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Nuclear Damage to Point Targets

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analyst to resort to machine calculations or to extensive sets of charts, tables, or graphs. We created nomograms and a slide rule to simplify and speed these calculations. These tools also reduce analyst-induced errors. They speed the calculation of the effects of nuclear weapons, thereby speeding the process of identifying means to harden equipment (used by friendly troops) against the effects of such nuclear weapons or to exploit the vulnerability of equipment (used by unfriendly troops) to the effects of such nuclear weapons. The report consists of two parts. The first part presents the unclassified results; the second (a supplement published under separate cover) presents the classified results.

CONTENTS

APPENDICES

1. INTRODUCTION

The objective of the study reported here is to completely characterize the damage to point targets that are exposed to the full spectrum of effects that originate with a nuclear weapon detonated some distance from the targets. Methods for calculating such damage are available to the analyst today (FM 101-31,[1] AP-550,[2] EM-1[3]); but these methods, which often yield conflicting results (such as those reported by Sommers and Vitello[4] of BDM Corporation, and Daniels[5]), have numerous drawbacks, not the least of which is their complexity. In this report, we address this complexity by developing nomograms and a slide rule with which to calculate damage to targets. These analysis aids use simple methods and a data base[6] that is far more accurate than those of the existing methods. Preliminary results of this study have been published in an internal memorandum at Harry Diamond Laboratories (HDL). The methods presented in this report have greater potential for application than survey of nuclear damage codes and their assessments.[7]

- The present method does not lump all targets of a type (e.g., wheeled vehicles) into the same vulnerability numbers category, as does FM 101-31. The associated uncertainties in damage probability in the present method should be far smaller than in FM 101-31.

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[1] *Department of the Army Staff Officers' Field Manual, Nuclear Weapon Employment Doctrine and Procedures, FM 101-31-1 (March 1977).*

[2] *Defense Intelligence Agency, Physical Vulnerability Handbook--Nuclear Weapons (U), AP-550-1-2-INT (June 1969). (CONFIDENTIAL)*

[3] *Defense Nuclear Agency, Capabilities of Nuclear Weapons (U), DNA-EM-1, parts I and II (1 July 1972). (SECRET)*

[4] *C. E. Somers, Jr., and A. P. Vitello, BDM Corporation, Comparison of FM 101-31 and AP-550 Nuclear Target Analysis Systems (U), Defense Nuclear Agency Report 4530F (10 January 1978). (SECRET RESTRICTED DATA)*

[5] *R. D. Daniels, Investigation of Calculational Aids for Estimating the Effects of Nuclear Weapons on Targets (U), Lulejian & Associates, Inc., Defense Nuclear Agency Report, DNA 411F, ADC 010837 (February 1976). (CONFIDENTIAL)*

[6] *W. L. Vault and W. E. Sweeney, Jr., Vulnerability Data Array Progress Report FY76, FY7T (U), Harry Diamond Laboratories PR-77-4 (December 1977). (SECRET)*

[7] *C. Stuart Kelley, Survey of Codes Employing Nuclear Damage Assessment, Harry Diamond Laboratories SR-77-4 (October 1977).*

- The present method does not resort to a governing effects calculation, as does AP-550, wherein damage is calculated only for the governing effect of the detonation. Using AP-550 methodology, the analyst cannot determine what caused the damage and therefore cannot recommend a hardening fix or recommend a method to exploit this weakness.

- The present methods deal with all environments that are likely to be major damage causers.

- As will be seen, the present methods are considerably simpler than those of FM 101-31 or AP-550.

In all the methods, to calculate damage, one inputs the values of the weapon yield and circular error probable (CEP), burst-to-target distance, and some form of vulnerability numbers.

This report is exclusively concerned with damage to point targets. Here we define a point target in somewhat different terms from those used (below) in FM 101-31[1] and AP-550.[2] Our definition is that over the dimensions of a point target the damage is approximately constant to considerably smaller subtargets (such as personnel) that make up the point target. The FM 101-31 definition of a point target is

> An area target is considered a point target when its radius is small with respect to the radius of damage. As a guide, when the radius of damage is 10 times (or more) as great as the radius of the target, the area target is considered a point target. Alternately, when the weapon circular error probable is 10 times (or more) as great as the radius of the target, the area target is considered a point target.

The FM 101-31 definition involves the concept of the weapon CEP, which originates with various errors in the delivery and results in the weapon actual ground zero (AGZ) being randomly displaced in a normal distribution with radius from the designated ground zero (DGZ). The CEP is defined as the radius of the circle about the weapon DGZ within which 50 percent of repeatedly fired rounds would fall. A somewhat different definition of a point target is taken from the AP-550 manual.[2]

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[1] *Department of the Army Staff Officers' Field Manual, Nuclear Weapon Employment Doctrine and Procedures, FM 101-31-1 (March 1977).*

[2] *Defense Intelligence Agency, Physical Vulnerability Handbook--Nuclear Weapons (U), AP-550-1-2-INT (June 1969). (CONFIDENTIAL)*

> A convenient rule of thumb for deciding when an area target is sufficiently small to be considered as a point target for probability purposes is to consider any target which has a greatest dimension less than 1/4 of the CEP as a point target. This rule insures that the difference in the probabilities of damaging the closest and farthest points of the target will not be over 0.05.

This report deals with such point targets as trucks, personnel, and command posts, which are consistent with the above three definitions. Not treated in this report is the aggregation of damage to such targets into damage to some parent body. Calculation of damage to these point targets proceeds in two steps: The first is a calculation of the nuclear environment to which the target is exposed; the second is a calculation of the damage this environment causes to the target.

Nuclear environments that can be considered major damage causers are

neutron fluence F_n (n/cm^2)
total radiation dose D (rads)
static overpressure ΔP (psi)
peak intensity of the vertical electric field of the electromagnetic pulse (EMP) E_θ (V/m)
peak gamma-ray dose rate $\dot{\gamma}_{max}$ [rads(Si)/s]
thermal fluence Q (cal/cm^2)
peak ideal dynamic pressure q (psi)
static pressure impulse I (psi-s)
ideal dynamic pressure impulse I_q (psi-s)

Each of the above environments interacts with the target in a different fashion to produce damage that can affect its military effectiveness. The intensity of each of the environments (generically designated E) depends on the weapon yield W and the distance r of the target from the detonation. It has been found for tactical warfare situations that simple algorithms like[8]

$$E = AW^D r^B e^{Cr} \tag{1}$$

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[8] *W. E. Sweeney, Jr., C. Moazed, and J. Wicklund, Nuclear Weapons Environments for Vulnerability Assessments to Support Tactical Nuclear Warfare Studies (U), Harry Diamond Laboratories TM-77-4 (June 1977). (CONFIDENTIAL)*

accurately characterize the $E(r,W)$ relation. These algorithms were developed for typical weapons and, as such, the data from which they evolved can represent several different specific weapon outputs. The algorithms are least-squares fits to data taken from the following sources (for specific references, see Sweeney et al; the references are listed in that report in more detail).

Defense Nuclear Agency (DNA) effects manual for blast[3]
Army Nuclear Agency reports for D and Q
DNA ATR code for F_n, γ
HDL reports for $\dot{\gamma}$
Kaman Science report for Q
Los Alamos Scientific Laboratory reports for LAEMP

The algorithms are simple and easy to use compared to the complex codes from which they evolved. The algorithms (with the exception of the EMP algorithms) are adjusted for optimum weapon height of burst (HOB) in accordance with the analyses in which they are expected to be used (tactical nuclear effects). The EMP algorithms are for surface bursts.

If the analyst knows the above algorithms (values of the constants for each environment in equation (1) will be found for each environment in table I), he can calculate the intensities of the nuclear environment at the target, given the weapon yield and the target-to-burst separation distance. He has now completed the first of the two steps needed to calculate the damage to the target.

The second step in calculating the damage to the point target is to specify an algorithm that relates the degree of damage to the value of the environment intensity and the values of some vulnerability parameters that quantify the response of the target to the environment intensity. It has been found experimentally that the response of equipment to a variety of E's is described by a cumulative lognormal distribution

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[3] *Defense Nuclear Agency, Capabilities of Nuclear Weapons (U), DNA-EM-1, parts I and II (1 July 1972). (SECRET)*

[8] *W. E. Sweeney, Jr., C. Moazed, and J. Wicklund, Nuclear Weapons Environments for Vulnerability Assessments to Support Tactical Nuclear Warfare Studies (U), Harry Diamond Laboratories TM-77-4 (June 1977). (CONFIDENTIAL)*

(see eq (2) below).[4] The measure of damage is specified by the probability that a given environment produces a specified degree of damage. A single example: roll-over of a wheeled vehicle is deemed moderate damage. A blast wave that would roll over a jeep when incident side-on (a distance r_0 from a burst) would, possibly, not roll it over face-on. Since the jeep would be randomly oriented with respect to the direction of the incident blast wave, all we can say with certainty is that, associated with the distance r_0, the weapon yield, and the identity of the target (jeep), there is some probability (say $P_d = 0.68$) of achieving moderate damage (roll-over). This concept of the probability of achieving a given degree of damage has been found useful for the other major damage causers as well as for blast.

When the weapon CEP = 0, so that the weapon DGZ equals the AGZ (or when the AGZ is known), P_d is related to E by an error function,

$$P_d = \frac{1}{2}\left\{1 + \operatorname{erf}\left[\frac{\ln\left(E/E_{50}\right)}{\sqrt{2}\,\sigma}\right]\right\}. \tag{2}$$

The vulnerability parameters σ and E_{50} characterize the response of the target to the environment in question. For $E = E_{50}$, $P_d = 0.5$, regardless of the value of σ.

As shown in section 2, the weapon CEP concept introduces uncertainty in the value of P_d because of uncertainty in weapon location, and this concept demands a probabilistic approach: all that can be predicted in most cases is what is most likely to happen, or what will happen on the average. The result is that P_d must be expressed as a cumbersome integral that cannot be analytically evaluated. Because of this complication, several methods have been devised to perform this integral by the use of extensive sets of tables, figures, and graphs. These methods are described and discussed in appendix A.

The mathematical and graphical methods developed in this report are based on a two-step procedure for calculating damage that involves equations (1) and (2). The methods presented here are new and, today, not widely used. The reasons for this follow.

(1) Accurate, simple algorithms for E(W,r) were not previously available.

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[4] *C. E. Somers, Jr., and A. P. Vitello, BDM Corporation, Comparison of FM 101-31 and AP-550 Nuclear Target Analysis Systems (U), Defense Nuclear Agency Report 4530F (10 January 1978). (SECRET RESTRICTED DATA)*

(2) Values of E_{50} and σ for many targets are just recently available (and, until recently, no procedures at all were available for calculating P_d for EMP in the laboaratory, let alone simple ones for widespread use).

(3) The $P_d(E)$ relation has been used elsewhere[2] as a cumulative lognormal relation in distance r rather than E (there is evidence[10] that this may accurately portray the P_d relation for limited cases).

2. MATHEMATICAL FORMULATION

As discussed in section 1, this report deals only with point targets and their response to the environments generated by a nuclear burst. The probability P_d of achieving some specified level of damage induced by the burst is found in a two-step process that can be visualized by considering a target's response to a burst for which the AGZ is known (or, alternatively, that the weapon CEP is zero).

The first step in calculating P_d is to calculate the intensity of the nuclear environment that is incident upon the target. In general, the environment intensity E is determined once one knows the identity of the weapon, the location of its burst point, the location of the target, the characteristics of the intervening terrain, and the atmospheric conditions. As might be expected, the calculation of all the E's of interest can be a very complex problem and indeed may not be possible under certain conditions. If, however, one is content with reasonably accurate approximations to the E's of interest, and can sacrifice this small error as the trade-off for the simplicity of algorithms having the form

$$E = AW^D r^B e^{Cr} \tag{1}$$

the algorithms developed by Sweeney et al[8] will be of interest. For the accuracies needed by current tactical nuclear warfare analysts these approximations are acceptable. The values of A, B, C, and D for each environment are listed in table I. Notice that the parameter C can be yield dependent. In order to specify the value of E, only the distance r from the burst to the target and the weapon yield W are needed. This,

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[2] *Defense Intelligence Agency, Physical Vulnerability Handbook--Nuclear Weapons (U), AP-550-1-2-INT (June 1969). (CONFIDENTIAL)*

[8] *W. E. Sweeney, Jr., C. Moazed, and J. Wicklund, Nuclear Weapons Environments for Vulnerability Assessments to Support Tactical Nuclear Warfare Studies (U), Harry Diamond Laboratories TM-77-4 (June 1977). (CONFIDENTIAL)*

[10] *C. Stuart Kelley, Distribution of Nuclear Damage Probability with Distance, Harry Diamond Laboratories TR-1866 (August 1978).*

TABLE I. CONSTANTS FOR USE IN ENVIRONMENT ALGORITHMS, EQUATION (3): r IN km, W IN kT.

