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TECHNICAL REPORT

U. S. NAVAL APPLIED SCIENCE LABORATORY

NAVAL BASE
BROOKLYN 1, NEW YORK

VULNERABILITY OF OPTICAL SYSTEMS TO THE

THERMAL RADIATION FROM NUCLEAR WEAPONS DETONATED

IN THE LOWER ATMOSPHERE:

A QUANTITATIVE APPROACH.

ZF-011-01-01, NASL [redacted]-IED-17 Progress Rep[redacted]t. 2

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ABSTRACT

A quantitative method of determining the vulnerability of optical systems to high levels of thermal radiation energy from nuclear weapons is developed. The scale employed is the volume of space in which detonation of the weapon would disable the system by imaging of the fireball on the sensor. System parameters which are considered as affecting vulnerability are angle of aperture, optical gain, transmission of the optics, and the radiant exposure required to disable the sensor.

Sample calculations are presented for a simple system.

SUMMARY

It has been shown that performance of optical systems in a nuclear environment can be degraded by thermal radiation effects at ranges where these systems may reasonably be expected to survive the blast loads. In this study, a scale for quantifying the vulnerability of such systems is developed. This scale is based on the "vulnerable volume", that is, the volume of space in which the detonation of the weapon would disable the system by imaging of the fireball on its sensor. Equations are developed for calculating this volume, and several sample calculations are performed.

Future work will include the calculation of the "vulnerable volume" for several optical systems of military interest, and an evaluation of the scale's utility based on this calculation.

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ADMINISTRATIVE INFORMATION

As part of its Independent Exploratory Development (IED) Program, The Naval Applied Science Laboratory is conducting research to determine damage to optical and electronic sensors exposed to the thermal radiation from nuclear detonations in accordance with the objectives set forth in NASL Program Summary dated 1 May 1967, ZF 011-01-01, IED-17. A technique for evaluating the vulnerability of optical systems to the thermal threat from nuclear weapons has been developed and the results are reported herein.

ACKNOWLEDGMENTS

The work reported herein was conducted under the direction of W.L. Derksen, Senior Task Leader, and under the general supervision of T.I. Monahan, Head, Physics Branch. Dr. Martin J. Kelly, Associate Professor of Physics, C.W. Post College, Long Island University, is consultant to this Laboratory on phenomenology of nuclear weapons effects.

OBJECT

The object of this study is to develop a method for estimating the likelihood of thermal radiation damage to optical systems from nuclear bursts in the lower atmosphere.

INTRODUCTION

It was shown in a previous report[1] that optical components are susceptible in varying degrees to damage by thermal radiation. Because an optical system forms an image of the nuclear fireball, the effect of thermal radiation does not fall off as the square of the distance from the burst point. Consequently optical components, particularly those located in or near the focal plane of the system, may be damaged at distances where blast and unfocused thermal radiation intensities are too low to damage the system.

It would be very convenient to have some sort of numerical measure of the vulnerability of an optical system to this focused radiation, a measure that would give some indication of the likelihood of the system being rendered inoperable in the event of nuclear attack. Such a measure would enable one to compare different systems as to their ability to survive a nuclear attack, and to set minimum standards for such ability.

The quantification of the notion of vulnerability of an optical system presents many difficulties. Before presenting the scale of vulnerability chosen, the factors that entered into this choice will be discussed.

PRELIMINARY CONSIDERATIONS

The following characteristics of an optical system have been considered as affecting its vulnerability:

1. Angle of aperture
2. Optical gain

3. Transmission of the optics

4. Radiant exposure required to disable its sensor.

This last consideration represents a considerable simplification of the problem in that the vulnerability of other components in the optical path is ignored. For systems in which this assumption is inapplicable, and reference 1 indicates that such systems are not uncommon, further refinements are necessary.

It would be very gratifying if vulnerability could be defined in terms of the system alone, but this does not appear possible. Vulnerability also depends on weapon yield and atmospheric transmittance. To find a suitable scale that takes account of all these factors, one must specify what characteristics the scale must have, and what characteristics it would be desirable that it have.

An essential characteristic of any scale is that is should enable one to order the elements to which the scale applies. Thus the vulnerability scale should enable one to say that, for certain conditions, one system is more vulnerable than another, even though the ratio of their vulnerabilities may have no significance. It would be convenient if this ordering were independent of weapon yield and atmospheric conditions but it does not appear possible to demand this, so yield and burst conditions must be considered.

