375 ft	± 10%	0.1
e_m	32 psi	--	--
γ - range scaling	4	--	--
β - yield scaling	3	--	--
CEP	375 ft	--	--

Table 4.1 Extension of Test Data to Full Scale Environment.

$$\overline{\Delta} r = \underset{\text{range}}{\underline{\overline{\Delta} r_o}} + \underset{\text{similitude}}{\underline{\frac{\overline{\Delta} Be}{\gamma}}} + \underset{\text{hardness}}{\underline{\frac{\overline{\Delta} I_o}{\gamma}}} + \underset{\text{base yield}}{\underline{\frac{\overline{\Delta} w_o}{\beta}}}$$

$$= 0.1 + \frac{0.3}{4} + \frac{0.1}{4} + \frac{0.1}{3}$$

$\overline{\Delta} r \cong 0.23$

With the aid of equation 15, one may now calculate $\overline{\Delta} P_k$. Since r_o = CEP, then $P_k = 0.5$

$\overline{\Delta} P_k = 2 \ln (2) * 0.23$

$\overline{\Delta} P_k \cong .32$

Using this $\overline{\Delta} P_k$ measure one can estimate that the given uncertainties could cause a P_k value of 0.5 to be in error by as much as ± 32 percent, i.e., $0.34 \leq P_k \leq 0.66$. It may be interesting to note that the $\overline{\Delta} P_k$ value increased 50 percent, from 21 percent, due to the biased error term. If funding is available, the engineer may consider an experiment which could address both target hardness and similitude, concurrently.

A convenient format for quickly assessing this type of information for a variety of weapon systems may be easily derived from equation 1, the expression for calculating P_k values.

$$P_k = 1 - \exp(-\ell n(2)\, r_o{}^2/CEP^2).$$

Now, $r_o = r_o$ (psi, yield)

$= r_o$ (psi, 1 KT) $* (W)^{1/\beta}$.

Let r_o (psi, 1 KT) = r_1, and $\Omega = CEP/W^{1/\beta}$.

Then, $P_k = 1 - \exp(-\ell n(2)\, (r_1/\Omega)^2)$. (16)

Therefore, given two weapon systems, A and B, such that $\Omega_A = \Omega_B$, then

$P_k (A) = P_k (B)$.

Given the information in Table 4.1 then,

$r_1 = 260$ ft,

$\overline{\Delta}_r = 0.23 \rightarrow 200 \text{ ft} \leq r \leq 320 \text{ ft}$

and, $\Omega = 260$.

Figure 4.2 depicts the variation in P_k values, attributable to the $\overline{\Delta}r$ term, as a function of Ω. Given the information in this figure there would appear to be no value in reducing existing uncertainties if all current and future weapon systems had an Ω value less than about 125 or greater than about 400.

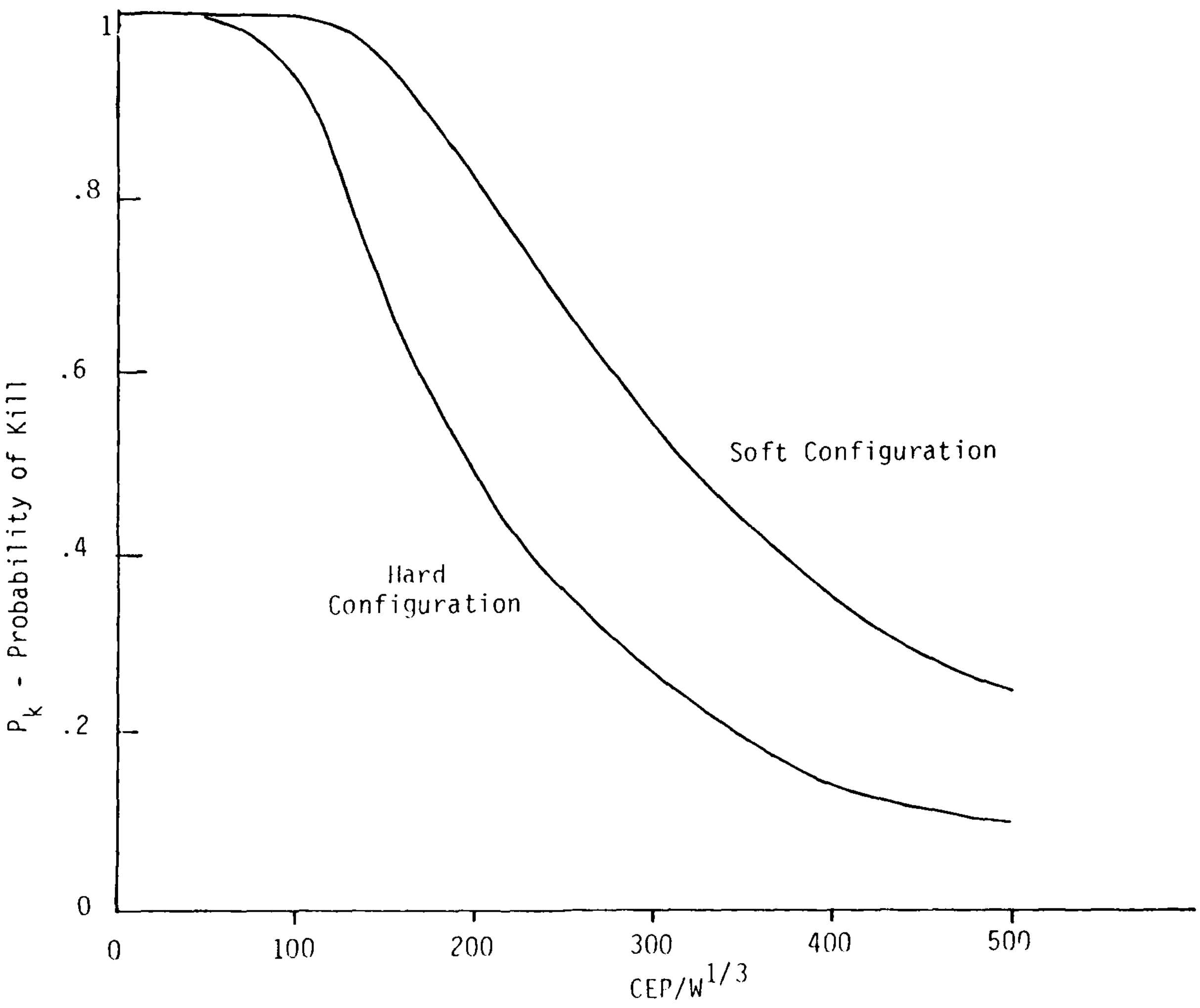


Figure 4.2. Implication of Uncertainties in a Targeting Context

5. PLANNING A RESEARCH PROGRAM

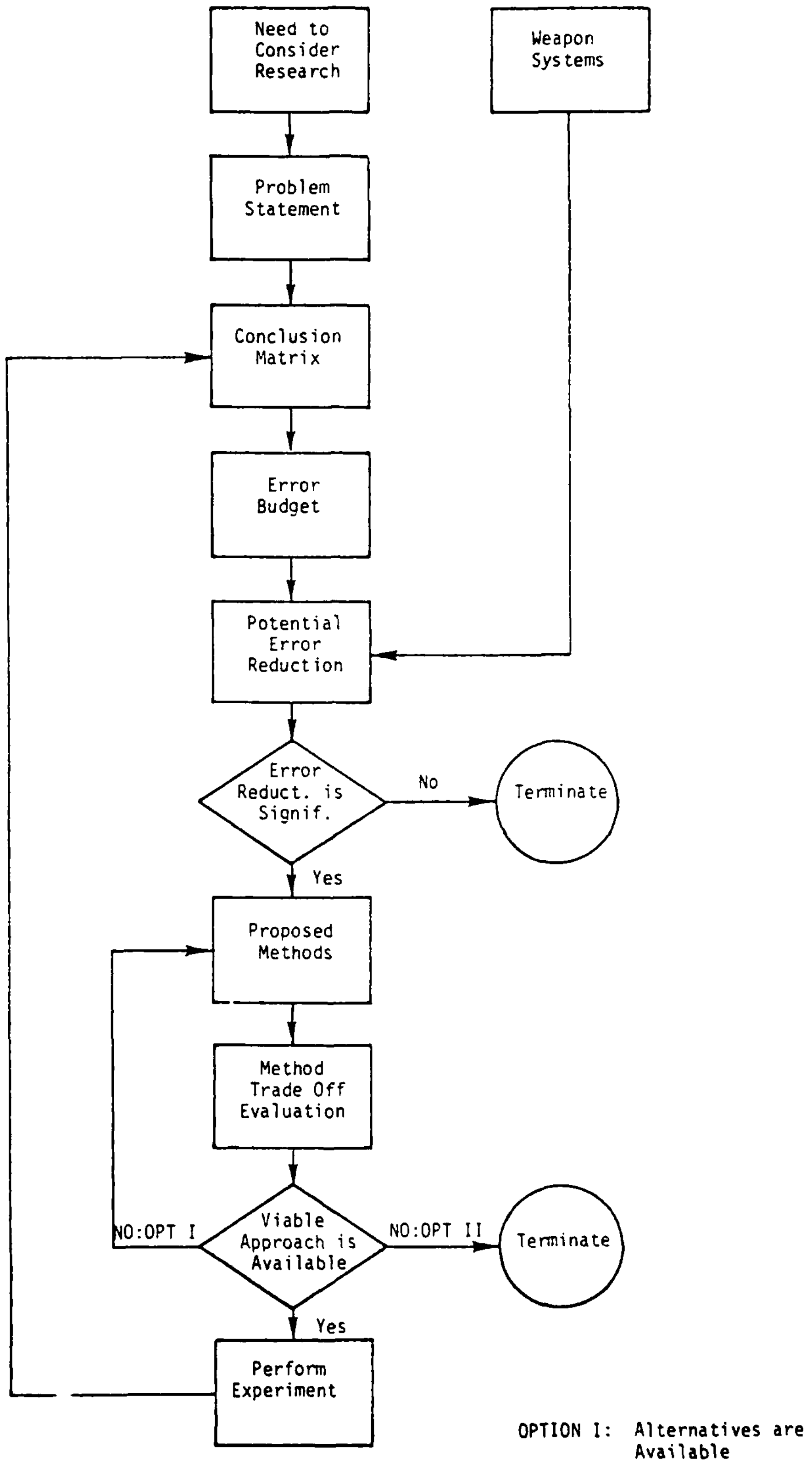
If the results of the exercise in Section 4 lead to the conclusion that a research program may be warranted, the engineer must now decide which problems are to be addressed, if they can be resolved, and how best to resolve them. Additional data may be desired to improve an estimate for target resistance, improve the capability to predict weapon effect phenomenon, or the engineer may consider initiating a pilot program to gather empirical data for validating theoretical analysis. Before the first step of a program is initiated, however, careful planning should be carried out to ensure the significant problems are addressed, proposed methods are technically feasible to resolve these problems, and research funds are allocated in an efficient manner.