Environment (units)	AW^D	B	C (km^{-1})
Neutron fluence			
F_n (1 MeV Si equivalent, in n/cm^2)	$4.82\times10^{12}W$	-2.00	-4.44
Peak gamma-ray dose rate $\dot{\gamma}_{max}$ [rads(Si)/s]	$6.45\times10^{9}W^{0.897}$	-2.79	-3.11
Total dose D (rads)	8528W	-2.485	-3.572
Thermal fluence Q (cal/cm^2)[a]			
Poor atmospheric conditions	2.03W	-2.23	-0.309
Average atmospheric conditions	2.88W	-1.99	-0.116
Good atmospheric conditions	3.95W	-1.84	-0.0843
Peak static overpressure ΔP (psi)	$1.61W^{0.567}$	-1.70	0
Overpressure impulse I_p (psi-s)	$0.351W^{0.604}$	-0.813	0
Peak dynamic pressure q (psi), ideal	$6.33\times10^{-2}W^{1.09}$	-3.28	0
Light dust loading[b]	$3.46\times10^{-2}W^{0.747}$	-2.24	$+0.596W^{1/3}$
Dynamic pressure impulse I_q (psi-s), ideal	$9.88\times10^{-3}W^{1.146}$	-2.44	0
Light dust loading[b]	$5.78\times10^{-3}W^{0.853}$	-1.56	$+0.522W^{1/3}$
E_θ (V/m, maximum)[c]	$-1.39\times10^{4}W^{0.215}$	-1.28	0
B_ϕ (Gauss, maximum)[c]	$-0.462W^{0.215}$	-1.28	0
E_r (V/m, maximum)[c]	$1.53\times10^{3}W^{0.4}$	-2.30	0

[a] *Because the peak thermal flux,* $\dot{Q} = Q\,(0.0415W^{0.44})^{-1}$, *both* $\dot{Q}$ *and* Q *are lumped together for consideration. For both* $\dot{Q}$ *and* Q, r *is the slant range (the separation between the burst at height* $60W^{1/3}$ *and the target at ground level) and not the ground range (the horizontal separation of the ground zero and the target).*

[b] *Form of equation (1) is* $E(r) = AW^D r^B e^{C/r}$.

[c] *Appropriate to surface detonations and for distances greater than* $1.582W^{0.134}$ *from the burst.*

of course, is an approximation in and of itself, since weapons having similar yields but having different internal construction will produce differing E's. Nevertheless, equation (3) is sufficiently accurate for nuclear weapon effects analysts.

The second step in the calculation of the damage probability is simply to determine the value of P from the environment intensity E. It has been found[5,6] that P can be accurately described by a cumulative lognormal distribution in E, that is, equation (2).

$$P_d = \frac{1}{2}\left\{1 + \mathrm{erf}\left[\frac{\ln\left(E/E_{50}\right)}{\sqrt{2}\,\sigma}\right]\right\} \qquad (2)$$

where the pair of vulnerability parameters represents the response of the target to the environment intensity. They must be determined, or estimated, for every target for which values of P are needed. Equation (2) is valid for situations where either the weapon CEP is small, or when the location of the AGZ is known.

For most weapons, delivery uncertainties (e.g., cross-wind errors and fuze uncertainties) are such that the weapon CEP is not small, the location of the AGZ is not precisely known, and the actual distance between the target and the AGZ is uncertain. This means that damage cannot be calculated with certainty; all that can be calculated is what is likely to occur.

The approach taken here to calculate P when CEP $\neq 0$ is to (1) find the probability that a weapon lands in the elemental area dA, (2) multiply this by the probability of causing damage (if the weapon lands in dA), and (3) sum this product over all areas. The result is the probability P_d of achieving damage to the target.

We take the elemental probability d^2P_w that the weapon lands in a small area dA to be Gaussian (and independent of azimuth angle θ) in distance ρ from DGZ, as shown in figure 1:

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[5] *R. D. Daniels, Investigation of Calculational Aids for Estimating the Effects of Nuclear Weapons on Targets (U), Lulejian & Associates, Inc., Defense Nuclear Agency Report, DNA 411F, ADC 010837 (February 1976). (CONFIDENTIAL)*

[6] *W. L. Vault and W. E. Sweeney, Jr., Vulnerability Data Array Progress Report FY76, FY7T (U), Harry Diamond Laboratories PR-77-4 (December 1977). (SECRET)*

$$d^2P_w = (\pi k^2/\ln 2)^{-1} e^{-\rho^2 \ln 2/k^2} dA \qquad (3)$$

The CEP (k) of the weapon is the radius (about the AGZ) within which the weapon lands 50 percent of the time.

$$\frac{1}{2} \equiv \left(\pi k^2/\ln 2\right)^{-1} \int_0^{2\pi} d\theta \int_0^k \rho d\rho e^{-\rho^2 \ln 2/k^2} . \qquad (4)$$

The standard deviation of this distribution is $k(2\ln 2)^{-\frac{1}{2}} = 0.849k$. The weapon CEP is a measure of the accuracy of the weapon system: high accuracy is characterized by small k.

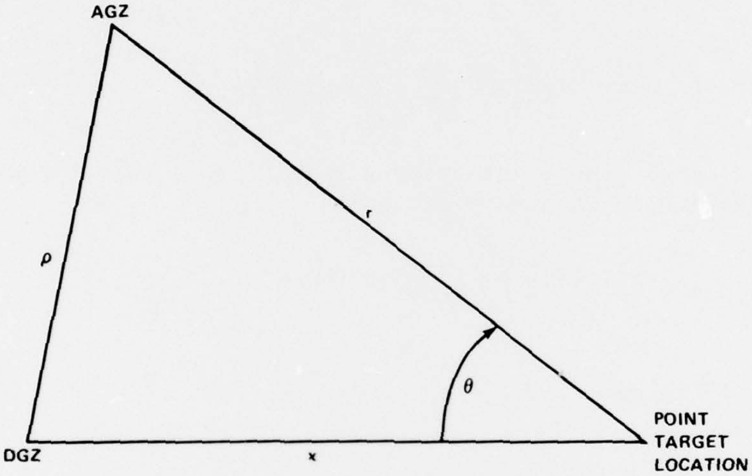

Figure 1. Relation of DGZ, AGZ, and target location needed for derivation of $P_d(r)$.

The azimuthal symmetry of d^2P_w in equation (3) does not accurately represent all weapon systems; for some weapons the distributions in range and cross-range differ, thereby requiring different values of k and a more complex form of equation (3). We do not introduce this complexity here.

The law of cosines, appropriate to figure 1, gives

$$\rho^2 = r^2 + x^2 - 2xr \cos\theta \qquad (5)$$

and will shortly be combined with equation (3) to eliminate the variable ρ.

The elemental probability d^2P_d that the weapon lands in the small area dA and damages the target is given by the product

$$d^2P_d = P\left(d^2P_w\right) \tag{6}$$

where P is given by equation (2). We now introduce the environmental intensity algorithm, equation (1), into equation (2), and insert the result into equation (6) together with equations (3) and (5). The result is then integrated over all differential areas dA to obtain the probability P_d of achieving a specified level of damage to the point target located a distance x from the DGZ.

$$P_d = \left(2\pi k^2/\ell n2\right)^{-1} \int_0^{2\pi} d\theta \int_0^{\infty} dr \; r \; \exp\left[-\frac{\ell n2}{k^2}\left(r^2 + x^2 - 2xr\cos\theta\right)\right]$$

$$\times \left\{1 + \operatorname{erf}\left[\frac{1}{\sqrt{2}\,\sigma}\,\ell n\left(AW^D\, r^B\, e^{Cr}/E_{50}\right)\right]\right\}. \tag{7}$$

When carried out, the θ integration results in a Bessel function J_0 of zero order having an imaginary argument:

$$P_d = \left(k^2/\ell n2\right)^{-1} e^{-x^2 \ell n2/k^2} \int_0^{\infty} dr \; re^{-r^2 \ell n2/k^2}$$

$$\times J_0\left(2ixr\ell n2/k^2\right)\left\{1 + \operatorname{erf}\left[\frac{1}{\sqrt{2}\,\sigma}\,\ell n\left(AW^D\, r^B\, e^{Cr}/E_{50}\right)\right]\right\} \tag{8}$$

Of the two terms in the brace, the first can be integrated to give simply 1/2, but does not materially simplify the equation. Either way, equation (10) is in the form of a Hankel transform,

$$f_v^*(u) \equiv \int_0^{\infty} f(t)\, J_v(ut)\, t\, dt \quad , \tag{9}$$

which is similar to a multiple Fourier transform, and for which there are only a few closed-form solutions. Unfortunately, the present expression, equation (8), is not among them. Accordingly, machine calculations must be used that rely on algorithms to approximate the components of the integrand of equation (8).[11] Series expansions for the troublesome components are available:

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[11] *Handbook of Mathematical Functions with Formulas, Graphs, and Mathematical Tables, M. Abramowitz and I. A. Stegun, ed., National Bureau of Standards, Applied Mathematics Series 55 (December 1972).*

$$J_0(z) = \sum_{k=0}^{\infty} \left(-z^2/4\right)^k (k!)^{-2} \tag{10}$$

$$\mathrm{erf}(z) = \frac{2}{\sqrt{\pi}} \sum_{n=0}^{\infty} (-1)^n z^{2n+1} \Big/ n!(2n+1) \tag{11}$$

as are other, simpler forms.[11]

For zero weapon CEP, equation (8) reduces to equation (2). For a zero offset distance (when the DGZ is the target location), equation (8) takes the form

$$P_d(x = 0) = \left(k^2/\ell n2\right)^{-1} \int_0^{\infty} dr\, r\, e^{-r^2 \ell n2/k^2} \times \left\{1 + \mathrm{erf}\left[\frac{1}{\sqrt{2}\,\sigma}\, \ell n \left(\frac{AW^D\, r^B\, e^{Cr}}{E_{50}}\right)\right]\right\} \tag{12}$$

Equation (8) gives the value of P_d once r, W, CEP, and the vulnerability parameters are specified. The equation cannot be integrated in closed form, nor are there appropriate approximations that render it more tractable. Hand calculations of P_d using equation (8) are tedious--machine calculations are required. The intent of this report is to present graphical methods for calculating P_d that are far faster than the hand calculations, and even quicker than the machine calculations. These graphical methods are developed in sections 3 and 4 and presented in appendix B and the classified supplement to this report.

We note in passing that, using the AP-550 methodology, one arrives at the result

$$P_d(\text{AP-550}) = \frac{1}{2}\left\{1 + \mathrm{erf}\left[\beta^{-1}\, \ell n \left(\frac{WR\, e^{-\beta^2}}{r}\right)\right]\right\} \tag{13}$$

for CEP = 0, which is analagous to equation (2). The differences between equations (2) and (13) are the appearance of the weapon radius WR and the vulnerability number β; furthermore, equation (13) is lognor-

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[11] *Handbook of Mathematical Functions with Formulas, Graphs, and Mathematical Tables, M. Abramowitz and I. A. Stegun, ed. National Bureau of Standards, Applied Mathematics Series 55 (December 1972).*

mal in r, not E. The AP-550 equation corresponding to equation (8) for nonzero CEP may be found elsewhere.[12]

3. CREATION OF THE NOMOGRAMS

The general expression for P_d, equation (8), is sufficiently complex that machine calculations are required for its determination. Previously, attempts were made to simplify the calculations. These attempts have dealt with special situations for which the calculation simplifies and for which approximations can be made that provide reasonable accuracy.[10,*,†]

Before the research which resulted in this report, the analyst had to resort to either the generic inaccuracies of FM 101-31, the inappropriate governing effect of AP-550, the tediousness of the machine calculations based on the results of section 2, or the limited applicability of approximations to the exact results of equation (8). As shown in this and in the next section, it is not necessary to accept these limitations and drawbacks for, in these sections, we develop nomograms and a slide rule that greatly simplify calculating P_d using the exact relations of section 2.

3.1 Creation of Zero-CEP Nomograms

The zero-CEP nomograms all use the simple algorithms that relate the environment intensity to weapon yield and burst-to-target separation distance, as in equation (1), repeated here,

$$E = AW^D r^B e^{Cr} \quad . \tag{1}$$

and equation (2), which relates E to P_d;

$$P_d = \frac{1}{2}\left\{1 + \text{erf}\left[\frac{\ln\left(E/E_{50}\right)}{\sqrt{2}\,\sigma}\right]\right\} \tag{2}$$

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[10] *C. Stuart Kelley, Distribution of Nuclear Damage Probability with Distance, Harry Diamond Laboratories TR-1866 (August 1978).*

[12] *Mathematical Background and Programming Aids for the Physical Vulnerability System for Nuclear Weapons, Defense Intelligence Agency 550-27-74 (1 November 1974).*

[*] *Nuclear Damage Calculations: Effects of Data Uncertainties, C. Stuart Kelley, Harry Diamond Laboratories Branch Memorandum, 9 December 1977.*

[†] *Mathematical Aids for the Calculation of Nuclear Damage to Extended Targets Composed of Discrete Points, C. Stuart Kelley, Harry Diamond Laboratories Branch Memorandum, 7 December 1977.*

Creation of the nomograms proceeds in two steps: first, obtain E from r and W; second, obtain P_d from E, σ, and E_{50}. Taking the natural logarithm of both sides of equation (1)

$$\ell n\, E = [\ell n\, A + D\, \ell n\, W] + [B\, \ell n\, r + Cr] \tag{14}$$

Three scales are needed for the nomograms: the first is linear in the quantity $\ell n\, A + D\, \ell n\, W$, the second is linear in $B\, \ell n\, r + Cr$, and the third is linear in $\ell n\, E$. Nomograms, like slide rules (see sect. 4), merely serve to add two quantities to get a third. Here the two quantities are the two square-bracketed expressions in equation (14). This observation means that the first step in calculating P_d by nomograms is feasible (namely that of determining E from r and W).