It is further required of the vulnerability scale that its orderings should not contradict the orderings of common sense. A scale that did not conform to common sense at least to this extent would not be acceptable. Moreover, it would be advantageous if the measure of vulnerability had a direct, common sense appeal, and did not appear artificial and contrived.

It would be advantageous if the ratio of the vulnerabilities of two systems, as measured on the proposed scale, were insensitive to weapon yield and atmospheric conditions. Finally, it is hoped that the measure of vulnerability can be used in making simple rough calculations, such as determining distances at which the system is vulnerable for various weapon yields and conditions of the atmosphere.

PROPOSED SCALE OF VULNERABILITY

In consequence of these considerations the following scale of vulnerability has been chosen. The vulnerability of a system for a weapon of a given yield and given atmospheric transmittance will be measured by the "vulnerable volume", that is, the volume of space in which the detonation of the weapon would disable the system by imaging of the fireball on the sensor of the system. Ignored is the volume of space which is outside the viewing angle of the optical system but where the weapon would still destroy the system by unfocused thermal radiation, blast, or ionizing radiation. At some future time, this ought to be included as part of the "vulnerable volume", but in these initial stages it is omitted in the interests of simplicity.

This measure of vulnerability appears to be a reasonable one. Application to specific cases will show how well it fulfills the various requirements discussed in the previous section.

DERIVATION OF THE VULNERABLE VOLUME

Assume that the weapon will be effective in disabling the system if the radiant exposure Q in the image of the fireball exceeds some critical value, Q_c, regardless of the fraction of the sensor covered by this image. Let the fireball be a disc of radius R miles at a range D miles, and the sensor be a disc of radius r inches. The focal length of the system, say a simple lens, is F inches. At distance D, a point as far as (r/F)D from the optic axis of the system will be imaged on the sensor. Therefore at least some portion of the fireball will be imaged on the sensor if the center of the fireball is located at a distance less than R + (r/F)D from the optic axis. (See Figure 1.) The cross-section of the "vulnerable volume", V_v, perpendicular to the optic axis at D is then $\pi[R + (r/F)D]^2$. Let D_c be the maximum distance at which the fireball is effective in disabling the sensor. Then the "vulnerable volume" is given by

$$V_v = \pi\int_0^{D_c}[R + (r/F)D]^2\, dD = \pi\left\{R^2 D_c + (r/F)RD_c^2 + (r/F)^2\frac{D_c^3}{3}\right\}mi^3 \qquad (1)$$

Note that (r/F) is half the angle of aperture measured in radians. R, the fireball radius, is a known function of weapon yield.

Now the maximum distance D_c at which a given weapon can disable a given sensor must be determined. Suppose that the maximum tolerable radiant exposure on the sensor is Q_c. Then all values of radiant exposure less than Q_c will leave the system functional, and all values greater than Q_c will result in system failure. If there were no atmospheric attenuation, the radiant exposure in the image would be independent of distance out to distances at which the size of the image is substantially affected by diffraction.

If the radiant exposure delivered to the image plane when the transmittance of the atmosphere is unity is given by Q_i, then the maximum distance D_c at which a weapon can disable the sensor is equal to the distance at which the transmittance of the atmosphere is equal to Q_c/Q_i. The unfocussed radiant exposure at distance D is given by reference 2 as

$$Q_o = (1.04 \times 10^3)\ \frac{WT}{D^2}\ \text{cal cm}^{-2}$$

where W is the yield in megatons, T, the atmospheric transmission, and D the distance in miles. Let a (inches) be the radius of the aperture of the system, S (inches) the radius of the fireball image, and assume the fireball radiates as a Lambert disc. Then for the case of no atmospheric absorption (T = 1), the radiant exposure in the image is related to that at the aperture by the expression

$$Q_i = AQ_o\Big|_{T=1}\ (a/s)^2\ \text{cal cm}^{-2}$$ ......A is the transmission of the optics. This may be rewritten as

$$Q_i = AQ_o\Big|_{T=1}\ (F/2fs)^2\ \text{cal cm}^{-2}$$ ....$f \equiv F/2a$

From Fig. 1, it is evident that

$$s = RF/D,$$

and therefore $$Q_i = AQ_o\Big|_{T=1}\ D^2/(2fR)^2\ \text{cal cm}^{-2}$$

or $$Q_i = (1.04 \times 10^3)AW/(2fR)^2\ \text{cal cm}^{-2} \qquad (2)$$

An expression for the fireball radius of an airburst at the second maximum is given by Martin & Holton[3] as

$$R = 0.41\ W^{0.35}\varepsilon^{0.0465\ \text{HOB}}\ \text{miles},$$

where W is the weapon yield in megatons & HOB is the height of burst in miles.

