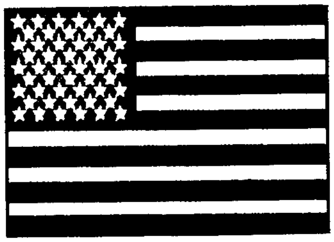

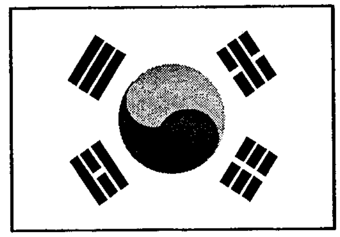

Contract Report SL-95-3
UAST-CR-94-001

JOINT U.S./ROK R&D PROGRAM FOR NEW UNDERGROUND AMMUNITION STORAGE TECHNOLOGIES

FINAL REPORT

DYNAMICS AND KINEMATICS OF OBLIQUE IMPACTS OF STEEL FRAGMENTS ON ROCK SURFACES

by

James A. Keller

Denver Research Institute
University of Denver
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April 1995

Prepared for U.S. Army Engineer Waterways Experiment Station
3909 Halls Ferry Road
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Approved for public release; distribution is unlimited

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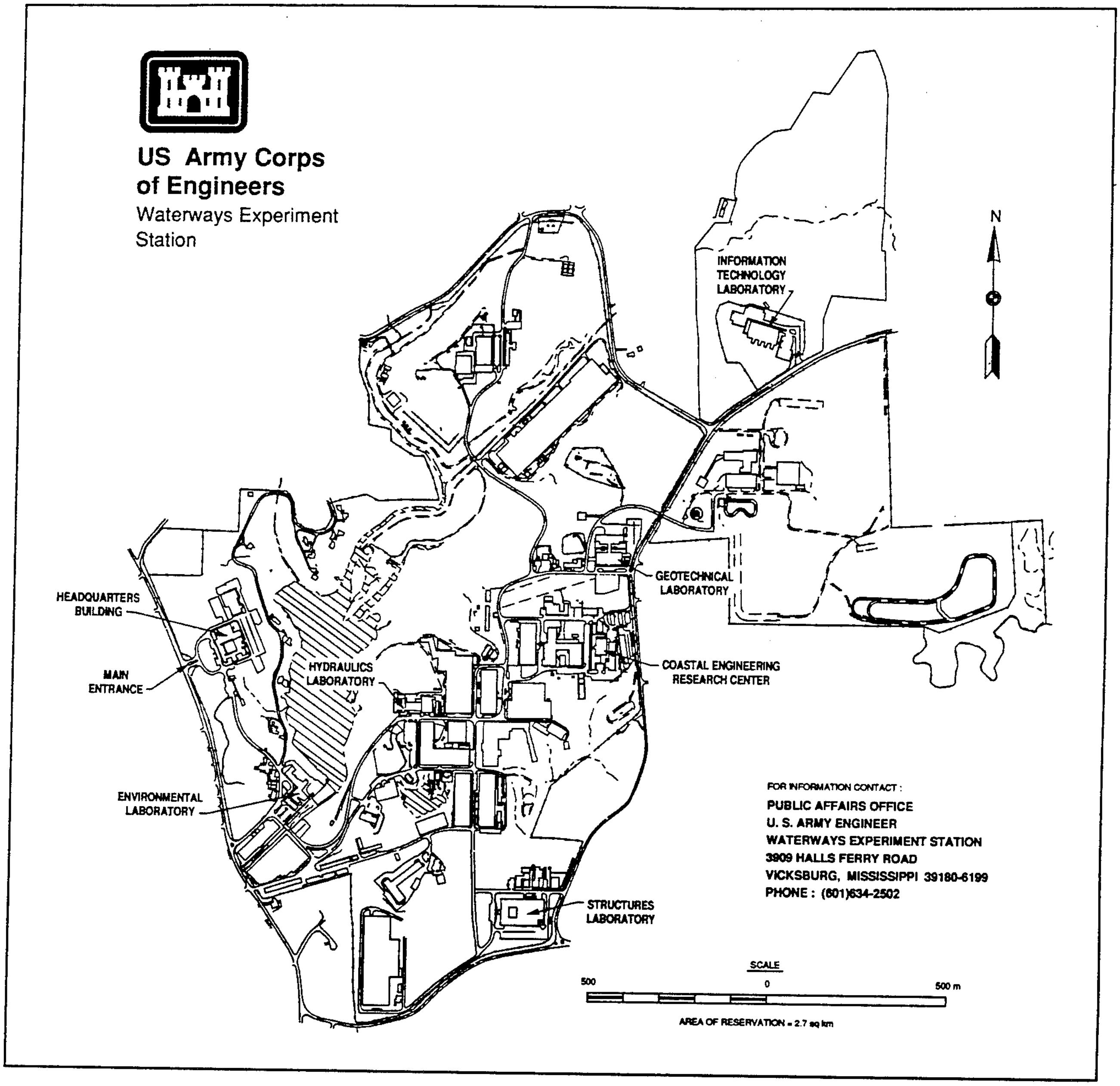

Waterways Experiment Station Cataloging-in-Publication Data

Keller, James A.
Dynamics and kinematics of oblique impacts of steel fragments on rock surfaces / by James A. Keller ; prepared for U.S. Army Corps of Engineers ; monitored by U.S. Army Engineer Waterways Experiment Station.
46 p. : ill. ; 28 cm. — (Contract report ; SL-95-3)(UAST-CR ; 94-001)
Includes bibliographical references.
1. Impact — Testing. 2. Projectiles — Testing. 3. Explosives, Military — Evaluation. I. United States. Army. ~~Corps of Engineers~~. II. U.S. Army Engineer Waterways Experiment Station. III. Structures Laboratory (U.S.) IV. Joint U.S./ROK R&D Program for New Underground Ammunition Storage Technologies. V. Series: UAST-CR ; 94-001. VI. Title.
VII. Series: Contract report (U.S. Army Engineer Waterways Experiment Station) ; SL-95-3.
TA7 W34c no.SL-95-3

PREFACE

The research reported herein was sponsored by the U.S. Army Engineer Waterways Experiment Station (WES), under Contract DACA39-93-K-0002. The goal of the work was to investigate the dynamics and kinematics of ricocheting steel fragments from exploding munitions, after impacts of the fragments on planar hard rock surfaces. The purpose of the research was to clarify these dynamics and kinematics, as they applied to analysis of underground magazine design concepts under the Joint U.S./Republic of Korea (ROK) R&D Study for New Underground Ammunition Storage Technologies. Technical Managers of the Joint US/ROK study were Mr. L. K. Davis of WES, for the U.S., and Dr. So-young Song of the Agency for Defense Development, for Korea.

The work was conducted by the University of Denver, the Denver Research Institute (DRI). Principal Investigator was Mr. James A. Keller. Technical monitoring of the work within WES was provided by the Structures Laboratory, Explosion Effects Division (EED). Mr. L. K. Davis was Chief, EED, during the performance of the work, and Mr. Charles Joachim was the technical monitor. The support and assistance of these individuals is gratefully acknowledged. At the time of publication of this report, Dr. J. P. Balsara was Chief, Geomechanics and Explosion Effects Division, which includes the former EED.