The second step in calculating P_d by nomogram is to create a nomogram that relates P_d to E, σ, and E_{50}. First, notice that, once the square-bracketed expression

$$\left[\frac{\ell n\left(E/E_{50}\right)}{\sqrt{2}\,\sigma}\right] \tag{15}$$

in equation (2) is known (or found on a nomogram), the value of P_d is automatically determined on a one-for-one basis. Thus, all that is needed is a nomogram to get from E and E_{50} to $\ell n\left(E/E_{50}\right)$ and then from $\ell n\left(E/E_{50}\right)$ and $\sqrt{2}\,\sigma$ to equation (15). Division of two quantities by nomogram is a straightforward process and can be done with ease. Note that when $E = E_{50}$, $P_d = 0.5$, regardless of what value σ assumes, and requires that the $\sqrt{2}\,\sigma$ scale be placed on the line that joins the value $E = E_{50}$ on the $\ell n\left(E/E_{50}\right)$ scale and the value 0.5 on the P_d scale. Setting out the P_d scale on the cumulative log basis requires a $\sqrt{2}\,\sigma$ scale that is, essentially, $1/\sqrt{2}\,\sigma$.

Appendix B and the classified supplement to this report present the nomograms we developed for F_n, D, ΔP, E_θ, $\dot{\gamma}_{max}$, Q, q, I_p, I_q, and ΔPI_q. The operating procedure is illustrated there using the ΔP nomogram as an example. These nomograms are accurate to within 1 percent.

Interestingly, one can use the same procedure as that above to obtain nomograms that are appropriate to the AP-550 methodology that uses the relation

$$P = \frac{1}{2}\left\{1 + \text{erf}\left[\frac{1}{\beta}\,\ell n\left(\frac{WR\, e^{-\beta^2}}{r}\right)\right]\right\} \tag{16}$$

Three lines are to be drawn upon the resulting nomogram, the same number as for the nomograms based upon equation (2).

3.2 Creation of Nonzero-CEP Nomograms

Creation of the nonzero-CEP nomograms differs somewhat from the method described in section 3.1 for the zero-CEP nomograms. The introduction of CEP greatly complicates the mathematics of the P_d relation by the introduction of an integral (see eq (11), for example). Nevertheless, it was found to be possible to create simple nomograms representing the P_d relationships for ΔP, F_n, D, and E_θ. The nomograms we obtained for these environments are displayed in appendix B and in the classified supplement to this report. Vulnerability parameters have been obtained only for airblast, TREE, EMP, and total dose to personnel. These environments also obey algorithms that have the same mathematical form as all the remaining environments (for which nonzero CEP nomograms have not been obtained), except for the algorithm ΔPI_q - k which has been found to be appropriate to vehicle response to blast. Thus, with the exception of ΔPI_q - K, the ability to construct nonzero-CEP nomograms for ΔP, D, F_n, and E_θ indicates that such nomograms for all the remaining environments can be constructed.

The technique used to obtain the ΔP nomogram does not differ appreciably from that used to obtain the other three nomograms. Accordingly, the ΔP nomogram illustrates the technique applied to these nomograms.

In constructing the ΔP nomogram, the analyst is confronted with the task of geometrically representing a function of five variables: $P_d(r,W,\Delta P_{50},\sigma,CEP)$. Because W and ΔP_{50} are related to r_{50} by equation (1),

$$\Delta P_{50} = 1.61\ W^{0.567}\ r_{50}^{-1.70} \tag{17}$$

two of the variables $\left(W \text{ and } \Delta P_{50}\right)$ can be replaced by a single variable $\left(r_{50}\right)$. Also, the distances r_{50} and CEP can be normalized by r to remove another variable (r). Then P_d is a function of just three independent variables: r/r_{50}, σ, and r/CEP. Two supplementary nomograms are provided for calculating r/r_{50} and r/CEP, but the crux of the ΔP nomogram is the representation of the $P_d\left(r/r_{50},\sigma,r/CEP\right)$ relationship.

The procedure used to display this relationship is best introduced by explaining how to construct a zero-CEP nomogram. This procedure is different from that in section 3.1. The first step is to display two scales: r/r_{50} on a log scale to the left, and P_d on a probabilistic scale to the right. The second step is to locate the σ scale that lies between these two on the nomogram. To do this, plot P_d versus r/r_{50} on a separate figure for a chosen value of σ, using lognormal paper. The result is a straight line whose slope is related to σ. This straight line on the lognormal plot corresponds to a single point (the pivot point) on the nomogram. If one picks two $(r/r_{50}, P_d)$ pairs from the straight line and draws two lines between the two corresponding r/r_{50} and P_d values on the nomogram, the lines intersect to define the location of the point, which is then labeled by the appropriate σ value. Thus, there is a dual relationship between points (lines) on the P_d versus r/r_{50} curve and lines (points) on the nomogram. By making other P_d versus r/r_{50} plots for different values of σ, and again using pairs of $(P_d, r/r_{50})$ values to obtain intersections on the nomogram, one constructs the entire σ scale.

The above procedure is also followed for the nonzero-CEP case. Now, however, the P_d versus r/r_{50} plot is parametrized not by just the value of σ (as was the case for the zero-CEP nomogram), but by the values of both σ and r/CEP. The analyst proceeds to construct, point by point, a mesh between the r/r_{50} and P_d scales. A mesh occurs because the values of two parameters (σ and r/CEP) are needed to locate the single point through which the analyst connects r/r_{50} and P_d.

4. TACTICAL NUCLEAR SLIDE RULE (TNSR)

This section considers the format of a slide rule as an alternative to the tables, graphs, and charts of AP-550 and FM 101-31, and to the nomograms of appendix B and the classified supplement to this report. As are the nomograms, the slide rule is oriented to tactical situations and to heights of burst of $60W^{1/3}$ meters, with W in kT. The TNSR described below was developed for cases where the weapon CEP is small or zero. Alternatively, it is appropriate when the AGZ of the weapon burst is known.

The format is geared to the E(r) algorithms--equation (3) and the P_d algorithm, equation (2)--appropriate to small CEP:

$$E(r) = AW^D\, r^B\, e^{Cr} \tag{1}$$

$$P_d = \frac{1}{2}\left\{1 + \operatorname{erf}\left[\frac{\ln\left(E/E_{50}\right)}{\sqrt{2}\,\sigma}\right]\right\} \tag{2}$$

There are basically three steps to the calculation of P_d, and these three steps are followed, in sequence, in the creation of TNSR. The first step is the creation of an "E" slide rule, that permits calculation of all the important environments from the weapon yield and AGZ-to-target separation distance. Taking the logarithm of both sides of equation (1) forms the basis for the E slide rule.

$$\ell nE = [\ell nA + D\ell nW] + [B\ell nr + Cr] \tag{18}$$

Thus, three scales were made up: the first is linear in ℓnE, the second is linear in the quantity in the first square brackets, and the third is linear in the quantity in the second square brackets. Adding linearly the values of the two square brackets gives the value of ℓnE or, correspondingly, the value of E. Unfortunately, the value of the ratio A/D is not common to all environments; nor is the ratio B/C. For this reason all the E scales of the slide rule can have at most one common scale (we choose the W scale), and all the r scales differ (as do the E scales). It is unfortunate that this is so, for if it were otherwise, the TNSR could be simplified to have a single W scale and a single r scale, and the analyst could read off at a single glance the values of all the environments. We have, however, aligned all the r scales at r = 1 km so that for this distance one can read off all environments at a single glance. This E slide rule is basically the front of the TNSR. The back is devoted to the P_d calculation.

The second step in the calculation of P_d is simply to calculate E/E_{50}. C and D scales are provided on the front of the TNSR for this purpose. The ratio E/E_{50} is calculated as one would normally use an ordinary slide rule.

The third and final step in calculating P_d is to use the values of E/E_{50} and σ to obtain the value of P_d. This is done by using log-log scales. Defining

$$Q \equiv \frac{1}{\sqrt{2}\,\sigma}\,\ell n\left(E/E_{50}\right) \tag{19}$$

and taking the log of both sides of the equation

$$\ell nQ = \ell n\left[\ell n\left(E/E_{50}\right)\right] + \left[-\ell n\sigma - \frac{1}{2}\,\ell n2\right] \tag{20}$$

three scales are devised. The first is linear in $\ell n\left[\ell n\left(E/E_{50}\right)\right]$, the second is linear in $-\ell n\sigma - (1/2)\ell n2$, and the third is linear in ℓnQ. Thus, adding the values of the first two scales gives the value of ℓnQ or, indirectly, the value of Q. Corresponding to the value of Q is a value of P_d.

The slide rule is depicted and described in appendix B (sect. B-2) along with operating instructions. It can be used to calculate the major damage-causing environments as well as the P_d resulting from these environments.

5. DISCUSSION

The TNSR permits the calculation of the environments to within a fractional error of 1 percent of the "exact" algorithms,[8] upon which the TNSR is based. The CEP = 0 nomograms give environments that are equal to the algorithms[8] to within the interpolation uncertainties on the nomograms. The TNSR is more accurate than the nomograms.

The EM-1 methodology was used in creating the Nuclear Bomb Effects Calculator (NBEC), so a comparison of the TNSR (equal to the algorithms of Sweeney et al[8]) to the NBEC is equivalent to a comparison of the TNSR to EM-1. The NBEC basically calculates only environments. The NBEC thermal results are virtually the same as the TNSR thermal results. The NBEC, however, gives values of ΔP and q that are consistently higher than those obtained by using the TNSR; the NBEC can give up to 50 percent higher results in some cases. The NBEC gives values of D that are typically 15 percent smaller than the TNSR values.

In treating damage to materiel, the AP-550 and FM 101-31 methodologies can address only the damage that results from airblast. Unlike the TNSR, they cannot handle damage resulting from such environments as TREE and EMP. The differences between the methods have been extensively discussed elsewhere,[4-6] and are only mentioned here by an example that points out the differences that occur: What is the probability of overturning a 2-1/2-ton truck (without shelter) that is 0.75 km from the detonation of a hypothetical howitzer-delivered 10-kT weapon (very small CEP) that has a trajectory of 2.2 km? The results are summarized below.

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[4] *C. E. Somers, Jr., and A. P. Vitello, BDM Corporation, Comparison of FM 101-31 and AP-550 Nuclear Target Analysis Systems (U), Defense Nuclear Agency Report 4530F (10 January 1978). (SECRET RESTRICTED DATA)*

[5] *R. D. Daniels, Investigation of Calculational Aids for Estimating the Effects of Nuclear Weapons on Targets (U), Lulejian & Associates, Inc., Defense Nuclear Agency Report, DNA 411F, ADC 010837 (February 1976). (CONFIDENTIAL)*

[6] *W. L. Vault and W. E. Sweeney, Jr., Vulnerability Data Array Progress Report FY76, FY7T (U), Harry Diamond Laboratories PR-77-4 (December 1977). (SECRET)*

[8] *W. E. Sweeney, Jr., C. Moazed, and J. Wicklund, Nuclear Weapons Environments for Vulnerability Assessments to Support Tactical Nuclear Warfare Studies (U), Harry Diamond Laboratories TM-77-4 (June 1977). (CONFIDENTIAL)*

Method	P_d
TNSR	0.37
FM 101-31	0.22
AP-55-	0.13

Because the nonzero-CEP airblast nomogram has not yet been developed (indeed, there are indications that it cannot be comprehensively constructed), we cannot compare nonzero-CEP P_d calculations with those of AP-550 and FM 101-31.

6. CONCLUSIONS

Of the various methods available for computing damage to point targets, the Harry Diamond Laboratories (HDL) lognormal-in-environment has the greatest potential for meaningful application for two reasons: (1) it deals with current, specific equipment items rather than archaic items or generic types, and (2) the identity of the environment that caused the damage is accessible, thus facilitating hardening or exploitation. There are two drawbacks to the HDL method. The first is the currently limited data base (but this may be greatly expanded for airblast effects by the recently determined correlation[10] that relates the HDL data base to that of AP-550). The second is that the calculations must be done by computer--there are no charts, graphs, or tables to facilitate analysis. The purpose of this study was to eliminate the second drawback by investigating the possibility of creating graphical aids for the analyst.

We created nomograms that make the calculation of P_d much quicker and easier for all nuclear environments of interest to the analyst for cases where the weapon CEP is small or where the AGZ of the detonation is known. Where the weapon CEP is not zero, we have created P_d nomograms for all environments for which vulnerability data now exist. These environments are neutron fluence, total dose to personnel, static overpressure, and electric field strength (for EMP). Also, we created the Tactical Nuclear Slide Rule (patent applied for) that greatly speeds the calculation of all damage-causing nuclear environments and their P_d when the weapon CEP is small. The nomograms and slide rule are accurate to within 3 percent of the algorithms upon which they are based.