For a 1-mile height of burst, this becomes

$$R = 0.43\ W^{0.35}\ \text{miles} \qquad (3)$$

Substituting (3) in (2), one obtains

$$Q_i = \frac{(1.48 \times 10^3)W^{0.30}}{f^2}\ \text{cal cm}^{-2}$$

As a first approximation to the atmospheric transmission, the form $\varepsilon^{-\alpha D}$ will be used. This is reasonable as scattered radiation is not expected to contribute significantly to the fireball image. The extinction coefficient α (mi^{-1}) will be taken as constant. This is strictly correct of course, only for media which absorb in a spectrally non-selective manner. To a reasonable approximation, this requirement is fulfilled by the atmosphere in the spectral region where the radiant outputs of most weapons of interest are concentrated. Setting $T = \varepsilon^{-\alpha D_c} = Q_c/Q_i$, one obtains

$$D_c = (1/\alpha)\ln\ (Q_i/Q_c)\ \text{miles}$$

Therefore
$$D_c = \frac{1}{\alpha}\ln\ \frac{1.48 \times 10^3\ AW^{0.30}}{f^2\ Q_c}\ \text{miles}$$

Substituting this last expression in equation (1), the vulnerable volume is completely specified as a function of system parameters, weapon yield, atmospheric transmission, and the susceptibility of the sensor to thermal radiation (Q_c).

SAMPLE CALCULATIONS

Consider a simple optical system with the following parameters:

Focal length	$F = 4.0$ inches
Radius of aperture	$a = 1.0$ inches
Transmission of system	$A = 0.6$
Radius of sensor	$r = 0.2$ inches
Critical radiant exposure	$Q_c = 10$ cal cm^{-2}

The f-number is given as $f \equiv (F/2a) = 2$. Using equations developed in the previous section, critical distances and vulnerable volumes are calculated for yields of 30, 100, 500, and 1000 kilotons. Calculations are also performed for a similar system in which $Q_c = 20$ cal cm^{-2}. An extinction coefficient (α) of 0.16 mi^{-1} is assumed. The results are presented in Table I, and plotted in Figures 2 & 3.

DISCUSSION

The efficacy of a scale based on the "vulnerable volume" concept will be apparent only by application to specific systems. Some features of this scale, however, are immediately obvious. Although a critical distance, D_c, is generated in the course of the computation, the volume concept is of far greater utility since it fits logically into a "threat model" or "war game" analysis. This volume clearly conveys more information regarding system vulnerability as systems with identical critical distances can have quite different vulnerable volumes due to differences in their fields of view.

The assumption that only the sensor is susceptible to thermal damage may or may not be valid. It would be quite feasible to develop a technique which would evaluate all the elements in the optical path, but such a procedure is outside the scope of this exploratory effort. It is also apparent that further effort is required in the definition of Q_c, as few systems will "fail" above some radiant exposure, and "not fail" below this radiant exposure. Indeed, acceptable performance criteria must be developed for each system with particular emphasis on transient effects.

FUTURE WORK

Future work will include an evaluation of the vulnerability scale presented in this report. The evaluation will be accomplished by applying the scale to several systems of military interest.

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2. Glasstone, S., "Effects of Nuclear Weapons", United States Atomic Energy Commission, Revised Edition Reprinted February 1964.

3. Martin, S.B. and Holton, S., "Preliminary Computer Program for Estimating Primary Ignition Ranges for Nuclear Weapons", U.S. Naval Radiological Defense Laboratory, June 1965.