The objectives of this phase of the methodology are intended to aid a research engineer in formulating a vulnerability program and to establish a means for comparing alternative approaches as his understanding of the solution progresses. Figure 5.1 depicts the steps in this phase of methodology, each of which are discussed in the following paragraphs.

5.1 STATEMENT OF THE PROBLEM

With this methodology, the first step to formulating a research program is to prepare a brief paper outlining the problem and desired objectives of a program. While this is an apparent obvious requirement it is one that is often only lightly addressed. Without a comprehensive definition, subsequent research will most often tend to be in a hit or miss pattern without a clear purpose.

Initially, problem definition may be the most difficult aspect of a research program. The problem should be broken down into components, and to such a level that one is able to address the feasibility of solution. For example, not knowing the vulnerability of a target does not constitute a statement of the problem but merely a consequence of the



OPTION I: Alternatives are Available

OPTION II: No Alternatives Remaining

Figure 5.1. Sequence of Steps to Program Planning

problem. While this statement may indicate a need for structures research, it does not help identify if and how a problem should be implemented.

In the process of problem definition one should be as specific as possible. In essence, the effort should be directed toward thinking through all aspects of the problem. As a necessary part of and as an aid to this exercise, one should attempt to detail all factors that may influence structural response in a weapon produced environment. In addition to the independent variables, one should also attempt to identify the dependent (response) variables and those mechanisms of the weapon-produced environment most likely responsible for inducing target response (e.g., blast, ground shock). This list of factors should be as complete as possible, and may initially be excessively large. However, after some deliberation among structural and weapon effects analysts the list will probably be reduced to a few recognized critical factors. Those factors which are measurable should be noted as well as those which are not. Special instrumentation may be required for measuring certain factors while nonmeasurable factors may need to be defined in terms of other variables.

This paper is to be distributed among a few key technical advisors for comment on the feasibility of research objectives, and tentative ideas for initiating a program. Advice should be sought from both weapon effect and structural engineering experts, including an estimate of what might be accomplished given available research funds and technical constraints under which the research community must perform experiments.

5.2 CONCLUSION MATRIX

The objective of this step, similar to that in Section 4, is to formulate conclusions (a priori) for the problems the engineer desires to address. Conclusions would be made for the dominant damage mechanism, engineering description of target resistance and subsequent response when interacting with the weapon produced effect environment, and target response dependency on geometric and material property characteristics. If applicable, conclusions will also be drawn on the influence of the weapon effect transport medium on resistance-effect interaciton and sensitivity of effect propagation to properties of the transport medium.

While some of these conclusions may already have been validated, others may be purely hypothetical based upon subjective or opinionated reasoning. Each conclusion is to be weighted according to its degree of known validity, on a scale of "guess" to "high." The conclusion matrix would resemble the example form depicted in Figure 5.2. For each of these 8 subjects, the engineer and his advisors would write their conclusions and one or two statements supporting their beliefs. Each of the 8 conclusions would then be entered into the matrix, arranged according to subject and their respective level of validity. For example, if the dominant damage mechanism could only be peak surface overpressure, this comment and a supporting statement would be entered opposite high level of validity. Conversely, if the influence of secondary loading parameters (e.g., rise time, duration) on target response were unknown, the hypothesized conclusions would be entered opposite "guess." A proposed set of criteria for rating level of validation is given in Table 5.1.

A completed conclusion matrix will reflect the engineer's initial understanding of the solution to a given problem. Accordingly, the indicated validation levels would also concur with the relative reliability of a proposed mathematical failure model to adequately predict target response. For example, if initial conclusions were rated "low" or "guess," the engineer may desire to consider approaches in addition to a probabilistic type design due to the dominant error(s) being non-random.

	Target			Weapon Effect			Transport Medium	
Level of Validation	Mode of Failure	Mode of Response	Resistance	Dominant Damage Mechanism	Range to Effect	Loading Parameters	Influence on Weapon Effect	Influence on Effect-Structure Interaction
High								
Intermediate								
Low								
Guess								

Figure 5.2. Conclusion Matrix.

Level of Validation	Supporting Criteria
High	extensive empirical data base; similitude with related observations
Intermediate	limited quantity empirical data base; extension of empirically derived model beyond data base, without significant (statistical) degradation; rigorous theoretical reasoning
Low	inconclusive small empirical data base; combination of intuition and theory, unsupported by empirical data; extension of empirically derived model beyond data base, with critical (statistical) degradation
Guess	plausible, but without supporting theory or data

Table 5.1. Proposed Criteria for Rating Conclusion Validity

5.3 ERROR BUDGET

The error budget is an accumulation of uncertainties exterior to the scope of a research effort, yet are present and may influence a damage prediction in an operational context. Targeting parameters, such as CEP, operational yield, and probability of arrival, will always be exterior to a vulnerability research program. Vulnerability parameters, such as range-to-effect, may not initially be part of the error budget. However, one may reach a level at which it is no longer feasible to work this problem, at which point the unresolved error would be entered into the error budget. With respect to the remaining uncertainties being addressed in a research program, one may reach a point beyond which these efforts will provide only a marginal return when measured in context with the error budget. The last example in Section 3 illustrated this point. If it were not feasible to work toward reducing the 10 percent uncertainty in range-to-effect, additional efforts to resolve target hardness between 500 psi and 700 psi would be of small benefit to the customer. Admittedly, the error budget may someday be reduced, again making target hardness the dominant problem. However, there will always be some residual error associated with the targeting parameters. As such, the research manager should recognize that there is some point at which further efforts will provide a very low return for money invested.

5.4 RESEARCH EVALUATION

Given extensive experience from previous research programs, knowledge of current research capabilities, and available funding, the engineer may be able to quantify the relative significance of a successful technical performance. To illustrate this concept, consider the hypothetical data given in Table 3.3.* The significant terms in $\overline{\Delta r}$ equation are uncertainty in target hardness (300 psi - 700 psi), and uncertainty in range-to-effect (± 10 percent). Given available funding, and other constraints, only the target hardness term can be addressed

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* Section 3.4.

at this time. Based on past performances, the nature of the problem, and research tools, the engineer may believe he can reduce this factor ($\overline{\Delta}I$) to about 10 percent. If the program is as successful as predicted, the $\overline{\Delta}r$ term would be reduced from the current value of 0.32 to a value of about 0.21. Although the engineer may not be able to assess the bounds for the reduced hardness spread, the estimated reduction in the $\overline{\Delta}r$ term would reduce the $\overline{\Delta}P_k$ value by about 34 percent.

5.5 PROPOSED METHODS

As the engineer begins to plan a research program he must be aware of the many factors that influence both the scope and format of a program. The scope of a program is principally influenced by available funding and research objectives. While both of these factors may also influence program format, the engineer must also consider initial understanding of the problem, and time to resolve the problem, when determining which tests should be performed and in which sequence. For example, if the conclusion matrix had all hypotheses rated low, it probably would not be prudent to perform a full scale, multiple structures-single weapon experiment early into a program. With respect to the overall format there may be several approaches, no one of which could be viewed as superior. Alternatively, a paper perfect program may require modification once the program is initiated. Unexpected observations, experimental failures, or the discovery of experimental biased error may require the engineer to restructure his entire program. Also, it may not be possible initially to plan a complete and concisive sequence to resolve the important issues. A portion of the research budget may be consumed in preliminary tests before the engineer can begin to plan a complete program, or even appreciate the scope of necessary work.

A sample of these planning factors are presented in the following paragraphs. These entries are probably not all inclusive, nor would all of those listed necessarily be applicable to every vulnerability research program. The objective of this step, however, is to suggest a method for planning a program in view of these factors and to devise an orderly sequence in which phases of the program would be executed. Figure 5.3 and 5.4 depicted in a general manner, the product of this exercise. The fundamental premise upon which these figures are based is that the rate at which funding is consumed would not exceed the engineer's capability to plan a successful experiment. Additionally, each successive experiment would be built upon and designed to extend results of the previous work. The following paragraphs briefly cover some of these planning factors.

Research Budget. Since this factor has been extensively discussed, it will only be noted that the engineer should strive to maximize problem resolution for a given level of funding.