The author wishes to acknowledge the outstanding assistance of Mr. David Gesler, Research Engineer, DRI Engineering Sciences Laboratory (ESL). Mr. Gesler directed and participated in all field tests during this program, and was instrumental in reducing the raw experimental data. Similarly, the assistance of Mr. Timothy Samaras, Manager of the DRI/ESL Instrumentation Group, and his personnel, is deeply appreciated.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. Commander was COL Bruce K. Howard, EN.

SUMMARY

This report describes research conducted from November 1992 through June 1993. The objective of this study was to determine by experiment the dynamics and kinematics of the residual fragments ricocheting from hard rock surfaces, after oblique impact. The fragments used were cubic mild steel, representative of the majority of fragments resulting from the detonation of a naturally fragmenting warhead or high explosive projectile. The specific goals of the research were to measure the residual kinetic energy of the primary ricocheting fragment, determine the angle of ricochet as compared to the angle of incidence, and to explore the effects of different types or strengths of rock as influences on the dynamics and kinematics.

During the program, a total of 23 individual tests were conducted. Single steel cube fragments were launched from a powder gun at velocities representative of explosive warheads or projectiles. The target rock slabs were smooth faced and were exposed at a range of obliquities. Size of the rock slab targets was sufficient to eliminate any finite dimension or free-edge effects.

It was determined that the initial impact of a fragment on a smooth rock face produces about 90 percent loss of incident kinetic energy and results in fracture of the incident fragment. The residual primary fragment will be smaller, have much lower velocity of travel, and be significantly less energetic than the incident fragment. Thus, analyses or simulations which utilize an ideal or perfectly elastic model of the encounter and ricochet process grossly overstate the post-impact dynamics of the event.

Results are presented which give some indication of the relative importance of different variables--obliquity, velocity, initial mass, and rock type--on the dynamics and kinematics of the encounter. While there are trends in the relative importance of

these variables, the data clearly indicate a strong degree of randomness in the process, so that caution should be used in attempting to derive too much fine detail.

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INTRODUCTION

This study was conducted to provide supporting information on the effects of accidental explosions of munitions stored in underground magazines constructed in rock geologies. The information was needed to help evaluate the extent to which various design concepts for underground magazines can contain the effects of accidental explosions of stored munitions.

The explosion of a cased charge such as a projectile or warhead produces a large number of steel fragments of the case. These fragments are projected outward at velocities which can exceed 2 km/sec (7,000 ft/sec). The fragments represent one of the possible mechanisms for initiating reaction in other munitions within a storage facility. This threat is recognized in facility designs, and is usually countered by the use of design techniques such as turns or corners in passages to preclude line of sight to other storage areas, or the imposition of physical barriers between adjacent stacks of munitions.

If such principles are followed in designing a storage facility, the fragments resulting from an accidental detonation will have to ricochet to eventually impact other munitions, beyond those in the immediate (i.e., unbarriered) vicinity of the donor charge. A key issue is raised by this fact--namely, what are the dynamics of the impact and interaction process when a steel fragment impacts a rock or concrete surface. More specifically, what is the angle of ricochet, what is the post-impact velocity, is the fragment fractured in the initial impact, and what fraction of the incident fragment kinetic energy is available after the impact? Since a fragment, which we assume has ricocheted to arrive at an "acceptor" charge, must have certain minimum kinetic energy to initiate a destructive reaction, these questions are all a part of the single over-riding question: "Can a ricocheting fragment retain sufficient kinetic energy to initiate a violent reaction in an acceptor charge?" Note that the acceptor charge is usually cased or contained within some exterior shell material. This study did not address the kinetics of shock initiation of explosives or propellants, which is obviously a key component of the overall problem, but one which has been extensively studied and reported.

The incident kinetic energy, *KE* (in), of an impacting fragment is given by the simple expression of Equation 1:

$$KE(in)=\frac{mv^2}{2} \tag{1}$$

where: m = mass of the impacting fragment

v = velocity of the impacting fragment

When a fragment impacts a "strong" material such as rock (or concrete, steel, or other hard material), there are several phenomenological effects which are endothermic--i.e., they require energy. Neglecting for the moment the thermal energy or heat energy of the fragment acquired during deformation and rupture of the case and launch of the fragment, the only source for these energy requirements is the kinetic energy of the fragment. Among the most significant energy "sinks" or endothermic requirements are:

E1 = the energy required to fracture or crater the impacted material and eject crater debris,

E2 = the energy required to plastically deform and fracture the incident fragment,

E3 = the energy consumed in raising the temperature of the fragment material under shock loading, and

E4 = the energy consumed in raising the temperature of the target material under shock loading.

If we assume that the summation of these energy requirements is less than the incident kinetic energy of the fragment, then the fragment will possess some residual kinetic energy. We can therefore write a simplified energy balance or conservation equation, such as Equation 2:

$$KE(in) = E1 + E2 + E3 + E4 + KE(resid) \tag{2}$$

We must recognize that the fifth term on the right in Equation 2 is actually a summation, over all residual fragments which may result from fracture of the incident fragment.

The simple form of Equation 2 allows a program of direct measurement, or experiment. What we are really interested in is the question posed earlier--i.e., does the residual fragment(s) possess sufficient energy to initiate a reaction. The value of KE(resid) in Equation 2 can be directly measured by collecting the residual fragment(s), and measuring their post-impact velocity. While the direct experimental approach taken herein did not allow a discrimination of the other energy losses into the terms E1 through E4, the equation can be recast as shown in Equation 3:

$$KE(in) = KE(loss) + KE(resid) \tag{3}$$

While of phenomenological interest, a discrimination of the components of the term KE(loss) is not critical to answering the principle question of this program.

A second question is posed if the first question is answered affirmatively--i.e., when the residual fragment(s) do possess sufficient energy to initiate a reaction. That question is, "What is the ricochet or residual trajectory angle of the post-impact fragments?" As discussed in the next section of this report, the experimental set-up was designed for direct measurement of this angle. In actual practice, the incident fragment usually breaks up, and a "spray" of secondary or residual fragments occurs, distributed in roughly a conic region with the apex at the point of impact. The experimental set-up allowed measurement of the extreme boundaries of this conic region, as well as the trajectory of the main (largest) residual fragment.

An experimental set-up was designed and constructed for accomplishing these tests, as described in the next section of this report. This set-up provided for the gun/launcher, associated stripper plates and velocity switches, the support and positioning of the rock target specimens, and recovery media for determining residual or ricocheting fragment mass and velocity. Provisions were made for high speed photography, as well.

