AD 744775

UNCLASSIFIED
Security Classification

## DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

| | |
|---|---|
| 1. ORIGINATING ACTIVITY (Corporate author)<br>Harry Diamond Laboratories<br>Washington, D.C. 20438 | 2a. REPORT SECURITY CLASSIFICATION<br>Unclassified<br>2b. GROUP |

3. REPORT TITLE

A RAIN IMPACT ANALYSIS FOR AN ARTILLERY PD SYSTEM

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

5. AUTHOR(S) (First name, middle initial, last name)

George K. Lucey, Jr.

| | | |
|---|---|---|
| 6. REPORT DATE<br>May 1972 | 7a. TOTAL NO. OF PAGES<br>22 | 7b. NO. OF REFS<br>11 |
| 8a. CONTRACT OR GRANT NO.<br>b. DA-1W564602D02806<br>c. AMCMS Code: 554B.12.24766<br>d. HDL Proj: 65391 | 9a. ORIGINATOR'S REPORT NUMBER(S)<br>HDL-TM-72-15<br>9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) | |

10. DISTRIBUTION STATEMENT

Approved for public release; distribution unlimited

| | |
|---|---|
| 11. SUPPLEMENTARY NOTES | 12. SPONSORING MILITARY ACTIVITY<br>U.S. Army Materiel Command |

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DD FORM 1 NOV 65 1473 REPLACES DD FORM 1473, 1 JAN 64, WHICH IS OBSOLETE FOR ARMY USE.

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A

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Security Classification

| 14. KEY WORDS | LINK A |  | LINK B |  | LINK C |  |
|---|---|---|---|---|---|---|
|  | ROLE | WT | ROLE | WT | ROLE | WT |
| Point detonation | 8 | 3 |  |  |  |  |
| Super-quick | 8 | 3 |  |  |  |  |
| Rain insensitivity | 8 | 3 |  |  |  |  |

B

UNCLASSIFIED
Security Classification

AD

DA-1W564602D02806
AMCMS CODE: 554B.12.24766
HDL Proj: 65391

# HDL-TM-72-15

# A RAIN IMPACT ANALYSIS FOR AN ARTILLERY PD SYSTEM

by

George K. Lucey, Jr.

May 1972

U.S. ARMY MATERIEL COMMAND
HARRY DIAMOND LABORATORIES
WASHINGTON, D.C. 20438

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## ABSTRACT

Stress-wave theories in the literature are reviewed to determine which equations should be used to design the XM587E2 Point-Detonating (PD) switch to preclude premature closure when an artillery projectile is fired into a typical rainstorm. But, because of wide variations in calculated impact pressures, the equations are not used. Experimental data are used instead to show that the projectile impact with a raindrop is almost a perfectly plastic momentum transfer; hence, a PD switch design based upon perfectly elastic impact theory contains an inherent factor of safety.

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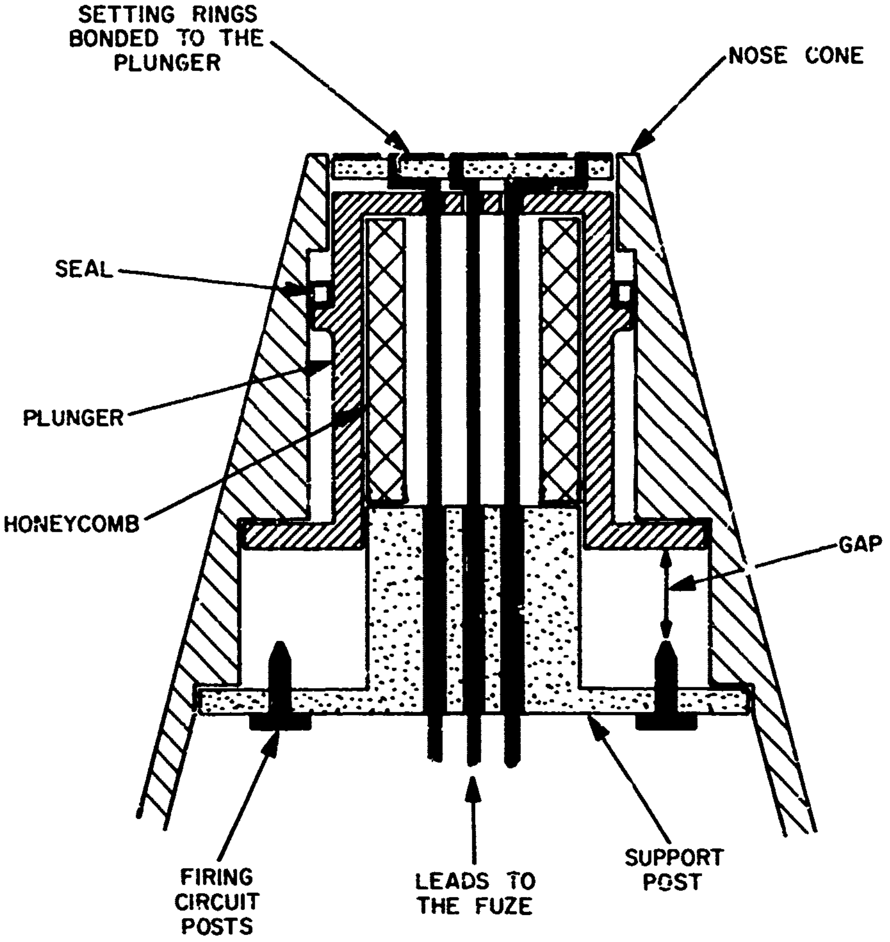