Experimental Time Frame. The format of a program could depend on time urgency of problem resolution, or quite simply, how quickly the customer needs an answer. One would not expect a six year program to be planned and executed in the same manner as a six month program. Judicious use of this parameter will allow the learning scale to increase proportionally with the cumulative budget consumption.

Mathematical (Failure) Model Reliability. One of the tools in research planning is a mathematical prediction model. Since the levels of assurance in the conclusion matrix are intended to be synonymous with mathematical model validity, experiments early in a program should be planned accordingly. If the conclusion matrix, initially, has low ratings for most entries, the engineer would probably be well advised to consider a rigidly controlled experiment (e.g., non-destructive, static loading, etc.). Conversely, if a program begins with matrix entries rated intermediate-to-high, a large scale destructive test may provide sufficient

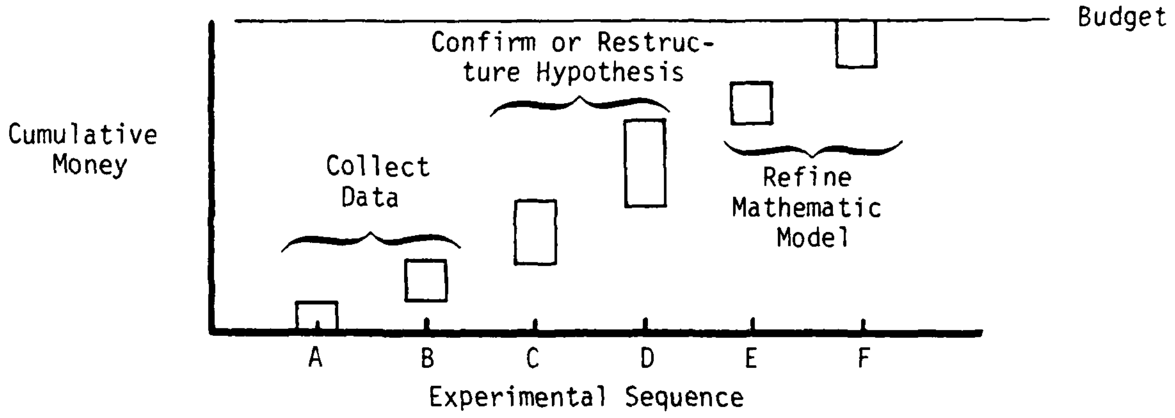

Figure 5.3. Objectives of Experimental Sequence

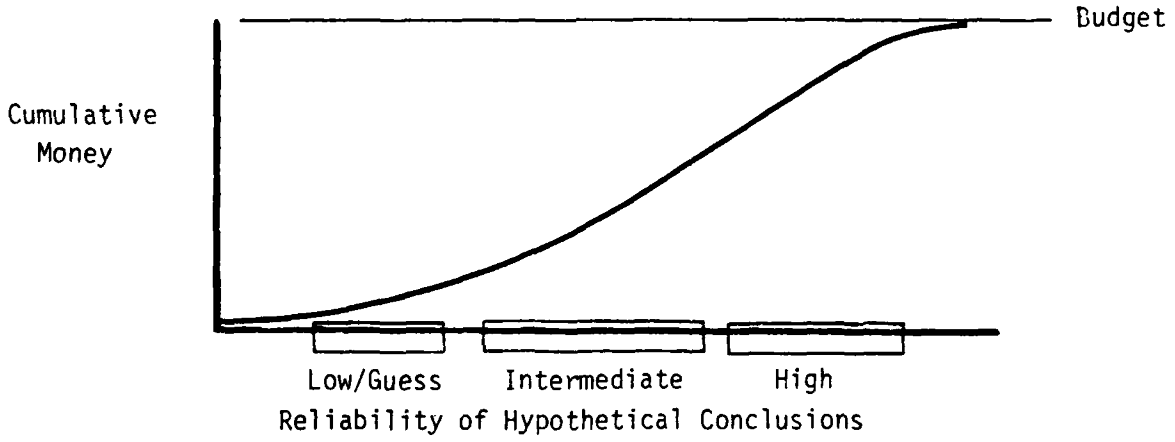

Figure 5.4. Funding as a Function of Problem Understanding

data to validate the mathematical model. Such an experiment, however, should be carefully planned to allow for properties of the structure, weapon effect, and experimental environment, which may demonstrate inherently random attributes.

Parametric Variations. An objective of the program will, most likely, be to measure the dependency of target vulnerability on variations in structural dimensions, material properties, weapon effect transport medium, and magnitude of the destructive (explosive) loading device. Economically, it may not be feasible to test all conceivable parametric values, nor is it necessary if a mathematical model is properly developed. However, the engineer should consider testing at least the bounding values for each critical parameter. Restraint must be exercised, however, when considering the number of parameters, and their respective ranges, to be tested at one time. There will, most assuredly, be scatter in the resultant data, requiring statistical and possibly subjective uncertainty interpretation. In addition to the parametric variations, factors such as measuring devices will also contribute to data scatter. If the statistical concepts are to be of any value for data interpretation and development of the mathematical model, the number of observations should be considerably larger than the number of parameters varied.

Similitude. Using a small scale model, or a component of the composite target, the engineer may be able to collect large quantities of data, otherwise not economically feasible. For some vulnerability problems, e.g., dams, a scale model target may be the only practical means for collecting empirical data. With respect to weapon effects, the engineer must often use non-nuclear devices to simulate weapon (nuclear) produced dynamic loading conditions, usually at an equivalent yield several orders of magnitude removed from that of an operational weapon system. The point to be made, of course, is that the engineer must have available, or develop, a means for extending this data to a full scale (operational) nuclear environment. This is most frequently accomplished by testing various size structures with equivalent normalized geometric parameters.

The engineer must be cautious, however, about inferring all inclusive similitude simply because he has apparent agreement between two data sets from very small scale structural models. Behavioral response characteristics of non-homogenous materials (e.g., reinforced concrete) may change as dimensions are reduced. If this phenomenon is occurring in a non-linear manner, a biased error may be introduced if data from two very small scale structures are used to infer characteristics of a considerably larger structure.

Properties of Test Environment. An important consideration in planning an experiment is the apparent inherent randomness of structural response, weapon effect, and environmental parameters. If previous observations have noted large parametric variation from test-to-test, the engineer must plan his experiments accordingly to enhance probability of a successful test.

Test Format. Frequently, the engineer will have two options for a series of tests. The first option will be referred to as one-on-one, i.e., one explosive charge for each structure. The alternative option will be denoted by one-on-multiple, i.e., one explosive charge for two or more structures. Each of these formats have favorable as well as undesirable characteristics. If a program is begun with low ratings in the conclusion matrix, a one-on-one series could be more desirable as it may allow for erroneous hypotheses to be corrected and verified prior to the last test. Alternatively, shot-to-shot data scatter may necessitate the use of statistical inference techniques, which in turn require large data bases. A one-on-multiple technique would alleviate most of the environment and effect induced variation in an observation. However, if these two factors are positively correlated and approach their extreme values for this single event, the result could be all structures experienced catastrophic failure, or no measurable damage was detected. Such results, of course, do not necessarily indicate the experiment was a failure. However, if the engineer already knew the structure would survive (say) 100 psi, further confirmation of this fact is of little value. Aside from these technical considerations, a one-on-one format would most likely cost more money than a comparable (scale, charge, etc.) one-on-multiple scheme.

5.6 EVALUATING PROPOSED METHODS

During the course of planning and executing a vulnerability program the engineer must frequently make decisions. Although the vlaue of resolving a given problem may be clearly defined, the manner in which the problem can or should be addressed is often unclear. Before committing research funds the engineer must decide if the problem is solveable, the manner in which it might be addressed, the feasibility of resolving the problem given economic and other constraints, and how the program results are to be incorporated into the target damage predictive scheme. If a program is initiated the decision process must remain dynamic for guiding, restructuring, or terminating the program as developments are evaluated.

The means by which these types of decisions are reached can be as varied and complex as the problems they are intended to address. The engineer may prefer a subjective approach based on intuitive reasoning and experience. Alternatively, the engineer may favor a probabilistic decision model designed to highlight the approach which affords the least risk or maximum return for dollars invested. While this latter approach may appear to be more scientific, the statistical decision concept is often merely an extension of the engineer's subjective reasoning into a quantitative format. For this reason, the engineer's experience and ability to think through the problem are often his most valuable assets for formulating a rational decision process. Whatever type of approach is favored, however, there are fundamental questions that must be addressed before a decision can be reached.

As a tool to aid the engineer with the decision process this methodology employs the use of a success (decision) tree. The tree is comprised of a series of statements general in content near the top and more specific toward the base. If desired, probabilities may be propagated through the tree to evaluate the change of success. It is recommended, however, that the engineer use the tree as a format for systematically evaluating a proposed experiment in a qualitative sense. An example tree, depicted in Figures 5.5 to 5.9, is intentionally formatted to address basic concepts in experimental planning and design. These concepts are emphasized in this methodology as they are believed to be the most important factors entering into the decision process. The following paragraphs briefly discuss these concepts.

The basic input to the decision tree is depicted in Figure 5.5. The top event, the decision to initiate proposed work, is a conditional statement requiring positive response from each of the five supporting statements. Each of these five statements are also conditional requiring positive response from more specific statements further down the tree. Figure 5.6 contains a further breakdown of information required to address the question of objectives. The intent in this branch of the tree is to determine if the proposed work is consistent with the engineer's objective for conducting the program. To assess this question the program itself must have defined objectives in response to a problem statement. Therefore, this branch of the tree can be adequately evaluated only if the program manager makes clear his intent of the research effort. While this is an apparent obvious requirement it is one that is often only lightly addressed. Without a comprehensive definition subsequent research will often be in a hit or miss pattern with a clear purpose.