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[10] *C. Stuart Kelley, Distribution of Nuclear Damage Probability with Distance, Harry Diamond Laboratories TR-1866 (August 1978).*

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(3) Defense Nuclear Agency, Capabilities of Nuclear Weapons (U), DNA-EM-1, parts I and II (1 July 1972). (SECRET)

(4) C. E. Somers, Jr., and A. P. Vitello, BDM Corporation, Comparison of FM 101-31 and AP-550 Nuclear Target Analysis Systems (U), Defense Nuclear Agency Report 4530F (10 January 1978). (SECRET RESTRICTED DATA)

(5) R. D. Daniels, Investigation of Calculational Aids for Estimating the Effects of Nuclear Weapons on Targets (U), Lulejian & Associates, Inc., Defense Nuclear Agency Report, DNA 411F, ADC 010837 (February 1976). (CONFIDENTIAL)

(6) W. L. Vault and W. E. Sweeney, Jr., Vulnerability Data Array Progress Report FY76, FY7T (U), Harry Diamond Laboratories PR-77-4 (December 1977). (SECRET)

(7) C. Stuart Kelley, Survey of Codes Employing Nuclear Damage Assessment, Harry Diamond Laboratories SR-77-4 (October 1977).

(8) W. E. Sweeney, Jr., C. Moazed, and J. Wicklund, Nuclear Weapons Environments for Vulnerability Assessments to Support Tactical Nuclear Warfare Studies (U), Harry Diamond Laboratories TM-77-4 (June 1977). (CONFIDENTIAL)

(9) C. Stuart Kelley, Stacey E. Gehman, John H. Wasilik, and William D. Scharf, Supplement to Nuclear Damage to Point Targets (U), Harry Diamond Laboratories TR-1876-S (November 1978). (SECRET)

(10) C. Stuart Kelley, Distribution of Nuclear Damage Probability with Distance, Harry Diamond Laboratories TR-1866 (August 1978).

(11) Handbook of Mathematical Functions with Formulas, Graphs, and Mathematical Tables, M. Abramowitz and I. A. Stegun, ed., National Bureau of Standards, Applied Mathematics Series 55, (December 1972).

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APPENDIX A.--CURRENT METHODS FOR CALCULATING DAMAGE

APPENDIX A

CONTENTS

APPENDIX A

In this appendix we present the methods that are currently available to the analyst for calculating damage to point targets.

A-1. AP-550 METHODOLOGY

To calculate the probability of achieving a specified level of damage using the AP-550 methodology,[1] the analyst needs to resort to a number of parametric curves that involve the weapon radius (WR) that forms a circle about the ground zero. This circle will contain as many targets undamaged to a specific level inside as there are targets damaged to a specified level outside: a concept similar to the weapon CEP (circular error probable). Accordingly, the weapon radius involves the vulnerability parameters of the target. We now illustrate the calculation of P for a hypothetical situation using the AP-550 methodology in a sequence of steps.

- Sort through tables a1 through a15 in AP-550 to find the vulnerabilty number (VN) that characterizes the point target of interest. Let us say we find that the vulnerability number 18P2 is appropriate.

- Resort to Figure b to adjust the VN for weapon yield. This involves the last digit of the VN number (called K) and the weapon yield. The adjustment value (say we find 0.5) is subtracted from the first two digits of the VN to get the adjusted VN number (17.5P2).

- Use Figure c to determine the scaled height of burst of the weapon from the yield and its height of burst.

- Find the scaled weapon radius from Figure d using the scaled HOB and the adjusted VN number.

- Determine the WR from figure c (as was used in step 3) from the weapon yield and the scaled WR.

- Calculate the ratio d/CEP that involves the DGZ-to-target (designated ground zero) distance d, and the ratio WR/CEP.

- Find the sigma number from the VN: a sigma of 20 is used for P targets (as is the case here); a sigma of 30 is used for Q targets. In the eighth step, the analyst chooses the P versus d/CEP curve parametrized by WR/CEP values that is appropriate to the sigma number (there are five such parametric curves), and reads off the value of P.

Appendix D is devoted to a method for simplifying this procedure that was developed in the course of the present study.

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[1] *Defense Intelligence Agency, Physical Vulnerability Handbook--Nuclear Weapons (U), AP-550-1-2-INT (June 1969). (CONFIDENTIAL)*

A-2. FM 101 METHODOLOGY

The basic procedure for calculating the damage to point targets using the Army's FM 101 technique[2] is similar in format to that used in the AP-550 methodology. The fundamental concept is that of the radius of damage, RD. The RD depends on the type of target, the delivery system and yield, the HOB (surface or air), and DGZ-to-target range. The RD is a distance at which a target element has a 50-50 chance of being damaged to the desired degree and, as such, includes the vulnerability parameters of the target. Rather than using the weapon CEP, the analyst uses the CD90 value. The CD90 value represents the radius of a circle within which 90 percent of the rounds will fall. The CD90 value is related to the CEP by CD90 = 1.83 CEP. We now illustrate the FM 101 calculational procedure by a hypothetical example in a sequence of steps.

- Locate the appropriate coverage table. To do this, one first identifies in FM 101 the correct chapter of the coverage tables by specifying the weapon system and type of burst (air or surface). Within this chapter, the analyst locates the correct coverage tables by specifying the identity of the table.

- Find the values of RD and CD90 from the coverage table by specifying the value of the firing range of the system.

- Compute the values of the ratios RD/CD90 and d/CD90.

- Obtain the value of P_d by interpolating between the curves, parametric in P_d, that appear on the RD/CD90 versus d/CD90, graph a. This can only be done if the value of the ratio RD/CD90 is less than 5 and if the value of the ratio d/CD90 is less than 2.2.

If these ratios are not within the above bounds, further steps are needed. These steps are (1) calculating the ratio d/RD and (2) entering the extension graph b with the value of d/RD, and reading off the value of P_d.

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[2] *Department of the Army Staff Officers' Field Manual, Nuclear Weapon Employment Doctrine and Procedures, FM 101-31-1 (March 1977).*

A-3. EM-1 METHODOLOGY

The Defense Nuclear Agency (DNA) manual,[3] known as EM-1, also permits the calculation of damage to point targets for each of several environments. The manual formed the basis for the Army Manual FM 101-31.[2] The format is, however, very academic, quite thorough, and for the most part is at the component level. Two examples are ignition thresholds for black α-celluous exposed to a simulated weapon pulse and semiconductor bond lift-off modes. The manual forms an excellent data base. Personnel casualties are considered in great detail. In the causes of casualties, one finds under the heading of blast such topics as debris and casualties in structures. In other sections of EM-1, part II, one can find cookie-cutter methods ($P_d = 0.5$), such as a plot of the scaled HOB ($HOB/W^{1/3}$) on which there are many parametric contours in various weapon yields.

The closest approach one finds to the types of calculations of interest here is typified by the following series of steps that results in the specification of the range in ground distances from a burst for which a given target responds in a specified fashion.

- Specify the damage category of interest. The analyst now performs three steps using the data in part II.
- Use Table a to find the environment that governs the response of the item. This is found by entering the table with the identity of the target which is to be damaged.
- Go from this governing environment to its Table b that specifies such parameters as equivalent overpressure and equivalent dynamic pressure for a 1-kT explosion.
- Find the equivalent HOB by scaling the weapon HOB by its yield.
- Go to either Figure a or b (found in part I of EM-1) to determine the distance at which the equivalent overpressure (say it is the dominant environment) found by step three occurs. This step requires careful interpolation in the figure.
- Take this "1-kT" equivalent distance and scale it by yield, as appropriate, to the actual distance at which the specified damage occurs.

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[2] *Department of the Army Staff Officers' Field Manual, Nuclear Weapon Employment Doctrine and Procedures, FM 101-31-1 (March 1977).*

[3] *Defense Nuclear Agency, Capabilities of Nuclear Weapons (U), DNA-EM-1, parts I and II (1 July 1972). (SECRET)*

Notice that this does not result in a value of P_d. There are isolated examples in EM-1 where values of P_d can be found: one example is a graph for a supply dump that allows one to calculate distances corresponding only to $P_d = 0.1, 0.5,$ and 0.9.

A-4. THE NUCLEAR BOMB EFFECTS CALCULATOR

This circular slide rule may be found as an enclosure in The Effects of Nuclear Weapons, edited by Glasstone and Dolan,[4] and it is based on data presented in that book. The slide rule can be used to calculate a wide variety of environments for zero weapon CEP. It does not address the question of damage.

By setting the weapon yield and the burst-to-target separation distance r, the analyst can determine the maximum overpressure, the maximum dynamic pressure, and the maximum wind velocity. By setting an additional marker to the yield, the analyst can find the arrival time of the blast wave and the duration of the positive-pressure phase of the blast wave. The calculator gives a one-to-one correspondence between the incident overpressure and the overpressure reflected from a wall that is perpendicular to the blast wave.

Thermal radiation can be found by setting values of W and r, aligning another tab, and flipping the slide rule over to find Q (cal/cm^2). Interpolation is quite difficult between the curves shown. By specifying the weapon yield, the analyst can immediately find the values of Q that produce first- and second-degree burns. It is also possible to find the rate of delivery of thermal radiation (for example, 50 percent in 0.7 s) by simply specifying the weapon yield.

The total initial nuclear radiation dose (neutrons plus gammas) is found in a way that is similar to the determination of Q. The interpolation required here is also difficult.

In addition to the above nuclear environments, the slide rule also permits calculation of translational velocities for man and window glass fragments, early fallout dose rate, crater dimensions, maximum fireball radius, and the HOB for neglible early fallout.

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[4] *The Effects of Nuclear Weapons, compiled and edited by Samuel Glasstone and Philip J. Dolan, prepared and published by U.S. Department of Defense and U.S. Department of Energy (1977), (3rd ed.).*

A-5. NOMOGRAM METHODS*

To determine the probability of damage using the nomograms, a total of four straight lines must be drawn on three nomograms.

- Identify the environment of interest and find from the vulnerability array the values of σ and E_{50} appropriate to the target.
- Draw a straight line on nomogram a between the E_{50} and W values to obtain the value of r_{50}.
- Calculate r/CEP, using nomogram b, if desired.
- Go to nomogram c and enter r_{50} and r; draw a straight line to an intermediate scale.
- Continue on nomogram c by drawing a straight line from the point on the intermediate scale through the grid (entered with the values of r/CEP and σ found earlier) to the value of P_d.

A-6. TACTICAL NUCLEAR SLIDE RULE (TNSR)

The TNSR can be used only for cases where the weapon CEP is small or when the actual ground zero (AGZ) of the detonation is known.

- Adjust the cursor to the range of interest on the environment scale of interest.
- Align the value of the weapon yield using the cursor.
- Read the environment intensity.
- Calculate E/E_{50} using the scales provided.
- Align the cursor with this ratio on the appropriate scale on the rear of the TNSR.
- Align the hash mark on the σ scale with the cursor.
- Align the cursor with the desired value of σ.
- Read, on the appropriate scale, the value of P_d that aligns with the cursor.

**Found in appendix B, section B-2 of this report.*

APPENDIX A

A-7. DISCUSSION OF METHODS

As may be seen from sections A-1 through A-6, the various methods are cumbersome and differ in their procedures for calculating P_d. What is not as obvious is that the answers differ.[5-7] This difference between the AP-550 and FM 101-31 methodologies sparked a recent investigation into quantifying these differences, and will, hopefully, act as a catalyst for developing common methodology. We briefly consider, in section 5, body of report, an example that illustrates these differences, more to point out that they occur, than to identify the physical reasons for their occurrence. The basic differences in methodologies are set forth in appendix A, sections A-1 through A-6, where their drawbacks are also listed. Daniels[5] has recently compared the calculation procedures and results of the AP-550 methodology with that of EM-1. In brief, he finds that AP-550 is not adequate for estimating collateral damage, that AP-550 is sometimes inconsistent with data, and that the AP-550 constant "Sigma," appears to depend upon weapon yield and upon the damage criterion.

The nomograms and the slide rule developed in this study provide simpler, yet more accurate methods for calculating P_d than do the existing methods. The advantage of these nomograms and slide rule is an increased speed of calculation, as applied to the necessity for hardening U.S. and North Atlantic Treaty Organization equipment presently in the design phase. Similarly, the nomograms and slide rule speed the analyst's recognition of areas to exploit in enemy equipment. Interestingly, under the direction of the Technical Director at DNA, work is progressing toward development of a hand-held calculator that will be able to perform many of the FM 101-31 damage calculations.