EXPERIMENTAL SET-UP

The experimental concept for this study involved the launch of cubic steel fragments from a smooth-bore powder gun. Fragment masses and velocities were to be varied. The fragment would impact a prepared sample of rock, with smooth surfaces, which was characterized for mechanical properties as a part of the project. A series of "make" switches was used to measure fragment impact velocity and provide reference times for the experimental firings. The rock sample was large enough to minimize the effects of lateral free edges on the cratering behavior of the specimen. A series of witness panels and recovery modules, using fiber board, was used to record the post-impact fragment distribution and the fragment residual velocity. This latter parameter was measured by covering the face of the primary witness panel with a foil "make" switch, and noting the arrival time at this switch as compared to the time of impact, sensed by a similar "make" switch on the face of the target rock sample.

The overall experimental set-up is illustrated in Figure 1. The powder gun launcher--in this case, a nominal 40-mm caliber--is situated in the cylindrical shelter in the left center of the figure. Immediately in front of the gun hut is a stripper plate and frame, required to intercept the aerodynamically separated parts of the sabot, or carrier for fragment launch, used during in-bore travel. Next down-range can be seen a velocity switch frame. The target rock specimen can be seen in the right center of the figure, with the impact switch in place on the face of the sample. The remaining elements in the figure are the witness panels and recovery modules.

The fragments typically left a significant crater in the rock target. Figure 2 illustrates the crater from a 240-grain cubic (mild) steel fragment, at 4,000 ft/sec

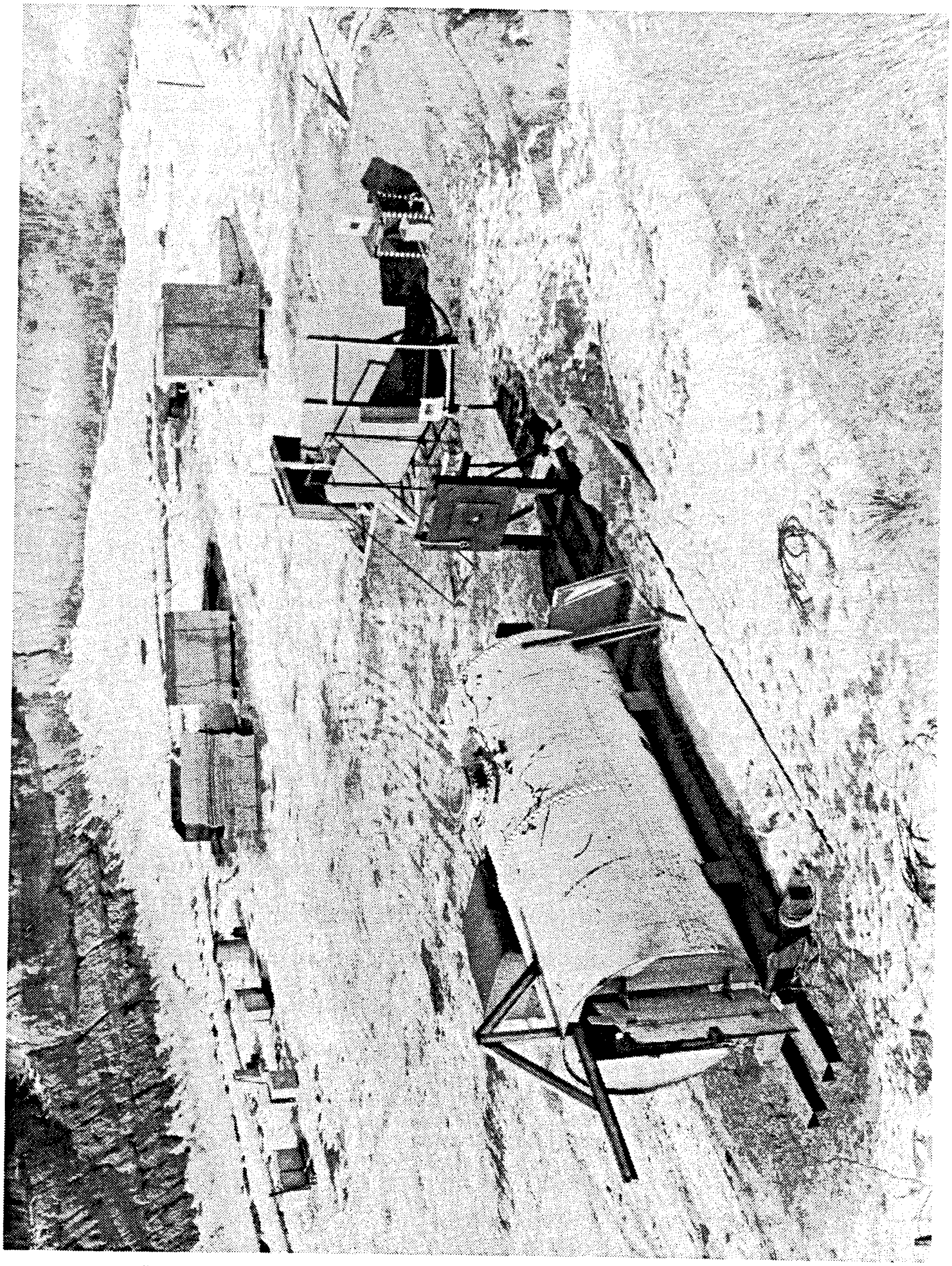

Figure 1. Overall Experimental Set-Up

impact velocity at 60 degrees obliquity, into a limestone target with nominal compressive strength of 10 ksi. Detailed crater measurements and photographs were made after each test.

Figure 3 illustrates the use of the witness panel to locate the residual fragments and determine their trajectory. The "bullseye" symbol painted on the target face indicates the theoretical point of impact, if residual obliquity is equal to incident obliquity. Note that in this shot (the same event as pictured in Figure 2), the fragment remained essentially intact, with only one residual fragment impact witnessed. Note also that the result indicates immediately that one cannot assume angle of ricochet obliquity equal to incident obliquity. Finally, the residual fragment(s) were recovered from the celotex module located immediately behind the witness panel, and weighed and measured to determine mass loss or deformation.

