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TECHNICAL NOTE

CRIMINALISTICS

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# Prediction of Projectile Ricochet Behavior After Water Impact*

**ABSTRACT:** Although not very common, forensic investigation related to projectile ricochet on water can be required when undesirable collateral damage occurs. Predicting the ricochet behavior of a projectile is challenging owing to numerous parameters involved: impact velocity, incident angle, projectile stability, angular velocity, etc. Ricochet characteristics of different projectiles (K50 BMG, 0.5-cal Ball M2, 0.5-cal AP-T C44, 7.62-mm Ball C21, and 5.56-mm Ball C77) were studied in a pool. The results are presented to assess projectile velocity after ricochet, ricochet angle, and projectile azimuth angle based on impact velocity or incident angle for each projectile type. The azimuth ranges show the highest variability at low postricochet velocity. The critical ricochet angles were ranging from 15 to 30°. The average ricochet angles for all projectiles were pretty close for all projectiles at 2.5 and 10° incident angles for the range of velocities studied.

**KEYWORDS:** forensic science, ricochet, water, projectile, angle, residual velocity

Military forces are called upon to work in different environments, and knowledge of projectile ricochet upon impact with water is of interest when there is possible collateral damage. Some papers (1–4) give information on soft projectile behavior after ricochet. It was assumed that military projectiles react differently because of the different characteristics required by the higher lethality requirements (e.g., higher diameter, density, and impact velocity). The lack of published work in this field motivated this study which had as its objective the development of simple methods that can help to assess ricochet behavior of military projectile impacts with water.

## Materials and Methods

Because projectiles can strike water at any angle and velocity, a range of scenarios had to be studied to develop a model. This study was limited to five projectile types and four equivalent ranges as shown in Table 1. Projectile velocities were set to replicate impacts at those ranges. This allowed the weapon to be placed roughly 5 m from the water impact point, simplifying the experimental set-up.

To perform the ricochet tests, a $3.6 \times 0.6 \times 0.3$ m deep pool was built as shown in Fig. 1. This pool was made of 6.35 mm mild steel with 12.7 mm polycarbonate windows. Extra steel plates were put on the pool's floor to avoid perforation when no ricochet occurred. A water tank was used to refill the pool after each impact. A grid was used on the rear wall of the pool as a reference for the high-speed video, and a yaw card was placed at the end of the pool to record projectile impact location and to confirm the projectile's integrity/stability after the ricochet. Figure 2 shows an example of the set-up for one of the incident angles.

A 10.5-GHz radar, placed behind the weapons, was used to measure the velocity of the projectile before impact with the water. Two Photron APX-RS high-speed video cameras Photron USA Inc., San Diego, CA) were placed at 0 and 90° to the water impact location (i.e., behind the weapon looking down the range and on the side of the pool facing the grid placed on the rear wall of the pool). The camera located at 0° was set to record at 10,000 fps with a resolution of $512 \times 512$ pixels while the camera at 90° was set to record at 12,000 fps with a $768 \times 320$ pixel resolution. The velocity of the projectile after impact was estimated using the images recorded by the two cameras unless the projectile was hidden by the water ejected upon impact. All analyses and tests were performed at Defence Research and Development Canada – Valcartier (DRDC Valcartier) with the technical support of the Munitions Experimental Test Centre.

## Results

### *Critical Angle*

The incident angles used to determine the critical ricochet angle were 2.5, 10, 15, 20, and 30°. The highest incident angle used was that which never produced ricochets. Results are shown in Table 2.

Burke and Rowe (1) reviewed papers on ricochet, which mention the complexity of predicting the ricochet behavior. Haag (2) has shown that critical ricochet angles on water for 0.30–06-, 0.38-, 0.22-, and 0.222-caliber projectiles were between 4 and 8°. Gold and Schecter (3) showed a critical angle of approximately 6° for the 9-mm Parabellum bullet. However, the five projectiles studied here had higher critical angles of between 15 and 30°.