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[5] *R. D. Daniels, Investigation of Calculational Aids for Estimating the Effects of Nuclear Weapons on Targets (U), Lulejian & Associates, Inc., Defense Nuclear Agency Report, DNA 411F, ADC 010837 (February 1976). (CONFIDENTIAL)*

[6] *W. L. Vault and W. E. Sweeney, Jr., Vulnerability Data Array Progress Report FY76, FY7T (U), Harry Diamond Laboratories PR-77-4 (December 1977). (SECRET)*

[7] *C. E. Somers, Jr., and A. P. Vitello, BDM Corporation, Comparison of FM 101-31 and AP-550 Nuclear Target Analysis Systems (U), Defense Nuclear Agency Report 4530F (10 January 1978). (SECRET RESTRICTED DATA)*

APPENDIX A

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APPENDIX B.--OPERATING INSTRUCTIONS FOR NOMOGRAMS AND TACTICAL NUCLEAR SLIDE RULE

APPENDIX B

CONTENTS

Figures

B-1. ZERO-CEP NOMOGRAMS

Using the methodology of section 3, body of report, nomograms were constructed for calculating P_d when the weapon circular error probable (CEP) is zero. These nomograms are accurate and simple to use. The limitations of the ranges of the variables indicated on the nomograms bound the cases of interest to the tactical nuclear analyst and also are consistent with the bounds on the data from which they were derived. Nomograms are presented for the following environments in figures B-1 through B-8 and in the classified supplement to the main report.[1]

F_n	Figure B-1	Q	Figure B-4
D	Figure B-2	q	Figure B-5
ΔP	Figure B-3	I_p	Figure B-6
E_θ	See classified supplement	I_q	Figure B-7
$\dot{\gamma}_{max}$	See classified supplement	ΔPI_q	Figure B-8

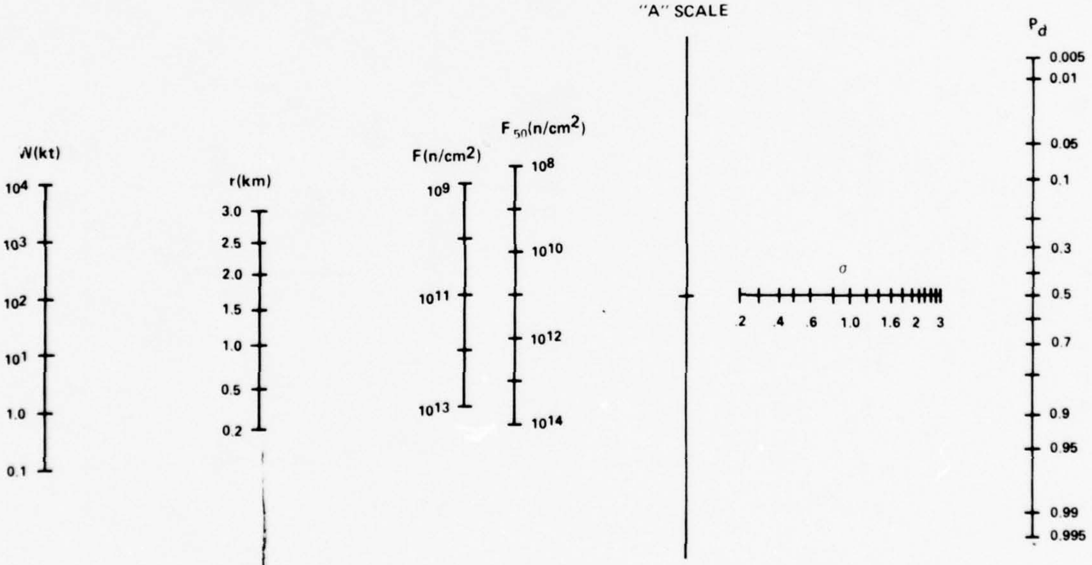

Figure B-1. Zero-CEP nomogram for neutron fluence (F_n).

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[1] *C. Stuart Kelley, Stacey E. Gehman, John H. Wasilik, and William D. Scharf, Supplement to Nuclear Damage to Point Targets (U), Harry Diamond Laboratories TR-1876-S (November 1978). (SECRET)*

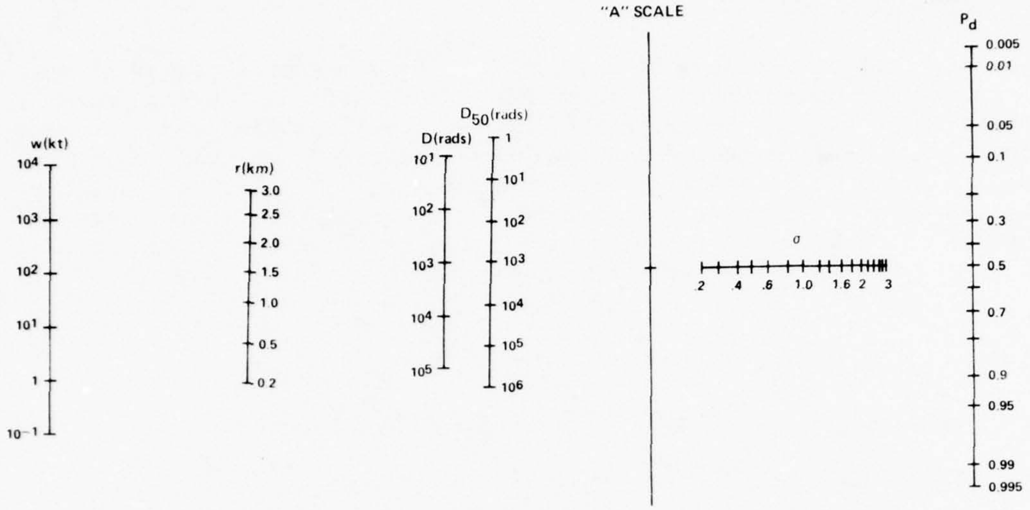


Figure B-2. Zero-CEP nomogram for total dose (D).

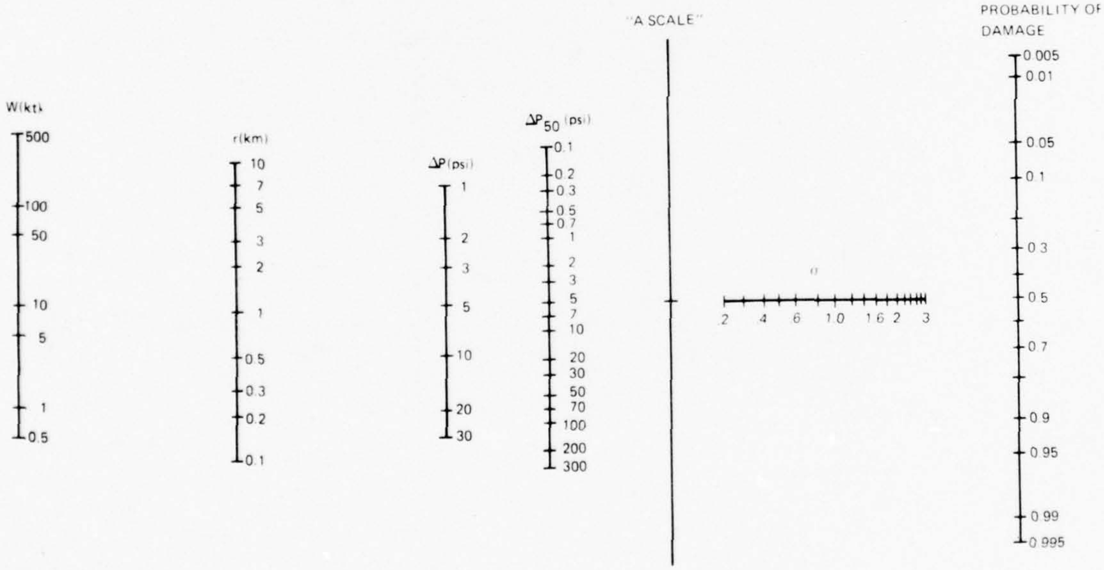


Figure B-3. Zero-CEP nomogram for static overpressure (ΔP).

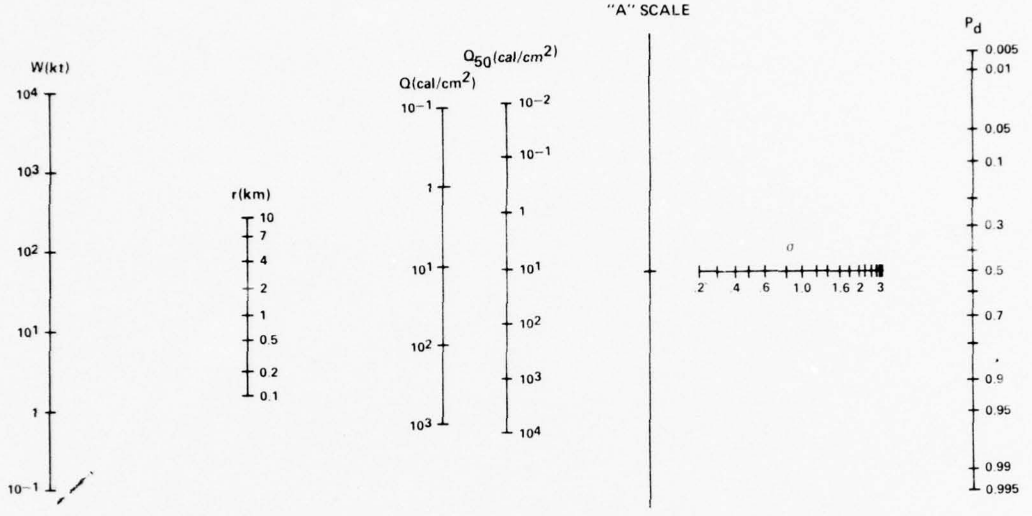


Figure B-4. Zero-CEP nomogram for thermal fluence (Q).

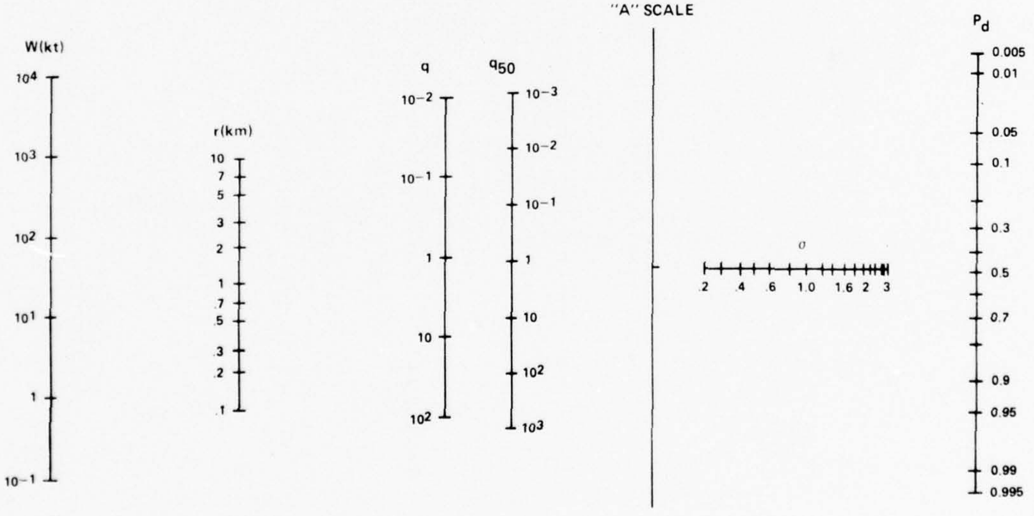


Figure B-5. Zero-CEP nomogram for dynamic pressure (q).

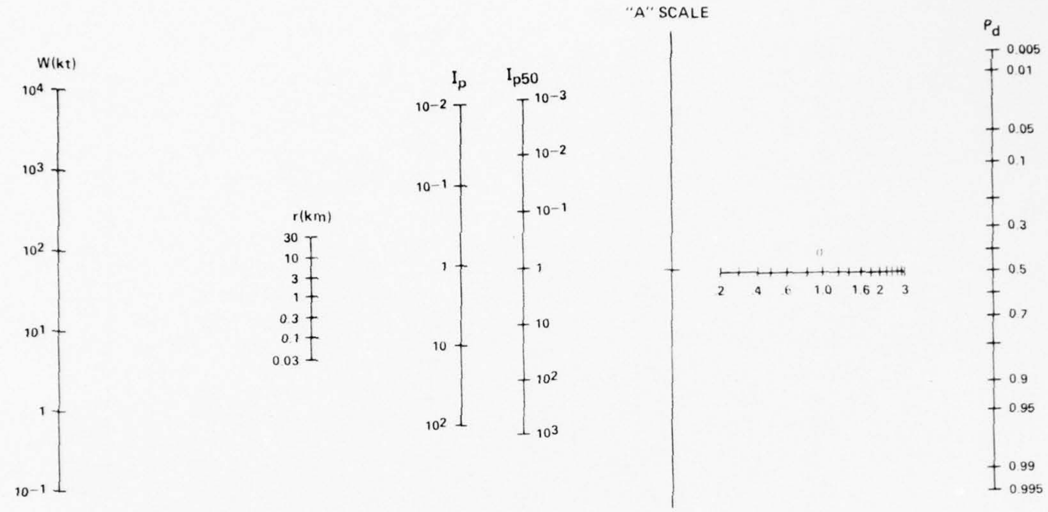


Figure B-6. Zero-CEP nomogram for static overpressure impulse (I_p).

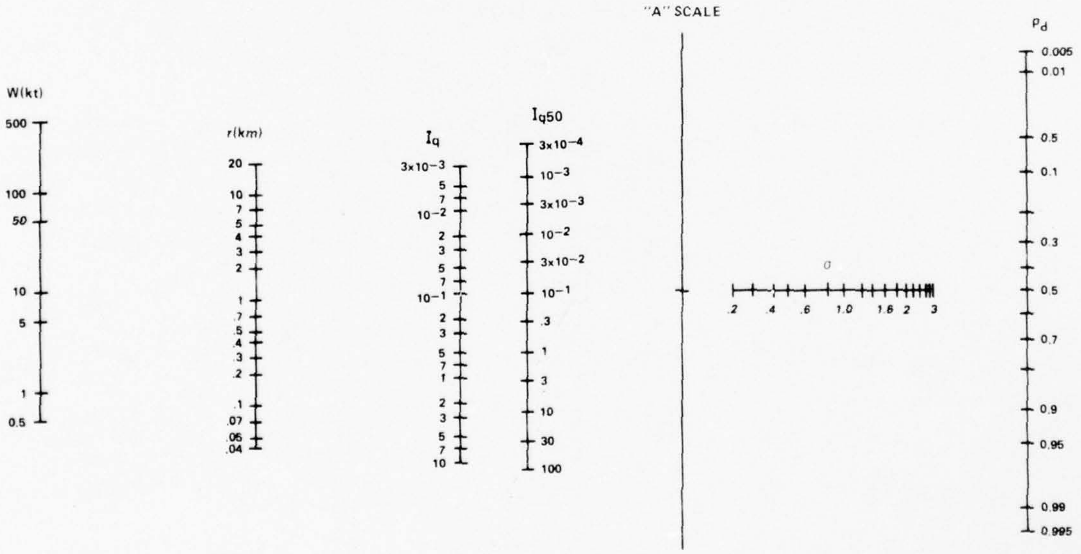


Figure B-7. Zero-CEP nomogram for dynamic pressure impulse (I_q).