Figure 1. Primary PD design for the XM587E2 fuze as patterned after the XM577 PD system. Impact forces the honeycomb to crush until the plunger completes an electrical connection.

## 1. INTRODUCTION

As presently designed, the Point-Detonating (PD) element proposed for the XM587E2 fuze (fig. 1) is expected to meet most, but not all, of the design requirements. These include superquick function on water at 400 ft/sec, although, based on XM577 data, 500 ft/sec is expected. Also, the PD element should be able to pass through 10,000 ft of a 7-in./hr rainfield at 3000 ft/sec without premature closure. But, extrapolated XM577 data indicate safe flight may be limited to 7,000 ft. Some changes in the design parameters are necessary, and an analysis of the mechanics of operation can guide these changes. The design is patterned after that used in the XM577 fuze, and a review of the analysis performed by the XM577 contractor showed: (1) a drag theory was used to calculated the force occurring during impact with a raindrop, while the conventional approach in the literature is to use stress-wave theory; (2) the area over which the water pressure acts was arbitrarily assumed to be the cross-sectional area of the droplet. Stress waves reflecting from the sides of the drop that diminish both the area and duration of contact were not considered (fig. 2).[1] As a result, this analysis was not used in the XM587E2 PD design. The literature was consulted to determine which equations could be used for an impulse analysis, and the results are summarized in table I. Calculations using these equations are shown in table II to have wide variations, so the impulse approach was abandoned in favor of a momentum analysis. The difference between the two appraoches is that the variables on the right side of Newton's law are treated rather than those on the left side.

$$\text{IMPULSE} = \text{MOMENTUM}$$

$$\int F dt = \int M dV$$

where F = force of raindrop impact
t = time
M = mass of the PD plunger
V = projectile velocity

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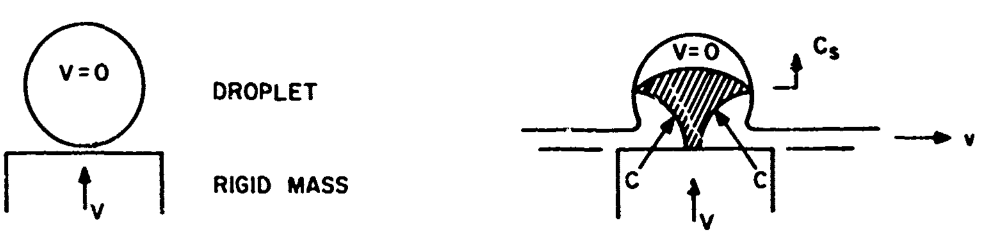
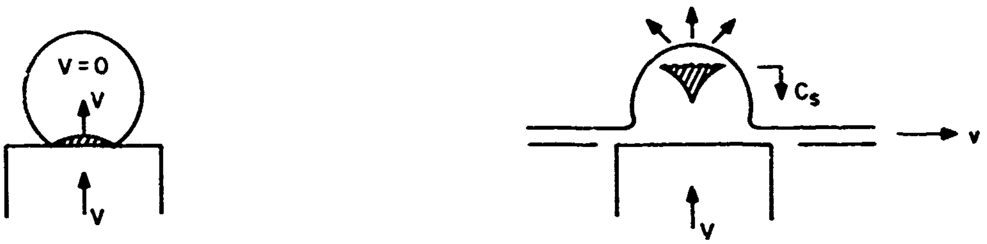
[1] Morris, J., Jr., "Supersonic Rain and Sand Erosion Research, Part II," AFML-TR-69-287, September 1969, p. 45.



