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AN ESTIMATION OF THE PERSONNEL HAZARDS FROM A
MULTI-TON BLAST IN A CONIFEROUS FOREST

E. R. Fletcher, et al

Lovelace Foundation for Medical Education and Research
Albuquerque, New Mexico

November 1967

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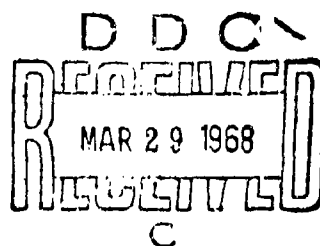
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NOVEMBER 1967



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**LOVELACE FOUNDATION FOR MEDICAL
EDUCATION AND RESEARCH
ALBUQUERQUE, NEW MEXICO**

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AN ESTIMATION OF THE PERSONNEL HAZARDS FROM A MULTI-TON BLAST IN A CONIFEROUS FOREST

**E. R. Fletcher
D. R. Richmond
I. G. Bowen
C. S. White**

Final Report on Contract No. DA-49-146-XZ-485

November 1967

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**LOVELACE FOUNDATION FOR MEDICAL
EDUCATION AND RESEARCH
ALBUQUERQUE, NEW MEXICO**

FOREWORD

This is the final report on Project 4.01, biomedical studies directed toward estimating the personnel hazards from a multi-ton blast in a forest. These studies were conducted on Event 4 of Operation Distant Plain, a hemispherical charge of 50 tons of TNT detonated on the surface, August 16, 1966, in a managed coniferous forest near Hinton, Alberta.

Much of the material in this report was presented on January 26, 1967, before those attending the Operation Distant Plain Symposium sponsored by the Field Command, Defense Atomic Support Agency, Sandia Base, Albuquerque, New Mexico. The text of the presentation is included in the proceedings of the symposium.

ABSTRACT

Experiments are described in which Styrofoam blocks were mounted in three orientations (upright, horizontal on the surface, and horizontal in shallow foxholes) in a managed coniferous forest at various ranges from a 50-ton TNT surface burst. From the number and sizes of the dents left in the blocks by tree fragments and crater ejecta, the secondary blast hazard to personnel was estimated as a function of range and type of exposure. The tertiary blast hazards were estimated using the measured blast wave parameters and a mathematical model of translation. Six anthropomorphic dummies were placed in the forest to obtain total displacements and thereby to partially verify the translational model.

The primary blast hazard was estimated from the measured blast wave parameters and earlier studies involving several mammalian species. The hazard was computed as a function of initial orientation for a man in the forest and in the open since pressure records in a cleared sector differed somewhat from those in the forest.

Measured steel-sphere velocities were used to further verify the translational model and to estimate the positive dynamic-pressure impulses at three ranges in the forest and in the cleared sector. These impulses agreed well with those obtained by other experimenters and, in general, the forest seemed to have little effect on the impulse although the shape of the wave was apparently changed.

The overall blast hazards to personnel in a forest and in an open area are discussed in terms of range, overpressure, and type of exposure.

ACKNOWLEDGEMENTS

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TABLE OF CONTENTS

	Page
Foreword	i
Abstract	ii
Acknowledgements	iii
Introduction	1
Objectives	1
Background	3
Experimental Procedures	3
General	3
Trees	3
Styrofoam Blocks	5
Sphere Traps	7
Dummies	8
Results	8
General	8
Trees	9
Styrofoam Blocks	20
Sphere Traps	24
Dummies	28
Estimated Primary Effects	32
Discussion	36
Bibliography	40
Appendix	

LIST OF TABLES

No.		
1	Trees Blown Down	8
2	Dummy Displacements and Velocities	25
3	Predicted Primary Blast Effects	31

LIST OF FIGURES

1	Layout of Program 4.01 projects in the forested sector. All the experimental objects in the forest are shown except the marked trees.	4
2	Six typical preshot views.	6
3	Six postshot views looking downwind from the indicated painted tree. R is the range of the tree from which the picture was taken.	10
4	Six postshot views of vertical Styrofoam blocks located at the indicated ranges (R). "Inc" is the derived percent incapacitation for a man whose presented area is the same as that of the block, 4.5 ft. ²	14
5	Six postshot views of horizontal Styrofoam blocks located at the indicated ranges (R). "Inc" is the derived percent incapacitation for a man whose presented area is the same as that of the block, 4.5 ft. ²	15

Table of Contents (continued)

<u>No.</u>		<u>Page</u>
6	Six postshot views of slit-trench Styrofoam blocks located at the indicated ranges (R). "Inc" is the derived percent incapacitation for a man whose presented area is the same as that of the block, 4.5 ft. ²	16
7	Computed percent incapacitation of personnel vs range for three types of exposure. The number of Styrofoam blocks used to compute each data point is indicated.	18
8	Measured impact velocity vs acceleration coefficient for the spheres in the cleared and forested sectors. The predicted curves were derived using the measured blast wave parameters.	21
9	Dynamic-pressure impulse vs range. The data were obtained by BRL (Reisler, 1967), Australian personnel (Howe, 1967), and The Lovelace Foundation (present report). The two curves, B and K, are predictions taken from Brode (1957) and Keefer (1966), respectively. The straight line, L, is the result of a regression analysis of all the data excluding the two indicated points.	23
10	Final resting positions for all six dummies. R is the initial range of the dummy from ground zero and "Disp" the total downwind displacement of the dummy.	27
11	Predicted survival from primary blast effects in the forested and cleared sectors. Curves were computed for men initially: (1) prone aligned with the wind (P_i), (2) perpendicular to the wind ($P_i + Q$), and (3) against a vertical reflecting surface (P_r).	30
A1	Impact energy vs volume of the impression for Type II and Type IV Styrofoam.	42

AN ESTIMATION OF THE PERSONNEL HAZARDS FROM A MULTI-TON BLAST IN A CONIFEROUS FOREST

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INTRODUCTION

Objectives

The primary objective of this study was to assess the hazards to personnel in the vicinity of a multi-ton surface burst in a managed coniferous forest such that a comparison could be made with exposure in the open. The hazards to be studied included falling trees and branches, ejecta, whole body translation, and primary blast effects. An additional feature of the experiment was the estimation of dynamic-pressure impulse at several locations in the forested and cleared sectors.

Background

The effects of large explosions on tree stands have been studied in Nevada (Sauer et al., 1954), on the Pacific Islands (Fons and Storey, 1955), in northern Australia (Bowe et al., 1964), and in Sweden (Oscarrson and Araskog, 1966). The Nevada test involved a small artificial stand of coniferous trees (145 ponderosa pines in a 320 ft x 160 ft rectangle) exposed at 4.5 psi, while the Pacific and Australian tests made use of natural stands of tropical trees and a rain forest respectively. Thus, the data obtained in these experiments had only limited applicability in trying to predict damage (over a wide range of pressure) to managed coniferous forests typical of those found in Europe. The biological hazards associated with a large explosion in such a forest were even more in doubt.

Tests involving dummy translation over open terrain have been conducted on nuclear detonations (Taborelli et al., 1959) and large conventional explosions (Bowen et al., 1965). Mathematical models were developed to predict the accelerative phase of the displacement (Bowen et al., 1961), and later the complete time displacement history (Fletcher and Bowen, 1966). The close agreement between theory and test results indicated that the displacement histories of dummies and goats (and presumably man) could be reasonably predicted provided the appropriate parameters of the blast wave were known. Although all of these experiments were conducted over open terrain, it is reasonable to assume that the predictions would also be fairly accurate in a forest provided (1) the blast wave could be determined and (2) the translating object did not impact with a tree or any other obstruction. Having predicted the "unobstructed" translation of a man, impacts with the ground, trees,

etc. could then be predicted from geometrical considerations. Some data are available to help assess the hazards associated with such impacts (White et al., 1965; White, 1966).

Data directly relevant to the personnel hazards from blast-induced translation in a forest were obtained during Operation Blowdown, a 50-ton TNT explosion on a tower in an Australian rain forest in August 1963 (Kelso and Clifford, 1964). Dummies placed in the rain forest at peak overpressure levels of approximately 15, 10, and 5 psi (440-, 550-, and 800-foot ground ranges) were undamaged by the blast although those at 15 psi sustained torn clothing. It was concluded that the trees had little or no effect on a dummy's maximum velocity by comparing the total distance of translation in the forest with predictions (Bowen et al., 1962) for a cleared sector. That the forest produced little attenuation of the blast wave (and subsequent dummy displacements) at these ranges was in agreement with the measured dynamic pressures; i. e., the dynamic pressures in the forest were reduced by 10 percent or less at 360 feet and the differences decreased at greater ranges.

In an attempt to detect high-velocity tree fragments, missile traps and screens were placed in the rain forest during Operation Blowdown at a ground range of 665 feet (~ 7 psi overpressure). No such fragments were gathered; however, no definite conclusions could be reached in regard to personnel hazards since beyond about 550 feet (~10 psi overpressure) portions of trees fell approximately straight down and the vertical orientation of the traps prohibited detection. Had the velocities of these falling fragments from trees been measured, their wounding power could have been estimated from data available in the literature (White et al, 1965; White, 1966; Anonymous, 1944). Because Operation Blowdown was a tower shot, no crater debris, or ejecta, was present as was the case for Operation Distant Plain. "An estimate of man's vulnerability to debris thrown up by bombs which burst in the ground" has been previously reported (Anonymous, 1944) as has a method of estimating the impact velocity of such debris (Bowen et al., 1965).

The technique of using the impact velocities of steel spheres trapped in layers of expanded polystyrene (Styrofoam) to estimate the dynamic-pressure impulse has been described previously (Fletcher et al., 1965a; Fletcher and Bowen, 1966). Similar procedures were used in the present study in both the cleared and forested sectors.

Although no experimental attempt was made during Operation Distant Plain to assess the lethal effects of overpressure per se, these effects were considered since they also represent a hazard. From laboratory experiments, full-scale testing, and theoretical studies, tentative criteria have been set forth which can be used to estimate the primary hazards due to blast if the conditions of exposure and appropriate parameters of the blast wave are known (White, 1966; Richmond et al., 1966b; Bowen et al., 1966; Bowen et al., in preparation). The overpressure hazards in the forested and cleared sectors were thus estimated from these criteria making use of the measured blast-wave parameters.

EXPERIMENTAL PROCEDURES

General

Some of the experiments in Project 4.01 of Operation Distant Plain were located in the forested sector and some in the cleared sector. These studies involved (1) painted and marked trees, (2) Styrofoam blocks arranged vertically, horizontally on the surface, and horizontally in slit trenches (shallow foxholes), (3) steel-sphere traps, and (4) anthropomorphic dummies. The locations of all the experimental objects placed in the forested area (except the marked trees) are shown in Figure 1 along with the station numbers which are used as the first part of the designator for the specific object. For example, the vertical block of Styrofoam labeled U2 in Station 15 in Figure 1 would be designated 15U2.

Trees

Ten trees were painted so that the fragment distribution could be determined. Two trees at each of the stations 30, 20, 15, 10, and 5 (see Figure 1) were sprayed with a water-based latex paint using a different color for each station. Unfortunately, only approximately the bottom three-fourths of the trees could be reached with the spray gun. These ten pine, spruce, and fir trees had an average height of 53.5 feet (45-70 feet) and an average diameter of 11.9 inches (9-17 inches) measured 4.5 feet above the ground.

As a possible aid in the post-shot analysis, most of the trees on the right side of the layout (see Figure 1) between the ranges of 220 and 460 feet, as well as a few trees between 600 and 700 feet, were marked with tape. These trees were numbered and their girths, species, and exact locations were recorded for later reference.

Styrofoam Blocks

In order to help evaluate the hazards to personnel due to missiles, Styrofoam blocks of two grades (Type II and Type IV) were placed in various orientations in the forest and used as "Styrofoam men." That is, if a missile strikes the Styrofoam it will leave an impression, the volume of which can be used to estimate the energy dissipated (see Appendix for details of impression volume vs energy). If a man had been in the exact location of the Styrofoam, he would have been struck by the same missiles that struck the Styrofoam and presumably he would have absorbed approximately the same amount of energy. Knowing the number and energy spectrum of the missiles striking a man, one may then attempt to estimate the hazards.