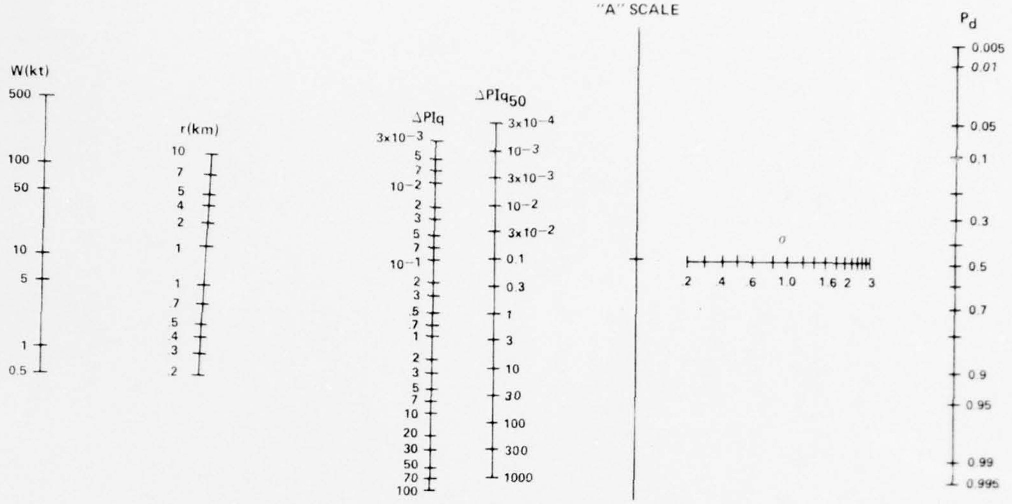


Figure B-8. Zero-CEP nomogram for product of static overpressure (ΔP) and dynamic pressure impulse (I_q).

Use of the nomograms is best illustrated by example. Figure B-9 is an example of the procedure for using each of the nomograms in this appendix. That figure solves the following problem: If r = 2 km, W = 5 kT, ΔP_{50} = 3 psi, and σ = 1.0, what is P_d? The solution is found by drawing a series of straight lines. Line 1 connects the values r = 2 km, and W = 5 kT to find that the static overpressure at the target is 1.2 psi. Line 2 connects the two points, ΔP = 1.2 psi and ΔP_{50} = 3 psi, to get a point on the "A scale." Line 3 is then drawn through this point on the "A scale" and the σ value of 1.0 to intersect the P_d scale at P_d = 0.18. This, and the other nomograms of appendix A, are accurate to $P_d \pm 0.01$. Notice that one can also use these nomograms to solve for either r, W, E_{50}, σ, or P_d once the remaining four parameters are known.

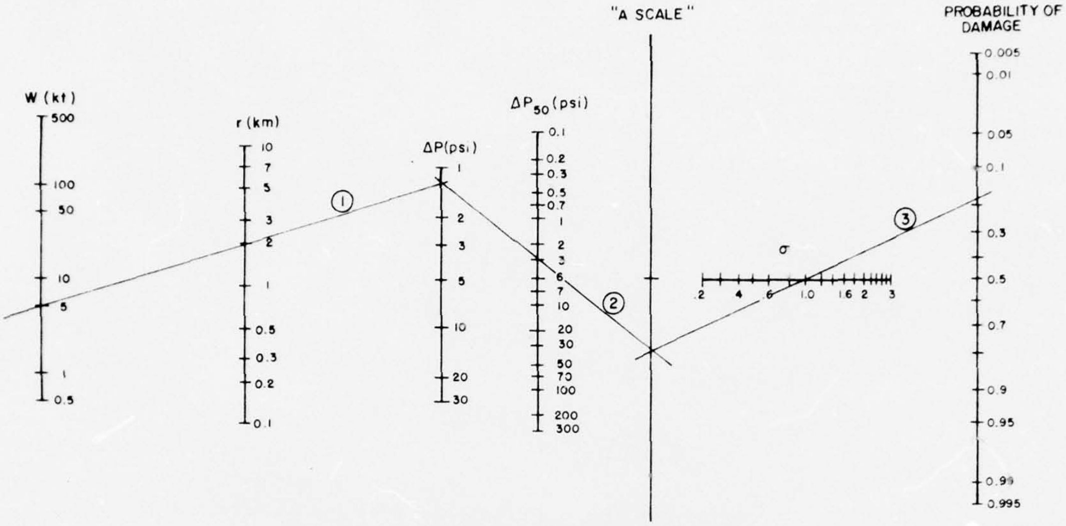


Figure B-9. ΔP nomogram, illustrating use of zero-CEP nomograms.

B-2. NONZERO-CEP NOMOGRAMS

Nonzero-CEP nomograms were constructed according to the methods described in section 3, body of report. These nomograms are more complex than those of appendix B-1 that are appropriate for zero CEP. As with those nomograms, these are designed for use by the tactical nuclear analyst, and are also consistent with the limitations of the data from which they were derived.

Nonzero-CEP nomograms are presented in figures B-10 through B-12 for the following environments:

ΔP	Figure B-10
D	Figure B-11
F_n	Figure B-12

Because of the complexity of these nomograms, we describe here the operation of each.

The ΔP nomogram, shown in figure B-10, is based upon the fact that P_d depends solely upon r_{50}/CEP, r/CEP, and σ. Thus, weapon yield is eliminated through the introduction of r_{50}. The value of r_{50} is found from the nomogram by striking a line through the r_{50} scale from points on the W and ΔP_{50} scales. Points on the r_{50} and r scales define a line that passes through the r/r_{50} scale. The point on the $r/r50$ scale and a point in the (r/CEP, σ) grid locate a line that passes through the desired value of P_d on its scale. For example, if W = 10 kT and ΔP_{50} = 10 psi, then r_{50} = 0.75 km; with r = 1 km and CEP = 0.05 km, then r/r_{50} = 1.33 and r/CEP = 2; with σ = 1, P_d = 0.33. If r/CEP > 10, P_d can be estimated by using the scale for r/CEP = 10. If $r/r_{50} < 1/8$, then the r/r_{50} scale is entered instead with the value of CEP/r_{50}, and instead of entering the grid, one uses the value of σ along the line labeled "for small r/r_{50}." For the above example with r = 0, CEP/r_{50} = 0.67, and P_d = 0.72. This procedure is also followed when $r/r_{50} < 0.25$ if $\sigma < 0.6$ and r/CEP < 0.35. The values of P_d for this ΔP nomogram are usually accurate to within 0.03 (of the machine calculations from which it was derived), but for a few pathological cases it can be as large as 0.07.

Unlike the ΔP nomogram, the D and F_n nomograms display P_d as a function of r_{50} even though σ, CEP/r_{50}, and r/CEP are fixed. Combining σ and r_{50} into the single variable $(3 - r_{50})\sigma$ empirically eliminates this additional dependence. That is, fixing $(3 - r_{50})\sigma$, r_{50}/CEP, and r/CEP, fixes the value of P_d for all values of r_{50}, r, CEP, and σ. Accordingly, the variables CEP/r_{50}, r/r_{50}, and $(3 - r_{50})\sigma$ were used as variables in the D and F_n nomograms. These two nomograms are very similar because of a corresponding similarity in the D(W, r) and F (W, r) algorithms.

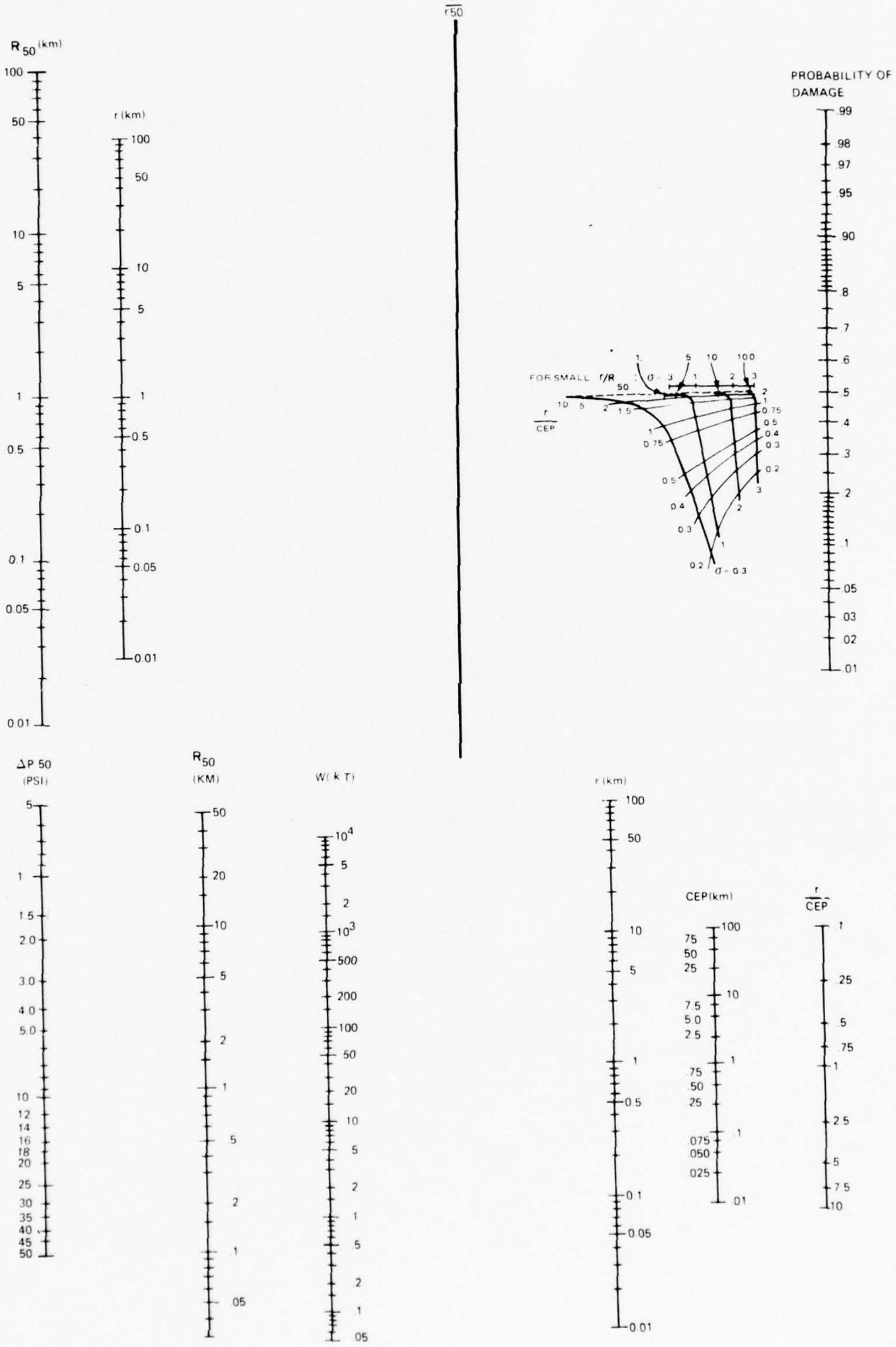


Figure B-10. Nonzero-CEP nomogram for static overpressure (ΔP).