(a) AS A RIGID MASS IMPACTS A STATIONARY DROP, A COMPRESSIVE WAVE IS GENERATED, AND WATER BEHIND THE WAVE MOVES AT THE MASS VELOCITY, V.

(c) THE SHOCK MOVES UPWARD AT THE SHOCK SPEED, Cs REFLECTED WAVES MOVE INWARD TO REDUCE THE AREA OF PRESSURE ACTING ON THE MASS. HIGH VELOCITY WATER JETS RADIALLY.



(b) THE WATER IN COMPRESSION IS SHADED. A STABLE SHOCK ATTACHES TO THE TERMINUS OF THE DROP AND MASS

(d) THE SHOCK REFLECTS AND WATER JUMPS AWAY LIKE A BALL FROM A BAT.

Figure 2. Events during an impact with a raindrop at high velocity.

## 2. THEORETICAL CONCEPT

Table II shows that the duration of contact of a drop on the PD element is very short; hence, there is little motion of the plunger in this time span. The impact simply imparts an initial velocity to the plunger relative to the projectile. The system under analysis, then, is the moving plunger with the force generated by the stagnated windstream acting on the front and the forces due to the crush element and internal pressure of the fuze acting on the back. The stagnation pressure of the windstream may be found from standard flow tables, so the only unknown in the system is the initial velocity of the plunger.

If the impact were perfectly elastic, the plunger velocity (relative to the projectile) would be a maximum, and this is given by

$$V_E = \frac{2V}{1 + M/m} \tag{1}$$

where $V_E$ = plunger velocity; perfectly elastic impact
$m$ = mass of a raindrop

If the impact were perfectly plastic, the velocity would be a minimum.

$$V_P = \frac{1}{2} V_E \tag{2}$$

where $V_P$ = plunger velocity; perfectly plastic impact

Figure 2 shows that water either flows with the plunger or radially away from the normal impact; hence, up to this instant (fig. 2c) the impact is primarily perfectly plastic. This assumption was used by Kosdnocky[2] in his XM557 PD analysis, but no firm basis for the assumption has been established. The reason for concern is that figure 2d

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[2] Kosdnocky, S., "Design and Evaluation of a Rain Insensitive Modification to the M557E1 Point Detonating Fuze," TR-3894, Picatinny Arsenal, New Jersey, April 1969, p. 100.

**Table I. Survey of rain impact equations in the literature compared with those of a contractor derived for the XM577 PD systems**

C = speed of sound in water; $C_D$ = drag coefficient; $C_T$ = speed of sound in the target; Z'/Z = accustic impedance; P = hydraulic pressure; L = length of track PD traversed into the rainfield; ρ = density of water without a subscript, and density of the target with a subscript t, d = diameter of a raindrop

| | Impact Pressure | Duration of Contact | Maximum Area of Contact | Constants |
|---|---|---|---|---|
| XM577 Contractor | $\frac{1}{2} C_D \rho V$ | $d/V$ | $\frac{\pi}{4} d^2$ | |
| Bowden[3] | $\rho C V$ | | | |
| Bowden[4] | | $\frac{d}{2V}\left[1-\left(1-\frac{V^2}{C_L^2}\right)^{1/2}\right]$ | $\frac{\pi d^2}{4}\left(\frac{V}{C_2}\right)^2$ | $C_L = C + 2V$ |
| de Haller[5] | $\frac{\rho V C}{1+\frac{\rho C}{\rho_T C_T}}$ | | | |
| Engel[6,7,8] | $\frac{\alpha \rho V C}{1+\frac{\alpha \rho C}{\rho_T C_T}}$ | | | $\alpha = \frac{0.41}{1+0.59\left(\frac{\rho C}{\rho_T C_T}\right)}$ |
| Heyman[9] | $\rho V C\left(\frac{V_S}{V}\right)\left[1 + 2\left(\frac{V}{C}\right)\left(\frac{V_S}{V}\right)\right]$ | | | $\frac{Z'}{Z} = \frac{\rho_T C_T}{\rho C}$ and<br>$\frac{V_S}{V} = \left[\left(\frac{1+Z'/Z}{4V/C}\right)^2 + \left(\frac{Z'/Z}{2V/C}\right)\right]^{1/2} - \left(\frac{1+Z'/Z}{4V/C}\right)$ |

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[3] Bowden, F. P. and Brunton, J. H., "The Deformation of Solids by Liquid Impact at Supersonic Speeds," Royal Society (London), Proceedings, Series A, 263, (October 10, 1961).