Sixty-five Styrofoam blocks (4.5 feet x 1 foot x 6 inches for Type II and 4.5 feet x 1 foot x 3 inches for Type IV Styrofoam) were placed in the forested sector (see Figure 1) with 25 blocks in an upright

LAYOUT OF PROGRAM 4.01 PROJECTS IN THE FOREST SECTOR

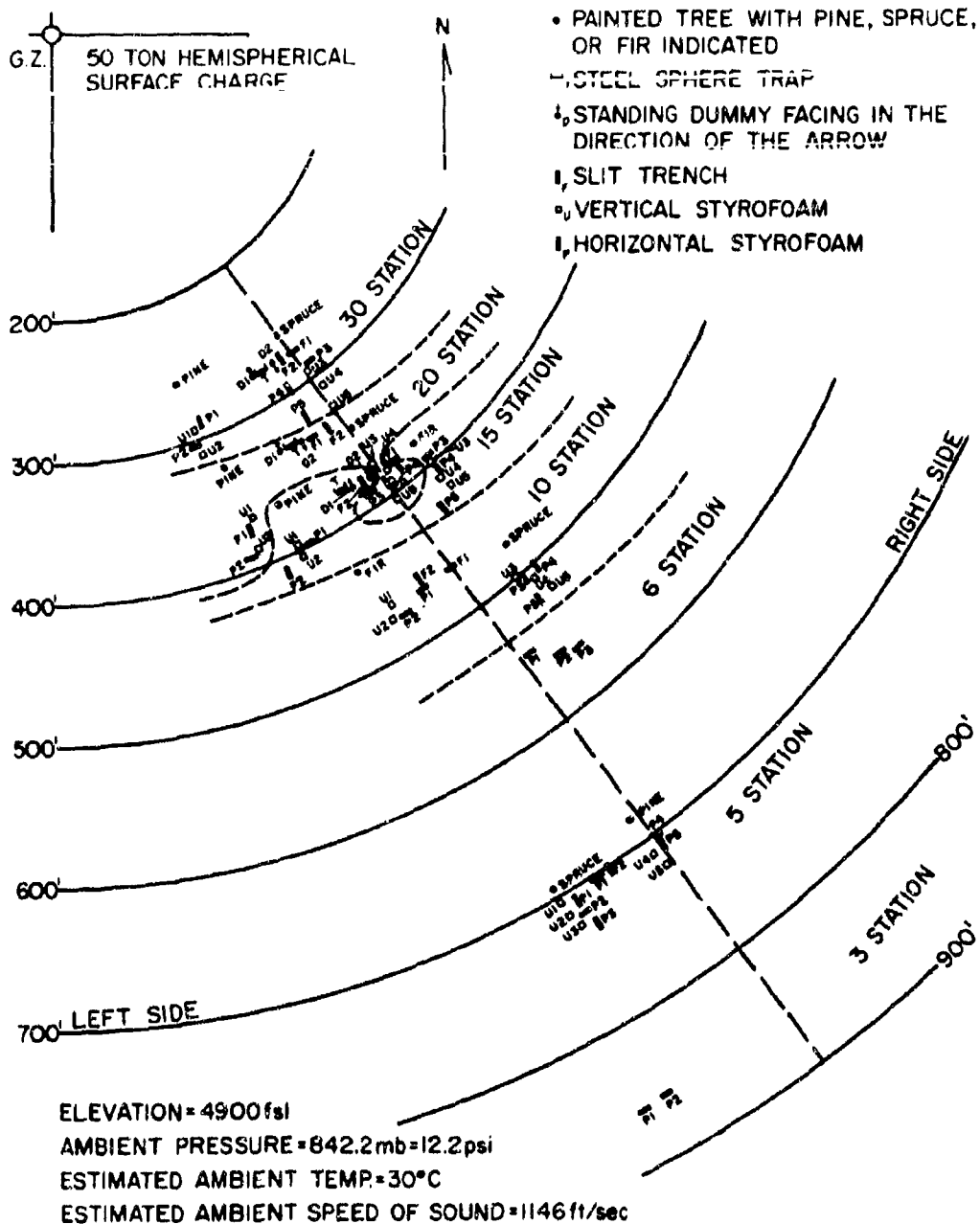


Figure 1. Layout of Program 4.01 projects in the forested sector. All the experimental objects in the forest are shown except the marked trees.

position, 30 blocks in a horizontal position on the surface and 10 blocks in a horizontal position in slit trenches (shallow foxholes). All of the Styrofoam blocks were cemented to 3/4-inch plywood for purposes of mounting. The vertical blocks were fastened on the upstream side of 12 x 12 inch pilings with the bottom of the block at approximately ground level (less than 6 inches above the surface). The blocks were staggered downstream from the painted trees (two behind the trees on the left side of the layout and three behind the trees on the right) in an attempt to catch fragments whose initial locations would be known. They were located approximately 30 to 60 feet downstream at the 30 and 20 stations and 20 to 40 feet downstream at the 15, 10, and 5 stations. Three typical vertical blocks of Styrofoam are shown in Figure 2.

The horizontal blocks on the surface were placed adjacent to the vertical blocks or, in a few instances, in the proximity of the slit trenches (see Figure 1). They were held in place by metal stakes fastened to the plywood backing, and the sides were mounded with earth to reduce the drag force of the winds and consequently the chance of the Styrofoam's coming loose during the blast experience. Some of the blocks were oriented end-on and some side-on to the blast wave. Figure 2 shows a preshot view of one of the horizontal blocks of Styrofoam.

Styrofoam blocks were fastened on the bottom of the slit trenches (6 feet long, 2 feet wide, and 2 feet deep) in the same way the horizontal blocks were mounted on the surface. A side-on and an end-on slit trench were located at each of the 30, 20, 15, 10, and 5 stations. Figure 2 includes a preshot view of one of the slit trenches containing a Styrofoam block.

By having the "Styrofoam men" in these three types of exposure, it was hoped that some idea of the relative hazards for each orientation could be obtained. Although the horizontal blocks on the surface and the blocks in the slit trenches might reasonably approximate men in similar positions, the vertical blocks should be thought of as approximating men against an object (e.g., a piling, building, or tree) and not men in the open for two reasons: (1) a man standing in the open might well have been knocked down by the winds before the arrival of the ejecta and (2) the pilings to which the vertical Styrofoam blocks were mounted served to partially protect the blocks by, for instance, supporting the weight of a falling tree. The fact that the Styrofoam blocks had a smaller presented area than the projected area of a face-on man could be accounted for statistically in estimating the hazards to personnel; differences in thickness could not be corrected for, however. It should be mentioned that all of the blocks were Type II Styrofoam except the 10 vertical and horizontal blocks on the surface at the 30 station where the heavier Type IV was used to insure that the Styrofoam would not be damaged by the effects of air pressure alone.

Sphere Traps

The sphere traps used during Operation Distant Plain are very similar to those used during Operation Snow Ball (Fletcher et al., 1965a).

TYPICAL PRESHOT VIEWS



Figure 2. Six typical preshot views.

As before, a sheet of Styrofoam (1 foot x 3 feet x 2 inches) was mounted vertically on the upstream side of a 12 inch by 12 inch piling. However, a different sphere mount was used. Square slots were cut completely across the flat surface of one-inch-diameter half-round steel bars. The slots had a depth and width equal to the radius of the spheres to be placed on them and a spacing equal to 5 radii, different bars being prepared for each of the 5 sphere sizes used ($1/2$ -, $3/8$ -, $1/4$ -, $3/16$ -, and $1/8$ -inch diameters). With the aid of angle iron bolted to the sides of the piling, these bars were mounted 1.6 feet in front of the surface of the Styrofoam at vertical distances of 6, 16, and 26 inches below the top of the Styrofoam. The flat surface was tilted slightly so that the spheres placed on the slots would tend to roll to the upstream edge of the bar. A fine piano wire was placed across the top of the upstream end of the slots to keep the spheres from rolling off. It was hoped that these new mounts would release the spheres more readily and uniformly than the old mounts and thereby a higher percentage of the spheres would be caught and the scatter in the impact velocities would be lowered. As in Operation Snow Ball (Fletcher et al., 1965a), the initial distance between the spheres and the Styrofoam was chosen to trap the spheres at approximately their maximum velocity. Figure 2 includes a view of four of the steel-sphere traps in the cleared sector.

Three sphere traps (labeled 30T, 20T, and 15T; see Figure 1) were placed in the forested sector at ground ranges of 277, 332, and 378 feet. Six sphere traps were placed in the cleared sector with two located at each of the ground ranges of 285 (labeled 30C1 and 30C2), 335 (labeled 20C1 and 20C2) and 380 feet (labeled 15C1 and 15C2). Type IV Styrofoam was used for traps 30T, 30C1, and 30C2, and Type II for the other traps. At each range the two traps in the cleared sector were located approximately 23 feet apart circumferentially, steel spheres of $1/2$ -, $1/4$ -, and $1/8$ -inch diameter being placed in front of one trap, and those of $3/8$ -, $1/4$ -, and $3/16$ -inch diameter in front of the other. Each of the three traps in the forested sector had $1/2$ -, $1/4$ -, and $1/8$ -inch diameter steel spheres in front of it. In each case the largest spheres were placed at the highest level and the smallest ones at the lowest. By having traps in both the forested and cleared sectors, the measured sphere velocities (see Appendix for details of sphere velocity vs depth of penetration) and the dynamic-pressure impulses derived from these velocities can be compared for the two exposures at comparable ranges.

Dummies

The six 165-pound anthropomorphic dummies used in this experiment were fully clothed in military fatigue uniforms including helmets, jackets, and canteens. These same dummies had been used during Operation Snow Ball and the tensions in their flexible joints were adjusted to the same values as before (see Table 1, Bowen et al., 1965). The dummies were exposed at three ground ranges (277, 332, and 378 feet) with one dummy facing upwind and one dummy facing downwind at each range (see Figure 1). They were all held in a standing position by leaning them at a slight angle against the downwind side of the horizontal member of a 2.5-foot high goal-post like structure (see two pictures in Figure 2). All the dummies were

placed so that there were no trees immediately downwind from them in order that their total "unobstructed" displacements could be determined.

RESULTS

General

All the Styrofoam blocks remained in position during the blast and none appeared to be compressed by the overpressure. However, the 20C1 and 20C2 Styrofoam sheets (Type II) used for the steel-sphere traps located in the cleared sector at a range of 335 feet were slightly compressed by the blast wave. The other sphere traps were undamaged including the 20T trap (also Type II Styrofoam) located at a range of 332 feet in the forested sector. The slit trenches were all undamaged, none of the sides having caved in. Some of the clothing was torn on the 30D1 and 30D2 dummies and all the helmets were gone.

Trees

Both of the painted trees at the 5 station (see Figure 1) appeared undamaged except that a few small branches evidently had been knocked off by crater ejecta.* One painted tree at the 10 station and one at the 15 station were still standing while the six remaining trees were all uprooted by the blast. The small crowns typical of this forest were apparently quite resistant to blast. Thus, except for those downed at the 30 station, the crowns of the uprooted trees remained relatively intact although some of the branches evidently broke off upon impact with the ground. Frequently the tree-fragment distribution consisted of little more than the intact but uprooted tree. Although the distribution of fragments from the painted trees was recorded, no analysis of these data was attempted as was done for those obtained during Operation Blowdown (Kelso and Clifford, 1964). The incidence of blow-down of the tagged trees (including the painted trees) in the forest appears in Table 1.

Table 1. Trees Blown Down

Range, ft	Overpressure, psi	Number Tagged	Number Down	Percent Down
220-280	29-18	20	20	100
283-330	18-14	23	23	100
331-380	14-11	17	15	88
380-462	11- 9	31	7	23
660-700	6	8	0	0

* The supposition that ejecta and not the winds knocked off these branches is supported by motion pictures taken of trees at similar ranges. Copies of these films were supplied to the Lovelace Foundation by James Zaccor of the URS Corporation.

-4-

In general, the blow-down data shown in Table 1 agree with those reported by Zaccor et al. (1967) at corresponding ranges. However, the 23 percent measured at the 380-462 foot range is lower than the corresponding value from Zaccor's data (~ 50 percent) although the number of trees tested was too small to indicate that the difference was significant. In addition to random variations in the strengths of individual trees, differences may also have resulted from variations in the soil conditions and the distributions of sizes and relative densities for the three types of trees tested (pine, fir, and spruce). Tree strength has been found to vary with ground drainage and with tree type and size (Zaccor et al., 1967).

Figure 3 shows six post-shot views, each looking downwind from one of the painted trees (see Figure 1). The station and tree type are indicated in the figure as is the ground range (R) from which each picture was taken. At R = 680 feet all of the trees are standing and only a few limbs (mostly knocked off by ejecta as mentioned earlier) are on the ground. The same general description holds for R = 478 feet except that more limbs are down. At R = 381 feet some trees are down and some are leaning over and are supported by the trees still standing. At R = 360 feet most of the trees are down. All the trees in the vicinity of R = 326 feet are down and a high concentration of needles, branches and limbs is apparent. At R = 260 feet the area has a much more stripped appearance, at least some of the smaller branches having apparently been blown further downwind. Note in the R = 260 foot picture the two tree trunks still leaning on the piling supporting a Styrofoam block.

Styrofoam Blocks

Nearly all of the Styrofoam blocks had some dents made by small stones and mud or clay ejecta from the crater, and many blocks had been damaged by falling trees or tree fragments. However, due to the relatively small crowns typically found in the coniferous forest and the low velocities, no painted tree fragments were caught in the vertical traps. Some of the wooden fragments were charred and apparently came from trees inside or near the fireball. Beyond the 10 station there was no evidence of wood having dented any Styrofoam, but charred wooden fragments still littered the area. All of the blocks were inspected and where possible the types of missiles making the dents were recorded before the Styrofoam was boxed and shipped back to the laboratory for analysis. Although most missiles had either broken up or fallen out of the dents they made, it was often still possible to determine the nature of the missile by the fragments left behind in the dent. In addition, post-shot photographs were taken of all the blocks before they were disturbed.