The statements in Figure 5.7 address the feasibility of realizing the stated objectives in an experimental environment. These statements are often argumentative with no apparent prior methods of solution. Aside from this possible dilemma; however, one must consider state-of-the-art techniques for addressing the stated problem with the desired objectives. For example, refining target resistance to within 5%, with 90 percent statistical confidence, may be impossible regardless of the experimental approach.

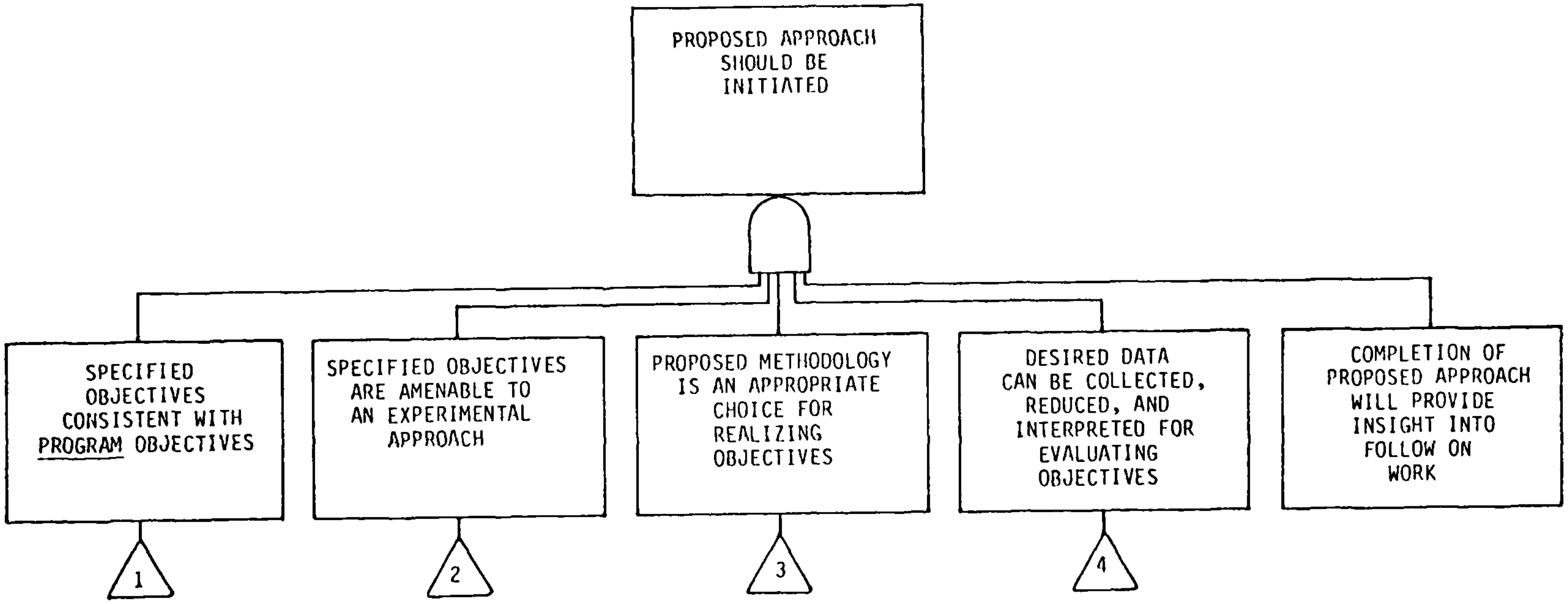

Figure 5.5. Fundamental Branches of Decision Tree

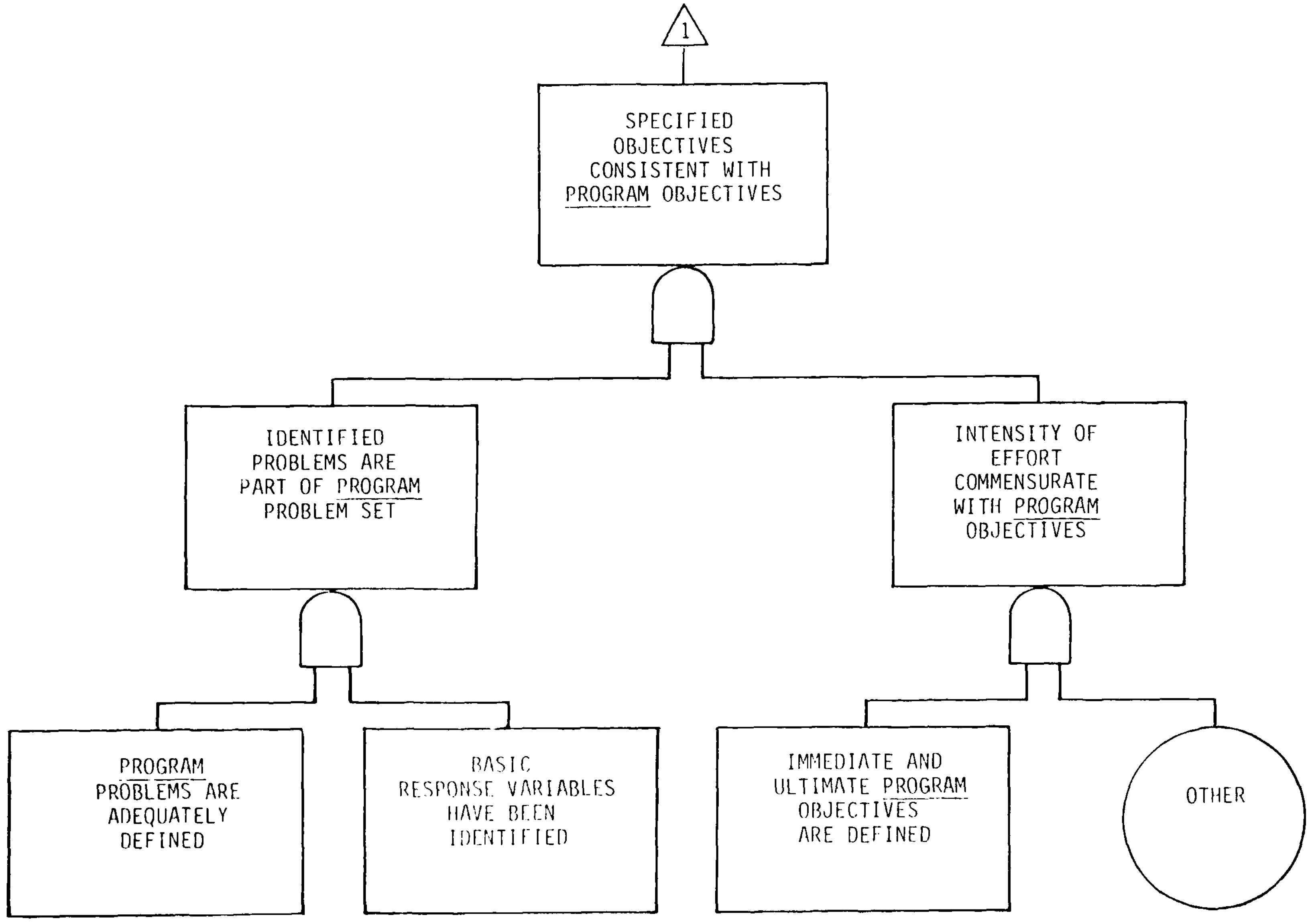

Figure 5.6. Research Objective Branch

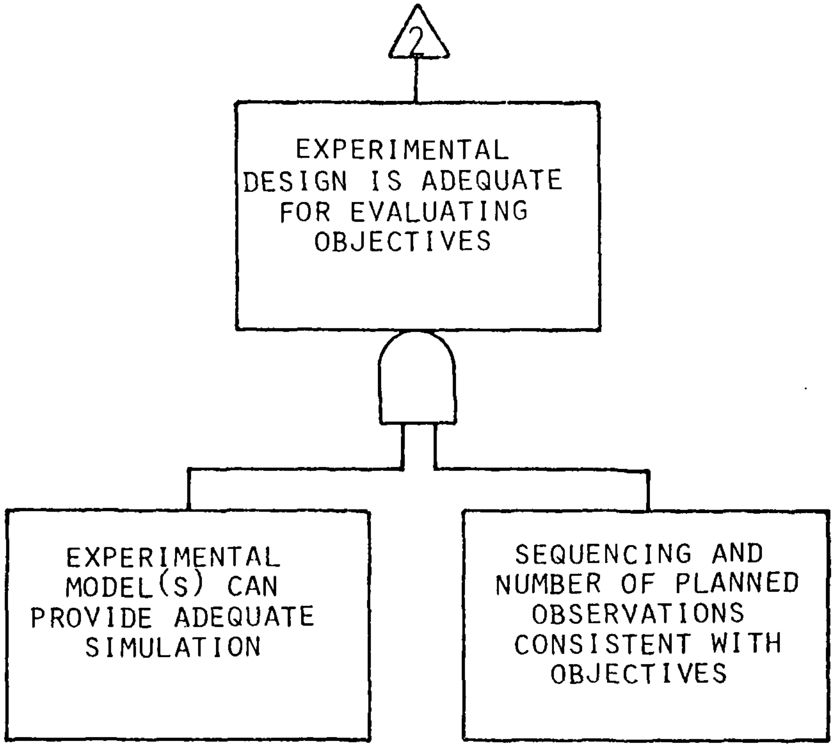

Figure 5.7. Experimental Feasibility Branch

The input to statements in Figure 5.8 address the proposed work itself from both an economic and design point of view. The design branch deals with the experimental plan and how it relates to program objectives. The cost performance, of course, addresses the question of return of informative information for costs incurred, and this rate of return with respect to alternative approaches.