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TABLE 1—*Projectiles studied.*

| Projectile Type | Muzzle Velocity (m/s) | Equivalent Range (m) |
|---|---|---|
| K50 BMG | 740 | 0, 200, 600 |
| 0.5-cal Ball M2 | 893 | 0, 600 |
| 0.5-cal AP-T C44 | 749 | 0, 600 |
| 7.62-mm Ball C21 | 879 | 0, 300 |
| 5.56-mm Ball C77 | 937 | 0, 300 |

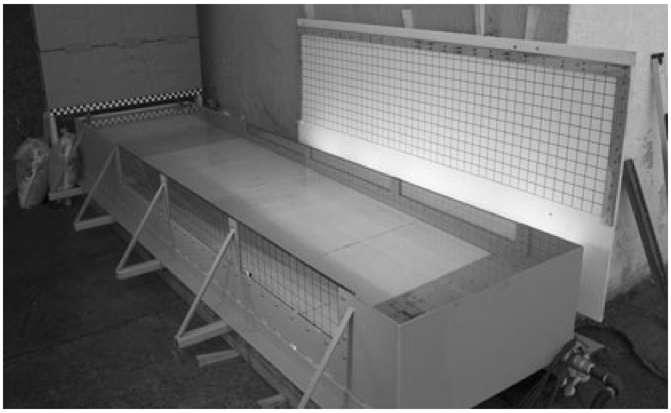

FIG. 1—*Pool used for ricochet tests.*

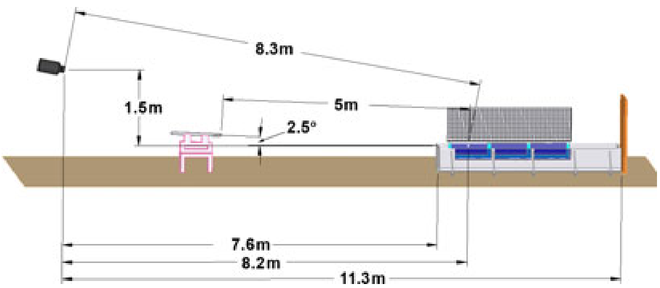


FIG. 2—*The 2.5° incident angle test set-up.*

TABLE 2—*Critical ricochet angle at muzzle velocity.*

| | Critical Ricochet Angle | |
|---|---|---|
| Projectile Type | Experimental (°) | Hutchings Prediction (°) |
| K50 BMG | 15–20 | 23 |
| 0.5-cal Ball M2 | 15–20 | 21 |
| 0.5-cal AP-T C44 | 15–20 | 18 |
| 7.62-mm Ball C21 | 15–20 | 17 |
| 5.56-mm Ball C77 | 20–30 | 19 |

The most accurate equation the authors found to predict the critical ricochet angle was from Hutchings (5). However, his equation was developed for a simplified spinning cylindrical shape moving in a plane perpendicular to its axis:

$$\text{Critical ricochet angle } (^\circ) = \frac{18.7\sqrt{1 + 1.6\frac{a\omega}{v}}}{\sqrt{\frac{\rho_p}{\rho}}} \qquad (1)$$

In this equation, $a$ is the cylinder radius, $v$ is the velocity of the projectile's center of mass, $\omega$ is the axial angular velocity (i.e., spin), $\rho$ is the water density, and $\rho_p$ is the projectile density.

A precise critical angle was not defined in the experimental results but rather a range of values that bound the critical angle. The higher values of the range are the angles that do not create any ricochet. The lower values are the angles at which ricochet occurred for at least one shot. More repetitions for each configuration would have been required to precisely measure the critical angle defined as the angle beyond which ricochet does not occur.

### *Ricochet Angle Versus Incident Angle*

For each projectile, the average ricochet angle was recorded for the different equivalent range velocities at incident angles of 2.5, 10, 15, and 20° as shown in Table 3. The number of repetitions is the number of shots that allowed measurement of all criteria (i.e., the shots that produced a ricochet and allowed observation of the projectile trajectory after ricochet). The higher the incident angle, the lower the number of ricochet was.

Low variability was observed for ricochet angles at low incident angles. The 5.56-mm projectiles broke in two pieces or more at high velocity. Figure 3 shows the results obtained for each projectile based on the average ricochet angle of all shots performed at the different velocities. Note that because of the low difference in projectile impact velocities, the ricochet angle did not seem to be strongly influenced by the impact velocity. This is why all the data were grouped irrespective of the impact velocity.