[4] Bowden, F. P. and Field, J. E., "The Brittle Fracture of Solids by Liquid Impact, by Solid Impact, and by Shock," Royal Society (London), Proceedings, Series A, 282, 331-52 (November 24, 1964).

[5] Thiruvengadan, A., "The Concept of Erosion Strength," Erosion by Cavitation or Impingement, ASTM-STP-408 American Society of Testing Materials, 1957, R22.

[6] Engel, O. G., "Waterdrop Collisions with Solid Surfaces," Journal of Research of the National Bureau of Standards, 54, 281-98 (May 1955).

[7] Engel, O. G., "Resistance of White Sapphire and Hot-Pressed Alumina to Collision with Liquid Drops," Journal of Research of the National Bureau of Standards, 64A, 499-512 (November-December 1960).

[8] Engel, O. G., "Note on Particle Velocity in Collisions Between Liquid Drops and Solids," Journal of Research of the National Bureau of Standards, 64A, 497-98 (November-December 1960).

[9] Heyman, F. J., "Eine Ubersicht Von Schusseln Zu den Verhaltnissen Zwischen der Erosion Geschwindigkeit and Aufschlags-Parameteun," Forschungs Konferenz Regenerosion, 16, 98-157 (August 1967).

Table II. Comparison of calculated effects of aluminum impacting a 5-mm water drop at 3000 ft/sec.

| | p | $\tau$ | A |
|---|---|---|---|
| | (lb/in.$^2$) | ($\mu$sec) | (in.$^2$) |
| XM577 Contractor | 121,000 | 5.4 | 0.03 |
| Bowden[3] | 202,000 | | |
| Bowden[4] | | 0.4 | 0.002 |
| deHailer[5] | 182,000 | | |
| Engel[6,7,8] | 75,000 | | |
| Heyman[9] | 322,000 | | |

Constants:

$V = 3000$ ft/sec $= 36{,}000$ in./sec
$C = 5000$ ft/sec $= 60{,}000$ in./sec
$\rho = 9.35 \times 10^{-5}$ lb-sec$^2$/in.$^4$
$C_T = 16{,}708$ ft/sec $= 200{,}500$ in./sec
$\rho_T = 25.8 \times 10^{-5}$ lb-sec$^2$/in.$^4$
$d = 5$ mm $= 0.196$ in.
$C_D = 2$ for a flat plate
$Z'/Z = 9.23$; $V_S/V = 0.81$
$\alpha = 0.385$

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[3] Bowden, F P. and Brunton, J. H., "The Deformation of Solids by Liquid Impact at Supersonic Speeds," Royal Society (London), Proceedings, Series A, 263, (October 10, 1961).

[4] Bowden, F. P. and Field, J. E., "The Brittle Fracture of Solids by Liquid Impact, by Solid Impact, and by Shock," Royal Society (London), Proceedings, Series A, 282, 331-52 (November 24, 1964).

[5] Thiruvengadan, A., "The Concept of Erosion Strength," Erosion by Cavitation or Impingement, ASTM-STP-408 American Society of Testing Materials, 1967, R22.

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[9] Heyman, F. J., "Eine Ubersicht Von Schusseln Zu den Verhaltnissen Zwischen der Erosion Geschwindigkeit and Aufschlags–Parameteun," Forschungs Konferenz Regenerosion, 16, 98-157 (August 1967).

shows that a stress wave transverses up the drop in the normal direction, so water can be expected to jump away from the plunger when the wave reflects from the free surface. Therefore, the overall momentum exchange must be somewhat between perfectly elastic and perfectly plastic, and a coefficient of restitution (r) may be required for a plausible momentum analysis. In this case, the plunger velocity relative to the projectile is

$$V_r = \frac{(1 + r)V}{1 + M/m} \tag{3}$$

where $V_R$ = plunger velocity; partially plastic-partially elastic impact

The value of r is unknown. The need for defining a coefficient, however, is determined by comparing the theoretical range of energy that can be transmitted to an XM577 PD passing through a rainstorm to energies absorbed in rocket sled tests.