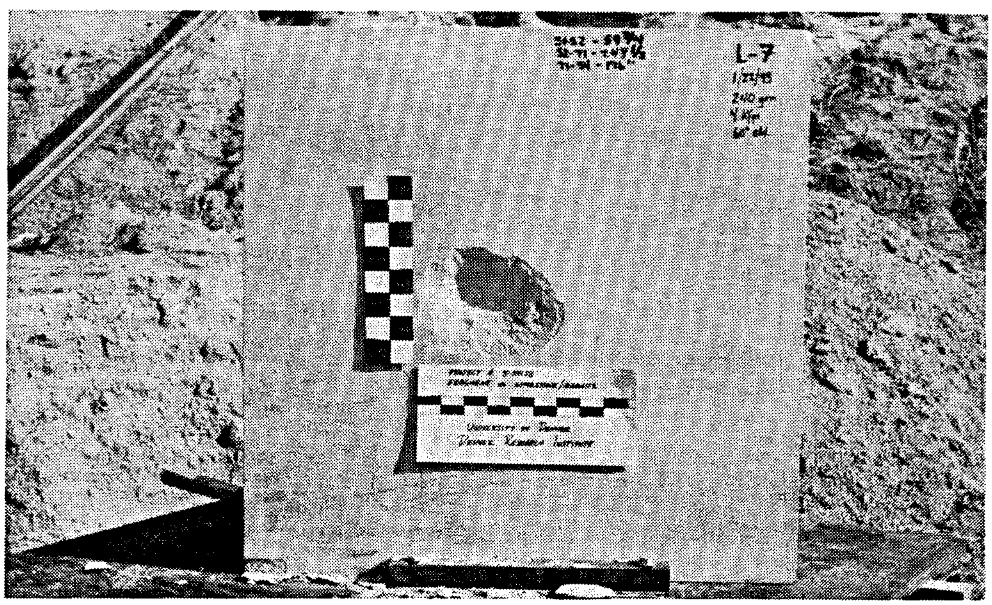

Figure 2. Impact Crater

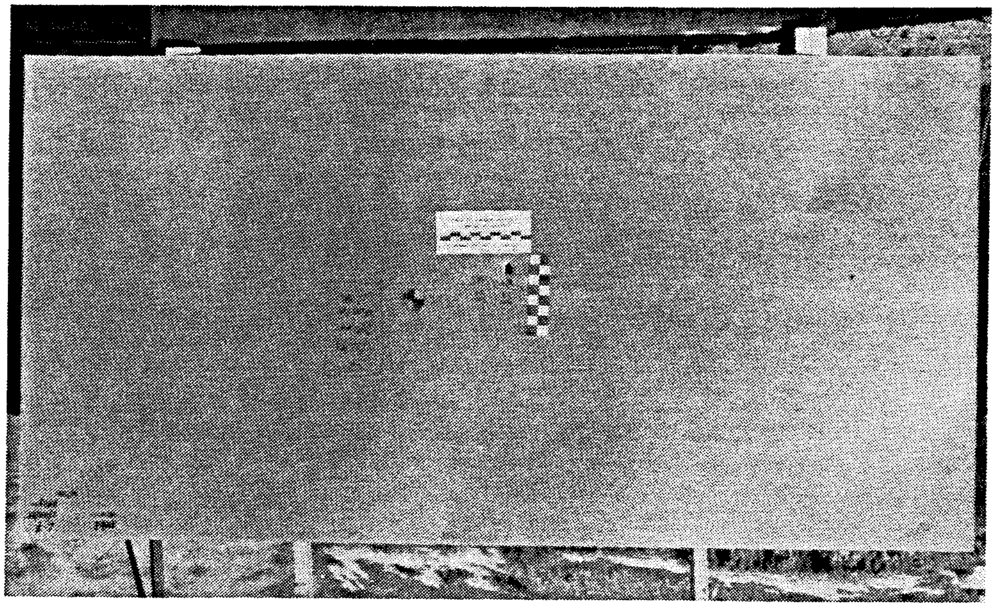

Figure 3. Witness Panel for Residual Fragment Location

Incident obliquity was varied by simple rotation of the rock specimen holding brackets on the sample table. The table was pre-drilled and registered to allow variations of obliquity in 15 degree increments, from 0 to 75 degrees (although not all values were used).

Fragment impact velocity was varied by varying the propellant charge in the gun/launcher, for a given fragment mass.

Two different rock types were used in this study; a close-grained, dense granite with nominal compressive strength of 30 ksi, and a fine-grained limestone with a nominal compressive strength of 10 ksi. The samples were smooth saw-cut to nominal dimensions of 24 inches square by 12 inches thick. Since these samples were furnished by a quarry operator who routinely furnishes finished architectural stone products, the dimensions were accurate to within 1/16 inch, when spot-checked on receipt of the samples. No specimens had cracks or other features constituting anomalies.

The next section of this report discusses the details of the test program.

EXPERIMENTAL PROGRAM

An initial test matrix was defined as indicated in Table 1. This matrix allowed exploration of residual energy and trajectory over two different rock types, three different fragment weights or masses, two different velocities, and three different obliquities. A total of 24 tests was initially planned.

A series of 23 tests were actually conducted. Of this total, 4 tests yielded only partial data, with two of these tests usable. Thus, a total of 21 usable tests were accomplished, for a yield of 87.5 percent. The other two tests were rejected from consideration due to improper function in the gun launcher, which resulted in questionable velocities. The test matrix is summarized in Table 2.

Prior to each test, the fragment was measured and weighed, and this data recorded. The propellant load for the launch gun was calculated by reference to historical, or empirical, data for the launcher system with comparable payloads, and verified by application of the IBHVG2 code. Fragment masses and dimensions were within 6.5 percent of design or nominal, and the launch or impact velocities achieved were within 12 percent of design or nominal. All calculations and data reduction, discussed in the next section of this report, utilized actual weights and velocities for determining incident kinetic energy.

The rock samples, or targets, for this program were provided with quarry test data on nominal unconfined axial compressive strength. The limestone samples averaged 10,000 psi, while the granite averaged 30,000 psi. In addition to these data, it was desired to determine the elastic constants of the materials. This was accomplished by coring 2-inch diameter samples from several target blocks of each rock type, and measuring the relative longitudinal and shear wave speeds through the samples, utilizing methods such as those of Obert and Duvall [1967]. The density of

Table 1: Planned Test Matrix

TEST NUMBER	FRAGMENT MASS (grains)	IMPACT VELOCITY (ft/sec)	OBLIQUITY (Degrees from Normal)	TARGET ROCK MATERIAL
1	250	4,000	30	GRANITE
2	250	4,000	45	GRANITE
3	250	4,000	60	GRANITE
4	500	4,000	45	GRANITE
5	500	4,000	60	GRANITE
6	700	4,000	45	GRANITE
7	700	4,000	60	GRANITE
8	250	6,000	45	GRANITE
9	250	6,000	60	GRANITE
10	500	6,000	45	GRANITE
11	500	6,000	60	GRANITE
12	700	6,000	45	GRANITE
13	700	6,000	60	GRANITE
14	250	4,000	45	LIMESTONE
15	250	4,000	60	LIMESTONE
16	500	4,000	45	LIMESTONE
17	500	4,000	60	LIMESTONE
18	700	4,000	45	LIMESTONE
19	700	4,000	60	LIMESTONE
20	250	6,000	45	LIMESTONE
21	500	6,000	45	LIMESTONE
22	700	6,000	45	LIMESTONE
23	TBD	TBD	TBD	TBD
24	TBD	TBD	TBD	TBD

NOTE: 1 gram = 15.42 grains. In other words, a 250 grain fragment has a mass of 16.21 grams.