Small-caliber projectiles seem to follow the same trend. Medium-caliber projectile ricochet angles are also grouped together. At high incident angle, medium-caliber projectiles seem to result in a higher ricochet angle than small-caliber projectiles. However, one should note that ballistic tests were performed for a limited velocity range that was deemed representative of possible engagement scenarios at short distances. Also, only a subset of possible incident angles was studied.

Figure 4 illustrates that the projectiles were stable at low incident angle (i.e., 2.5°) and were unstable and tumbled at angles >10°. For the 10° incident angle, the tumbling of the projectile can even be seen in the shape of the perturbed water through the pool windows. This instability need to be studied well in order to be able to estimate how far the projectile could travel following the ricochet off the water surface. Even under stable conditions, the video showed a high degree of yaw.

Gold and Schecter (3) have shown that ricochet angle increases in a linear fashion until the bullet becomes unstable at angles >4.7° for the 9-mm Parabellum bullet (at 407 m/s). As the authors observed that the transition from a stable to an unstable state occurred between incident angles of 2.5 and 10° during their tests, a discontinuity would probably have been recorded if additional tests had be performed in that range.

### *Percentage of the Velocity Drop Versus Incident Angle*

A trend appears when the percentage of velocity drop is reported as a function of the incident angle, as in Eq. 2.

$$\text{Velocity drop}(\%) = 100(\text{Impact velocity} - \text{postricochet velocity}) / \text{impact velocity} \qquad (2)$$

TABLE 3—*Summary of the values recorded after projectile ricochet.*

| Projectile | Equivalent Range (m) | Incident Angle (°) | Average | | | | | | | | Number of Repetition Involved |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Impact Velocity (m/s) | STDEV. | Postricochet Velocity (m/s) | STDEV. | % Velocity Drop | STDEV. | Ricochet Angle (°) | STDEV. | |
| K50 BMG | 0 | 2.6 | 695 | 37 | 627 | 37 | 9.6 | 5.4 | 9.0 | 1.6 | 9 |