The statements in Figure 5.9 address the utility of collected data from the specified approach. The underlying questions in this branch pertain to what kind of data should be collected, the means (instrumentation) by which it will be collected, and how the data will be reduced into a format amenable to evaluating objectives. The supporting conditional statements in the tree are almost intuitively obvious and of course are themselves conditional statements. This entire branch is so obvious, in fact, that it is often neglected in experimental planning. The experimental planners must think ahead and attempt to "visualize" what format their data will actually be in. Given this format, and all of the factors to be observed, one must also consider how the data will be reduced for subsequent interpretation. Finally, one must also consider the techniques available for interpreting the reduced data and if the experimental objectives can be evaluated by these techniques.

The fifth branch of the tree is concerned with whether the proposed effort can be integrated into the continuity of the program. This branch is intended to generate thinking as to the work that may be required following successful completion of this proposed effort. It would seem desirable that the proposed effort, when completed, would either be an end in itself, or provide insight into the next logical phase of the research program. The program manager should also consider what type of follow-on work may be necessary because of this proposed approach.

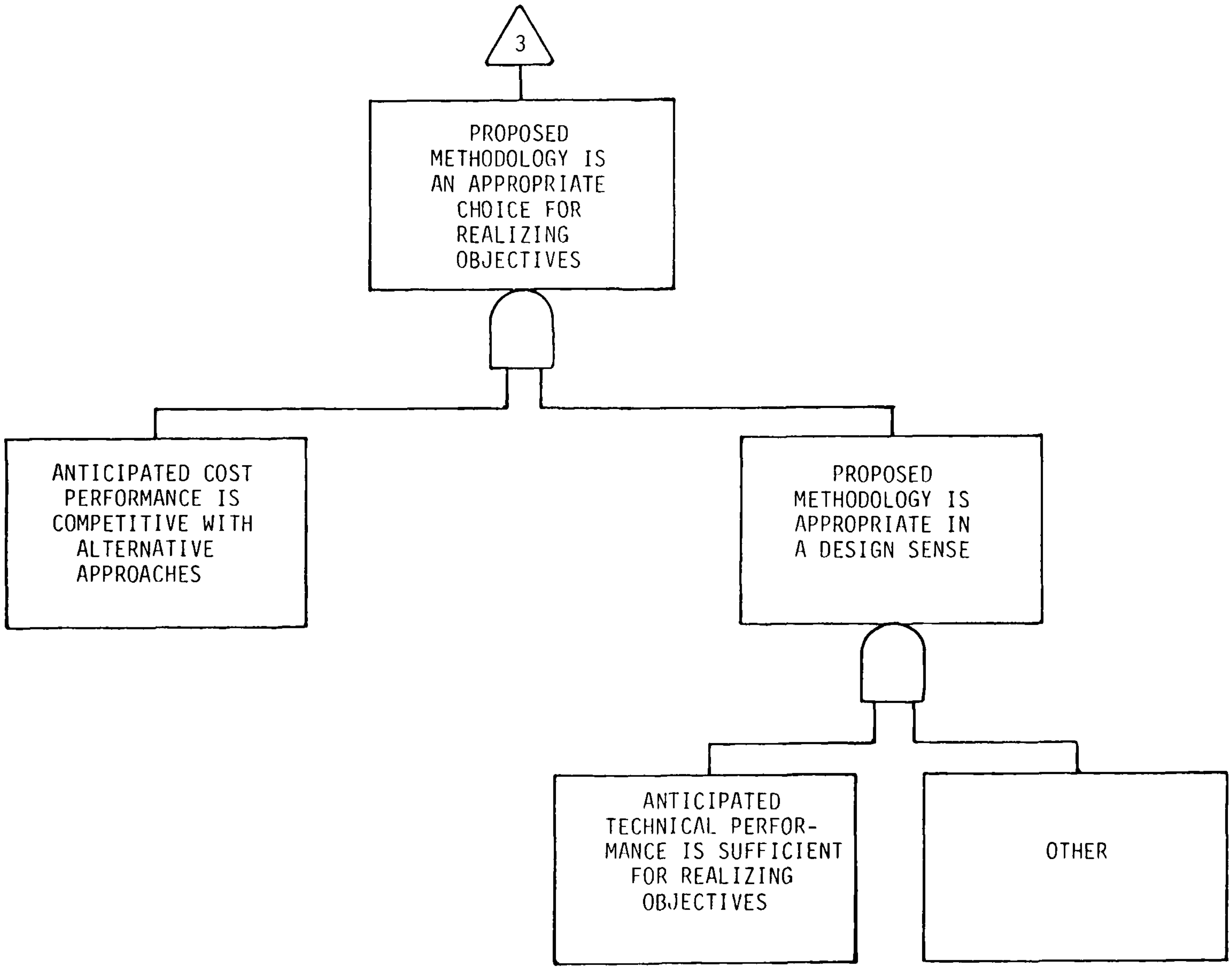

Figure 5.8. Experimental Design Branch

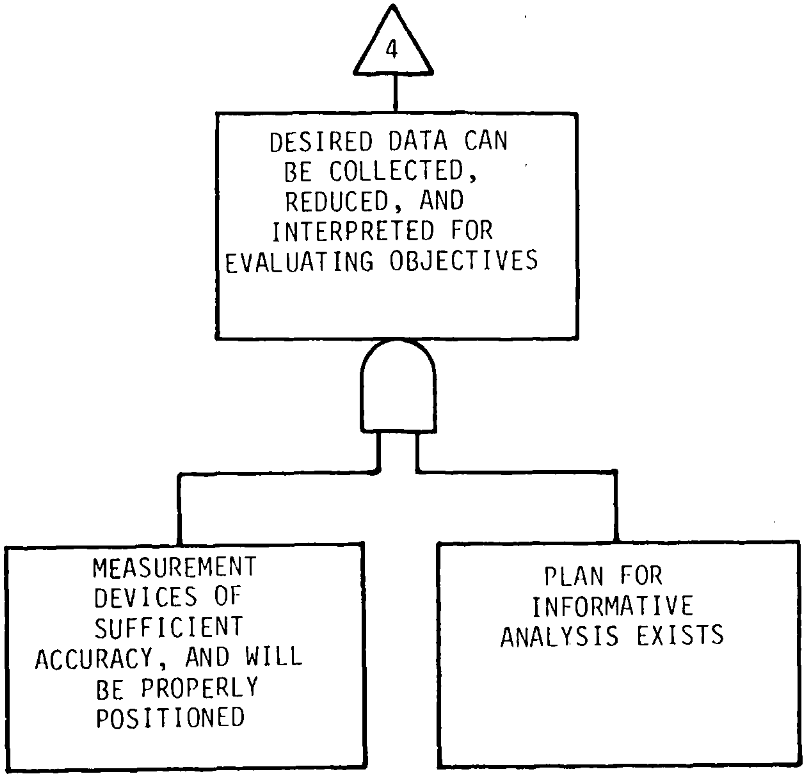

Figure 5.9. Data Utility Branch

6. APPLICATION OF METHODOLOGY

The remainder of this document is intended to demonstrate application of the previously discussed methodology to a specific targeting problem. The objectives of this task are to determine the practical relevancy of the methodology, and demonstrate how a research program might be organized if this particular methodology were used. With the concurrence of DNA,a buried reinforced concrete bunker was selected as a suitable example problem. This particular structure is currently being studied by DNA as part of a relatively new program designed to assess vulnerability levels for shallow buried structures. As the overall program is in a relatively early stage of development,it is anticipated to be a worthwhile example for application of the methodology to the decision making processes.

6.1 DESCRIPTION OF RESEARCH PROGRAM

The shallow buried structure program is a relatively new DNA sponsored effort to assess the vulnerability of buried structures to an aboveground air blast environment. Current efforts are focused on flat-roofed reinforced concrete structures, with plans to eventually include arch-roofed structures.

This program began in response to a suspected error in the current vulnerability value estimate suggested for buried structures of this type configuration. The suspected error, an underestimate of target hardness, was demonstrated when a scale model structure survived a dynamic loading environment significantly greater in intensity than the current estimate for inducing severe structural damage. Subsequent to this test, physical and calculational experiments have continued to support this suspected error in the guideline vulnerability estimate.

To date, 9 physical experiments have been performed by the Waterways Experimental Station (WES) on a composite box structure and a roof slab element. Summary observations from these experiments are presented in Table 6.1. One additional composite box structure experi-

Table 6.1. Summary of Experiments Performed at WES on Shallow Buried Structures

	STRUCTURE	GEOMETRIC SCALE	TRANSPORT MEDIUM	DEPTH OF BURIAL	OBSERVATIONS
Dynamic	Box 1	1/4	Sand	Span/2	1/2" permanent deflection at center of roof span. Simulation: 1300 psi at 0.3 kt, to 700 psi at 8 kt.
	Box 2	1/4	Sand	Span/2	Structural collapse 3600 psi at 10 kt.
	Roof Element 4	1/8	Sand	Span/2	Collapse 2700 psi at 0.3 kt, to 2000 psi at 0.7 kt.
	Roof Element 5	1/8	Clay	Span/2	4/5" permanent deflection at center of span 400 psi at 0.17 kt, to 250 psi at 0.22 kt
Static	Box	1/8	Sand	Span/2	Capacity 620 psi
	Box	1/8	Clay	Span/2	Capacity 240 psi
	Roof Element	1/8		Surface Flush	Capacity 175 psi
	Roof Element	1/8	Sand	Span/2	Capacity 820 psi
	Roof Element	1/8	Clay	Span/2	Capacity 175 psi

ment is scheduled for November 1978, and plans are currently being formulated for 1979. In addition to the work being performed at WES, a parallel effort is being initiated by SRI International using a very small scale composite box structure. At this time there is no information to report from this new effort.