The volumes of the dents were measured by the same method used during the calibrations (see Appendix) and the impact energies were computed from these values using the equations given in Figure A1. In cases where the complete missile was still embedded in the Styrofoam (and thus the total impact energy had been absorbed by the Styrofoam), it was possible to also measure the mass and thus to compute the impact velocity. It should be noted that had the missile ricocheted off the Styrofoam, it would not have

OVERALL POSTSHOT VIEWS

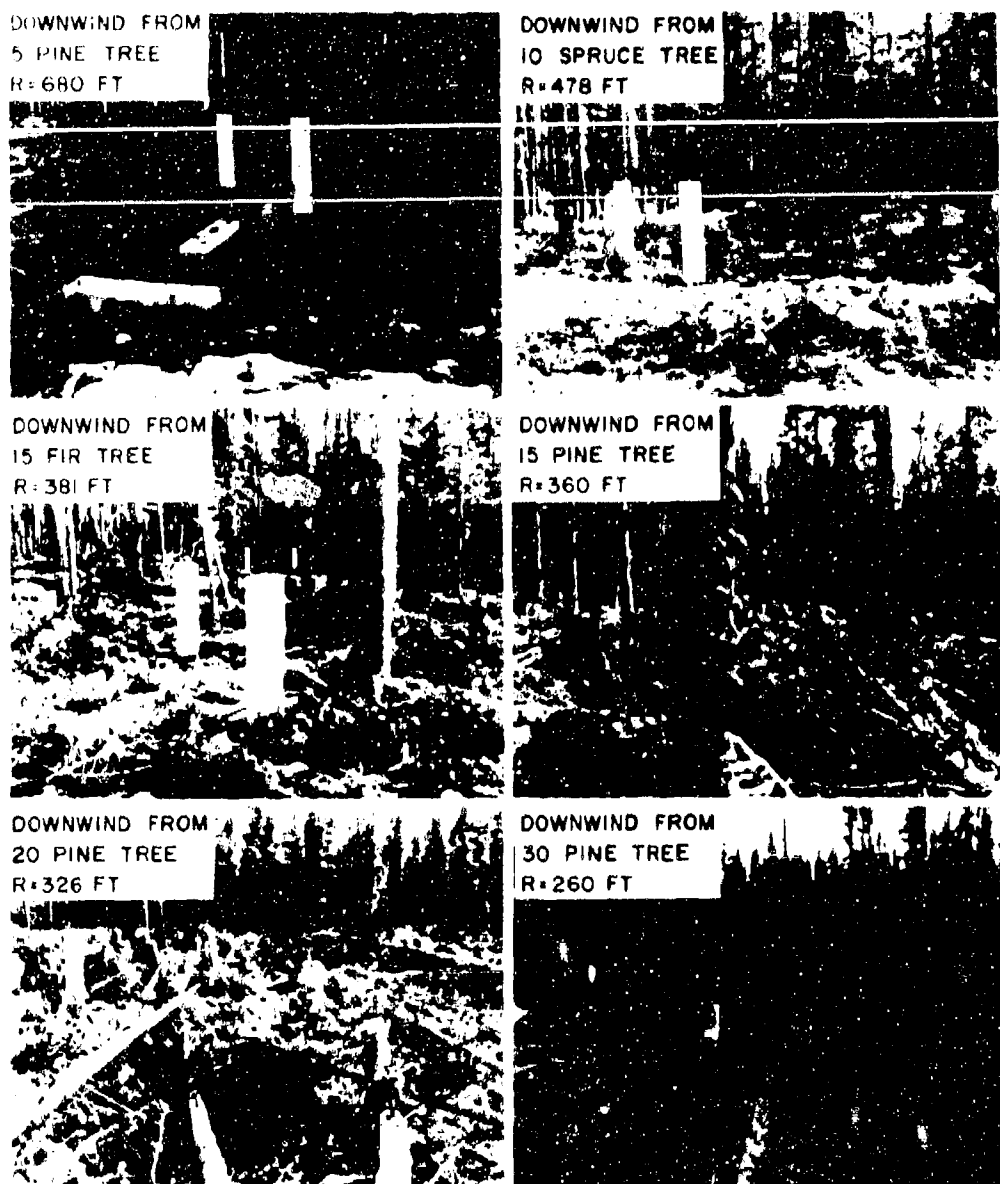


Figure 3. Six postshot views looking downwind from the indicated painted tree. R is the range of the tree from which the picture was taken.

been possible to compute the impact velocity in this manner since only a portion of the impact energy would have been absorbed by the Styrofoam.

A total of only 23 intact stone and mud missiles remained embedded in all the Styrofoam blocks, 2 in the vertical blocks, 2 in the slit-trench blocks, and 19 in the horizontal blocks--all located between 335 and 850 feet from ground zero. The masses of these missiles ranged between 1.1 and 657 grams, the bigger masses being found predominately at the shorter ranges. The computed velocities showed no trend with range or mass and a geometric mean velocity of 97 feet per second was calculated, the 23 individual velocities ranging from 69 to 130 feet per second. This is somewhat higher than the "average striking velocity of debris from 500 pound MC bombs" given as about 60 feet per second (cited by Anonymous, 1944).

A total of only 14 wooden fragments (all charred) remained embedded in all the Styrofoam blocks, 13 in vertical blocks and one in a horizontal block. These blocks were located between 277 and 420 feet from ground zero. Most of these wooden fragments were quite small, 10 of them having masses less than 1 gram. The computed velocities ranged from 150 to 670 feet per second.

In order to help estimate the number of incapacitations that might be anticipated if personnel were struck by the same missiles that struck the Styrofoam, a report from the Department of Human Anatomy at Oxford (Anonymous, 1944) was consulted. In general the procedure followed by the Oxford group was to define arbitrarily certain biological end points, relate these to selected physical parameters of missiles called "strikers" impacted against animals, test the concepts where feasible using human material, and write biomedical criteria relating chosen biological and physical descriptors. Briefly the procedure involved the following steps:

1. Mice, rats, guinea pigs, rabbits, human skulls (filled with gelatine and covered with inner tubing to simulate skin), and human and animal femora (embedded in gelatine with a rubber covering) were struck at various velocities by metal and plasticine strikers used to simulate actual debris. (The points of impact on the animals were the head, thorax, abdomen and limbs.) The metal strikers (called hard strikers) were cylindrical iron or brass rods of various lengths and the plasticine strikers (called soft strikers) were plasticine spheres of different weights. In some cases the target was "fixed" (i. e., the part struck was held firmly against a metal anvil) and in other cases the target was "free" (i. e., the part struck was held lightly against an air-filled sorbo-rubber cushion 4-9 inches thick). In all cases it was assumed that all of the kinetic energy of the striker at impact was transmitted to the part struck.

2. Biological end points adopted for the animals were death; concussion for a few seconds (characterized by loss of corneal reflexes, inability to stand, no response to pinching); fracture of skull and jaws, thoracic cage, shoulder girdle, spine, and limbs; dislocation of vertebra; intracranial hemorrhage; hemothorax; severe lung hemorrhage; perforation of the hollow organs (stomach, intestines, bladder); and rupture of the "solid" organs (liver, spleen and kidneys).

3. Biomedical criteria for "incapacitating" lesions relating physical and biological parameters extrapolated from animals to man were established and based on the assumptions that: (a) all endpoints, except lethality, noted in paragraph 2 above would be "incapacitating" in the sense that the injury constituted a cause of hospitalization in all human cases and (b) scaling procedures from small to large animals including man (based variously on body weight; surface area; bone mass, size, shape, and thickness; and striker energy and velocity at impact) were rational and tentatively acceptable.

From these experimental studies composite curves were derived for incapacitation for men lying flat on the ground in the open; one curve for hard strikers and one for soft strikers with the target assumed to be "fixed" in both cases. Since hard strikers seemed more appropriate for the typical missiles in the present study, it was decided to use these data which were presented in tabular form as missile energy vs percent incapacitation (see Table VII, Appendix II, Anonymous, 1944). When these data were plotted on log-probit paper it was found that they could be reasonably approximated by a straight line. Therefore, a probit analysis was performed giving

$$Y = -3.3494 + 2.5968 \log_{10} E$$

where Y is the probit for percent incapacitation and E is the missile's total kinetic energy in foot-pounds (ft-lb). According to this formula, 50 percent of the people struck by a missile having an energy of 1640 ft-lb, or 51.0 ft-lb, would be incapacitated. Since all the kinetic energy was assumed to be absorbed by the target, E can also be thought of as the energy absorbed by the target. Thus, using the above equation and the equations in Figure A1, the incapacitation of personnel from a missile can be predicted from the volume of the impression it left in Styrofoam. Note that if the Styrofoam is a vertical block it must again be assumed, as it was earlier for other reasons, to correspond only to a man against a building or some other vertical surface. This is so because the equation applies only to "fixed" targets.

For want of a better approach, it was assumed that when a man is struck by more than one missile, they act independently of one another in regard to incapacitation. In other words, it was assumed that if some (one or more) missiles strike a man and do not incapacitate him, later hits by other missiles will not be more than usually effective (for their energies) at producing incapacitation because of some lingering effects from the non-incapacitating missiles which preceded them. Thus, if n missiles strike a man and each has a probability of P_i of producing an incapacitating injury, the probability P of incapacitation from all missiles combined will be

$$P = 1 - \prod_{i=1}^n (1 - P_i)$$

where Π indicates the product of all the $(1 - P_i)$ values. In this way the missiles striking each Styrofoam block were "summed" to obtain a percent incapacitation for personnel if each man had been struck by the same missiles that struck a particular block. It should be noted that whereas the Styrofoam blocks have a frontal area of only 4.5 square feet, a "typical" man has a face-on projected area of about 6.2 square feet (Taborelli et al., 1959). Nonetheless, percent incapacitation provides a meaningful and convenient way to compare the relative damage to various blocks of Styrofoam.

Figures 4, 5, and 6 present typical post-shot views of the vertical, horizontal, and slit-trench Styrofoam blocks, respectively. The block number, its range (R) from ground zero, and the percent incapacitation (Inc) as computed above are given in the upper left hand corner of each picture.

Block 5U4 in Figure 4 had Inc = 0 percent at a range of 709 feet. The protection provided by the piling can be seen for Block 10U2 which had an Inc equal to only 1 percent even though a tree fell directly across it. 15U3 had Inc = 54 percent due primarily to one major dent near the bottom of the block. 20U2 had an Inc = 100 percent due to the impression in the lower half of the block rather than to the blow from the tree which fell across the top of the piling. Note the large charred wooden fragment embedded in 20U4 which produced an Inc = 99 percent. The two large dents in the upper half of 30U1 are due to mud clods, portions of which remained in the impressions.

Near the top edge of horizontal block 3P2 (see Figure 5) several dents can be seen, the combined effects of which produced an Inc of 59 percent even though this block was located at a range of 850 feet. Although several wooden fragments are lying on top of 6P1, there was no damage to the Styrofoam and Inc = 0 percent. Note the heavy damage to 10P5 which produced an Inc of 100 percent. Block 15P1 was found under a tree but suffered relatively little damage (Inc = 9 percent) because the trunk of the tree was supported by its branches. 20P2, on the other hand, was found under two logs and had an Inc equal to 100 percent. 30P3 was partially under a log but had an Inc of only 12 percent.

Styrofoam blocks 5F2 and 10F2, both located in slit trenches (see Figure 6), suffered relatively little damage (Inc = 11 percent and 3 percent, respectively). Block 15F2, however, had an Inc = 59 percent due to ejecta though some small branches fell across the slit trench. Block 20F1 had an Inc of 0 percent even though four trees fell across the trench. 30F1 had an Inc = 100 percent due to ejecta and not wooden fragments. Block 30F2 had an Inc of 0 percent even though the end of a broken tree trunk was actually in the slit trench. It is possible that the tree trunk, having missed the Styrofoam, could have helped shield the block from ejecta which may have arrived after the trunk.