| | 200 | 2.5 | 606 | 17 | 577 | 22 | 4.9 | 2.9 | 8.5 | 1.8 | 5 |
| | 600 | 2.6 | 436 | 13 | 407 | 6 | 6.6 | 3.3 | 6.25 | 0.5 | 4 |
| | 0 | 10.0 | 714 | 17 | 200 | 165 | 72.2 | 22.6 | 12.5 | 3.6 | 4 |
| | 200 | 10.1 | 579 | 20 | 192 | 96 | 66.8 | 17.2 | 13.15 | 2.5 | 4 |
| | 600 | 10.7 | 414 | 20 | 94 | 29 | 77.4 | 5.9 | 14.35 | 1.2 | 2 |
| | 0 | 16.5 | 675 | 3 | 14 | 14 | 98.0 | 2.0 | 60.65 | 1.5 | 2 |
| | 200 | 16.4 | 613 | 50 | 17 | 9 | 97.4 | 1.2 | 36.7 | 32.5 | 2 |
| | 600 | 15.2 | 395 | 19 | 16 | 4 | 95.9 | 1.3 | 36.8 | 13.4 | 2 |
| 0.5-cal. Ball M2 | 0 | 2.6 | 832 | 43 | 749 | 31 | 9.7 | 5.5 | 7.5 | 0.6 | 7 |
| | 600 | 2.7 | 713 | 24 | 644 | 12 | 9.7 | 2.6 | 8.2 | 5.1 | 5 |
| | 0 | 10.2 | 800 | 20 | 85 | 10 | 89.4 | 1.1 | 12.6 | 3.8 | 5 |
| | 600 | 11.0 | 714 | 34 | 69 | 54 | 90.4 | 7.5 | 12.2 | 2.3 | 5 |
| | 0 | 14.9 | 777 | 35 | 24 | 9 | 96.9 | 1.1 | 64.3 | 10.7 | 3 |
| | 600 | 14.5 | 709 | – | 32 | – | 95.9 | – | 57.7 | – | 1 |
| 0.5-cal. AP-T C44 | 0 | 2.5 | 720 | 24 | 620 | 22 | 14.0 | 2.0 | 6.5 | 0.6 | 6 |
| | 600 | 3.1 | 577 | 46 | 527 | 55 | 8.9 | 4.0 | 6.5 | 0.2 | 5 |
| | 0 | 10.7 | 709.3 | 22 | 27 | 6 | 96 | 0.8 | 14.8 | 2.2 | 4 |
| | 600 | 10.7 | 612.7 | 31 | 30 | 19 | 95 | 3.3 | 16.2 | 1.7 | 5 |
| | 0 | 14.2 | 701.6 | – | 49 | – | 93 | – | 51.1 | – | 1 |
| | 600 | 15.6 | 574.4 | 41 | 11 | 12 | 98 | 2.2 | 42.0 | 15.1 | 4 |
| 7.62-mm Ball C21 | 0 | 2.7 | 868.9 | 10 | 753 | 16 | 13 | 2.1 | 7.5 | 0.5 | 7 |
| | 300 | 2.5 | 610.0 | 20 | 566 | 20 | 7 | 2.6 | 5.9 | 0.9 | 5 |
| | 0 | 10.3 | 830.4 | 29 | 168 | 95 | 80 | 12.3 | 11.9 | 1.8 | 5 |
| | 300 | 10.2 | 608.6 | 5 | 45 | 17 | 91 | 0.9 | 12.8 | 1.3 | 2 |
| | 0 | 15.5 | 794 | – | 10 | – | 98.7 | – | 21.8 | – | 1 |
| | 300 | 15.9 | 583.0 | 17 | 18 | 13 | 98 | 2.0 | 28.8 | 2.4 | 3 |
| 5.56-mm Ball C77 | 0 | 2.8 | 897.6 | 13 | 782 | 26 | 13 | 3.0 | 8.8 | 1.1 | 5 |
| | 300 | 2.8 | 643.1 | 51 | 582 | 35 | 9 | 2.6 | 7.6 | 0.3 | 5 |
| | 0 | 10.5 | 908.0 | 29 | 332 | 28 | 63 | 4.0 | 13.5 | 2.2 | 6 |
| | 300 | 10.3 | 625.7 | 17 | 144 | 28 | 77 | 4.5 | 12.2 | 1.3 | 5 |
| | 0 | 20.9 | 901.1 | 14 | 43 | 31 | 95 | 3.4 | 25.0 | 14.1 | 4 |
| | 300 | 20.3 | 600.0 | 29 | 42 | 16 | 93 | 3.0 | 34.3 | 5.2 | 2 |