6.2 SCOPE OF METHODOLOGY APPLICATION

The methodology, as outlined in the two previous sections, suggests that the program manager initiate action with a review of existing information. Since the shallow buried structure program is already in progress, however, application of this methodology will demonstrate the significance of observations to date as measured in a targeting context. The utility of the qualitative decision tree as a management tool, however, was not completely evaluated during the course of this work. Accordingly, efforts toward evaluating this portion of the methodology are not presented in this document.

6.3 IMPLICATION IN A TARGETING CONTEXT

Evaluating vulnerability research progress and defining further requiremetns can often be appreciated by analyzing existing information in a targeting context. Since application of the research results will be employed in this manner by the customer, the decision to continue or expand a program may depend to a large extent on this means of measurement. To demonstrate how this approach can provide useful input to the program decision process, the data obtained from the buried box experiments will be analyzed in the following paragraphs. For the purpose of this exercise, the box data in Table 6.1 will be interpreted to mean that the actual target hardness, for roof collapse, is contained within the interval 1000 psi to 3500 psi, peak surface overpressure (P_{SO}), for a weapon yield in excess of 100 KT. This interpretation is based on extension of the box test results to that of a full size structure.

Figure 6.1 illustrates this extension, and compares these observations with hardness values obtained from the current estimating procedure used for similar structure type configurations.

The information contained in Table 6.1 could be interpreted to mean that the vulnerability of a shallow buried flat roof structure is at least 1000 psi hard, but not in excess of 3500 psi, for collapse of the roof. While these two values apparently bound the actual target vulnerability there is no supporting information from which one could infer any single value in this range as being a relatively accurate assessment. As will be demonstrated in the following paragraphs, however, this lack of relative precision may not be a serious problem for the customer. As such, further refinement of vulnerability bounds for this particular target geometry and transport medium may be of marginal value. Additionally, one might also infer that physical experiments of other geometries or transport medium may also be unnecessary, or may only need to be minimal in number for the purpose of providing the customer with sufficiently accurate vulnerability information.

For purpose of demonstration three hypothetical weapon systems will be assumed available for targeting a shallow buried structure. The characteristics of these three systems, designated A, B, and C, are detailed in Table 6.2. For the targeting application the weapon aim point coincides with the target and probability of kill values are for a single warhead. The results of targeting

WEAPON SYSTEM	YIELD	CEP	$CEP/W^{1/3}$
A	100 KT	700 FT	150
B	500 KT	2000 FT	250
C	1000 KT	1750 FT	175

Table 6.2. Hypothetical Weapon Systems and their Parameters

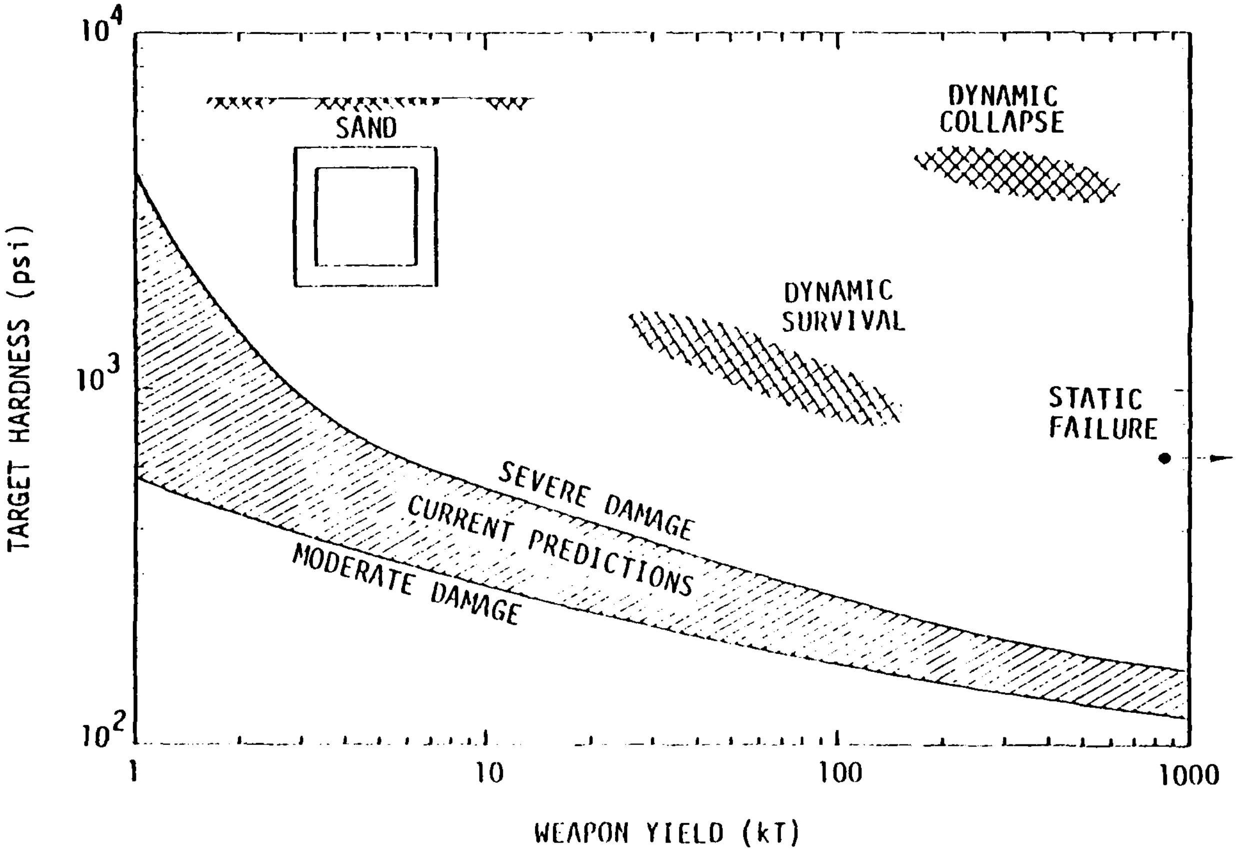

Figure 6.1. Hardness vs. Yield for Shallow-Buried Structure in Sand (DOB ~ L/2)

in such a fashion against the bounding hardness values are presented in Figure 6.2. As noted on this set of curves the implication of vulnerability uncertainty in the context of system A is a spread of about 20 percentage points. The significance of this vulnerability ignorance is about the same for system C and appears to be of small consequence in the context of system B. Obviously, if system B was the only one of the three systems available for a targeting scenario, there would be no appreciable concern for the limited understanding of target vulnerability. This argument may be applied to most candidate weapon systems as will be demonstrated in the next several paragraphs.

An alternative approach for visualizing the implication of target hardness uncertainty, and one which may be used to recommend a value to the customer, is derived as follows. Consider the ground range to both 1000 psi and 3500 psi centered about a point target as depicted in Figure 6.3.

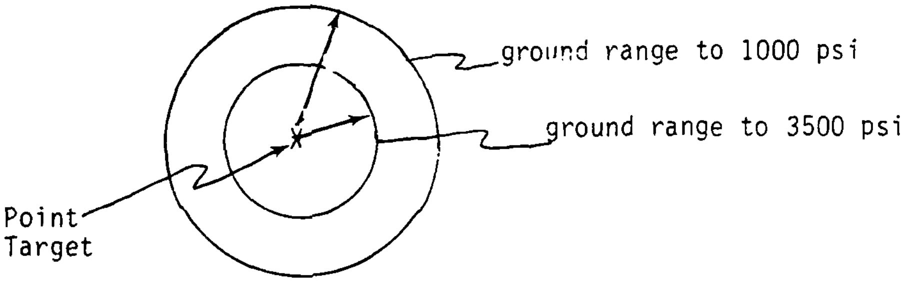

Figure 6.3. Point Target Iso-Damage Contours

For a given weapon system, with yield W (kt) and CEP (C), there is a P_k value for 1000 psi, P_S, and P_k value for 3500 psi, P_H. Let the average P_k value, P_A, be defined by,

$$P_A = \frac{P_S + P_H}{2} .$$

Based on the weapon system characteristics, and the P_A value, there is a corresponding peak surface overpressure value, $P_{SO}(A)$, i.e.,