Because of the large scatter in the Styrofoam-block data, it was decided to group the blocks by range before trying to use these data to assess the missile hazards to personnel as a function of type of exposure

VERTICAL STYROFOAM

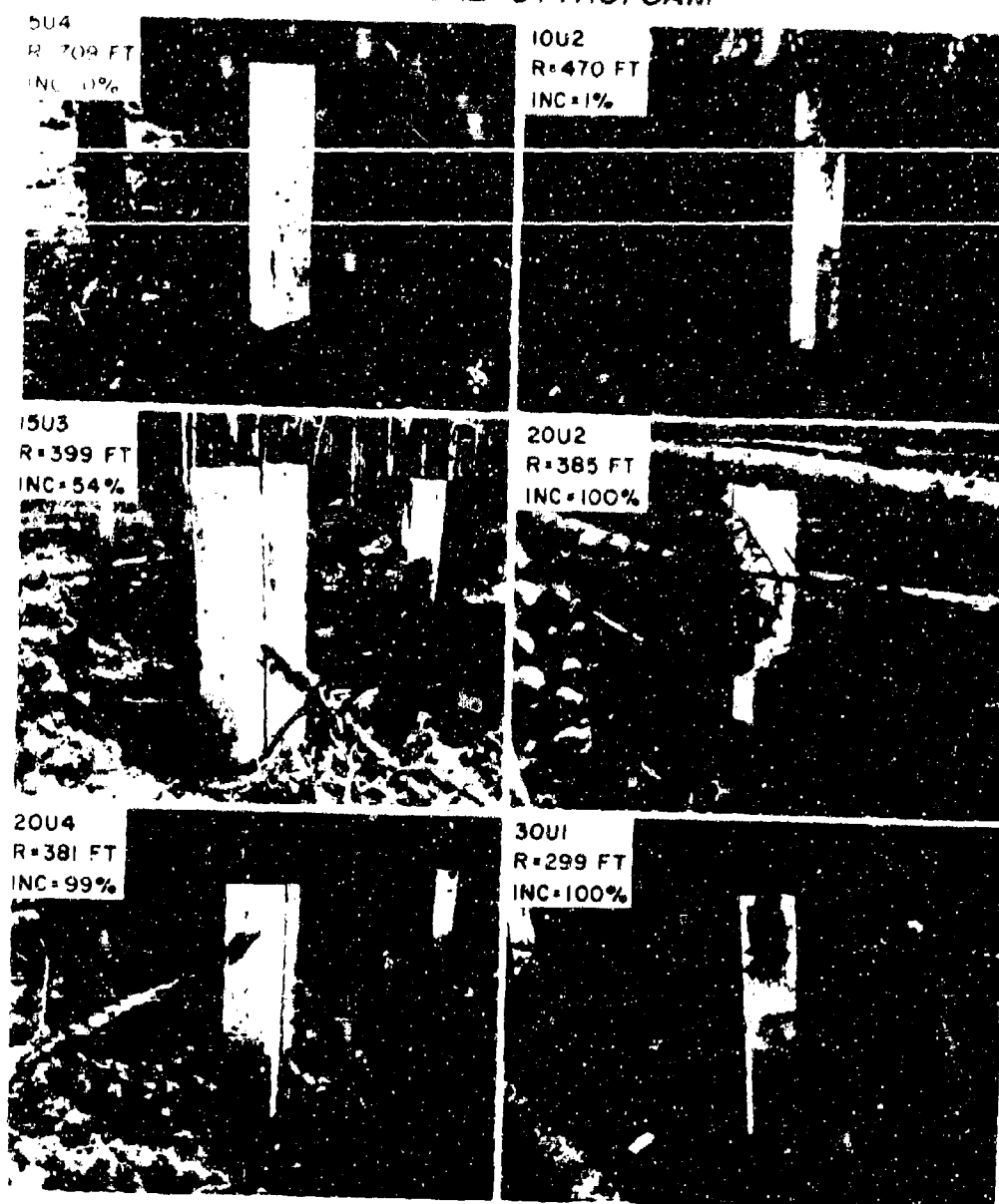


Figure 4. Six postshot views of vertical Styrofoam blocks located at the indicated ranges (R). "Inc" is the derived percent in-capitation for a man whose presented area is the same as that of the block, 4.5 ft.²

HORIZONTAL STYROFOAM

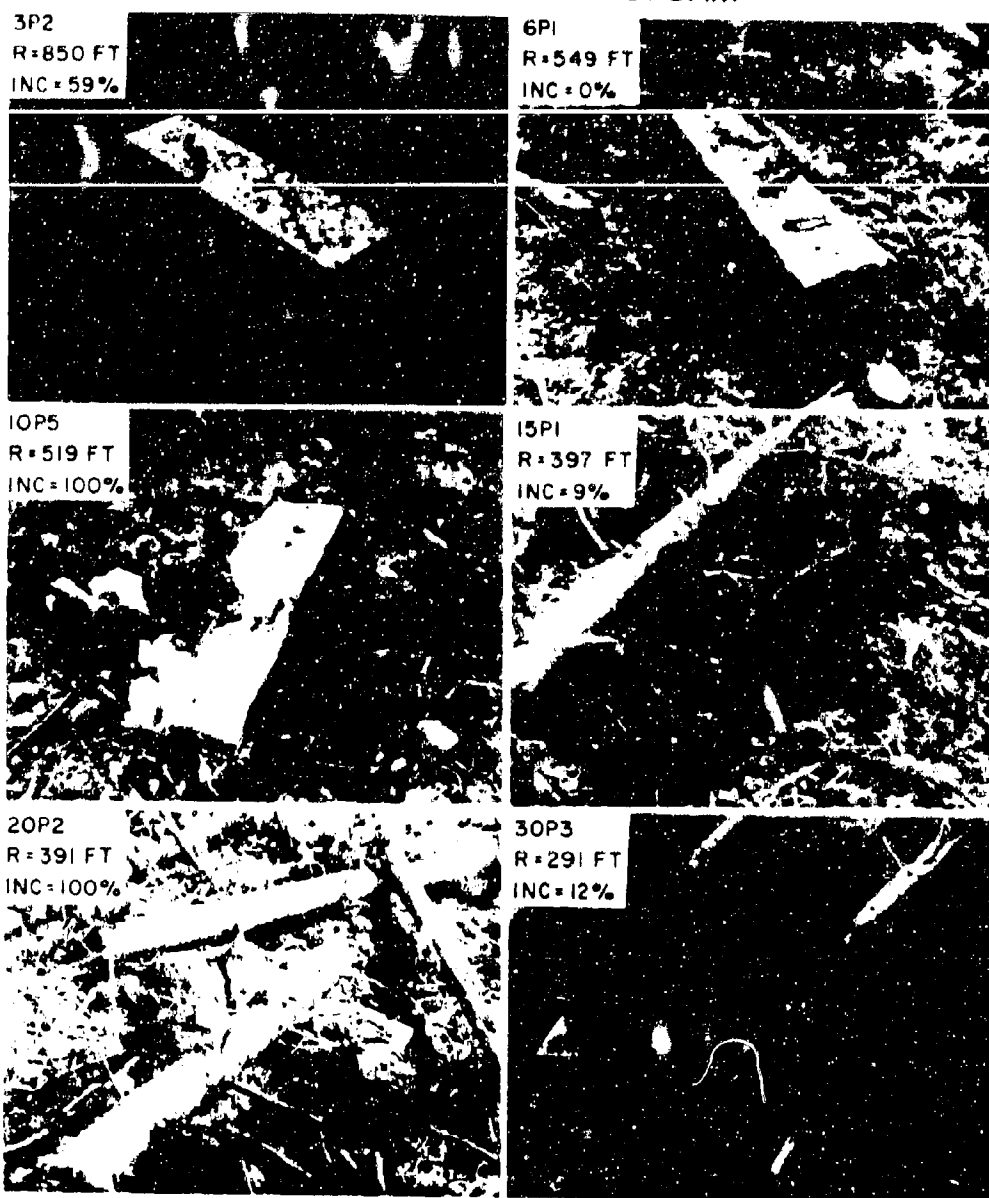


Figure 5. Six postshot views of horizontal Styrofoam blocks located at the indicated ranges (R). "Inc" is the derived percent incapacitation for a man whose presented area is the same as that of the block, 4.5 ft.²

SLIT TRENCH WITH STYROFOAM

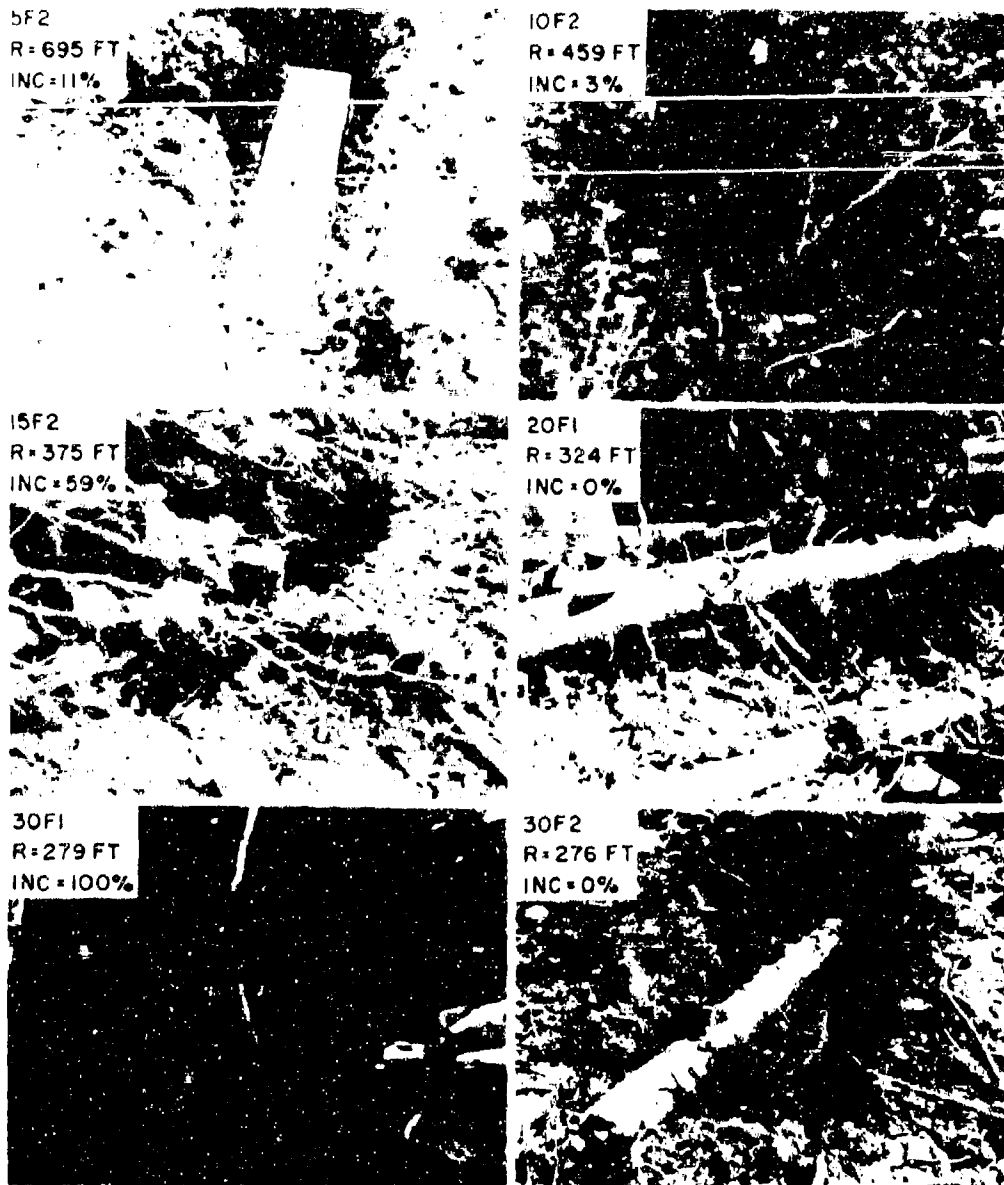


Figure 6. Six postshot views of slit-trench Styrofoam blocks located at the indicated ranges (R). "Inc" is the derived percent incapacitation for a man whose presented area is the same as that of the block, 4.5 ft².

(vertical, horizontal, or in a slit trench) and range. All the missile data were separated into 12 groups representing the three types of exposure and the four range intervals of 260-360, 361-460, 461-660, and 661-860 feet. If all the Styrofoam blocks in each of these groups are thought of as a single large block, and all the missiles which struck the smaller blocks are assumed to have struck the large composite block in random positions, it is possible (again assuming the missiles act independently of one another) to predict an average probability of incapacitation (P) to personnel by the following formula

$$P = 1 - \prod_{i=1}^n \left(1 - \frac{A_m}{A_c} P_i \right)$$

where n is the total number of missiles striking the composite block, P_i is the probability of the i 'th missile producing an incapacitation, A_m is the projected area of the man (assumed to be 6.2 square feet), and A_c is the area of the composite block in square feet. This formula is analogous to the formula given earlier for a single block, but the factor A_m/A_c has been included. This factor represents the probability that each of the missiles which struck the composite Styrofoam block would have struck a man provided (1) the man occupied any area, A_m , of the total composite block and (2) every missile striking the composite block did so in a random position. Whereas an adjustment was made to compensate for the difference in area between a man and a block, no such adjustment was made in the case of thickness. Since a man is probably thicker, on the average, than the Styrofoam (6 inches for Type II and 3 inches for Type IV), the damage to the horizontal blocks may be somewhat low.

Figure 7 represents the results of the above described analysis where the data points are plotted at the average range of all the Styrofoam blocks represented by a point; the number of such blocks is indicated. Since only one slit trench was located in the 461-foot to 660-foot range interval, and it had a range of only 463 feet, this block was grouped with the 361- to 460-foot slit trenches which accounts for the presence of only three slit-trench data points instead of four. Note that the percent incapacitation increases with decreasing range for all three types of exposure except for a reversal of the two horizontal-block points. Because of the small sample size, this reversal may not be significant. There may, however, be an actual tendency for the percent incapacitation for the horizontal position to at least "level off" with decreasing range corresponding to the tree debris which had a peak density about 300 to 350 feet from ground zero (Zaccor et al., 1967). Apparently some of the tree fragments originating at the closer ranges are blown further out by the blast winds. Thus, if most of these fragments do not strike the ground until after they have been displaced some distance, that portion of the hazards (in the horizontal and slit-trench positions) due to tree fragments would not necessarily increase and might even decrease at the shorter ranges.