STDEV., standard deviation: $\sqrt{\frac{\sum (x-\bar{x})^2}{(n-1)}}$.

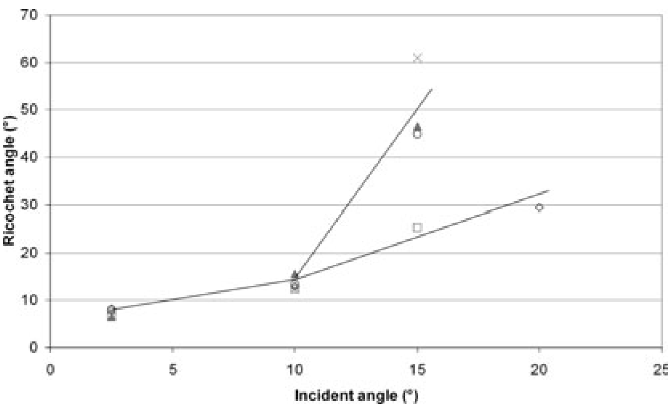


FIG. 3—*Average ricochet angle as a function of the incident angle for all projectiles. Diamond = 5.56 mm C77; square = 7.62 mm C21; triangle = 0.5 AP-T C44; x = 0.5 Ball M2; circle = K50 BMG.*

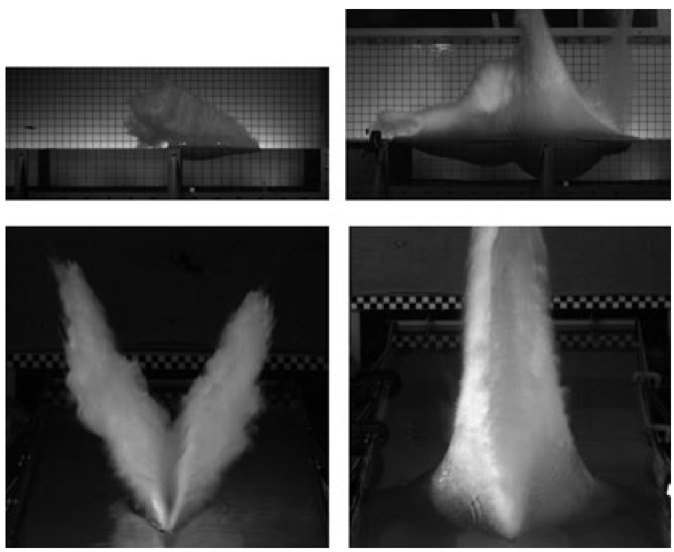

FIG. 4—*The 0.5 Ball M2 at muzzle velocity; the projectile is stable at an angle of 2.5° (right) and unstable at 10° (left).*

All impact velocities resulted in the average velocity drop approaching a single value that is a function of the incident angle and projectile type. Figures 5 and 6 show all data recorded for 0.5-cal. Ball M2 and 5.56-mm Ball C77 projectiles (a similar trend was observed for other projectiles). A Weibull cumulative distribution function was proposed to allow interpolation between results. This distribution, described in Eq. (3), used the parameters presented in Table 4 to best fit the experimental data.

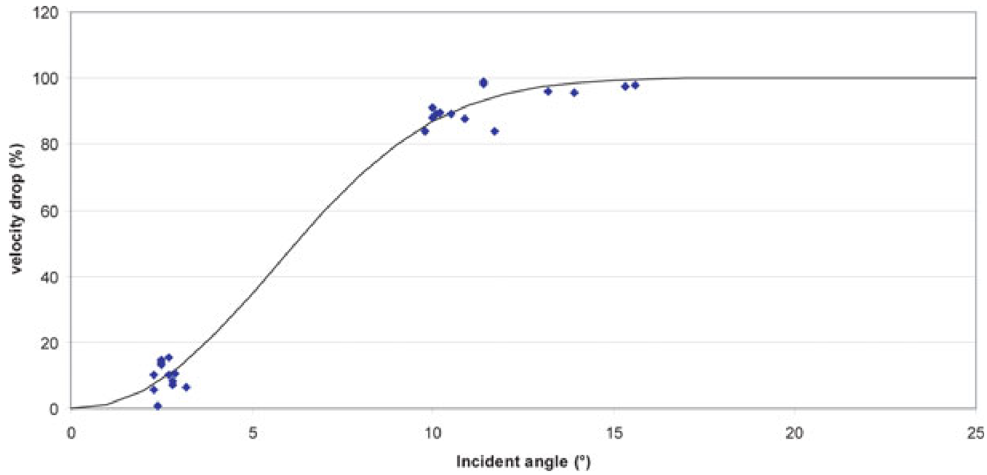


FIG. 5—*Velocity drop for 0.5-cal. Ball M2 for different impact velocities. Diamond = experimental data; solid line = Weibull cumulative function.*

TABLE 4—*Optimized values for b and λ parameters of Eq. (3).*

| Projectile Type | b | λ |
|---|---|---|
| K50 BMG | 0.009 | 2.107 |
| 0.5-cal Ball M2 | 0.011 | 2.258 |
| 0.5-cal AP-T C44 | 0.010 | 2.500 |
| 7.62-mm Ball C21 | 0.017 | 1.980 |
| 5.56-mm Ball C77 | 0.022 | 1.698 |