Table 2. Actual Test Matrix

TEST NUMBER	FRAGMENT MASS (grains)	IMPACT VELOCITY (ft/sec)	OBLIQUITY (Degrees from Normal)	TARGET ROCK MATERIAL
1 (G7)	248.4	4,562	30	GRANITE
2 (G4)	248.3	4,410	45	GRANITE
3 (G8)	248.4	4,324	60	GRANITE
4A (G5)	489.9	2,119	45	GRANITE
4B (G5B)	490.0	2,910	45	GRANITE
5 (G9)	490.2	4,001	60	GRANITE
6 (G6)	699.6	4,450	45	GRANITE
7 (G10)	699.8	4,379	60	GRANITE
8 (G1)	248.7	6,380	45	GRANITE
9 (G11)	248.4	6,271	60	GRANITE
10 (G2)	490.2	6,416	45	GRANITE
11 (G12)	490.0	6,055	60	GRANITE
12 (G3)	700.1	5,983	45	GRANITE
13 (G13)	699.3	6,621	60	GRANITE
14 (L1)	248.9	3,802	45	LIMESTONE
15 (L7)	248.4	4,384	60	LIMESTONE
16 (L2)	490.2	4,584	45	LIMESTONE
17 (L8)	490.0	4,481	60	LIMESTONE
18 (L3)	699.8	4,456	45	LIMESTONE
19 (L9)	700.8	3,953	60	LIMESTONE
20 (L4)	248.6	6,046	45	LIMESTONE
21 (L5)	489.7	6,041	45	LIMESTONE
22 (L6)	700.4	6,108	45	LIMESTONE

each rock type was measured for each of the cored samples, and an average obtained. Data from these laboratory tests is shown in Table 3.

Table 3. Measured Rock Properties

PROPERTY	GRANITE	LIMESTONE
LONGITUDINAL WAVE SPEED (ft/sec)	10,560	13,202
SHEAR WAVE SPEED (ft/sec)	6,404	7,398
UNIT WEIGHT (lb/cu ft)	168	169

If one knows the longitudinal wave speed, the shear wave speed, and the density of the material, the elastic modulus can be determined from Equation 4, and Poisson's ratio can be determined from Equation 5. From the classical relations

$$E = \frac{V_s^2 \gamma}{g} \left[\frac{3(V_p / V_s)^2 - 4}{(V_p / V_s)^2 - 1} \right] \tag{4}$$

$$\nu = \frac{1}{2} \left[\frac{(V_p / V_s)^2 - 2}{(V_p / V_s)^2 - 1} \right] \tag{5}$$

V_p = longitudinal wave speed

V_s = shear wave speed

γ = unit weight

g = accel. due to gravity

ν = Poisson's ratio

among elastic constants, or moduli, one can find the bulk modulus if one knows the elastic modulus and Poisson's ratio, as shown in Equation 6.

$$K = \frac{E}{3(1 - 2v)} \tag{6}$$

The data shown in Table 3 can be used to determine the various moduli from Equations 4, 5, and 6. Application of these formulae yielded the results shown in Table 4.

The range of fragment weights and impact velocities chosen for these tests, and shown in Table 1, were selected to produce a wide range of impact energies--adequate to span the reasonable range of energies for fragments from the detonation of a high explosive-filled projectile or warhead. The range of impact energies is shown graphically in Figure 4.

The next section of this report presents the results of the experiments.

Table 4. Calculated Properties of Rock Samples

PROPERTY	GRANITE	LIMESTONE
ELASTIC MODULUS (psi)	3,650,000	5,080,000
POISSON'S RATIO	0.231	0.269
BULK MODULUS (psi)	2,260,000	3,660,000

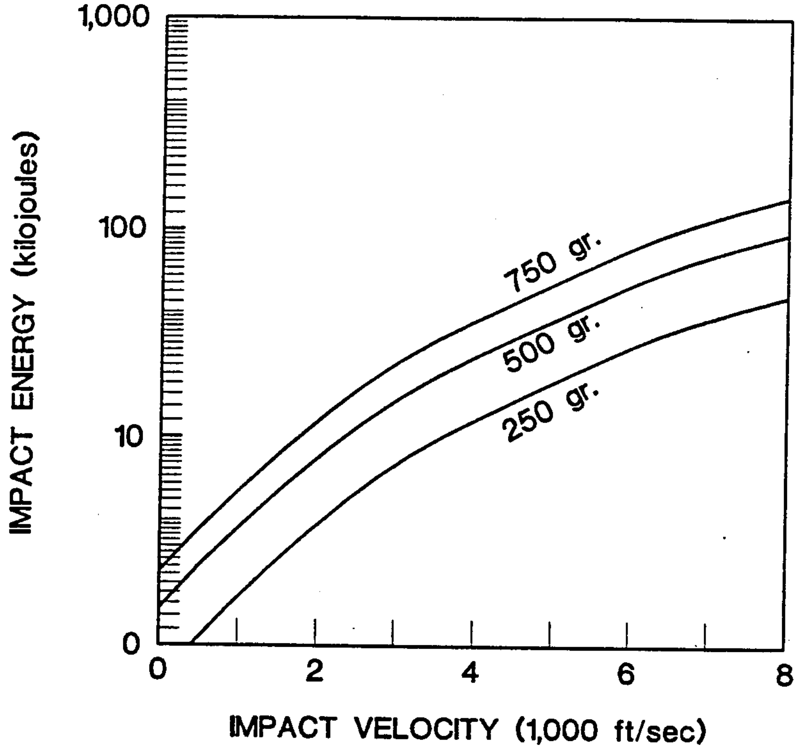

Figure 4. Impact Energies of Design Fragments

The actual impact energies obtained in the tests are indicated in Figure 5. It will be noted that these actual energies are close to the intended, or design, energies of impact.

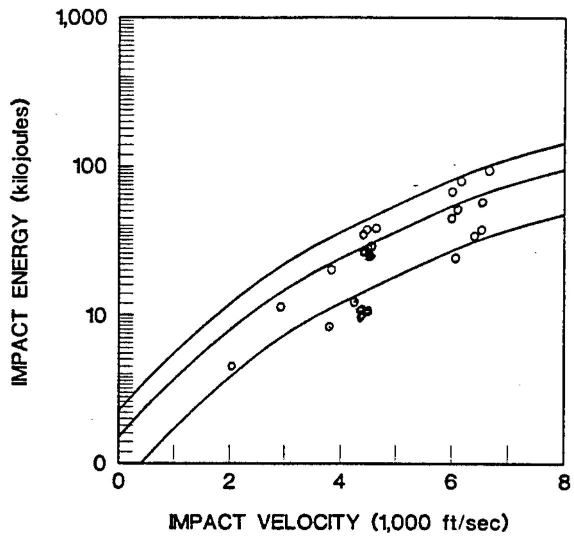

Figure 5. Actual Fragment Impact Energies (data points) Compared to Design Energies (curves)

As discussed previously (see Equation 2), there are several forms of energy loss connected with the impact of a steel fragment on a hard rock sample. The term "E2" in Equation 2 represents the energy loss associated with plastic deformation and fracture of the incident fragment. The mass lost by a fragment was investigated by comparing the ratio of the weight of the primary post-impact (residual) fragment to the weight of the incident fragment for each test. The results of the experiments in terms of these weight ratios are presented in Table 5. Examination of the weight ratio data shows a wide variation in the results. The overall average value shown implies that a steel fragment impacting rock over a range of velocities and obliquities will suffer about 31.3 percent loss of mass as a result of the impact. In other words, the largest single post impact fragment, representing the primary post ricochet threat to other munitions or stored items, will average about 69 percent of the weight of the incident fragment.