$$P_{SO}(A) = \text{function } (W, C, P_A).$$

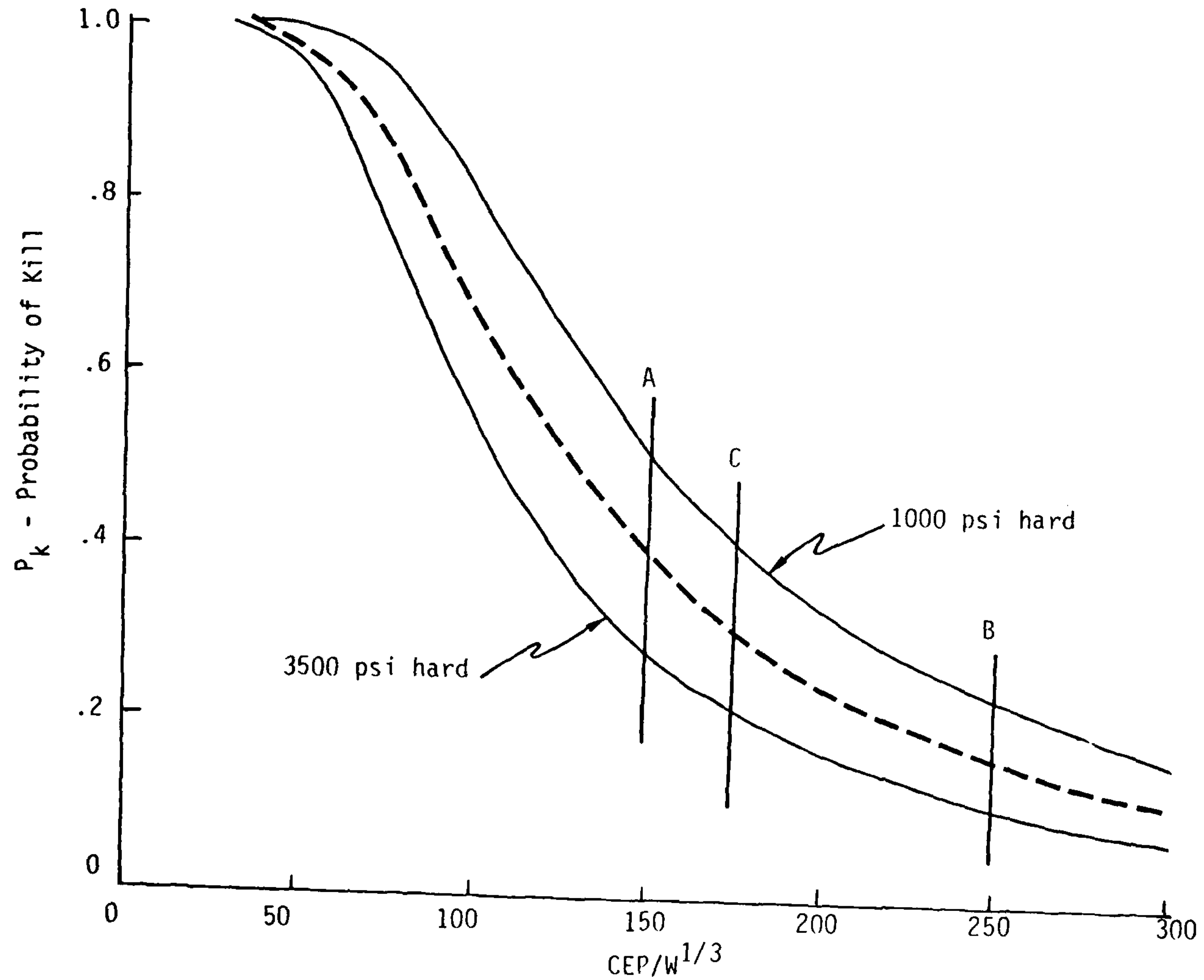

Figure 6.2. Implication of Vulnerability Uncertainty in a Targeting Context

In a targeting context, the implication of using this P_A value is that the damage prediction could be in error by as much as $\pm \Delta P_k$ probability points where,

$$\Delta P_k = (P_A - P_H) = (P_S - P_H).$$

It should be noted that this error is either positive or negative for all events and, as such, is not intended to indicate a random error. The results of performing this operation are depicted in Figure 6.4. Included in this figure are the $P_{SO}(A)$ values, $P_k(A)$ values, and ΔP_k values as a function of scaled CEP. Implicit to this information are the bounding hardness values of 1000 psi and 3500 psi.

The information presented in Figure 6.4 suggests that the ΔP_k value could be as large as 14 percentage points for a scaled CEP value of about 100. To some extent, however, this ΔP_k curve is misleading in the sense that it was based on a definite target hardness value, $P_{SO}(A)$. In the targeting methodology a recommended vulnerability number (VN) value is considered to be no more accurate than about ± 1 VN value. For overpressure sensitive targets this level of precision equates to an error factor of about 1.2 in the target hardness estimate. For example, the precision of a 1600 psi value, in the VN system, would be no better than about ± 300 psi. Considering this reliability factor the ΔP_k values in Figure 6.4 should also be viewed in this context. Figure 6.5 depicts consideration of this additional information for comparison against the current understanding of target hardness. The shaded area depicts the targeting implication of precision in the recommended hardness values, $P_{SO}(A)$, shown in Figure 6.4. The ΔP_k values outside the shaded region, and between the bounding curves, represent the targeting uncertainty attributable to hardness values outside the range of precision but contained within the research derived hardness bounds. Viewed in this manner the spread in target hardness values could account for at most a spread of ± 8 percentage points beyond the acceptable range of precision. For scaled CEP values other than about 100 the ΔP_k spread beyond the acceptable range is relatively small.

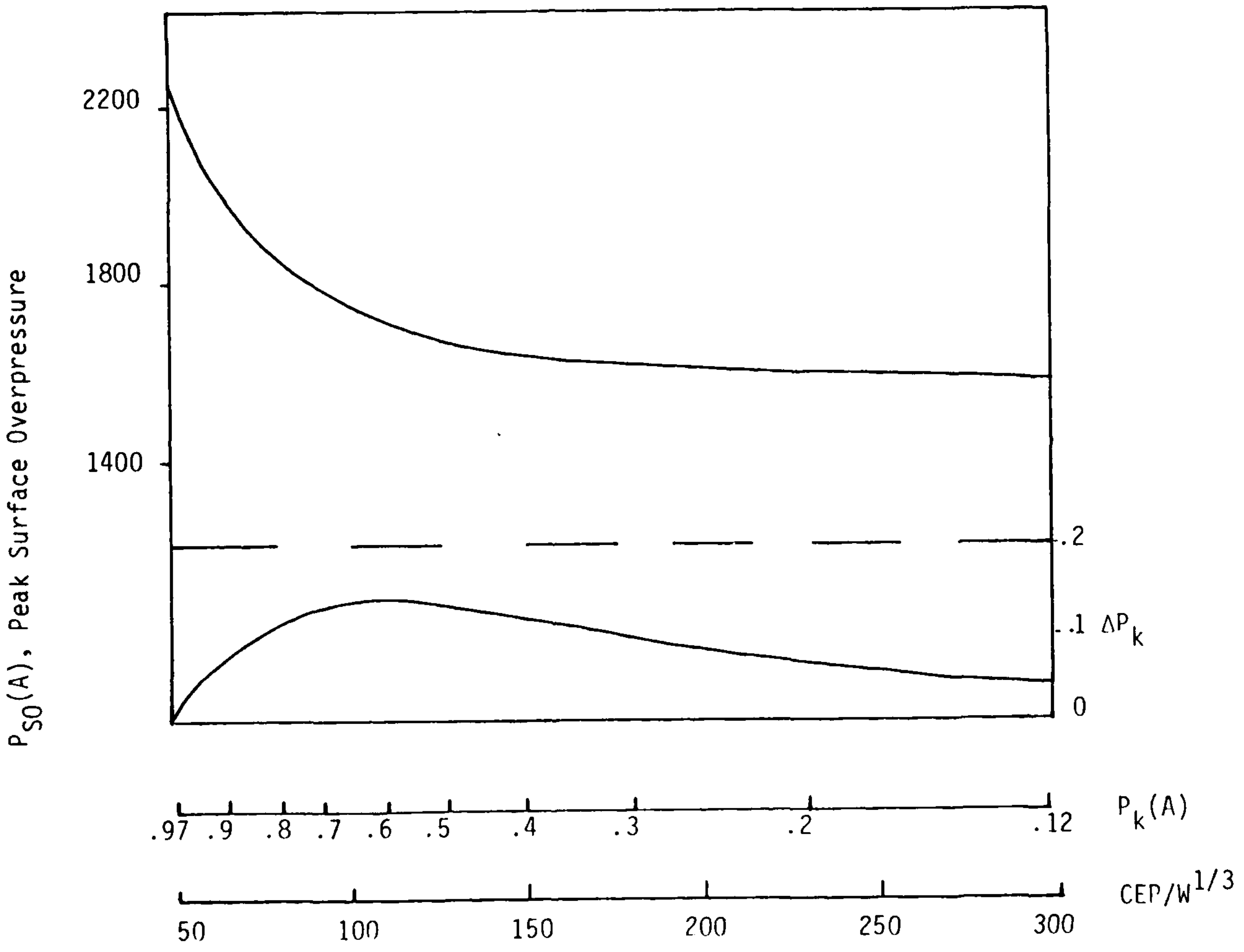

Figure 6.4. Significance of Research Results Assessed in Targeting Context

Assessing the interpreted results of the box experiments in the format presented in Figure 6.4 the research engineer may consider suggesting a hardness level of 1600 psi to the targeting community. Aside from weapon systems with a scaled CEP value between about 75 and 175, the recommended hardness, for targeting purposes, is relatively accurate. If the customer felt the maximum potential error to be excessive, however, a single experiment demonstrating survival, or failure, at about 1500 psi would reduce the implication of the remaining bounds to a level of inconsequence. Figure 6.6 depicts the implication of the bounding values for target survival at 1500 psi and failure at 3500 psi.