That the horizontal orientation is more dangerous than the vertical orientation at large ranges is probably because most of the ejecta arrived

COMPUTED PERCENT INCAPACITATION VS RANGE FOR THREE TYPES OF EXPOSURE

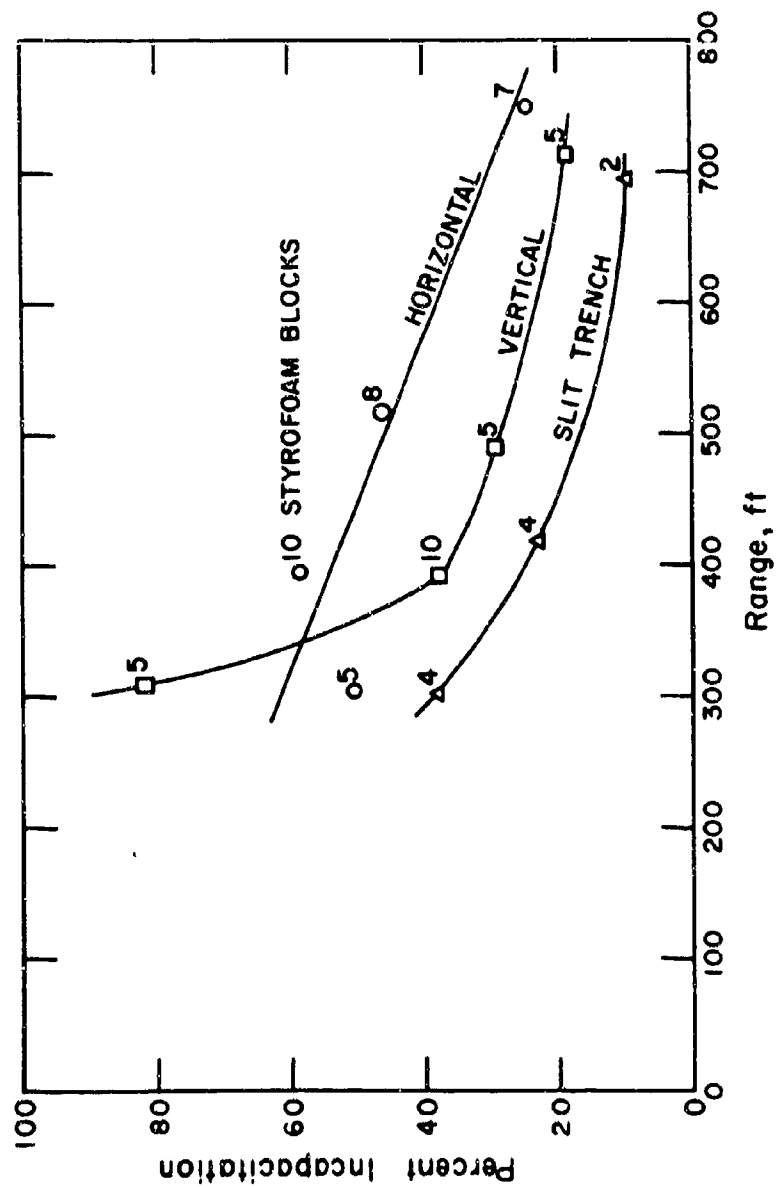


Figure 7. Computed percent incapacitation of personnel vs range for three types of exposure. The number of Styrofoam blocks used to compute each data point is indicated.

at angles greater than 45 degrees with respect to the horizontal and hence the horizontal traps presented a larger projected area. Impact angles between 60 degrees and 80 degrees have been reported for smaller charges (cited by Anonymous, 1944). At ranges less than 340 feet the vertical orientation appears to be more hazardous than the horizontal one. This could be caused by flatter trajectories for ejecta at these ranges and also the presence of wooden-fragment missiles. It would seem reasonable to suppose that the wooden fragments with the higher energies had larger horizontal components of velocity than vertical components. This view is supported by the fact that only one wooden missile remained embedded in all the horizontal and slit-trench Styrofoam blocks. It might thus be supposed that for ranges less than 340 feet, the ejecta arrives at an average angle of less than 45 degrees with respect to the horizontal. It should be remembered that the vertical orientation represents a man standing against a vertical surface, and not in the open.

As expected, the slit-trench position appears to be safer than the horizontal position at all ranges (see Figure 7). The slit-trench position also appears to be safer than the vertical position at all ranges which may not, in fact, be the actual case for the greater ranges. Certainly at the close-in ranges, where the vertical position is more dangerous than the horizontal position, one would expect the slit-trench to be safer than either of the other types of exposure. However, at the greater ranges one might expect the slit-trench position to be more hazardous than the vertical position due to the steep angle of descent of the ejecta. By choosing a not unreasonable average angle for the incoming debris (57 degrees with respect to the horizontal) one can use either the curve for the horizontal or the curve for the vertical position to predict that the percent incapacitation for the slit trench position at a range of 700 feet (averaging over the end-on and side-on orientations of the trench) should be approximately 24 percent instead of the 9 percent shown in Figure 7. This would place the slit-trench incapacitation above the level shown for the vertical position at 700 feet. The actual slit-trench incapacitation might indeed be as high as 24 percent at a range of 700 feet since, as can be seen in Figure 7, only two slit-trench blocks of Styrofoam were used to estimate the incapacitation at this range; thus, with a total area of only 9 square feet (less than 1.5 times the projected area of a man) the uncertainty in this point is very large.

Since the end-on slit-trench Styrofoam is less shielded by the upwind wall of the trench than the side-on slit-trench Styrofoam, one would expect the side-on to have a lower incapacitation than the end-on at the same range. This was found to be true for the 5, 10, 15, and 20 stations--only the 30 station showing a reversal on this trend. Since these two orientations of the trench represent the limiting conditions, one would expect that the slit-trench curve on Figure 7 (which was obtained by combining equal numbers of the two orientations) would approximate the condition of a randomly oriented slit-trench.

Sphere Traps

Approximately 30 percent of the steel spheres placed in front of the traps struck the Styrofoam and left impressions (some of the 1/8-inch diameter spheres remained embedded at recovery time) which could be used to compute the sphere impact velocities. Although more spheres actually hit the Styrofoam, those spheres which struck the 20C1 and 20C2 traps in the area crushed by the overpressure were not used since it was not known how the crushing would affect the physical characteristics of the Styrofoam. Even so, 30 percent success is as high as that obtained during Operation Snow Ball, 28 percent (Fletcher, et al., 1965a), presumably as a result of the improved sphere holder used during Operation Distant Plain.

The geometric mean impact velocities were computed (see Appendix) for each sphere size and for each of the six traps. These velocities are plotted in Figure 8 against the acceleration coefficient, α , of the spheres. Two points are missing because no spheres were caught in those particular groups. Since 1/4-inch diameter spheres ($\alpha = 0.0696$ square feet per pound) were used with all traps, two cleared-sector data points are plotted for this α for each range shown in Figure 8 (note that one of the relevant data points is missing at the 335-foot range) corresponding to the two traps in the cleared sector. The close agreement of these points indicates that the blast wave did not vary greatly across the 23-foot circumferential spacing of the two traps at each range.

Since the cleared-sector sphere data were approximately linear at each range (see Figure 8), a linear regression analysis was performed. In all three cases the best fit was a line with a slope less than, but not significantly different from, 1.0. For this reason, another analysis was performed to obtain the best straight line fits with slopes of 1.0. It was previously shown for experiments of this kind with relatively low yield detonations that the following formula is reasonably accurate (Fletcher et al., 1965a);

$$V = I\alpha$$

where V is the impact velocity of the spheres, α the acceleration coefficient, and I the dynamic-pressure impulse. Care must be taken to put all these quantities in consistent units.**

* Defined as the projected area of the sphere multiplied by the drag coefficient (assumed to be 0.47) and divided by the mass; α is usually given in terms of square feet per pound.

** In the English system of units, V would be in feet per second, I in (poundals per square foot) times seconds, and α in square feet per pound.

MEASURED SPHERE IMPACT VELOCITY(V) VS ACCELERATION COEFFICIENT (a)

Theoretical curves were computed using the measured pressure records.

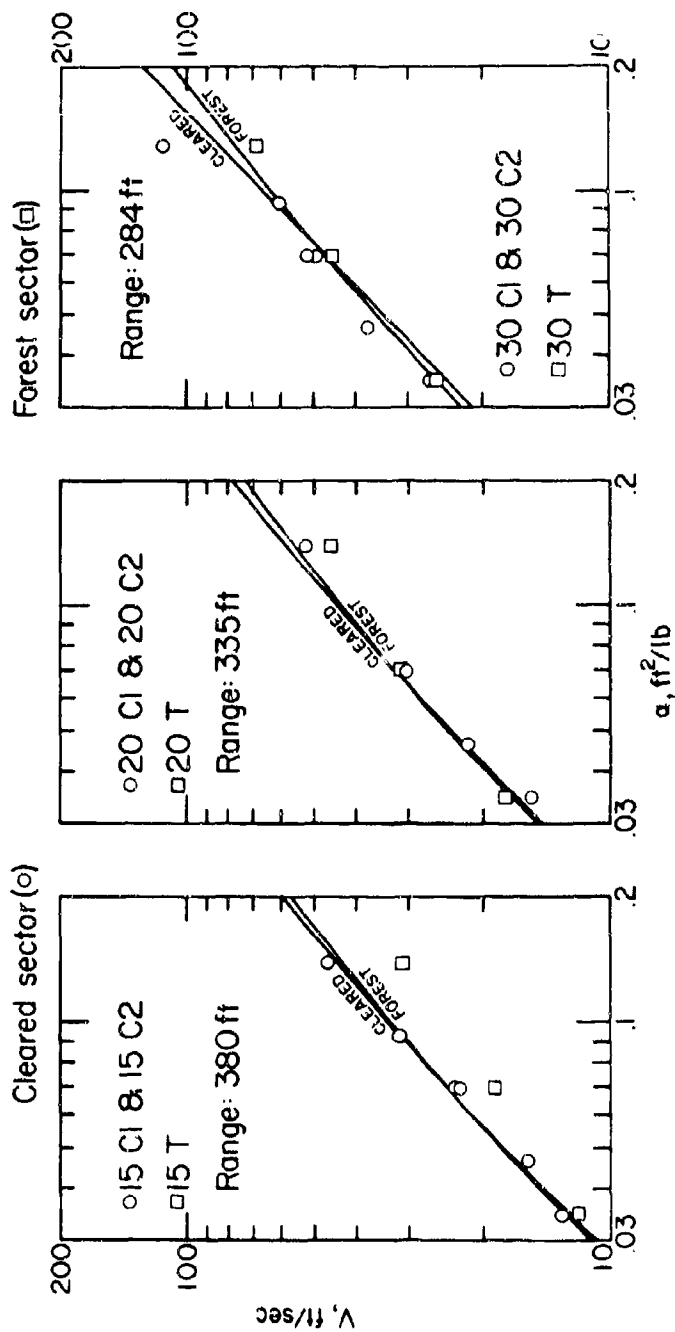


Figure 8. Measured impact velocity vs acceleration coefficient for the spheres in the cleared and forested sectors. The predicted curves were derived using the measured blast wave parameters.

Since the cleared-sector data in Figure 8 were approximated by the type of equation given above, the computed regression coefficients could be interpreted as dynamic-pressure impulses. These derived impulses are 73.8, 93.1, and 161 psi-msec for the 380-, 335-, and 284-ft ranges in the cleared sector, respectively.

The forested-sector sphere data shown in Figure 8 appeared, in general, to be concave downward rather than linear. The trap ranges for the cleared sector (given in the figure) are approximately equal to those for the forested sector, the differences being not greater than 8 feet. Since the forested-sector data could not be well approximated by straight lines with slopes of one, the dynamic-pressure impulses cannot be estimated in the manner they were in the cleared sector. Note that whereas for the lower α 's (≤ 0.06) the velocities are approximately equal in the forested and cleared sectors, for the higher α 's (≥ 0.1) the velocities in the forested sector are less than those in the cleared sector. This behavior could be explained if the dynamic-pressure impulses were about equal (at corresponding ranges) in the forest and in the open, but the dynamic-pressure curve had a lower peak value and a longer duration in the forest. The pressure records (Reisler, 1967) seem to indicate that this is indeed at least part of the explanation for the measured sphere velocities. Thus the peak overpressures (and presumably hence the peak dynamic pressures) were higher in the clear than in the forest (for the ranges of interest), whereas the dynamic-pressure impulses were about equal as will be shown later. The higher pressures in the cleared sector undoubtedly account for the two compressed Styrofoam sheets mentioned earlier. Using the pressure records and the new translation model (Fletcher and Bowen, 1966), curves of predicted sphere impact velocity vs acceleration coefficient were computed and these are also shown in Figure 8. Note that although these curves do predict higher velocities for the larger α 's in the cleared than in the forested sector, the predicted separation does not seem to be as great as was observed. For the smaller α 's the curves predict the velocities to be approximately equal and, in fact, indicate slightly higher velocities in the forested than in the cleared sector, an indication not incompatible with the data (see data for $\alpha = 0.0348$ at 335-ft range, Figure 8). It would thus seem that the curves in Figure 8 fit the data fairly well although there are possible differences between theory and experiment. The data are too sparse to conclude whether these differences are significant or merely the result of random variations.