LIST OF SYMBOLS

R	Fireball radius (statute miles)
D	Distance from burst point to system (statute miles)
r	Radius of photo sensor (inches)
F	Focal length (inches)
V_v	Vulnerable volume (statute miles^3)
D_c	Critical distance (miles)
Q_c	Critical radiant exposure (cal cm^{-2})
Q_i	Radiant exposure in image plane (cal cm^{-2})
Q_o	Radiant exposure (cal cm^{-2})
W	Weapon yield (megatons)
T	Transmission of the atmosphere (numeric)
a	Radius of aperture of the system (inches)
s	Radius of fireball image (inches)
A	Transmission of the system (numeric)
α	Extinction coefficient (mile^{-1})

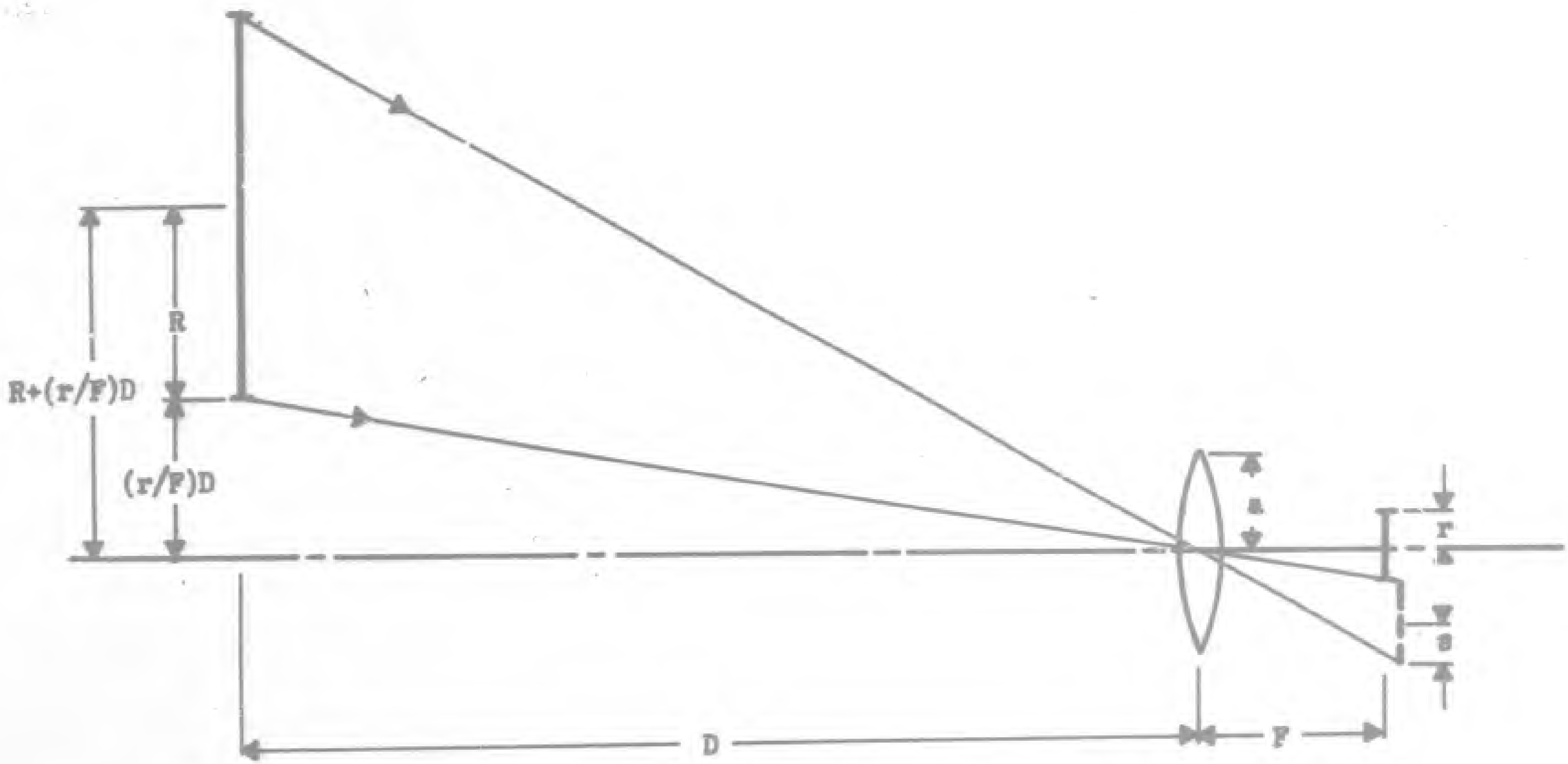

Fig. 1 - Geometrical Relationships in Simple Optical System (Limiting Case)