Table 5. Weight Ratios for Rock Impacts

TEST NUMBER	INCIDENT WEIGHT (grams)	RESIDUAL WEIGHT* (grams)	RATIO Wr/Wi
1	16.11	12.70	0.788
2	16.10	8.20	0.509
3	16.11	11.60	0.720
4A	31.77	24.30	[0.765]
4B	31.78	30.10	[0.947]
5	31.79	28.00	0.881
6	45.37	35.60	0.785
7	45.38	26.80	0.590
8	16.13	7.60	0.471
9	16.11	6.10	0.379
10	31.79	13.70	0.431
11	31.78	7.90	0.248
12	45.40	23.50	0.518
13	45.35	17.80	0.392
14	16.14	13.30	0.824
15	16.11	15.7	0.974
16	31.79	31.79	1.000
17	31.78	31.40	0.988
18	45.38	35.60	0.784
19	45.45	45.10	0.992
20	16.12	11.80	0.732
21	31.76	22.80	0.718
22	45.42	31.90	0.702
AVERAGE			**0.687 Sigma = 0.225**

* For the primary, or single largest, post-impact residual fragment.
[ ] Values not used in computing averages, due to questionable performance of gun/launcher.

Further investigation into the data shown in Table 5 was made, to determine which of the primary variables exercised the greatest influence on the results. First, the effects of rock type were investigated. Recall that we are dealing with two types of rock targets--a fine-grained limestone and a granite. Tests 1 through 13 in Table 5 were fired against the granite specimens, and Tests 14 through 22 were fired against the limestone. Cursory inspection indicates differences in the range of weight ratios the two rock types. The data were examined in two strata, granite and limestone. Results are shown in Table 6.

Table 6. Weight Ratios as Function of Rock Type Only

ROCK TYPE	AVERAGE VALUE Wr/Wi	STANDARD DEVIATION
GRANITE	0.559	0.195
LIMESTONE	0.857	0.130

The results presented in Table 6 are not surprising. In essence, they demonstrate statistically significant differences in the energy loss due to fragment plastic deformation and fracture, with the harder rock (granite) producing a greater fracturing than the softer limestone.

A second way to view the data of Table 5 is to determine whether impact velocity is a significant influence on weight loss or deformation/fracture energy loss. The data shown in Table 5 were re-stratified to look at this variable only. The results are shown in Table 7.

Once again, the data in Table 7 clearly indicate variation in the extent of mass loss, or deformation/fracture energy loss, as a function of velocity. The data in Table 7 do not include the two shots at less than 4,000 ft/sec shown in Table 5, since only a single sample at each of these velocities was available--these events were unplanned, and resulted from improper function of the gun launcher.

Table 7. Weight Ratios as Function of Impact Velocity Only

IMPACT VELOCITY	RATIO, Wr/Wi	STANDARD DEVIATION
4,000 ft/sec avg.	0.820	0.160
6,000 ft/sec avg.	0.510	0.172

It might be conjectured that impact obliquity would exert an influence on the degree of deformation energy loss, since more oblique impacts could imply greater dynamic shear stress in the compact (cubic) fragment. The Table 5 data were investigated with incident obliquity as the only stratification. Results are shown in Table 8.

Table 8. Weight Ratios as Function of Impact Obliquity Only

INCIDENT OBLIQUITY	RATIO, Wr/Wi	STANDARD DEVIATION
45 deg	0.679	0.176
60 deg	0.684	0.293

The data in Table 8 show that there is no statistically significant effect on mass loss or deformation/fracture energy magnitude due solely to obliquity. It appears therefore, that the differences shown earlier, in Tables 6 and 7, apply over the range of obliquities tested.

Finally, one might conjecture that there could be variation in the mass loss fraction resulting from variation in the initial mass or size of the incident fragment--it could be that the smaller and larger fragments would deform or fracture to different extents. The Table 5 results were stratified to investigate this parameter only, and the results are shown in Table 9.

Table 9. Weight Ratios as Function of Incident Fragment Weight Only

INCIDENT WEIGHT	RATIO, Wr/Wi	STANDARD DEVIATION
250 grain nominal	0.658	0.213
500 grain nominal	0.711	0.310
700 grain nominal	0.680	0.197

While the results in Table 9 indicate some minor variation with nominal weight of the incident fragment, we observe that (1) there is no apparent reason for the trends in the variation, and (2) more importantly, the differences do not appear to be statistically significant, due to the scatter in the data, as evidenced by the standard deviations shown in Table 9. Hence, we can state further that the observed deformation mass loss will be approximately constant for all fragment sizes of interest.

It is instructive to combine the two principal influences on mass loss--the rock type and impact velocity (Tables 6 and 7)--and to investigate the combination of these two variables. The results of such a grouping are shown in Table 10.

The data in Table 10 show these variations. Higher velocity impacts, in harder rock, cause significantly greater deformation mass loss, and hence represent relatively greater degrees of loss of kinetic energy. While the same trend is observed in the softer limestone, the magnitude of the energy or mass loss is less at each velocity than seen in the harder granite.

Table 10. Variation in Weight Ratio as Function of Rock Type and Velocity

ROCK TYPE	IMPACT VEL. (ft/sec)	WEIGHT RATIO (Wr/Wi)	STANDARD DEVIATION
GRANITE	4,000	0.712	0.138
GRANITE	6,000	0.406	0.093
LIMESTONE	4,000	0.927	0.096
LIMESTONE	6,000	0.717	0.015

The results of these experiments clearly show that impacts against harder rocks result in greater fragment mass loss than impacts against softer rock. The effect of rock type is significant, and should be taken into account when choosing potential sites for underground munitions storage. Likewise, the greater the impact velocity, the more damage is done to the fragment, resulting in a smaller primary residual fragment. Fragment mass loss does not appear to be significantly dependent on obliquity of impact, or initial fragment weight or size.

The other principle component of the residual kinetic energy of a post-impact fragment is the residual velocity. Both incident and residual velocities were measured in these tests, as described previously. Data on the ratio of residual to incident velocity is presented in Table 11.

Table 11. Residual versus Incident Velocity Results

TEST NUMBER	IMPACT VELOCITY (ft/sec)	RESIDUAL VELOCITY (ft/sec)	RATIO: Vr/Vi
1	4,562	1,174	0.257
2	4,410	1,467	0.332
3	4,324	2,297	0.531
4A	2,119	1,089	[0.513]
4B	2,910	1,320	[0.454]
5	4,001	2,218	0.554
6	4,450	1,594	0.358
7	4,379	N/A	N/A
8	6,380	2,978	0.467
9	6,271	2,151	0.343
10	6,416	1,762	0.274
11	6,055	1,744	0.288
12	5,983	2,657	0.444
13	6,621	1,722	0.260
14	3,802	502	0.132
15	4,384	1,294	0.295
16	4,584	951	0.207
17	4,481	1,199	0.267
18	4,456	1,317	0.296
19	3,953	1,312	0.332
20	6,046	2,943	0.487
21	6,041	1,884	0.312
22	6,108	2,748	0.450
AVERAGE			0.344 Sigma = 0.111

[ ] Data not used in averages

Although these two sets of results can provide sufficient information to conclude that the initial oblique impact is a major energy reduction event, it is still instructive to investigate the effects of the different experimental parameters on the velocity reduction, in a manner similar to that used in investigating the weight ratio or deformation mass loss sensitivity.