$$F(x) = 1 - e^{-bx^{\lambda}} \quad (3)$$

*Azimuth of the Projectiles Versus Relative Velocity of the Projectile*

After ricochet, the deviation in the projectile trajectory (i.e., to the left or to the right) was recorded when the amount of water projected upon impact was small enough to allow for proper visibility. Because all projectiles had a clockwise axial angular velocity (i.e., when looking at the downrange), their trajectory went to the right if the postricochet velocity was high enough. For lower postricochet velocities, however, a general trend was an increase of the dispersion in terms of azimuth. The azimuth angles were reported as positive if the projectile moves to the right following the ricochet and negative when it moved to the left. Zero degrees would mean that the projectile trajectory did not change in azimuth, only in elevation, following the ricochet off the water's surface. As all projectiles showed similar trends according to their postricochet velocity, results were reported based on a normalized postricochet velocity (i.e., postricochet velocity divided by the impact velocity). Figures 7 and 8 present all of the experimental data collected, for the medium-caliber and small-caliber projectiles, respectively, with the lower and upper dotted lines bounding the data. The data seem to be distributed randomly between those two limits except for the AP-T C44 projectile, where all ricochets resulted in a trajectory that deviated to the left at low impact velocities.

Experimental data from the small-caliber projectiles studied showed that the projectiles typically deviated to the right after the ricochet. The maximum azimuth angle obtained is also much higher to the right (i.e., 66°) than to the left (−18.4°). Medium-caliber projectiles seem to present positive azimuth at high velocity and more negative azimuths at low velocity and this is again reflected in the limit values (i.e., 25.5° right and −54° left).

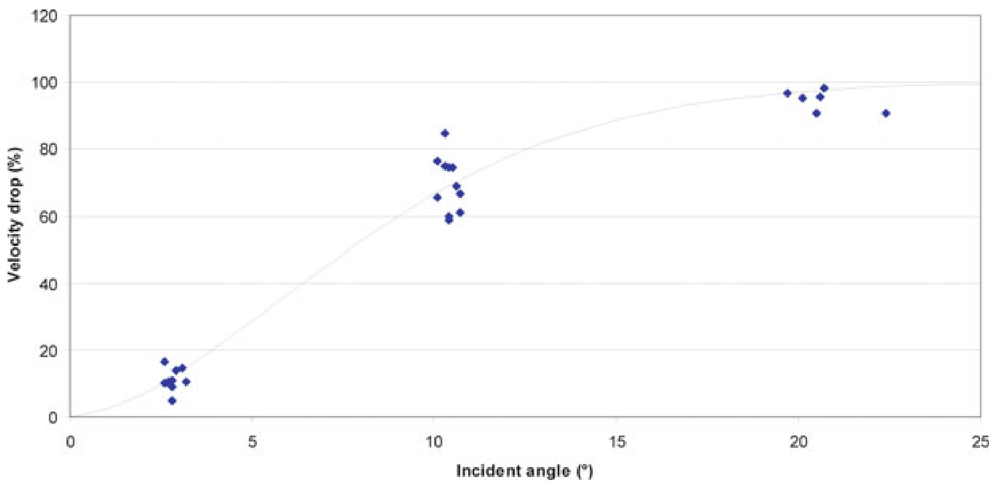


FIG. 6—*Velocity drop for 5.56-mm Ball C77 for different impact velocities. Diamond = experimental data; solid line = Weibull cumulative function.*

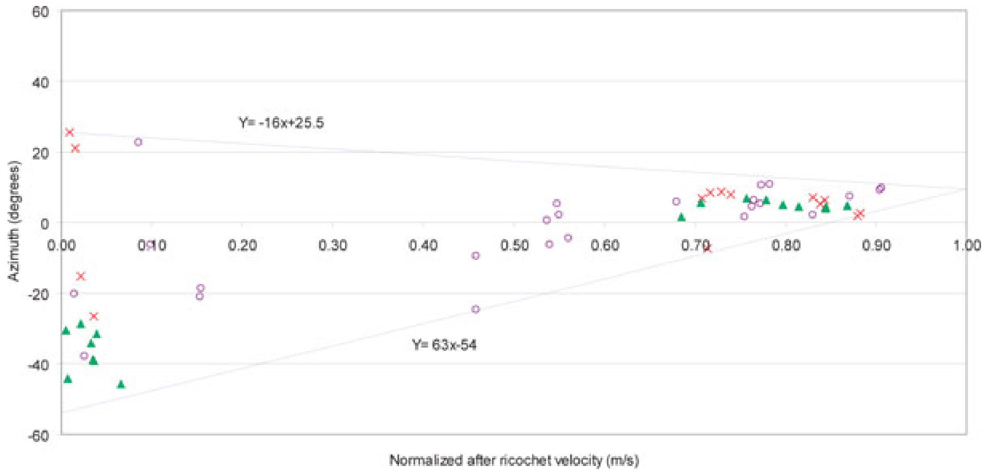


FIG. 7—*Postricochet azimuth angle for medium-caliber projectiles. Triangle = 0.5 AP-T C44; x = 0.5 Ball M2; circle = K50 BMG.*