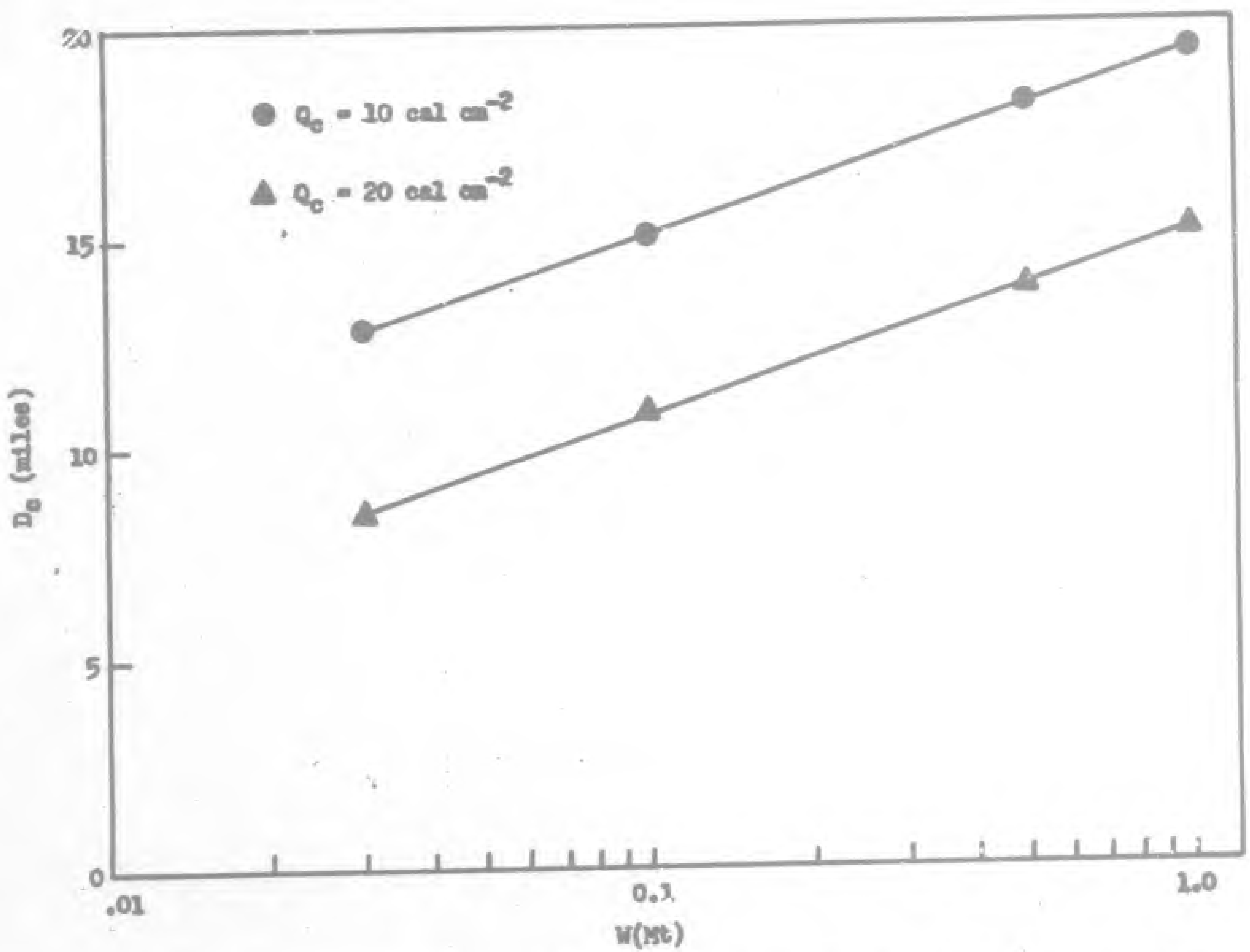

Fig. 2 - Critical Distance as a Function of Weapon Yield for Two Critical Radiant Exposures