If N drops of a single diameter are impacted on the XM577 PD on the rocket sled, the total energy that is delivered to the crush element by the impact force and by the air pressure differentiation on the plunger is

$$E = N(K.E.) + (P_o + P_i)AS \tag{4}$$

where E = energy
N = number of drops impacting A
K.E. = kinetic energy
$P_o$ = stagnation pressure of the windstream
$P_i$ = atmospheric pressure at the rocket sled launch site
S = total deflection of the plunger
A = frontal area of the PD

The value of N for a trajectory through a rainfield of uniform drop size is[2]

$$N = \beta AL \tag{5}$$

where $\beta$ = density of droplets in the rainfield
L = length of track PD traversed into the rainfield

However, an actual rainfield is composed of a spectrum of drop sizes, and a value of N can be defined for each. The total energy that would be absorbed by a crush element behind the plunger is actually

$$E = (N_1KE_1 + N_2KE_2 + N_3KE_3 + \ldots.) + (P_o + P_i)AS \tag{6}$$

The various values of N are calculated using eq (5) and the values of $\beta$ shown in figure 3. This droplet density spectrum represents the output of the nozzles at Holloman Air Force Base (HAFB) used in the XM577 PD rocket-sled tests. (The nozzles used were the VEEJET H 1/2 U-80-200 series operated at 6 lb/in.$^2$ manifold pressure.)

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[2] Kosdnocky, S., "Design and Evaluation of a Rain Insensitive Modification to the M557E1 Point Detonating Fuze," TR-3894, Picatinny Arsenal, New Jersey, April 1969, p. 100.

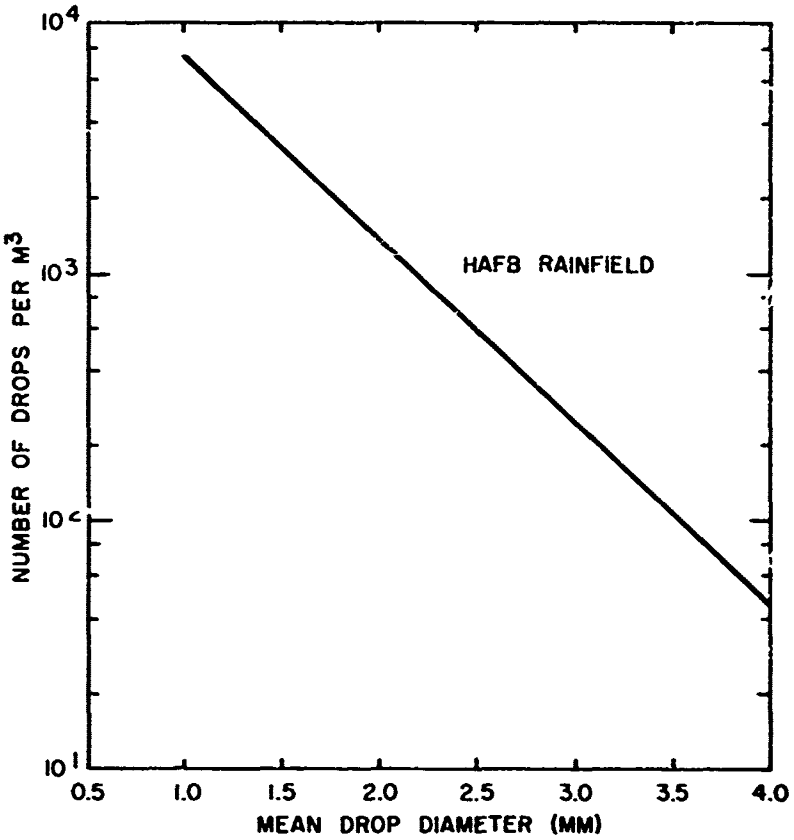

Figure 3. Droplet density data. (These data were provided by HAFB.)

The mean drop size shown on the abscissa represents the average diameter value for drops counted within a range of diameters; i.e.,

| Range of Drop Diameters (mm) | Mean Diameter (mm) |
|---|---|
| 0.25 - 0.75 | 0.50 |
| 0.75 - 1.25 | 1.00 |
| 1.25 - 1.75 | 1.50 |

The density spectrum shown in figure 3 is an average of 96 measurements made at different positions along the test track. Figure 4 shows that large variations occurred during some of these measurements; therefore, some inaccuracies from eq (5) are expected.