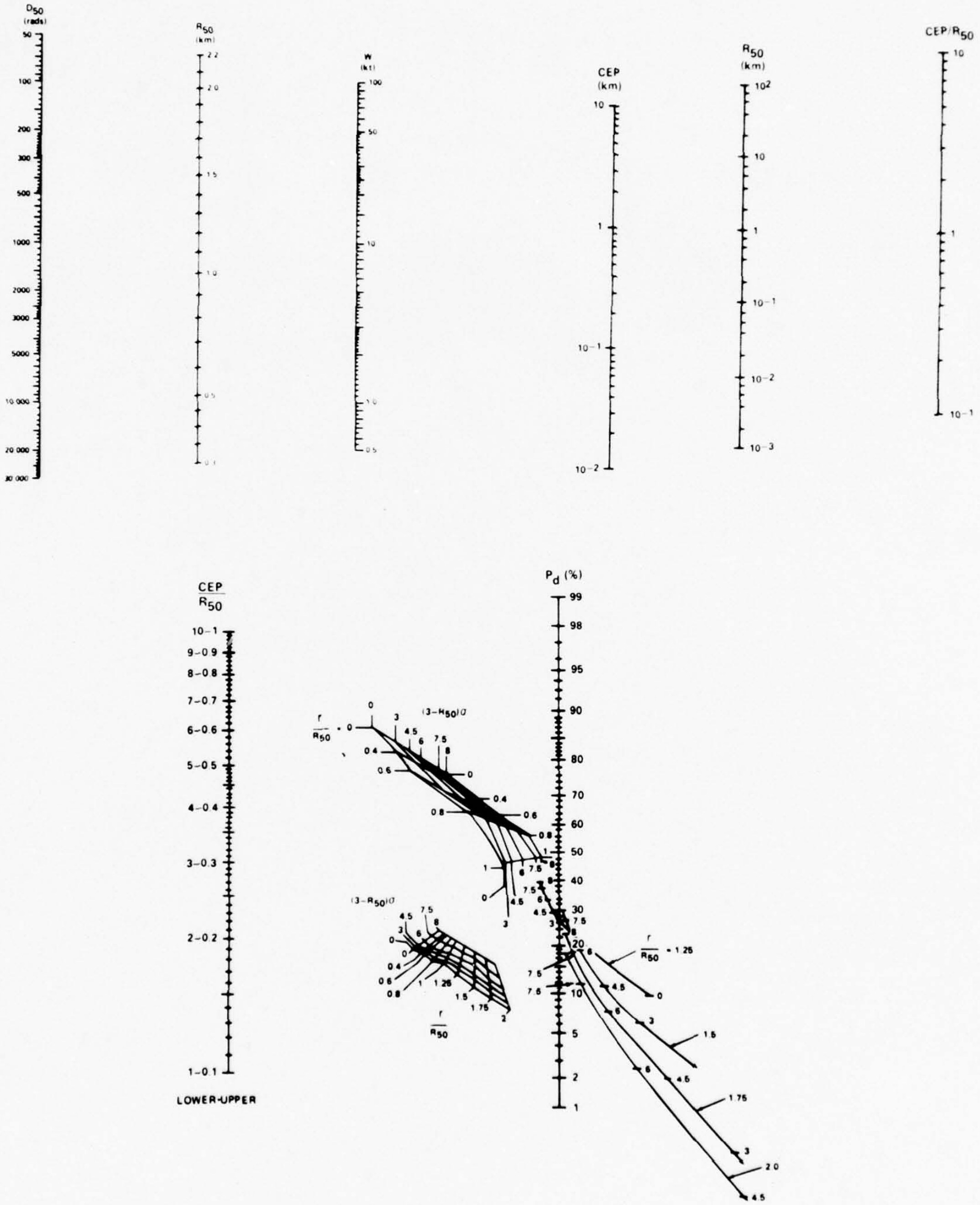


Figure B-11. Nonzero-CEP nomogram for total dose (D).

APPENDIX B

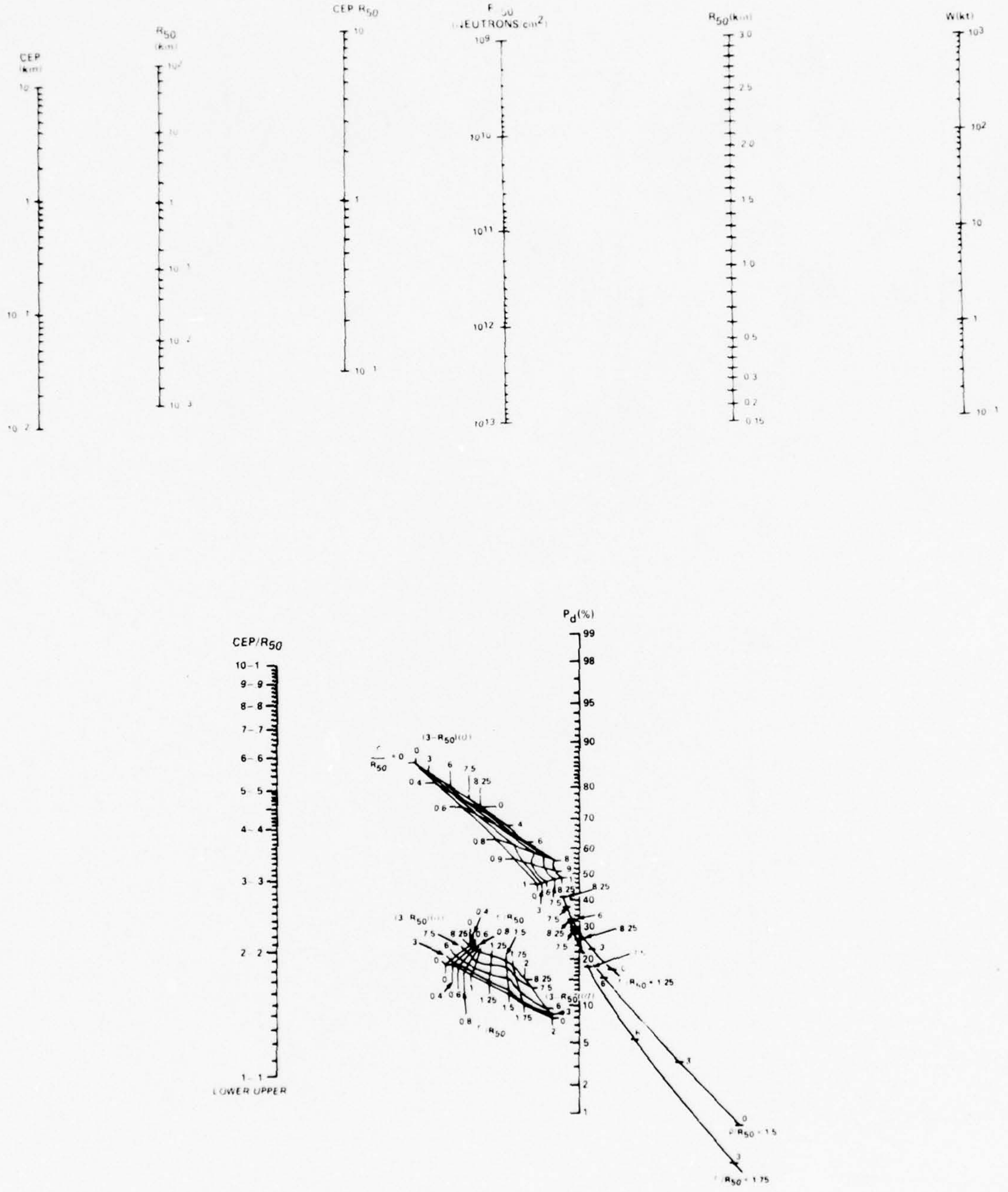


Figure B-12. Nonzero-CEP nomogram for neutron fluence (F_n).

To use the nomograms, a technique is used that is similar to that used for the ΔP nomogram. For increased accuracy, however, the F_n and D nomograms have split CEP/r_{50} scales and two corresponding grids. For $CEP/r_{50} = 1$, it is more accurate to use the upper grid (and the corresponding $1 < CEP/r_{50} < 10$ scale). It is not possible to interpolate between the grid lines on the upper grid; a value should be found for each of the closest r/r_{50} lines (if $r/r_{50} = 1.1$, these lines are 1.0 and 1.25), and a linear interpolation performed between these two P_d values. For example, if $CEP/r_{50} = 0.55$ and $r/r_{50} = 1.1$, then taking $r/r_{50} = 1.0$ gives $P_d = 0.37$, and taking $r/r_{50} = 1.25$ gives $P_d = 0.22$, the interpolation giving $P_d = 0.37 - (11/25)(0.15) = 0.30$--the machine-calculated answer being 0.32. The same is true for the F_n nomogram.

The D and F_n nomograms should not be used for $CEP/r_{50} < 0.2$ or for $CEP/r_{50} > 4$. For $CEP/r_{50} < 0.2$, either the probability obtained at 0.2, or that obtained from the CEP = 0 nomogram can be used. Such answers will not be significantly in error. For $CEP/r_{50} > 4$, the P_d values are accurate, and are less than $P_d = 0.09$.

B-3. TACTICAL NUCLEAR SLIDE RULE

The Tactical Nuclear Slide Rule (TNSR) was constructed according to the methods described in section 4, body of report, and is depicted in figure B-13. In creating the TNSR, we have kept to the ranges in input parameters (W, r, E_{50}, and σ) and environments that are important to the tactical analyst, and to the bounds of applicability of the algorithms. The environments that can be calculated with the TNSR are, in order from top to bottom of the front of the TNSR above the window,

Neutron fluence F_n (n/cm^2)

Total radiation dose D (rad)

Static overpressure ΔP (psi)

A: Peak vertical EMP electric field (V/m)

and below the window,

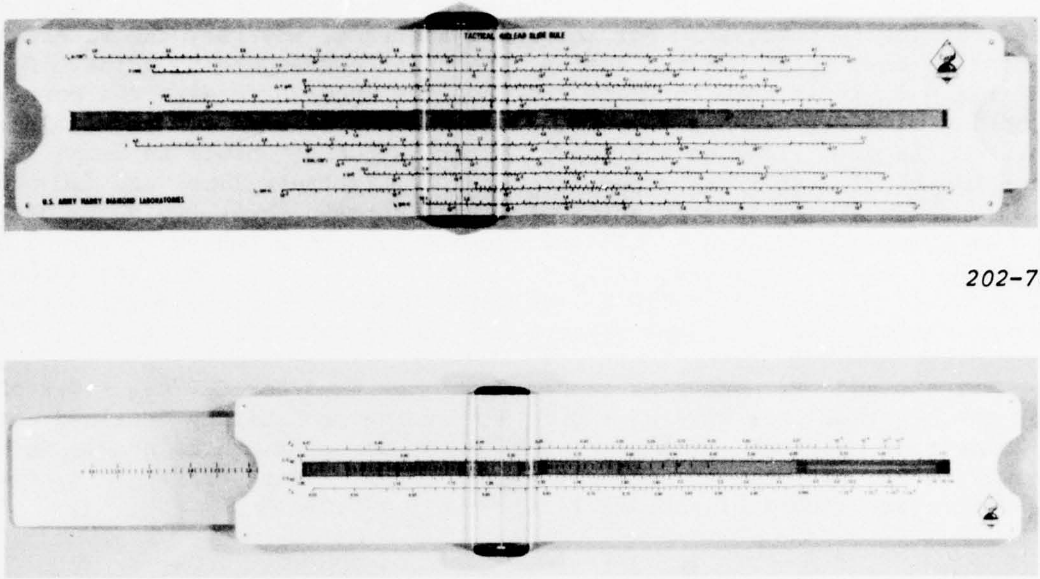
B: Peak gamma-ray dose rate [rads(Si)/s]

Thermal fluence (average atmospheric transmissivity) Q (cal/cm^2). Here r is the slant range.

Peak ideal dynamic pressure q (psi)

Static overpressure impulse (I_p) (psi-s)

Ideal dynamic pressure impulse I_q (psi-s)



202-78

203-78

Figure B-13. The Tactical Nuclear Slide Rule (a) front and (b) back.

Operation of the TNSR is best illustrated by example. Consider the problem of finding the probability of damage due to static overpressure given that

$W = 3$ kT

CEP = 0

$r = 0.9$ km

$\Delta P_{50} = 2.4$ psi

$\sigma = 0.4$

The solution to this problem typifies the operation of the TNSR. Adjust the sliding cursor to align with the value of the ground range (0.9 km) that is on the upper part of the ΔP scale,* move the sliding W scale that is within the window until the mark at $W = 1.0$ kT aligns with the cursor. Then move the cursor to align with the value of W (3 kT) and read from the cursor location on the ΔP scale (the lower part of the ΔP scale)* the value $\Delta P = 3.6$ psi that is the value of the static

---

**The upper part of each scale is reserved for r values in km; the lower part of scale is reserved for the value of the environment intensity E.*

overpressure to which the target is exposed. The ratio $\Delta P/\Delta P_{50}$ is found by using the C and D scales in the conventional way to give $\Delta P/\Delta P_{50}$ = 1.50 (referred to henceforth as E/E_{50}); the TNSR is turned over and the diamond mark on the σ scale *near* $\sigma = 0.7$ is aligned with the value $E/E_{50} = 1.50$ on the appropriate scale (above or below the window in which σ appears--in this case below) of the two E/E_{50} scales. The cursor is aligned with the value of σ (0.4), and the value of P_d (0.84) is on the P_d scale that is above or below the window according to whether E/E_{50} was entered on the upper or lower scale, respectively. Thus, the answer to the posed problem is that a probability of damage of

$$P_d = 0.84$$

arises from this combination of nuclear environment, target, and relative separation.

This example is meant to typify the operation of the TNSR. Eight environments other than static overpressure can be used. The TNSR can also be used to solve for any one of the values of r, W, E_{50}, σ, or P_d when the remaining four are known.

There is a point that the analyst must keep in mind when using the TNSR. One can calculate values of P_d only in the ranges

$$10^{-6} < P_d < 0.47$$

and

$$0.53 < P_d < 1 - 10^{-6}$$

but not in the range $0.47 < P < 0.53$ because of the log-log nature of the scales. The analyst must recognize that $P_d = 0.5$ whenever $E = E_{50}$, regardless of the value of σ.

The TNSR was designed to permit rapid calculation of the major nuclear environments and, when coupled with a vulnerability array (basically a listing of E_{50},σ pairs for items and environments; see the classified supplement[1]), calculation of P_d. Patents on the TNSR have been applied for. It is not readily obvious that a TNSR for nonzero values of the weapon CEP can be created for all the environments listed above.