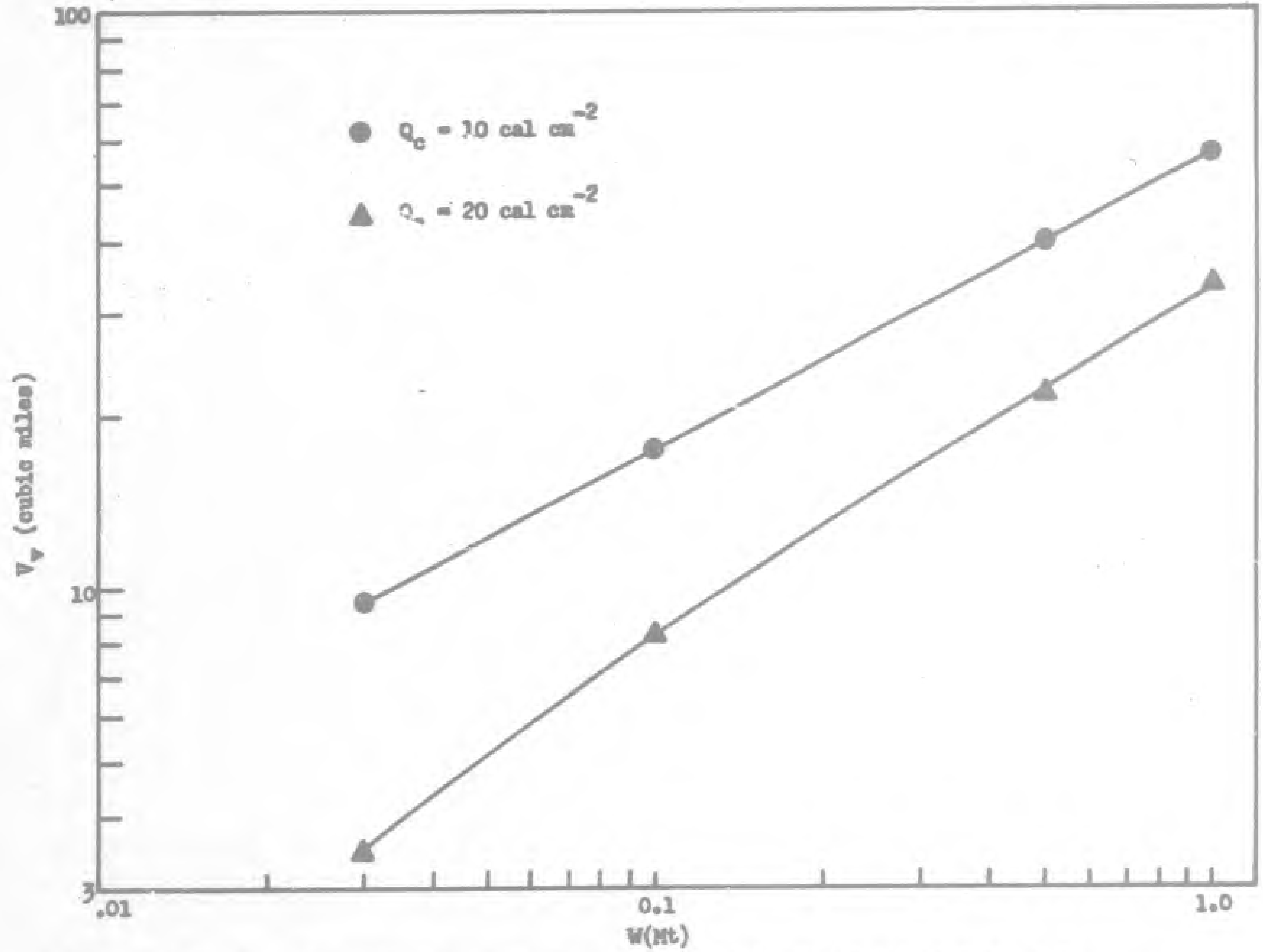

Fig. 3 - Vulnerable Volume as a Function of Weapon Yield for Two Critical Radiant Exposures

TABLE I

Critical Distances and Vulnerable Volumes for Four Weapon Yields

and Two Critical Radiant Exposures

W (megatons)	D_c (miles)	V_v (miles^3)
	$Q_c = 10$ cal cm^{-2}	
0.03	12.8	9.4
0.1	15.1	17.5
0.5	18.1	39.5
1.0	19.4	55.7
	$Q_c = 20$ cal cm^{-2}	
0.03	8.5	3.5
0.1	10.9	8.2
0.5	13.8	21.7
1.0	15.1	33.3

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