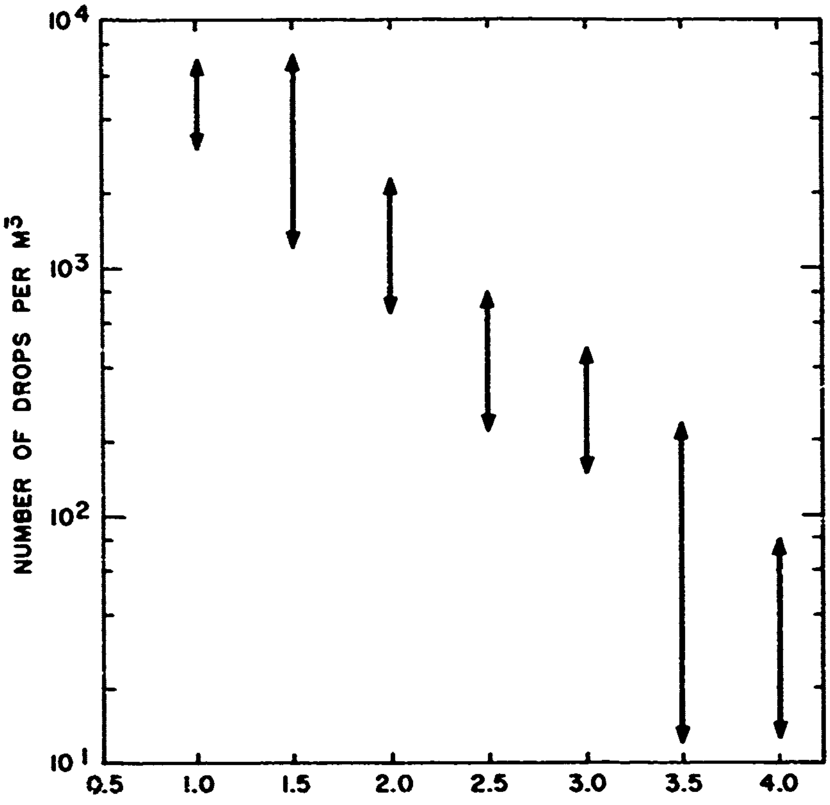

Figure 4. Spread in values for 14 of the samples used to construct figure 3. (The data were provided by HAFB.)

## 3. CALCULATIONS

During rain sensitivity tests on the XM577 PD, one element depressed 0.288 in. after two sled tests amounting to a total of 3440 ft. of a 25-in./hr rainfield. The sled velocity was about 3000 ft/sec, the frontal area of the plunger was 0.196 in.$^2$ (0.5-in. diameter), and the plunger weight was 2.9 g. Two reports from the National Advisory Committee for Aeronautics show the stagnation pressure was

$$P_o = 337 \text{ psi} \tag{7}$$

if the standard sea level conditions of 59°F and 14.7 psi are assumed for the test site. The work done by the windstream on the honeycomb is then

$$(P_o - P_i)AS = 18.2 \text{ lb-in.} \tag{8}$$

This calculation fulfills one part of eq (6), and table III shows the range of energy that could be imparted to the crush element by the raindrops as calculated from 1, 2, 4, 5, and the density data in figure 3. Substituting the totals from table III and the value from eq (8) into eq (6) shows

$$69 \le E \le 222 \text{ lb-in.} \tag{9}$$

The two summations of calculated energies in table III may be compared to the energy actually absorbed by the affected honeycomb. The crush strength was a constant between 200 and 300 lb, and the total crush was 0.288 in.; hence, the energy absorbed is

$$58 \le E \le 86 \text{ lb-in.} \tag{10}$$

The strain rate sensitivity of the honeycomb shown in figure 5 is neglected in this calculation because the plunger velocity is relatively small (table III).

The calculated versus measured energy comparison is more effective when additional data are included. Table IV shows deflection and distance measurements made on several XM577 samples, and figure 6 shows that the theory of perfectly plastic impact best describes the measured crush energies. As a result, the coefficient of restitution in eq (3) is taken to be 0. The discrepancy between the data and theory is probably caused by inaccuracies in the rain conditions assumed for the test, or by the assumption that the sled had no velocity decay in the rainfield. Another factor may be that the acceleration of the sled toward the rainfield is sufficiently slow that the pressure inside the fuze approaches the windstream stagnation pressure, in which case eq (9) reduces to

$$51 \leq E \leq 204 \tag{11}$$

Table III. Energy calculations for the XM577 PD moving through the heavy HAFB rainfield. The sled velocity was 3000 ft/sec, the length of rainfield was 3440 ft, and the plunger properties were $M = 16.5 \times 10^{-6}$ lb-sec$^2$/in. and $A = 0.196$ in.$^2$