The Table 11 data were stratified successively by incident weight only, incident obliquity only, incident velocity only, and rock type only. No statistically significant variations were found in any of these single parameter investigations. Even when the parameters were considered in sets of two--e.g., rock type and impact velocity or rock type and incident obliquity--no statistically significant variations were found. It appears therefore that the average of 0.344 ratio of residual velocity to incident velocity is a satisfactory engineering value, over the range of rock strengths, impact velocities, obliquities, and compact fragment weights studied.

Having investigated the energy balance question, the remaining factor of interest is a comparison of the incident obliquity to the post-impact obliquity, or the reflection angle versus the impact angle. In many analyses, these angles are treated as equal. If one is using some sort of ray trace model, this can be a critical assumption when treating arrangements of several barrier surfaces intersecting at various angles.

The data were reduced to give the post-impact obliquity, or θr, as a fraction of the impact obliquity, or θi. In both cases, obliquity is defined as the angle between the fragment trajectory and the normal to the rock target surface. In other words, obliquity is the complement of impact angle, in normal terminology. An obliquity of 0 degrees would correspond to an impact angle of 90 degrees, or normal to the rock target surface. The data are shown in Table 12.

Table 12. Post Impact Obliquity versus Incident Obliquity

TEST NUMBER	INCIDENT OBLIQ. (degrees)	POST-IMPACT OBLIQ. (degrees)	RATIO: θ_r/θ_i
1	30	21	0.70
2	45	32	0.80
3	60	20	0.33
4A	45	13	0.29
4B	45	19	0.42
5	60	19	0.32
6	45	35	0.78
7	60	20	0.33
8	45	46	1.02
9	60	30	0.50
10	45	46	1.02
11	60	32	0.53
12	45	44	0.98
13	60	36	0.60
14	45	51	1.13
15	60	33	0.55
16	45	52	1.16
17	60	32	0.53
18	45	46	1.02
19	60	33	0.55
20	45	70	1.56
21	45	66	1.47
22	45	63	1.40
AVERAGE			0.78 Sigma = 0.386
[ ] Data not used in averages			

The data in Table 12 illustrate several immediately apparent factors. First, the post-impact obliquities are nearly always less than the incident obliquities; i.e., the fragment will tend to ricochet in a direction more nearly normal to the face of the rock (13 out of 21 tests). This trend is indicated by the average ratio, but is clearly violated frequently in tests 14 through 22--the shots into the softer limestone. Stratification of the data shown in Table 12 by rock type leads to the results shown in Table 13.

Table 13. Variation in Ricochet Angle as Function of Rock Type Only

ROCK TYPE	RATIO: $\theta r/\theta i$	STANDARD DEVIATION
GRANITE	0.616	0.269
LIMESTONE	1.04	0.410

The results shown in Table 13 indicate a significant variation in ricochet angle due to rock type. In the case of impacts on the harder granite, the primary residual fragment tends to depart the rock face at an angle more near to the normal to the face of the rock. For impacts on the softer limestone, the post-impact angle of obliquity is greater than the incident angle, or the ricocheting fragment is departing the rock face at an angle further away from the normal. The effect of incident fragment weight was analyzed separately from the other variables, and found to have no significant influence on the pre- and post-impact obliquities. This left the variables of impact velocity and impact obliquity to be investigated individually.

The dependence on impact velocity alone is shown in Table 14. The data implies a significant effect due to impact velocity. The average values indicate that the faster the fragment is traveling at the time of impact, the more likely the post-impact (ricochet) angle of obliquity will be equal to or greater than the impact (incident) angle of obliquity.

Table 14. Influence of Fragment Impact Velocity on Ricochet Angle

IMPACT VELOCITY (ft/sec)	RATIO: $\theta r/\theta i$	STANDARD DEVIATION
2,000 nominal	0.29	**
3,000 nominal	0.42	**
4,000 nominal	0.68	0.302
6,000 nominal	1.01	0.407
** Not computed--single data points only, shown for comparison.		

Table 15. Effect of Incident Obliquity on Ricochet Angle

INCIDENT OBLIQUITY (degrees)	RATIO: $\theta r/\theta i$	STANDARD DEVIATION
45	1.00	0.372
60	0.471	0.112

The effect of fragment impact obliquity alone are shown in Table 15. As one would expect, the results indicate a strong influence of impact obliquity on post-impact obliquity. However, over the restricted range of values tested, the greater impact obliquity (60 degrees) produced the smaller post-impact obliquities. At first consideration, this result could seem anomalous. However, when one considers that a steel fragment traveling at a high velocity will normally produce an impact crater in rock, and that the fragment actually departs the rock, not from the face, but from the bottom of this crater, one could suggest that this result would redirect the fragment's ricochet to a direction closer to 90 degrees from its impact angle. Of course, it must be recognized that at some incident obliquity greater than 60 degrees, this trend will diminish. If the fragment impacts at an angle near 90 degree obliquity--i.e., parallel to the rock face--it will simply produce more of a shallow gouge or scrape, rather than a crater.

Next, the effects of rock type and impact obliquity were separated. The results shown in Table 16 imply a dependence on both rock type and incident obliquity. For a given obliquity, impacts against the harder rock tend to produce ricochet obliquity angles which were less than the incident obliquity. The same was true for the higher impact obliquity angle in the softer rock, but not for the smaller obliquity angle.

Table 16. Influence of Rock Type and Incident Obliquity on Ricochet Angle

ROCK TYPE	INCIDENT OBLIQUITY (deg)	RATIO: $\theta r/\theta i$	STANDARD DEVIATION
GRANITE	45	0.758	0.295
GRANITE	60	0.435	0.123
LIMESTONE	45	1.290	0.216
LIMESTONE	60	0.543	0.012

As a final step in this analysis, the influence of rock type and impact velocity on ricochet obliquity was investigated. The results are shown in Table 17. These data indicate that velocity played a significant role, for fragments impacting the limestone. The effect of velocity when impacting the granite was much less than that for the softer limestone, however. In general, harder rock tends to decrease the obliquity of ricochet, while higher velocity tends to increase the obliquity of ricochet.

The final category of results to be reported is the comparison of pre- and post-impact kinetic energies using Equation 3. Earlier discussions of the test results with respect to pre- and post-impact weights, velocities, and obliquities provide one look at the problem being investigated. However, the overall influence of mass reduction and impact velocity can be investigated by comparing the residual kinetic energy to the impact kinetic energy. The results of this comparison are shown in Table 18.