This relative insignificance of hardness uncertainty as measured in a targeting context is characteristic of structures with a hardness level in excess of about 1000 psi peak surface overpressure. As was shown through expressions presented in Section 3, uncertainty in target hardness is reduced by about 2/3 when expressed in terms of ground range. In a targeting situation, this annulus of uncertainty, as depicted in Figure 6.3, can be of small consequence as determined by the distribution of weapon detonation points. For example, the predicted difference in scaled ground range, between 3500 psi and 4500 psi, is less than 10 feet. As such, for most scaled CEP values the ΔP_k value attributable to this spread in P_{SO} values would be very small. For this reason the information in Figure 6.4 would be about the same had the box test results been interpreted to be between 1000 psi and 4500 psi. The significance of these observations from a research position is that further physical experiments may provide only a marginal return to the customer in terms of increased reliability of target damage predictions. Therefore, additional physical experiments may prove of value to the customer only for structural configurations apparently softer than 1000 psi. Of course, this type of information can serve only as input to the management decision process, and does not necessarily constitute all of the information required for overall program guidance.

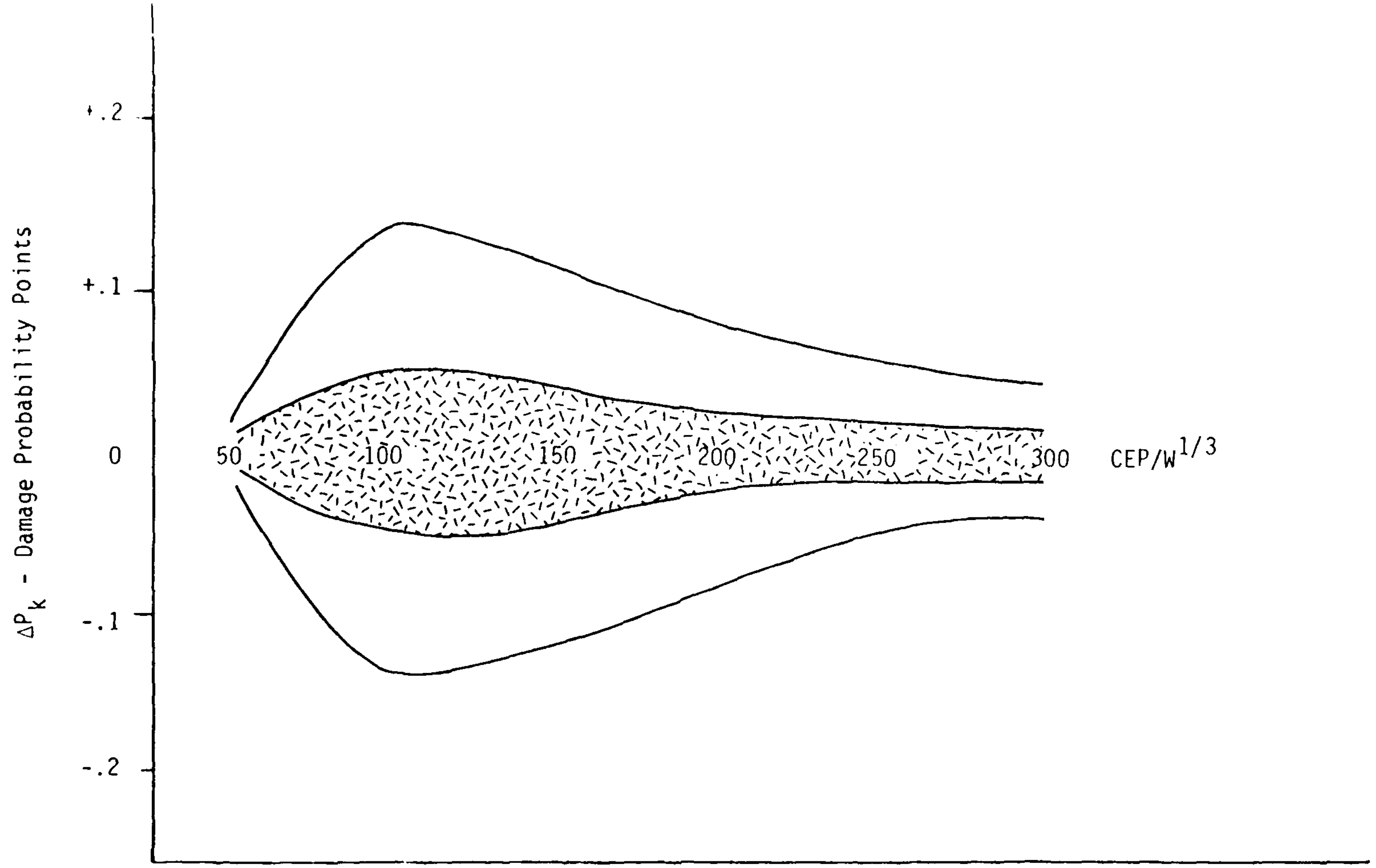

Figure 6.5. Comparison of Research Results vs. Operational Errors Assessed in Targeting Context

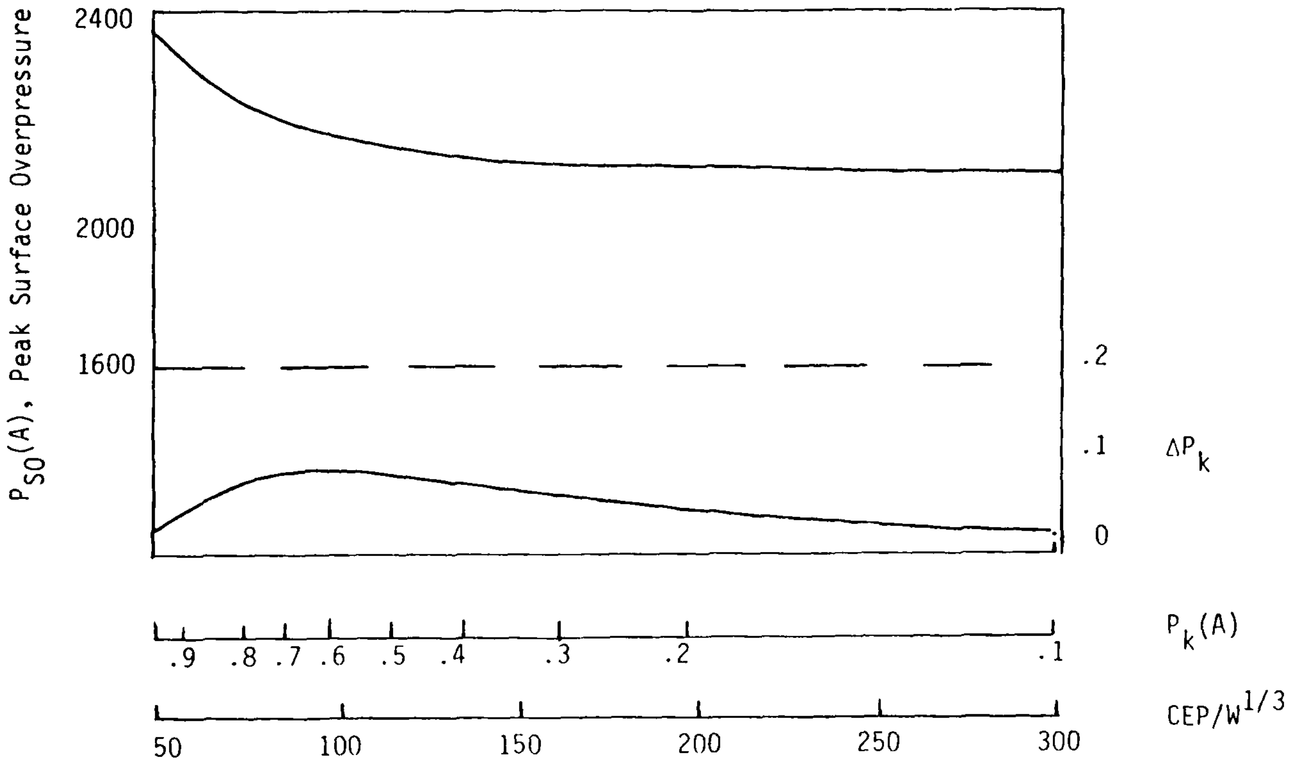

Figure 6.6. Significance of Refined Research Results Assessed in Targeting Context

7. SUMMARY

This report presents a methodology to assist a research program manager with making decisions. The approach is specifically oriented toward a target vulnerability program, and is designed to be easily implemented in a book-keeping type fashion. The methodology itself, however, does not provide final solutions to management problems. This approach is structured to obtaining the information which is necessary input to a decision process. The methodology's input is derived from (1) user requirements as measured in a targeting context, (2) basic planning factors for designing physical experiments, and (3) recommendations from all principal participants involved with a research program.

With regard to the demonstration of this methodology, the dominant result is that a large uncertainty in vulnerability estimates for very hard targets tends to be absolved in a targeting context. Given the rapid decrease of peak surface overpressure with increasing ground range, an annulus of target damage radius ignorance appears to be insignificant in the targeting of very hard structures. Accordingly, given the previously stated interpretation of current test results one might infer that additional physical experiments may produce only a marginal return to the user.

Conversely, evaluating experimentally derived inferences in a targeting context should not be the only measure considered for future planning purposes. Foremost of all research objectives is the desire to gain a fundamental understanding of the physics inherent to structural response and failure. The engineering target model used in the buried structure research program is merely an economically convenient generalization of the actual targets of interest. Accordingly, the insight to the response physics gained from this program will serve as the basis from which inferences will be made with regard to the nuclear vulnerability of deployed targets. As such, the insensitivity of interpreted experimental results in an operational context should be construed as favorable only if accompanied by an understanding of the structural response physics.

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