| Mean drop size, d | Density, | Mass | Plunger Crush Velocity | | Energy/hit | | Hits, N | Energy/Run | |
|---|---|---|---|---|---|---|---|---|---|
| | | | $V_s$ | $V_p$ | $(K.E.)_s$ | $(K.E.)_p$ | | $N(K.E.)_s$ | $N(K.E.)_p$ |
| (mm) | (drops/m$^3$) | (lb-sec$^2$/in.) | (in./sec) | (in./sec) | (lb-in.) | (lb-in.) | (#) | (lb-in.) | (lb-in.) |
| 0.5 | 18,000 | 0.0003 | 1 | 0.8 | 0.00002 | 0.000005 | 2376 | 0.05 | 0.01 |
| 1.0 | 7,500 | 0.0029 | 13 | 6 | 0.001 | 0.0003 | 990 | 1.4 | 0.3 |
| 1.5 | 3,200 | 0.010 | 43 | 21 | 0.01 | 0.003 | 422 | 7 | 1.7 |
| 2.0 | 1,400 | 0.023 | 103 | 51 | 0.08 | 0.02 | 250 | 16 | 4 |
| 2.5 | 600 | 0.046 | 202 | 101 | 0.3 | 0.08 | 79 | 27 | 7 |
| 3.0 | 250 | 0.080 | 349 | 174 | 1 | 0.2 | 33 | 33 | 8 |
| 3.5 | 100 | 0.128 | 553 | 276 | 2 | 0.6 | 13 | 33 | 8 |
| 4.0 | 50 | 0.191 | 822 | 411 | 5 | 1 | 6 | 37 | 9 |
| 4.5 | 19 | 0.272 | 1165 | 582 | 11 | 2 | 3 | 28 | 7 |
| 5.0 | 8 | 0.373 | 1589 | 794 | 20 | 5 | 1 | 22 | 6 |
| | | | | | | TOTAL | | 204 | 51 |

Note The number of significant figures in these columns is limited so as not to leave the impression that the calculations are highly accurate

Table IV. Crush measurements made on the XM577 PD elements after repeated rocket sled passes through a 2000-ft rainfield

| XM477 Sample (#) | Total rain exposure (ft) | Total honeycomb crush (in.) |
|---|---|---|
| 4 | 2000 | 3/32 |
| 4 | 4000 | 3/32 |
| 4 | 6000 | 5/32 |
| 6 | 2000 | 5/32 |
| 9 | 3440 | 9/32 |

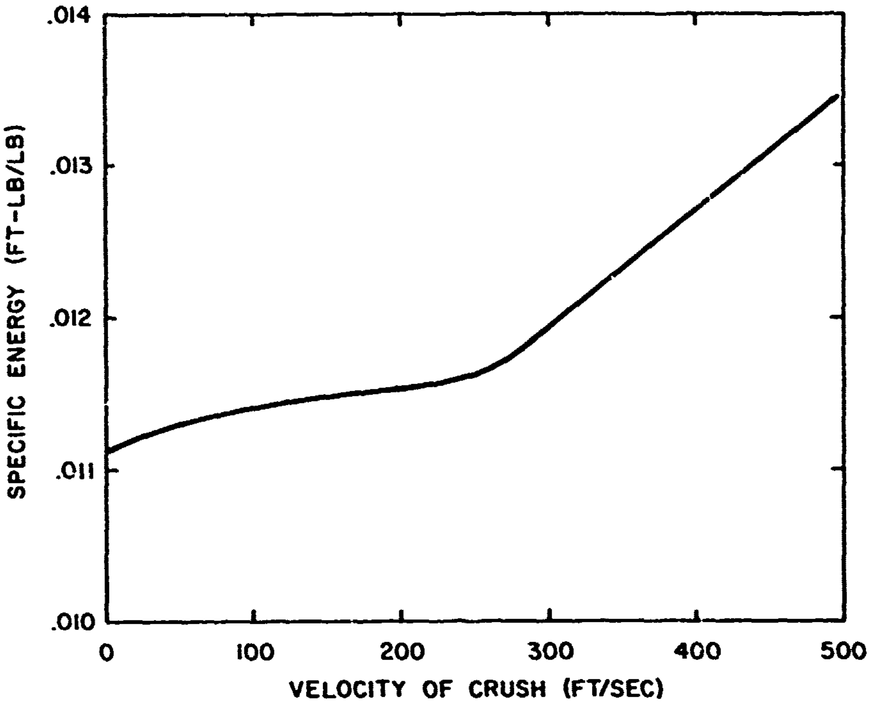

Figure 5. Strain rate sensitivity of one type of aluminum honeycomb that was considered for the XM577 PD system.