Table 17. Influence of Rock Type and Impact Velocity on Ricochet Obliquity

ROCK TYPE	IMPACT VELOCITY (ft/sec)	RATIO: $\theta r/\theta i$	STANDARD DEVIATION
GRANITE	4,000	0.543	0.240
GRANITE	6,000	0.775	0.256
LIMESTONE	4,000	0.823	0.310
LIMESTONE	6,000	1.480	0.080

These data indicate that velocity plays a significant role, as indicated earlier in the results of considering that variable alone. When one combines that variable with the rock type (or rock strength) variable, one clearly sees the combined effect. Harder rock tends to decrease the obliquity of ricochet, while higher velocity tends to increase the obliquity of ricochet.

The final category of results to be reported is the comparison of pre- and post-impact kinetic energies, or the direct comparison of KE(in) and KE(resid) from Equation 3. Earlier discussions of results with respect to pre- and post-impact weights and velocities, considered independently, provide one look at this problem. However, it is instructive to compare the direct computation of residual energy by test event with the actual incident energy. Results of this comparison are shown in Table 18.

The Table 18 results indicate that, over the range of velocities, obliquities, and fragment weights, and rock types tested that the average impact resulted in about 90 percent kinetic energy loss--i.e., KE(resid) = 0.9 KE(in), in the terms of Equation 3.

Table 18. Comparison of Incident and Residual Kinetic Energies for the Primary Residual Fragment

TEST NUMBER	INCIDENT K.E. (KJ)	RESIDUAL K.E. (KJ)	RATIO: E(resid)/E(in)
1	11.47	0.597	0.052
2	10.72	0.605	0.056
3	10.31	2.097	0.203
4A	4.88	0.985	0.202
4B	9.20	1.794	0.195
5	17.40	4.713	0.271
6	30.75	3.093	0.100
7	29.78	N/A	N/A
8	22.44	2.230	0.099
9	21.68	0.963	0.044
10	44.74	1.456	0.032
11	39.85	0.822	0.021
12	55.58	5.678	0.102
13	68.08	1.805	0.026
14	7.97	0.115	0.014
15	10.60	0.890	0.084
16	22.84	0.983	0.043
17	21.82	1.545	0.071
18	30.83	2.112	0.068
19	24.26	2.654	0.109
20	20.15	3.497	0.174
21	39.67	2.767	0.070
22	57.93	8.243	0.142
AVERAGE			**0.089** **Sigma = 0.066**

The range was from a minimum kinetic energy loss of 73 percent of incident to a maximum of 98.6 percent of maximum. The scatter in the data shown in Table 18 indicated a need to determine whether any particular variable was most contributory to the magnitude of the kinetic energy loss. Rock type, incident velocity, incident obliquity, and incident fragment weight were all investigated independently, with no statistically significant trends found.

Comparing the average value of the ratio of residual kinetic energy to incident kinetic energy from the Table 18 results to the combination of the earlier results of the weight and velocity ratios yielded approximately the same result--0.089 ratio for KE(resid)/KE(in) from Table 18, and 0.082 for the calculation from the independent analyses of weight and velocity ratios. This is well within the scatter of the data.

CONCLUSIONS

After analysis of all data from these tests, we conclude as follows:

1. The impact of a compact steel fragment with competent rock such as limestone or granite, will result in the loss of an average of 90 percent of the incident kinetic energy. That is, the primary post-impact fragment will retain only about 10 percent of the kinetic energy of the incident fragment.

2. The weight of the primary residual or post-impact fragment will be 69 percent of the incident fragment weight on the average, with harder rock (granite) producing greater fracture (Wr/Wi = 0.559) than the softer limestone (Wr/Wi = 0.857).

3. The average post-impact, (or ricochet), velocity of the primary fragment will be only about 34 percent of the impact velocity of the complete fragment.

4. The primary post-impact fragment will ricochet, or leave the rock face, at an obliquity angle of only about 0.82 times the incident obliquity angle, on the average. However, this angle is very sensitive to rock type, and cratering morphology, with the ricochet angles from the softer limestone being roughly equivalent to the incident obliquity, while the harder granite produces ricochet obliquities of significantly lower value (more nearly normal to the face).

5. Models or analyses which utilize the perfectly elastic or ideal impact simulation will grossly overstate the post-ricochet damage capability of steel fragments after impacts against hard rock surfaces. Indeed, it

appears that initial impacts with a rock surface (up to impact obliquities of 60 degrees or more) may effectively neutralize fragments from exploding munitions as a viable mechanism for initiating other stored munitions.

RECOMMENDATIONS

In view of the results obtained during this research, we recommend that analyses of potential storage facilities consider the average results obtained, unless the rock type and strength is significantly different from that tested. Specifically, we recommend that:

1. The residual kinetic energy of munition fragments ricocheting from rock surfaces be modeled as only 10 percent of the impact kinetic energy, for compact steel fragments at normal fragment velocities.

2. The obliquity of the ricocheting fragment be modeled as roughly equivalent to the impact obliquity, unless it is known that the facility being analyzed is situated in very competent rock, such as granite. In this case, the ricochet obliquity should be considered to be less than the incident obliquity, as indicated in this report.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
April 1995

3. REPORT TYPE AND DATES COVERED
Final report

4. TITLE AND SUBTITLE
Dynamics and Kinematics of Oblique Impacts of Steel Fragments on Rock Surfaces

5. FUNDING NUMBERS
Contract No.:
DACA39-93-K-0002

6. AUTHOR(S)
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
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Denver Research Institute
University of Denver
Denver, CO 80208

8. PERFORMING ORGANIZATION REPORT NUMBER
ESLF 9414
UAST-CR-94-001

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Engineer Waterways Experiment Station
Structures Laboratory
3909 Halls Ferry Road, Vicksburg, MS 39180-6199

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
Contract Report
SL-95-3

11. SUPPLEMENTARY NOTES
Available from National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

A series of 23 experiments were conducted to evaluate the dynamic and kinematic changes induced by the impact of steel cubes against rock surface. The cubes were intended to simulate metal fragments from accidental munition explosions in underground magazines. Test parameters included rock type (limestone and granite), impact velocity (nominally 4,000 and 6,000 ft/sec), fragment weight (250, 500, and 700 grains), and angle of obliquity (30, 45, and 60 degrees). The data analyses indicate that 90 percent of the incident kinetic energy is lost as a result of fragment impact on a smooth rock surface. The steel cubes fractured upon impact, resulting in an average weight of the recovered largest fragment that was 56 and 86 percent of the pre-impact weight for granite and limestone, respectively. These limited test results indicate that munition fragments impacting rock surfaces at obliquities up to 60 degrees (impact angles of 30 degrees or more) will lose enough kinetic energy to greatly reduce the likelihood of secondary detonations initiated by their subsequent impact against other munitions.

14. SUBJECT TERMS
Fragment dynamics
Fragment impact
Fragment kinematics
Post-impact energy

15. NUMBER OF PAGES
46

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	