That the dynamic-pressure impulses in the forested and cleared sectors were approximately equal is indicated by Figure 9 which includes the impulses obtained (1) by BRL using strain gauges and the BRL self-recording gauge (Reisler, 1967), (2) by Australian personnel using a passive-type permanent-deformation gauge (Howe, 1967), and (3) by The Lovelace Foundation using the steel spheres described in the present report. Note that the data from all three sources seem to agree fairly well with no apparent difference between the forested and cleared sector data and no apparent trend with gauge elevation. Further, all the data seem to fall along a straight line (on log-log paper) except for two BRL

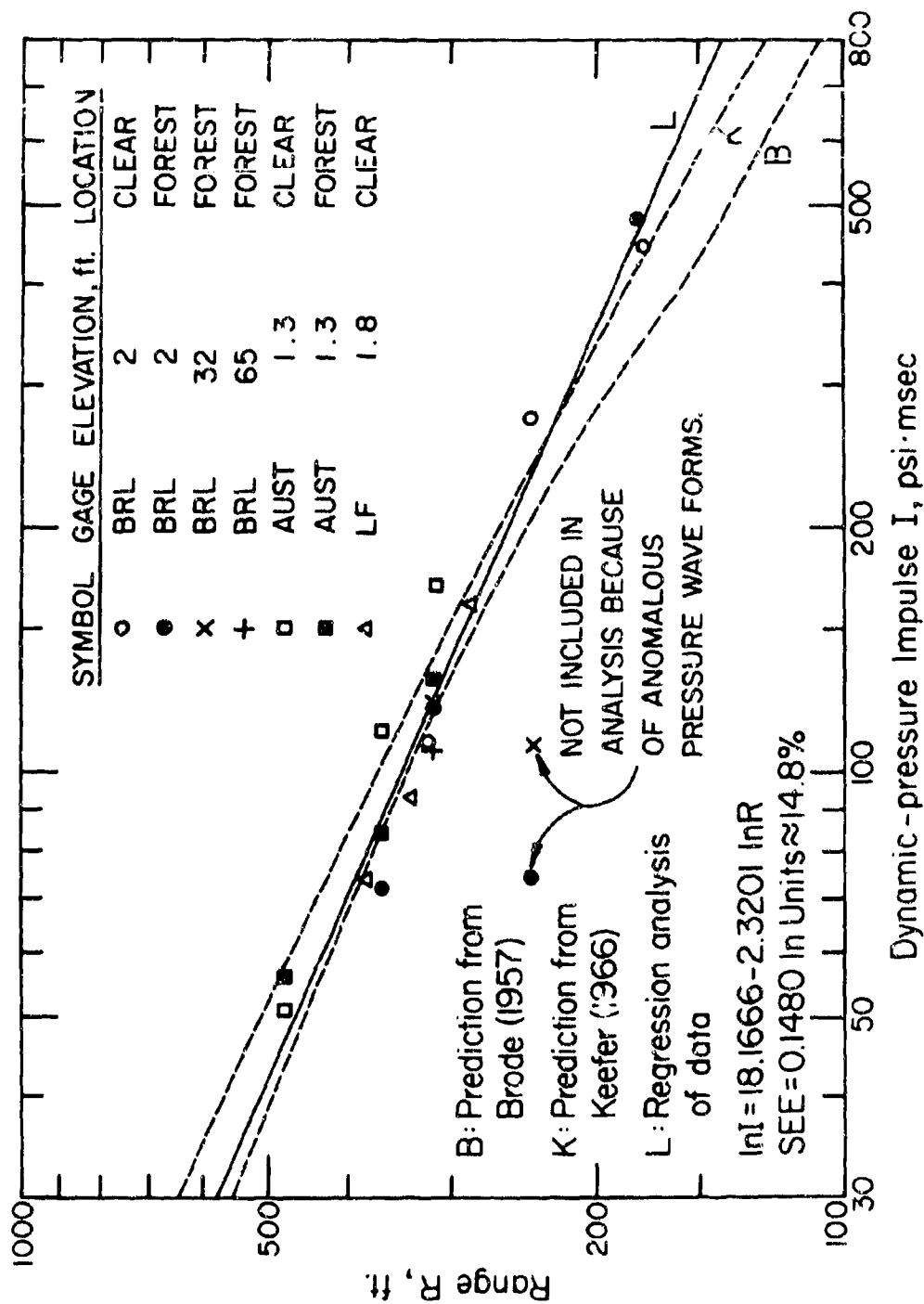


Figure 9. Dynamic-pressure impulse vs range. The data were obtained by BRL (Reisler, 1967), Australian personnel (Howe, 1967), and The Lovelace Foundation (present report). The two curves, B and K, are predictions taken from Brode (1957) and Keefer (1966), respectively. The straight line, L, is the result of a regression analysis of all the data excluding the two indicated points.

points corresponding to the only station where the pressure records exhibited multiple shocks. For these reasons a regression analysis was performed on all the data (excluding the two anomalous points) and the regression line, L, is plotted in Figure 9 along with the equation. The standard error of estimate for the dynamic-pressure impulse was computed to be about 14.8 percent over the range interval tested (170-480 ft). The B and K curves in Figure 9 are predictions taken from Brode (1957) and Keefer (1966), respectively. Brode's prediction was determined from a curve of scaled dynamic-pressure impulse vs overpressure (cleared-sector values used) by assuming an ambient pressure of 12.2 psi, an ambient speed of sound of 1146 ft/sec, a yield of 50 tons, and a reflection factor of 1.63 (which has been used previously; Fletcher and Bowen, 1966). In general, the B curve predicts smaller impulses and fits the data better at the greater ranges while the K curve predicts greater impulse and fits the data better at the smaller ranges. For this reason, it is difficult to say which prediction is better.

Dummies

The measured total displacements of all six dummies are given in Table 2. In every case the dummy's initial and final positions fell almost exactly along the same radial line from ground zero. At each range, the dummy initially facing downwind went farther than the dummy initially facing upwind, but these differences may not be significant. However, if the winds on the legs of a dummy initially facing downwind caused the knees to give way, the weight on the feet would be reduced and thus the friction between the dummy's shoes and the ground would not be as effective at retarding the motion. In the case of a dummy initially facing upwind, the winds on the legs would tend to "lock" the knees.

The predicted velocities and displacements in Table 2 were obtained using the revised translation model (Fletcher and Bowen, 1966). An α of $0.052 \text{ ft}^2/\text{lb}$ was assumed for both orientations of the dummies and the blast wave parameters were estimated from the experimental records (Reisler, 1967) and theoretical calculations of Brode (1957). A similar procedure was employed in connection with Operation Snow Ball (see computation of "C" curves in Figure 4, Fletcher and Bowen, 1966) except that, in the present case, the measured side-on positive overpressure impulses were used rather than the predicted impulses (from Brode) which were used before. The predicted displacements agree reasonably well with the measured displacements at the 20 and 30 stations, but at the 15 station the measured displacements are too great. Notice that the dummies at the 15 station (range of 378 feet) were actually displaced farther than the dummies at the 20 station (range of 332 feet) even though the sphere data at the same locations did not suggest that the 15 station dummies should have had greater velocities (see Figure 8). The same kind of reversal in displacement with range occurred for dummies at the 965- and 790-foot ranges during Operation Snow Ball (Fletcher and Bowen, 1966). That is, the dummies at the 965-foot range went farther than predicted and farther than the dummies at the 790-foot range which behaved approximately as expected. From motion picture coverage

TABLE 2. DUMMY DISPLACEMENTS AND VELOCITIES					
STATION	RANGE	PREDICTED* VELOCITY	PREDICTED* DISPLACE- MENT	MEASURED DISPLACEMENT	
				OF D1 (INITIALLY FACING UPWIND)	OF D2 (INITIALLY FACING DOWNWIND)
15	378	16.5	7.8	12.3	12.8
20	332	22.7	12.7	9.2	9.5
30	277	35.1	25.0	19.4	24.8

* Predictions were made using a combination of the measured blast wave parameters (Reisler, 1967) and the theoretical calculations of Brode (1957) in connection with the new translation model (Fletcher and Bowen, 1966). An α of 0.052 ft²/lb was assumed for both orientations of the dummies.

* Predictions were made using a combination of the measured blast wave parameters (Reisler, 1967) and the theoretical calculations of Brode (1957) in connection with the new translation model (Fletcher and Bowen, 1966).
An α of 0.052 ft²/lb was assumed for both orientations of the dummies.

of the dummies and analysis of the data, it was determined that the extended displacements at the 965-foot range were due to anomalous winds which persisted well beyond the predicted positive-phase duration and, in fact, did not seem to have a negative phase. The spheres did not receive the full effect of these extended winds because they impacted the Styrofoam after only 4 feet of travel, at which time the winds were still blowing. The similarities between the dummy and sphere behavior during Operations Distant Plain and Snow Ball suggest similar mechanisms may have been responsible for these effects.

Figure 10 shows the final resting positions of each of the six dummies initially placed at the indicated ranges (R). All the dummies appeared to be in good condition but each had lost its helmet. Note that a big tree fell across the 15D2 and a small tree fell across the 20D2 dummy. The clothing appeared to be intact on the dummies at the 15 and 20 stations. At the 30 station, however, the clothing was torn on the legs of both dummies (see Figure 10) and the jacket was torn on the left shoulder of dummy 30D2. Note that the goal-post like arrangement supporting the 20D2 dummy was bent by a tree falling across it.

In order to assess the personnel hazards from translation, it is necessary to have some idea of man's susceptibility to impact. A rule-of-thumb that has been used in the past is that the threshold for injury during total-body impact occurs at an impact velocity of 10 ft/sec (White, 1966). Therefore, for want of a better criteria, the threshold for translational injury (in the forested or in the cleared sector) was assumed to occur at the range where the maximum unobstructed translational velocity was predicted to be 10 ft/sec for man. Because of the low α 's for man and the relatively short blast-wave durations, the peak velocity would be achieved after a short distance of travel, particularly at the greater ranges. It is thus reasonable to assume that a man's orientation would change little during the acceleration phase; i. e., his α would be nearly constant. Further, he is likely (depending on his initial orientation) to remain relatively free of the ground over the short distance he travels in achieving peak velocity; i. e., the effects of ground friction are likely to be small. Under these conditions, the maximum translational velocity can be approximated by multiplying the dynamic-pressure impulse (see Figure 9) times the acceleration coefficient for a man in a particular initial orientation (see analysis of sphere velocities). Acceleration coefficients (α 's) have been previously reported (Fletcher, 1965b) for a man:

1. standing broadside to the wind: $\alpha = 0.052$
2. crouching broadside, standing sidewise, or prone perpendicular to the wind; (i. e., these orientations are approximately equivalent): $\alpha = 0.021$
3. prone aligned with the wind: $\alpha = 0.0063$.

Using the equation in Figure 9, the ranges where threshold translational injury should occur were computed as 500, 340, and 200 feet for the three α 's listed above, respectively. Since the equation in Figure 9 applies

DUMMIES

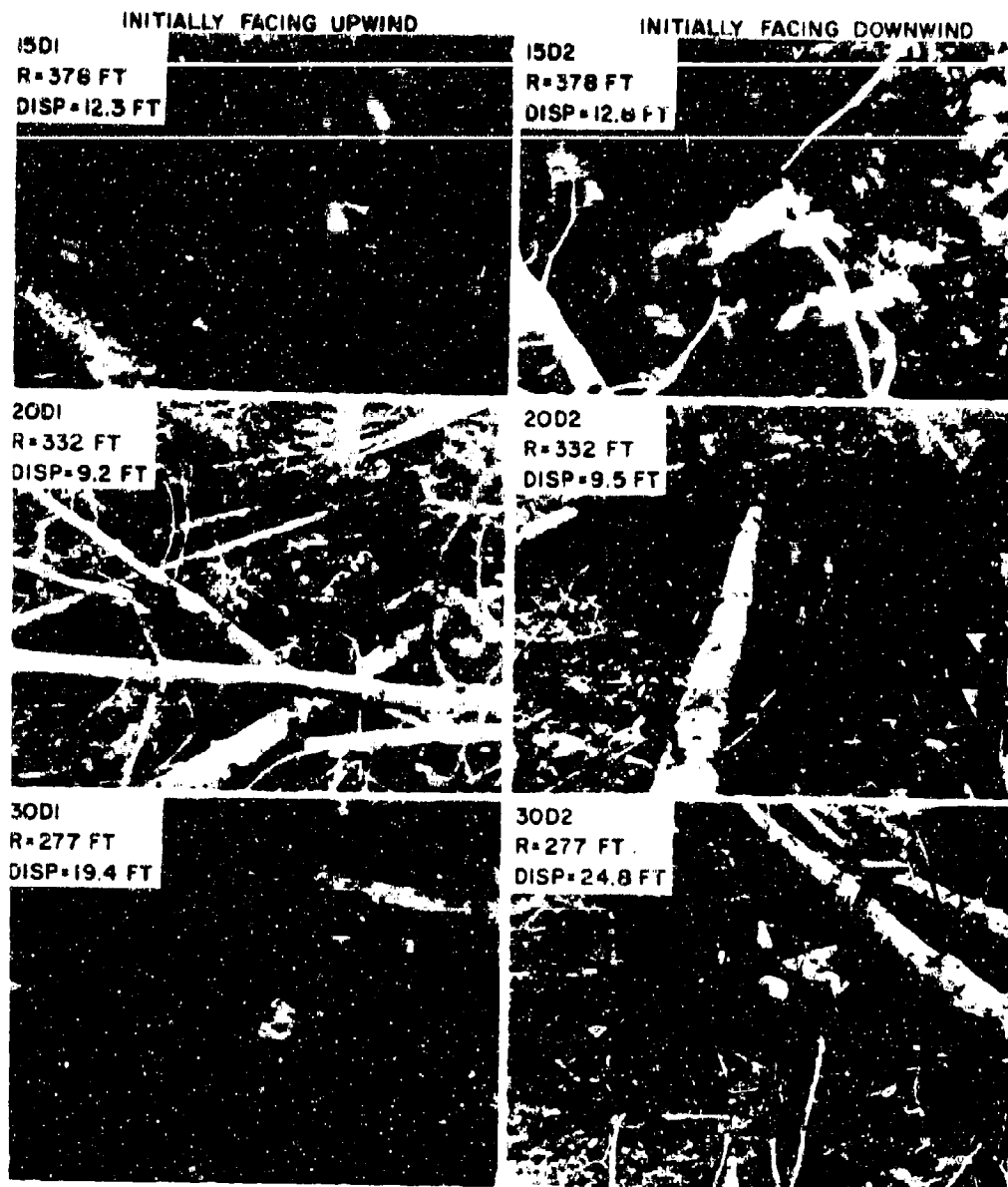


Figure 10. Final resting positions for all six dummies. R is the initial range of the dummy from ground zero and "Disp" the total downwind displacement of the dummy.

to both the forested and cleared sectors, these ranges should also apply to both sectors even though the peak incident overpressure varied (at the same range) between the forested and cleared areas.