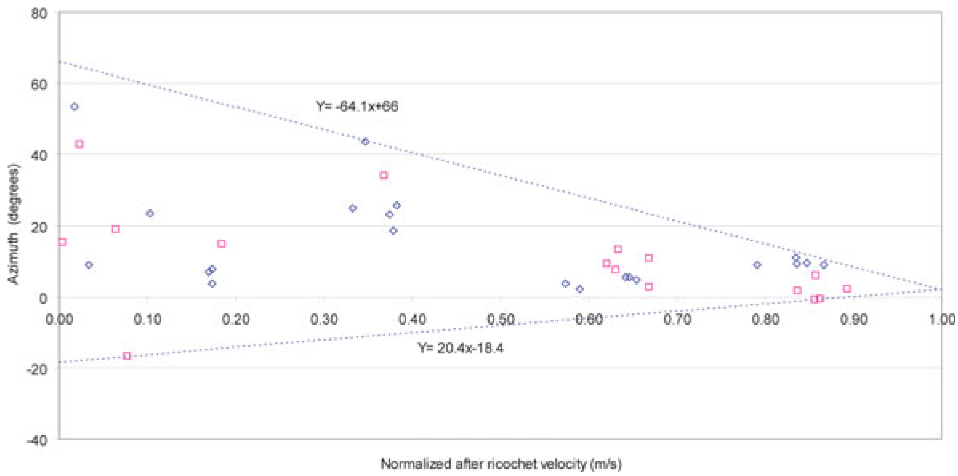


FIG. 8—*Postricochet azimuth angle for small-caliber projectiles. Diamond = 5.56 mm C77; square = 7.62 mm C21.*

Experimental data did not allow a precise trend for the azimuth to be defined as even repetitions with the same ballistic configuration resulted in the azimuth being distributed between these two limits. The projectile axial angular velocity and the offset of the projectile nose from the shot line (yaw), either left or right when striking the water, are parameters that should affect the final azimuth angle. Shooting at different distances from the water in real scenarios would result in a different projectile axial angular velocity when compared to short-range shooting at equivalent velocity (i.e., using a reduced quantity of powder to lower the muzzle velocity of a given projectile). Extra tests would be required to show how important variations in angular velocity and yaw are on azimuth angles.

## Experimental Limitations

Very limited studies have been performed to investigate the impact of military projectiles on water. This article presents a preliminary study to help understand the observed postricochet behavior. As tests are costly and time consuming, a limited number of projectiles have been fired in this study. In this article, the authors tried to define a methodology to predict the postricochet behavior of the projectile but the models would need to be improved with more data to increase the accuracy of the predictions. One should note the following caveats:

- Limited number of repetitions.
- Limited range of velocities.
- Limited number of incident angles so that transition effects between stable and unstable need to be verified.
- The modified projectile velocity obtained with a reduced quantity of powder in the cartridge is not fully representative of an actual firing scenario. Impact upon water at a real distance would result in a slightly different projectile axial angular velocity as well as a different yaw.

## Conclusions

When a target is engaged, there is always a risk of missing it and creating unwanted collateral damage. Ricochet is one of the worst situations because the projectile can travel varying distances in different directions based on the parameters characterizing its impacts. This is particularly true for impacts on water. Five military projectiles were studied to assess ricochet behavior after impact with water. Given the limited amount of data, one could focus on the average estimate of the ricochet angle and velocity and statistically select the exit azimuth angle to get a rough idea of the possible ricochet trajectories.

Results showed a higher variability for azimuth ranges at low postricochet velocity than at high postvelocity where projectiles were pretty much restricted to a single deviation side. The critical ricochet angles were ranging from 15 to 30°. The average ricochet angles for all projectiles were pretty close for all projectiles at 2.5 and 10° incident angles for the range of velocities studied.

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