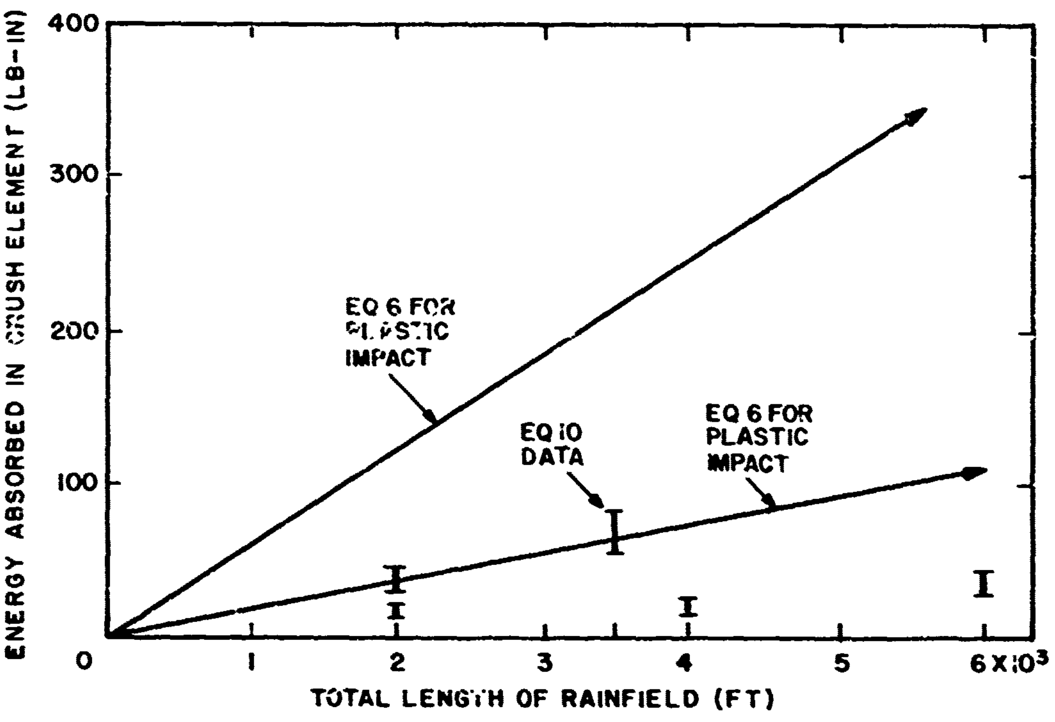

Figure 6. Comparison of the energies calculated from crushed XM577 honeycombs to the ranges in theoretically available energies.

## 4. RECOMMENDATIONS

The theory of perfectly elastic impact should be used to change the critical parameters of the XM587E2 PD system. This will include an inherent safety factor in the final design.

Rain tests scheduled for the XM587E2 PD system should include HAFB droplet density measurements to assist in analysis of the results; also, a drop catcher should be mounted on the rocket sled to check the accuracy of the calculation of the number of drops impacted. Additional evidence about the number and size of drops hit should be collected by providing a sample that is marked, but not eroded, by the raindrops, thereby allowing a visual count of the impacts. A linear spring-mass system should be included to obtain additional data about the maximum energy transferred by the rain impact.

An impulse analysis should be performed with each of the equations listed in table I to determine which equation best agrees with the XM577 test results. This will provide a design guide for nose-cone erosion studies and future PD systems. It will also permit calculations to be made on the rain sensitivity of inertial impact switches now used in artillery and rocket fuzes.

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## GLOSSARY OF TERMS

| | |
|---|---|
| A | Frontal area of the PD |
| $\beta$ | Density of droplets in the rainfield |
| C | Speed of sound in water |
| $C_D$ | Drag coefficient |
| $C_S$ | Shock speed in water |
| $C_T$ | Speed of sound in the target |
| d | Diameter of a raindrop |
| $\delta$ | Amount of honeycomb crush |
| E | Energy; subscripts e and p denote calculations for totally elastic and plastic impacts |
| F | Force of raindrop impact |
| K.E. | Kinetic energy; subscripts e and p denote energy associated with perfectly elastic and plastic collisions, respectively |
| L | Length of track PD traversed into the rainfield |
| m | Mass of a raindrop |
| M | Mass of the PD plunger |
| N | Number of drops impacting A; subscripts 1, 2, and 3 denote the number associated with particular mean drop sizes |
| P | Hydraulic pressure |
| $P_o$ | Stagnation pressure of the windstream |
| $P_i$ | Atmospheric pressure at the gun launch site |
| r | Coefficient of restitution |
| $\rho$ | Density of water without a subscript, and density of the target with a subscript t |
| T | Time |
| $\tau$ | Duration of contact between impacting plunger and drop |
| V | Projectile velocity |
| $V_E$,$V_P$<br>$V_r$ | Plunger velocity; subscripts e and p refer to perfectly elastic and plastic impacts; subscript r refers to impact partially plastic and partially elastic |
| v | Radial jet velocity of an impact raindrop |
| Z/Z' | Acoustic impedance |