ESTIMATED PRIMARY EFFECTS

In order to use the measured blast-wave parameters (Reisler, 1967) to assess the hazards from primary blast effects, it is necessary to have some idea of man's susceptibility to such effects. In a forthcoming DASA report (Bowen et al., in preparation) a study involving 13 mammalian species is analyzed and used to predict the survival of men exposed against a reflecting surface to normally-incident approximately-classical shock waves produced by high explosives or by shock tubes. For a 70-kg man and an ambient pressure of 12.2 psi, the prediction is given by the following equation:

$$P_r = 51.04 \left[1 + 7.465 t_+^{-1.064} \right] \exp \left[0.1788 (5 - Z) \right]$$

where P_r is the peak overpressure at the reflecting surface in psi, t_+ the duration of the positive overpressure at the reflecting surface in msec, and Z is the survival in probit units. Although all the data used to derive the equation were obtained in a reflective geometry, there is experimental evidence (Richmond et al., 1966b) that the predictions can be extended to free-field cases in the following ways:

1. The equation will approximately apply to a man prone aligned with the winds (i. e., feet or head toward the blast) if P_r is assumed to be the peak incident overpressure and t_+ is assumed to be the duration of the positive incident overpressure.
2. The equation will approximately apply to a man perpendicular to the winds (i. e., standing facing in any direction or prone perpendicular to the winds) if P_r is assumed to be the sum of the peak incident overpressure and the peak dynamic pressure and t_+ is again assumed to be the duration of the positive incident overpressure.

The peak dynamic pressure and the peak reflected overpressure can, of course, be computed from simple shock-wave theory if the peak incident overpressure is known. Thus, if at a given range the peak value and the duration of the positive incident overpressure (which is assumed to be equal to the duration of the positive reflected overpressure) are known, the mortality due to primary blast injury can be estimated as a function of initial orientation.

In the manner described above, the survival from primary blast effects was predicted* as a function of orientation and range for both the forested and

* In the forest it is assumed that the personnel are located far enough from trees that the incident blast wave is essentially undisturbed.

cleared sectors. These predictions are shown in Figure 11 where the P_i (i. e., incident overpressure) curves apply to a man initially prone aligned with the wind, the $P_i + Q$ (i. e., incident overpressure plus dynamic pressure) curves apply to a man initially perpendicular to the wind, and the P_r (i. e., reflected overpressure) curves apply to a man initially against a vertical reflecting surface. This figure clearly indicates the protection from primary blast effects afforded by the forest as opposed to the threshold for translational injury which was essentially unaffected by the forest.

The threshold for lung damage (hemorrhage) occurs at much lower pressures than those required to produce death. A rule-of-thumb (taken from Richmond et al., 1966b and White, 1966) is that for each orientation, the threshold for lung injury will occur at the range where the appropriate pressure (P_i , $P_i + Q$, or P_r) has one-fifth the value that would produce 50 percent mortality if the duration at that range were unchanged. It is interesting to note that according to the previously given equation for survival, this rule-of-thumb threshold lung injury condition should produce only one death in about nine quintillion (9×10^{18}) people. The ranges for threshold lung damage were computed in a manner analogous to the computation of the survival vs range curves. These threshold ranges as well as the ranges for 99, 50, and 1 percent lethality are listed in Table 3 for the three orientations and for both the forested and cleared sectors. Also given are the peak incident overpressures and the durations of the positive incident overpressures at these ranges. Note that although the range where a given effect occurs varies between the forested and cleared sectors, the peak incident overpressure does not. This is because all the durations are long compared to the response time of man, and thus a change in the duration has a much smaller effect on lethality than a comparable change in the peak incident overpressure. At the shorter ranges occurring in Table 3, the experimental records indicate that the overpressures were higher in the clear than in the forest while at the greater ranges the opposite is true, the crossover point occurring at about 450 feet.* As a result, every effect in Table 3 occurs at a greater range in the cleared sector than in the forested sector except for the two effects which occur at ranges greater than 450 feet; namely, threshold lung damage for a man initially against a vertical reflecting surface and for a man initially perpendicular to the wind. Thus, the earlier conclusion that the forest afforded some protection against primary blast effects is still true except for ranges ≥ 450 feet where the hazard was relatively small in any case. It should be noted that whereas, in general, the overpressures are significantly different at the same range in the forested and cleared sectors, the experimental records indicate that the durations of the positive incident overpressures are essentially the same.

* It has been suggested that the lower pressures in the open beyond ~450 feet may be due to the contour of the terrain (Reisler, 1967).

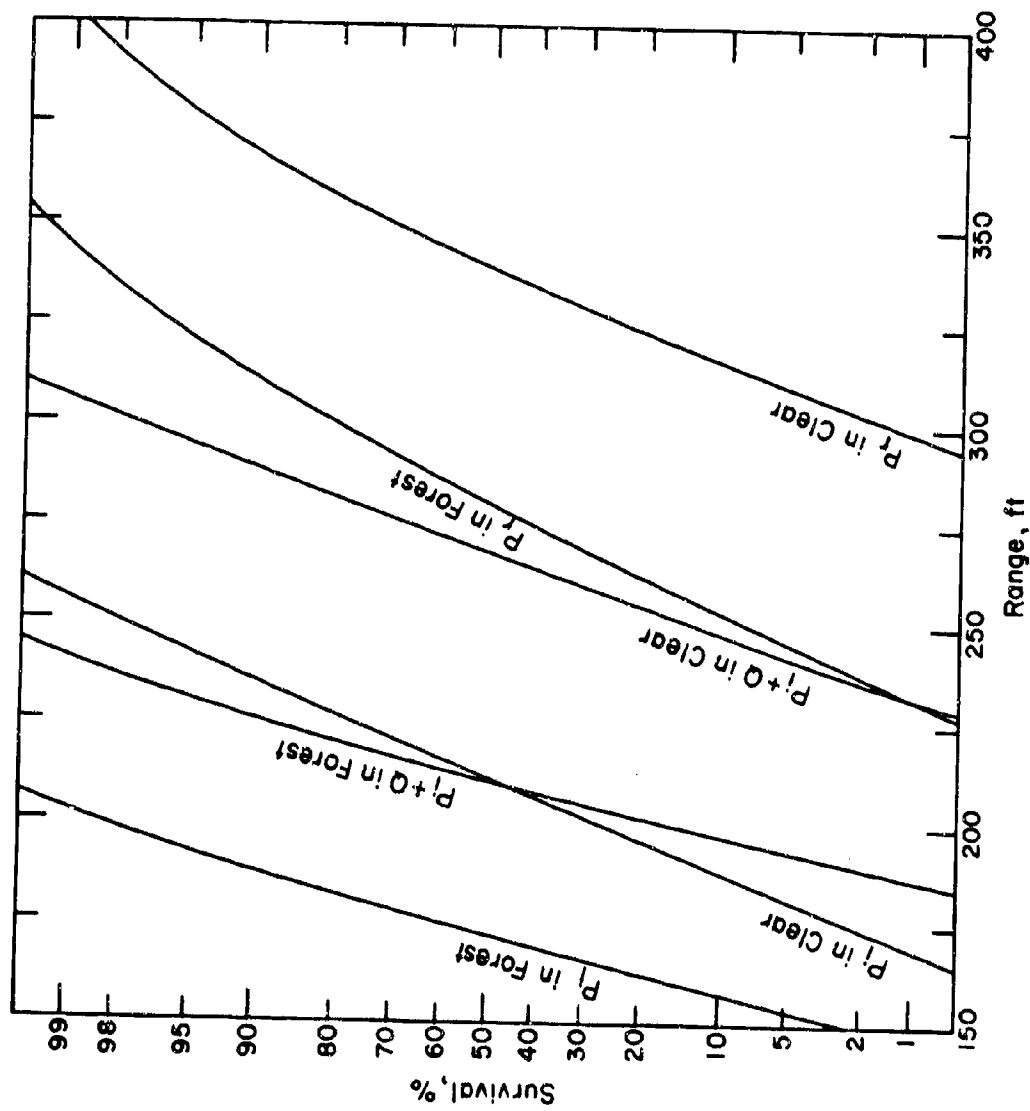


Figure 11. Predicted survival from primary blast effects in the forested and cleared sectors. Curves were computed for men initially: (1) prone aligned with the wind (P_i), (2) perpendicular to the wind ($P_i + Q$), and (3) against a vertical reflecting surface (P_r).

TABLE 3. PREDICTED PRIMARY BLAST EFFECTS

	FORESTED SECTOR				CLEARED SECTOR			
	Range, ft	Peak Incident Overpressure, psi	Duration of Positive Incident Overpressure, msec	Range, ft	Peak Incident Overpressure, psi	Duration of Positive Incident Overpressure, msec		
Initially prone aligned with the wind	150	86	43	170	86	51		
	170	56	51	210	56	63		
	200	36	61	260	36	75		
	390	11	100	420	11	110		
Initially perpendicular to the wind	190	45	56	230	45	69		
	210	33	63	270	33	78		
	250	22	74	310	22	87		
	460	8.7	120	460	8.7	120		
Initially against a vertical reflecting surface	230	25	69	300	25	85		
	280	18	81	340	18	94		
	340	13	94	400	13	100		
	850	4.5	150	680	4.5	140		

DISCUSSION

The sphere and dummy experiments in the present study provided further verification of predictive techniques that had been developed earlier (Fletcher and Bowen, 1966). That is, the predicted and experimental sphere impact velocities (Figure 8) agreed fairly well, with both indicating higher velocities in the cleared sector than in the forest for the larger a 's (≥ 0.1) and approximately equal velocities for the smaller a 's (≤ 0.06). Further, the dynamic pressure impulses derived from the sphere data agree with the impulses from other sources as is indicated by Figure 9. The measured impulses appear to be about equal in the forested and cleared sectors and agree fairly well with the predictions of Brode (1957) and Keefer (1966).

The predicted and measured dummy displacements are in fair agreement (see Table 2) except at the 15 station where the prediction is too low. Since the measured sphere velocities were close to the predictions, this suggests that the winds (at the 15 station) continued beyond the transit time of the spheres from their mounts to the Styrofoam sheets similar to the situation encountered in Operation Snow Ball (Fletcher and Bowen, 1966).

The ground ranges where threshold translational injury should occur were computed to be: 500 feet for man standing broadside to the wind; 340 feet for a man crouching broadside, standing sidewise, or prone perpendicular to the wind; and 200 feet for a man prone aligned with the wind. Since these ranges were based only on peak translational velocity considerations, they should be approximately correct even if the measured total displacements did not correspond to theory. Thus the threshold condition is not assumed to depend on the proximity of obstacles such as trees although, in general, translation maybe more hazardous in the forest than in the open. At ranges where the complete "unobstructed" time-displacement history of a dummy can be reasonably approximated, the personnel hazards due to translation can be estimated by geometrical considerations. In particular, if the initial position of a dummy (relative to the down-wind obstacles) is postulated, the dummy's velocity can be computed at the point where it would strike one of the obstacles (assuming it strikes one at all). This velocity would then be used to estimate hazards to personnel (White et al., 1965; White, 1966). As a first approximation, it would not be unreasonable to assume that if any of the six dummies in the present study had struck an obstacle, they would have had, on the average, one-half the appropriate predicted velocity (listed in Table 2) at the moment of impact. It should be noted that trained troops would, however, probably drop to the ground upon seeing the flash from an explosion.