---

[1] *C. Stuart Kelley, Stacey E. Gehman, John H. Wasilik, and William D. Scharf, Supplement to Nuclear Damage to Point Targets (U), Harry Diamond Laboratories TR-1876-S (November 1978). (SECRET)*

APPENDIX C.--SIMPLIFIED AP-550 NOMOGRAM

APPENDIX C

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Page

FIGURES

The procedure set forth in appendix A-1 for calculating damage to point targets using the AP-550[1] methodology can be somewhat simplified to require reference to no more than three nomograms. This technique is described below. Values of the probability of damage obtained by this method are within 0.05 of those found by the more lengthy AP-550 technique.

The calculation of damage begins with specification of the weapon yield and CEP, the vulnerability number for the target of interest, and a separation distance between the target and the designated ground zero (DGZ). Identifying the target simultaneously specifies the vulnerability number (such as 12P3) that characterizes that target. The first number (here 12) is the relative hardness of the target to a 20-kT weapon. The letter P or Q that follows the first number denotes whether the target is primarily sensitive to overpressure (P) or dynamic pressure (Q). The second number (here, 3) represents the target's ductility and is known as the k number. Specification of whether a target is P type or Q type also identifies a sigma for the target. These are listed in AP-550 for various targets, but in general, P-type targets correspond to a sigma of 20, while Q-type targets correspond to a sigma of 30.

After specifying the weapon yield and CEP, the DGZ-to-target separation distance, and the target's vulnerability number, the analyst makes a correction to the first vulnerability number using figure C-1. Which quadrant to use in figure C-1 depends on the weapon yield and whether the target is P or Q type. Then the analyst strikes a straight line from the value of the weapon yield W through a point on the grid specified by W and the value of k to get the correction to the first vulnerability number. As an example consider W = 1 kT, CEP = 0.5 km, r = 0.5 km, and a 12P3 target. Using W = 1 kT and k = 3, the correction is found to be +3. This correction is then applied to the vulnerability number to obtain an adjusted vulnerability number (15P3).

The next step in the calculation is to use figure C-2 to get the weapon radius (WR) from W and the adjusted vulnerability number. For the present example, enter the P scale of the adjusted vulnerability number scale with 15 and draw a straight line to the weapon yield of 1 kT. The line crosses the weapon radius at WR = 0.25 km.

The next step is to enter the left-hand side of figure C-3 with the WR and the DGZ-to-target separation distance r to obtain their ratio (r/WR = 2.0). Then calculate r/CEP = 1.0 again, using the left-hand side of figure C-3, but entering the WR scale with the value of the CEP (0.5 km).

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[1] *Defense Intelligence Agency, Physical Vulnerability Handbook--Nuclear Weapons (U), AP-550-1-2-INT (June 1969). (CONFIDENTIAL)*

APPENDIX C

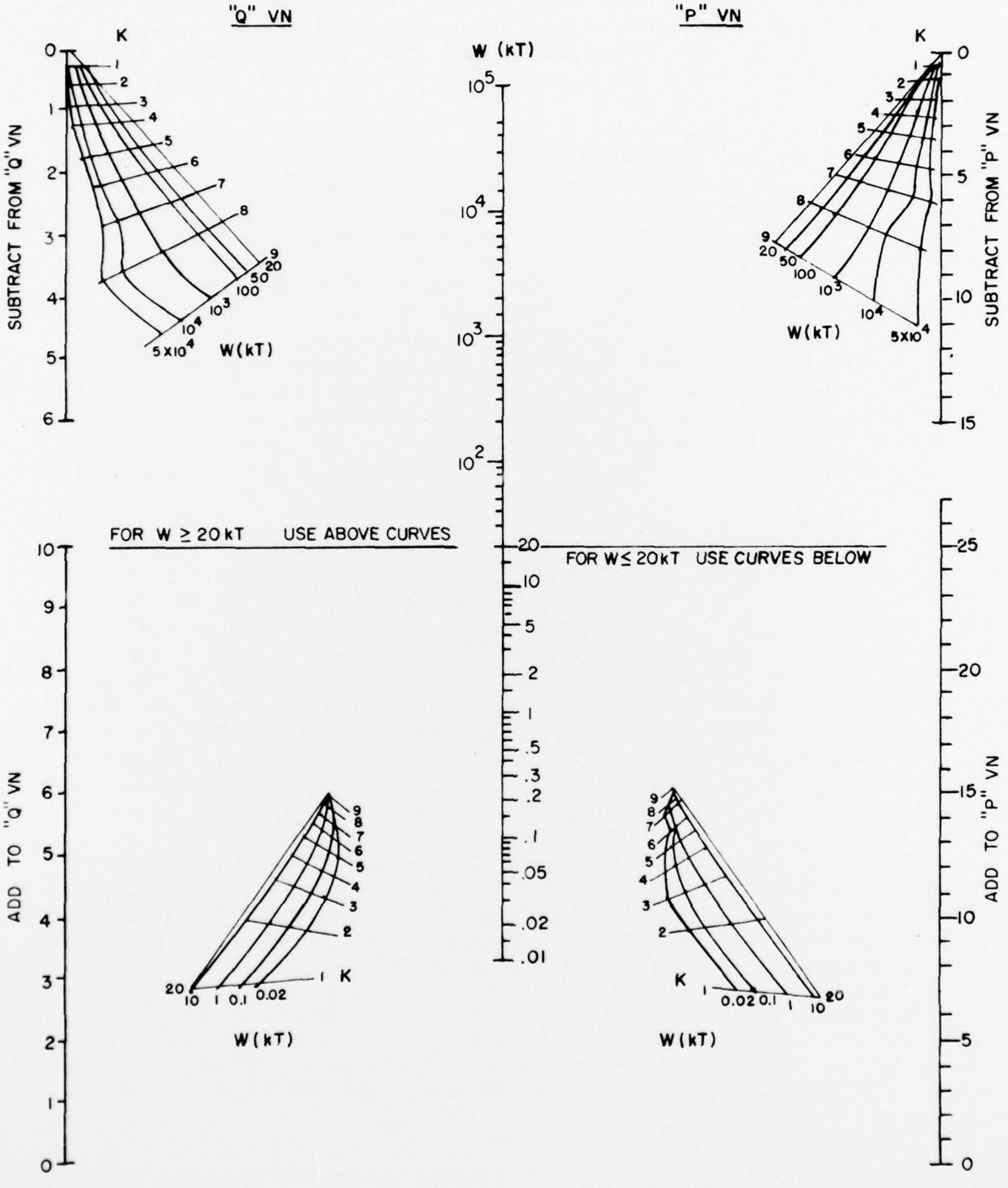

Figure C-1. Adjustment values for"Q" and "P" vulnerability numbers.

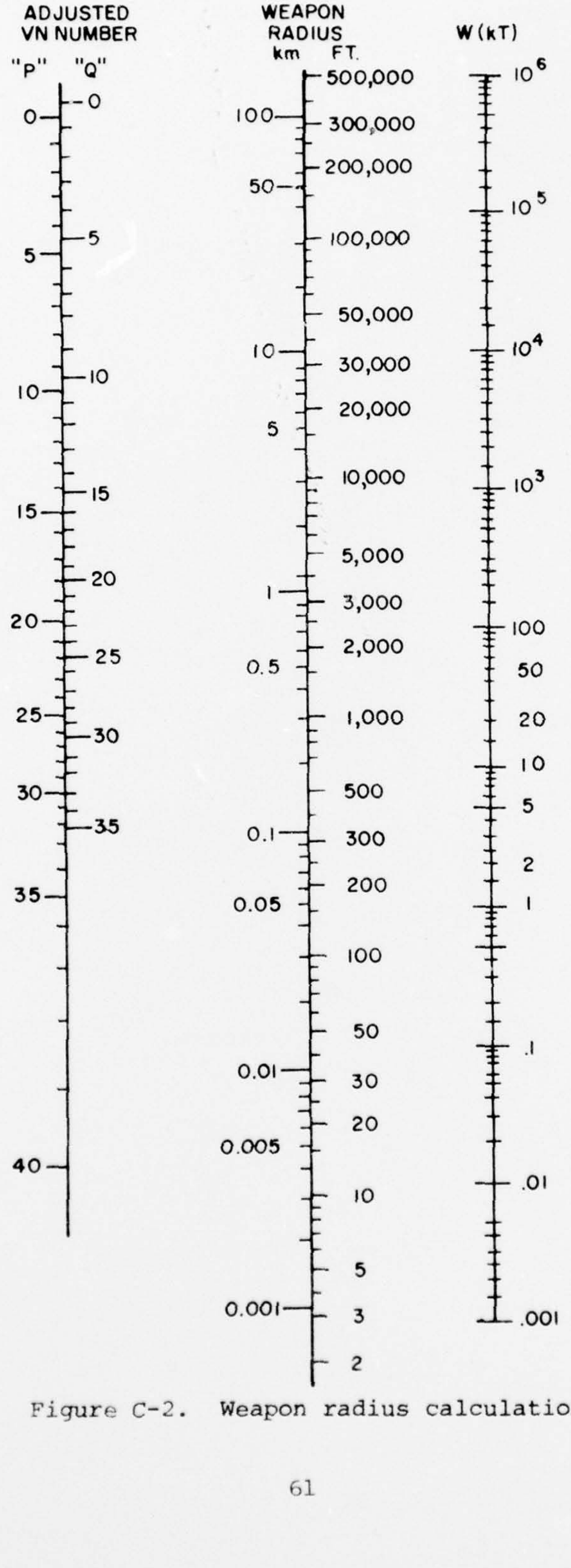

Figure C-2. Weapon radius calculation.

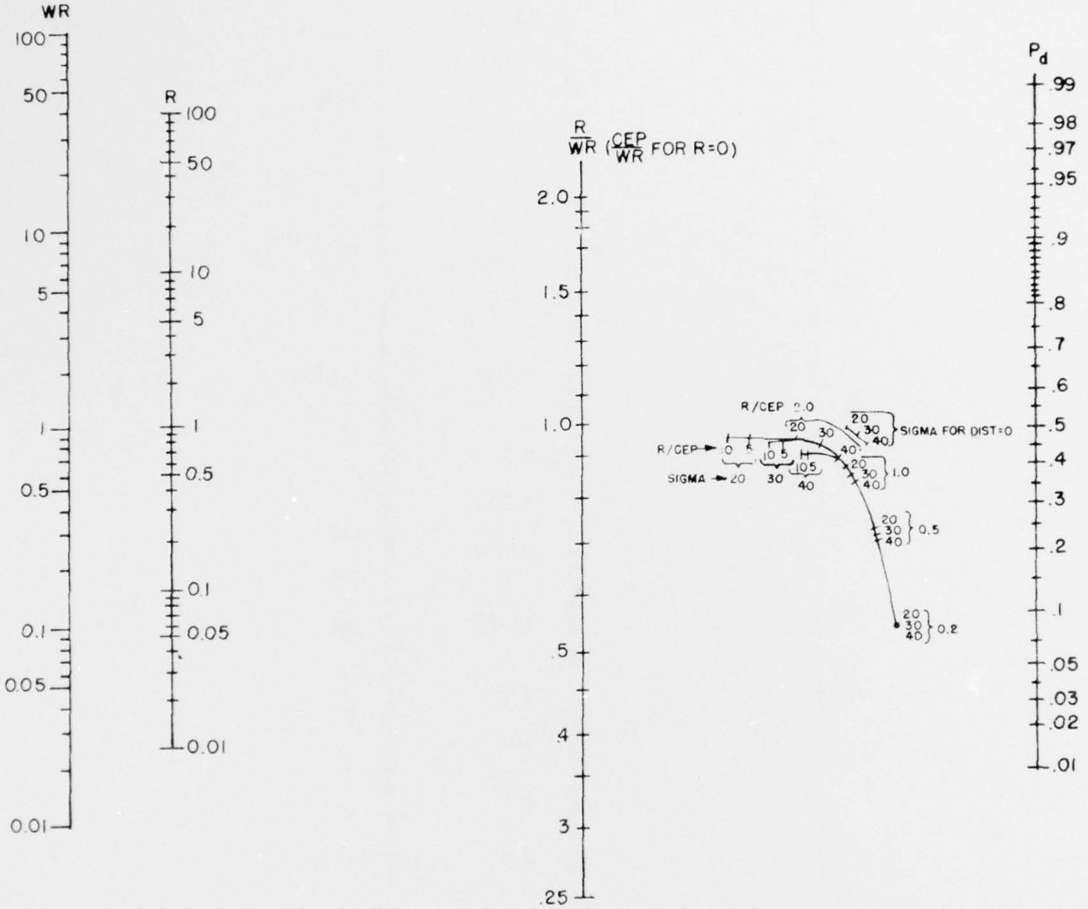

Figure C-3. P_d nomogram.

The final step in the calculation is to use the right-hand side of figure C-3 to find P_d. Enter the r/WR scale with the appropriate value (here, 2.0) and draw a line through the relevant point on the intermediate curve by specifying r/CEP and σ (here, respectively, 1.0 and 20 for this P-type target), and extend the straight line to intercept the P_d scale at 0.05.

These nomograms can also handle calculations when $r = 0$. The only changes are that in the right-hand side of figure C-3 one enters the CEP/WR (here 2.0) value on the r/WR scale. A straight line is then extended through the appropriate σ value (20) on the short scale labeled "sigma for r = 0" to the P_d scale. For this example, one obtains $P_d = 0.13$.

For values of $r/WR < 0.25$ and $r/CEP < 0.2$, the above procedure for $r = 0$ may be used with $CEP/WR = (r/WR)/(r/CEP)$.

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