Estimations are presented in Figure 7 of the personnel hazards from missiles (crater ejecta and falling trees and tree fragments) generated by a 50-ton surface detonation in a coniferous forest. The relative percent incapacitations for the three types of exposure are as expected except that the slit-trench position seems unaccountably safe at the greater ranges

considering the reported average angle of impact for crater debris (60-80 degrees; cited by Anonymous, 1944) which constitutes the primary missile hazard at the greater ranges. However, because of the small sample size it might indeed be the case that at a range of 700 feet, the slit-trench position is more dangerous than the vertical position (but not more dangerous than the horizontal position). It should be remembered that the curves in Figure 7 take into account falling trees and tree fragments with the understanding that the vertical position represents a man standing against a rigid vertical surface protecting him to some extent from overhead blows.

The hazards to standing personnel not against a vertical surface would include whole-body translation in addition to missiles. It is possible, however, that some personnel might grab a support (assuming they had not been instructed to drop to the ground upon seeing the flash from an explosion) and thus still be standing when the trees fall. In this case the hazards could be estimated by using the distribution of fallen trees and tree fragments to predict a percent incapacitation which would have to be statistically combined with the percent incapacitation due to missiles as shown in Figure 7. From the number and type of painted tree fragments obtained, it appears that the tree trunks alone would account for most of the increased hazard. The number of falling trees could be estimated from the tree density and the percent which fell as a function of range (see Table 1).

Although it was impossible to determine the nature of many of the missiles that left dents in the Styrofoam blocks, it was noted that ejecta impacts appeared to be much more frequent than tree-fragment impacts. Thus, the ejecta and tree-fragment effects could not be completely separated; however, a few general comments can be made concerning the hazard due to tree fragments alone. For ranges beyond about 520 feet (~ 7.7 psi) the tree-fragment hazard is probably negligible since essentially none of the trees were down and, as mentioned earlier, the trunks apparently account for most of the hazards associated with tree fragments. Of course, even at these ranges, it would still be possible for a man to be thrown against a standing tree by the winds, but the impact velocity would be too small to be considered dangerous. From 520 feet (~ 7.7 psi) to 340 feet (~ 13 psi), as the number of trees blown down increases from 0 to 100 percent, the tree-fragment hazards should increase partially due to the greater number of trees down and partially due to more branches being stripped off the trees such that the trunks are more likely to impact the ground instead of being supported on the branches. Even if the trees are all down, the percent incapacitation is not necessarily 100 percent as can be seen in Figure 7. Nonetheless, at ranges where all the trees are down, the hazards due to tree fragments might continue to increase somewhat with decreasing range as a result of higher velocities and fewer branches left to support the trunks. In addition to the tree fragments falling with relatively small horizontal velocities, high-speed charred wooden fragments (which were detected out to a range of 420 feet) also constitute a hazard. Similar fragments were found on the ground at ranges well beyond 420 feet but they were small and apparently not energetic enough to represent

a significant hazard (i. e., none were caught in the Styrofoam blocks). Since these fragments were all charred, they apparently came from inside or near the fireball, and therefore might not have been produced if the point of detonation had been somewhat above the trees.

The predicted survival from primary blast effects is shown in Figure 11 as a function of ground range and initial orientation for both the forested and cleared sectors, and the ranges for 99, 50, and 1 percent lethality as well as those for threshold lung damage are given in Table 3. Also included in Table 3 are the peak incident overpressures and the durations of the positive incident overpressures at these ranges. Although the range where a given effect occurs varies between the forested and cleared sectors, the peak incident overpressures does not. This is because all the durations are long compared to the response time of man and thus, a change in the duration has a much smaller effect on lethality than a comparable change in the peak incident overpressure. At the shorter ranges occurring in Table 3, the experimental records indicate that the overpressures were higher in the clear than in the forest while at the greater ranges the opposite is true, the crossover point occurring at about 450 feet. As a result, every effect in Table 3 occurs at a greater range in the cleared sector than in the forested sector except for the two effects which occur at ranges greater than 450 feet; namely, threshold lung damage for a man initially against a vertical reflecting surface and for a man initially perpendicular to the wind. Thus, the forest afforded some protection against primary blast effects except for ranges $\geq$ 450 feet where the hazard was relatively small in any case. It should be noted, however, that orientation influenced mortality more than the presence or absence of the forest.

Based on the above findings, the following would probably be observed in connection with blast hazards on a similar test without ejecta:

1. Below ~ 8 psi, no significant hazard was present in either the forest or the open.
2. From ~ 8 psi to ~ 30 psi the principal hazards in the forest were due to tree blow-down and whole body translation. Therefore, personnel in the open were probably safer in this pressure region.
3. Above ~ 30 psi the primary blast hazard was predominant and the forest afforded some protection against this. Nonetheless, it is unlikely that mortality would be much smaller (at a given range) in the forest than in the open due to the increased secondary and tertiary blast hazards in the forest.
4. The shallow foxholes provided good but not complete protection against fragments from the small-crowned coniferous trees found in this forest.

It would thus seem that, in general, the forest is more hazardous than the open from the point of view of blast effects. Of course, thermal

and initial ionizing radiation would also have to be considered if the explosion were nuclear.

Whereas the blast parameters (and therefore presumably the primary blast effects) may scale fairly well for forest shots of varying yields, other parameters do not. For example, gravity and the forest itself will not scale with yield or, in other words, the ejecta and the tree hazards do not scale. The problem is perhaps more complicated for ejecta than for trees since damage to trees can probably be related to partial dynamic-pressure impulse; i. e., the impulse of the dynamic-pressure wave up to a critical time corresponding approximately to one-fourth the natural periods of the trees. The concept of partial impulse has previously been used to assess the primary biological effects of air blast (Richmond et al., 1966a; Bowen et al., 1966) and also to predict the response of structural targets (Sewell, 1964; Sewell and Kinney, 1966). One prediction resulting from the partial-impulse concept would be that blast damage to trees, like blast damage to humans, would essentially be a function of overpressure alone for sufficiently large yields, (i. e., yields large enough to give durations long compared to the response times of the exposed trees or men).

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40

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APPENDIX

Calibrations

The two grades of Styrofoam, Type II and Type IV, used in the present study had similar but not identical physical characteristics to the Type II and Type IV Styrofoam used in Operation Snow Ball.* A calibration for steel-sphere impact velocity (V) as a function of sphere radius (R) and the depth of penetration (S) was accomplished, as before, by dropping the spheres from heights between 15.45 and 74.46 feet and computing the impact velocities. The data fit the same form of equation as was previously used, namely:

$$\log_{10} V = K_1 + K_2 \log_{10} f(S/R) + K_3 \log_{10} R$$

$$\text{where } f(S/R) = (S/R)^2 (3 - S/R) \quad S/R \leq 1$$

$$= 3 S/R - 1 \quad S/R \geq 1.$$

With S and R measured in inches and V in ft/sec, the new regression coefficients and standard errors of estimate (SEE) for the two types of Styrofoam are

	Type II	Type IV
K_1	1.2828	1.7126
K_2	0.5485	0.4406
K_3	0.0160	-0.0139
SEE of log V, log units	0.0238	0.0390
SEE of V, percent	5.5	9.0

The limits of the data are approximately the same as before except the largest steel sphere used had a radius of 0.25 inches.

In addition to the sphere calibrations, both types of Styrofoam were also calibrated for irregular objects in anticipation of the Styrofoam's being struck by tree fragments, rocks, mud clods, etc. Irregular pieces of wood (various lengths of 2" x 2", 2" x 4", 4" x 4", and 6" diameter stock)

* Fletcher, E. R., I. G. Bowen and R. F. D. Perret, "Impact Velocities of Steel Spheres Translated by Air Blast," Technical Report DASA-1656. Department of Defense, Washington, D. C. Also in Symposium Proceedings: Operation Snow Ball Vol. 1: 454-481. Department of Defense, Washington, D. C., 1965.

with masses between 116 and 1420 grams were dropped in random orientations on the Styrofoam from the same heights as those used for the steel spheres. Wooden spheres (0.62" to 3.26" diameters) with masses between 1.63 and 251 grams were also used as calibration objects. When the volume of the impression for either type of Styrofoam was plotted on log-log paper against the impact energy, the data could be approximated by a straight line with near the theoretical slope of one (i. e., the volume is approximately proportional to the energy). Further, the steel and wooden sphere data fell along this same line (see Figure A1). Consequently a regression analysis was performed on the combined irregular-wood, wooden-sphere, and steel-sphere data for both types of Styrofoam where only impressions with volumes near or greater than 0.5 cm^3 were used, this being a practical lower limit. Volume was determined by filling the impression with a rather coarse but uniform sand (fish-bowl gravel) which was then transferred to a graduated cylinder. For volumes less than 0.5 cm^3 , irregularities in the Styrofoam and sand and inaccuracies in reading the graduated cylinder made the volume determination uncertain. Fortunately, it was found that for both types of Styrofoam the energy required to produce this volume was small enough to be of little interest when considering the impacting object as a missile striking a human target, unless a sharp object and a vulnerable area or organ such as the eye were involved.

The calibration regression equations for irregular objects are presented in Figure A1. As expected the percent error in the impact energy of an irregular object computed from the volume of the impression is quite large compared to the percent error in the impact velocity of a steel sphere computed from the depth of penetration, the standard errors of estimate being approximately 22 percent for Type II and 28 percent for Type IV Styrofoam compared to 5.5 percent and 9.0 percent, respectively, for the steel-sphere calibrations. Note that the greatest energy obtained in the calibration experiments was approximately 5700 foot-pounds or 180 ft-lb.

IMPACT ENERGY VS VOLUME OF IMPRESSION

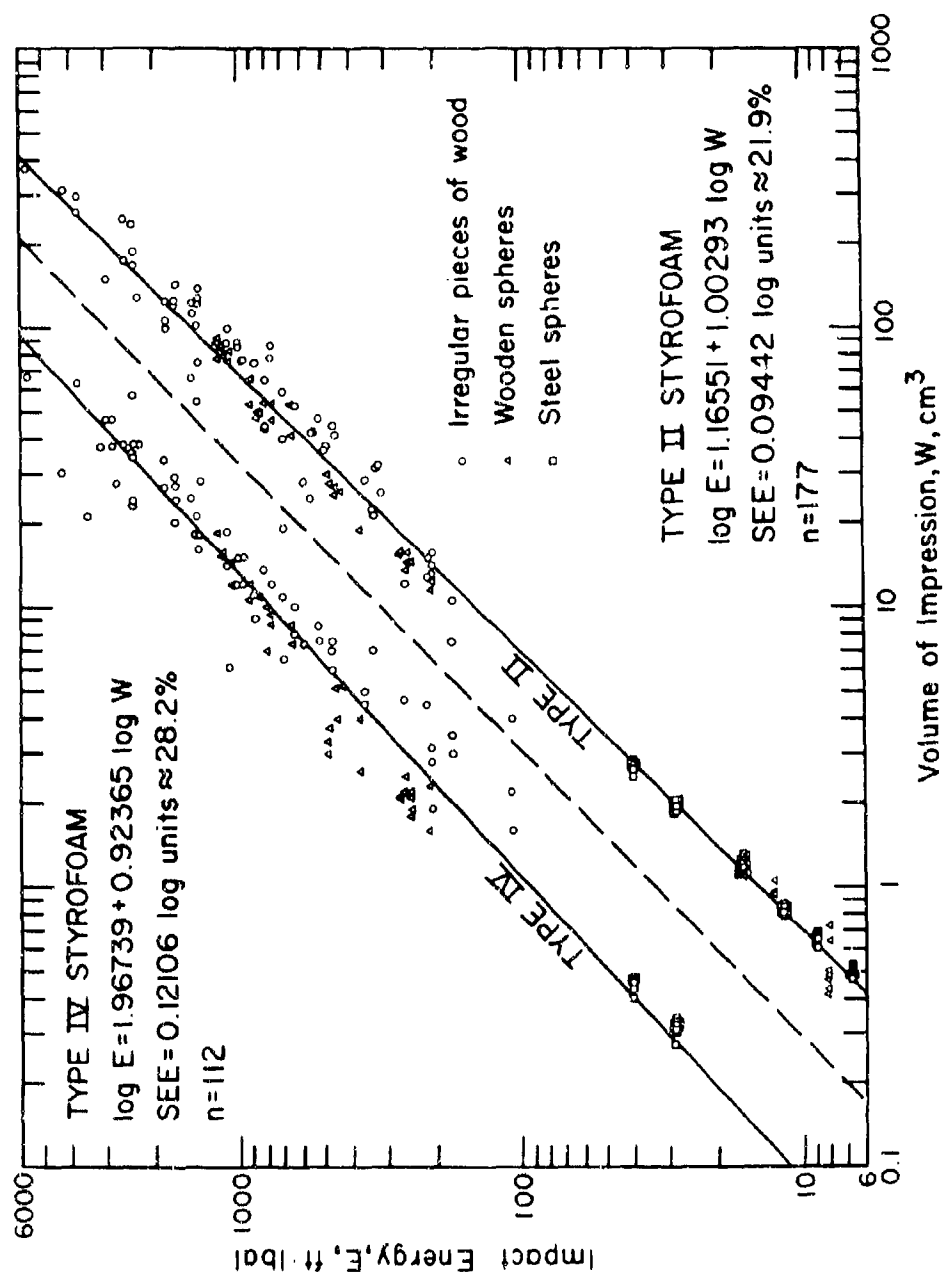


Figure A 1. Impact energy vs volume of the impression for Type II and Type IV Styrofoam.

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