

FLYROCK RE-VISITED.....On the Web

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Over the past year I had reason to become re-acquainted with, and educated about, the fundamentals of flyrock ballistics.

For almost a decade during the previous century I was fortunate to be part of a group at the Lawrence Livermore Laboratory that focused on the technology and feasibility of using large explosive charges for excavation. An example was digging an interoceanic sea-level canal through Panama with nuclear explosives, a project that eventually suffered a quiet political and public-relations demise. Flyrock, known to us then as 'crater ejecta', was a relatively minor concern, ranking considerably below radioactive fallout. We did, though, acquire hard, empirical data from cratering experiments with nuclear explosives at the Nevada Test Site, e.g., 'Cabriolet', 'Schooner' and 'Buggy', the latter consisted of the simultaneous detonation of five 1.1-kiloton nuclear 'devices' to rapidly excavate a rather impressive trench in the Nevada desert (Google Earth fans can go to 37°00'27.3"N, 116°22'18.3"W to view this relic of the Plowshare program).

My interest in 'ejecta' was recently rekindled by some litigation in which personal injuries are claimed to have been inflicted by flyrock from a construction blast. My intent is not to comment on any specific aspect of this litigation, but rather to present some of the basics of projectile ballistics and to attempt answers to the four questions stated below. Nor will this article discuss possible origins or mechanisms of flyrock creation, such as insufficient stemming or burden. The questions are:

What is the optimum launch angle so that a piece of flyrock will travel the farthest for a given launch velocity?

What is the effect of air drag?

Do little rocks travel farther than big, heavy rocks for the same initial conditions?

What is a plausible range of distances for small fragments of rock from a typical construction blast?

Much literature on explosives was reviewed, including all papers presented at ISEE meetings since its inception through 2009, in an attempt to learn what 'the state-of-the-art' is for flyrock ballistics and how it could be applied in the specific instance of the lawsuit. There are case histories and anecdotal accounts of flyrock incidents but, with one exception cited below, little quantitative analysis that can be readily applied. A paper by Cameron McKenzie titled "*Flyrock Range & Fragment Size Prediction*" presented at the 2009 ISEE meeting is relatively outstanding and quite thorough in its discussion of the topic. As pointed out by McKenzie, and as shown later in Figs. 2 and 3, any flyrock analysis which ignores the effects of air drag is totally unrealistic.

Despite the excellence of McKenzie's work, the most fruitful and flexible sources of information about projectile ballistics were found on the internet, particularly a site operated by Colorado State University at Boulder (CSU) [http://phet.colorado.edu/sims/projectile-motion/projectile-motion_en.html]. The CSU site allows the user to calculate projectile distances by specifying the weight, diameter, drag coefficient, altitude, and the initial velocity and launch angle of the object. The site is easy to use and, therefore, one can readily conduct parametric analyses of flyrock trajectories on the basis of first principles. There are other, similar websites that can be used to confirm or verify results. About twenty five years ago I used a scientific-type pocket calculator to compute flyrock trajectories with air drag. The problem is non-linear and the calculation requires that the ballistic path be computed in small increments of time... the word "tedious" is totally inadequate to describe the task.

To answer the first question, a series of calculations based on two plausible (but probably low) values of drag coefficient (C_d) and three values of launch velocity for a small piece of flyrock demonstrate that the launch angle for maximum distance depends on the launch velocity. This outcome is illustrated by the results plotted in Fig. 1, which show that the optimum launch angle for a small stone varies from about 25° at 1000 ft/sec to approximately 40° at 100 ft/sec. Some of us may vaguely recall from high-school physics that for any given velocity the maximum projectile range will be achieved at a launch angle of 45°, but this only applies in a vacuum. Further, Fig. 1 also shows that for any given launch velocity the maximum distance does not vary by more than 10% over a fairly wide range of angles.

The influence of air drag is significant, and a reasonable value for the drag coefficient must be selected for the projectile under consideration. The drag coefficient C_d is defined by the following relation:

$$F_d = \frac{1}{2}(C_d V^2 \rho A)$$

Where F_d is the drag force, V is the projectile velocity, ρ is the air density (primarily a function of altitude), and A is the cross-sectional area. Note that the drag force varies as the square of the velocity. Drag coefficients can be measured in a wind tunnel, but an exact value need not be known because calculations can easily be performed for a range of plausible values. A general discussion of drag coefficient and some typical values associated with common shapes can be found on Wikipedia. The CSU site allows calculations to be done with either user-defined properties or with pre-set values for ordinary items such as a baseball ($C_d = 0.4$) or a piano ($C_d = 1.2$). Other representative values of C_d are 0.8 to 1.05 for a cube (depending on its orientation), 0.4 for a rough sphere, 0.24 for a golf ball and 1.28 for a flat plate perpendicular to the stream flow. The drag coefficient for a given object can vary with the speed of the airflow, but appears to vary little for subsonic velocities. I believe that a credible, but probably conservative, value of C_d for a rough, irregular shard or piece of flyrock is in the range of 0.6 to 0.8., i.e., the same values that were assumed in constructing the curves in Fig. 1.

The influence of the weight and drag coefficient of a projectile on its range is illustrated in Fig. 2. In this figure it is assumed that a projectile is launched at an angle of 35° with an initial velocity of 200 ft/sec, a value that is at least twice that of typical burden velocities. The curves in Fig. 2 represent the distance traveled by roughly-spherical, granitic rocks (2.7 gm/cm³) with C_d 's of 0.6 and 0.8. Also shown are the maximum ranges for particular items ranging from a Ping Pong ball to a bowling ball. The item designated "Average E-stones" is representative of the samples of alleged flyrock in the referenced litigation. At the top of Fig. 2 is the range of all objects in a vacuum. Clearly, the heavier the object, the farther it is capable of traveling through the air; when an object weighs several thousand pounds, air drag is not much of a factor. The figure also explains why flyrock can be large and lethal at considerable distances from a blast, but smaller pieces cannot travel very far simply because of air resistance. Figure 2 also illustrates why you can throw a golf ball a lot farther than a Ping Pong ball, i.e., the density of the object is also important... all other things being equal, objects with higher densities travel farther. Wes Bender has succinctly described the influence of weight as follows: "*Take three nearly identical pieces of rock approximately the size of a baseball. Leave one intact. Crush one to gravel size. Grind the third to sand. Throw each as far as you possibly can and compare the results.*"

Finally, the effects of launch velocity and drag coefficient on the maximum distance are shown in Fig. 3, which answers the question of what is a plausible range of distances for small pieces of flyrock. The values of weight (~ 1 oz) and approximate diameter (~ 1 in) for the 'stones' in Fig. 3 are close to the average of the measured properties of the pieces of alleged flyrock in the referenced incident. Calculations of flyrock distances in Fig. 3 did account for the variation of optimum launch angle with launch velocity illustrated in Fig. 1. It is evident that a representative or typical value of burden velocity for a construction blast, say 50 to 100 ft/sec, would imply a maximum distance of less than 200 ft for such small stones. Further, even if the launch velocity of these stones implausibly approached the speed of sound, the upper limit is still less than 700 ft and, for a more realistic C_d of 0.8, only slightly greater than 500 ft. As can be seen once again in Fig. 3, neglecting air drag in any calculation of flyrock distance will result in a gross overestimate.

The reader is encouraged to experiment with the CSU site.... if nothing else, you can find out how far you can hurl a piano.

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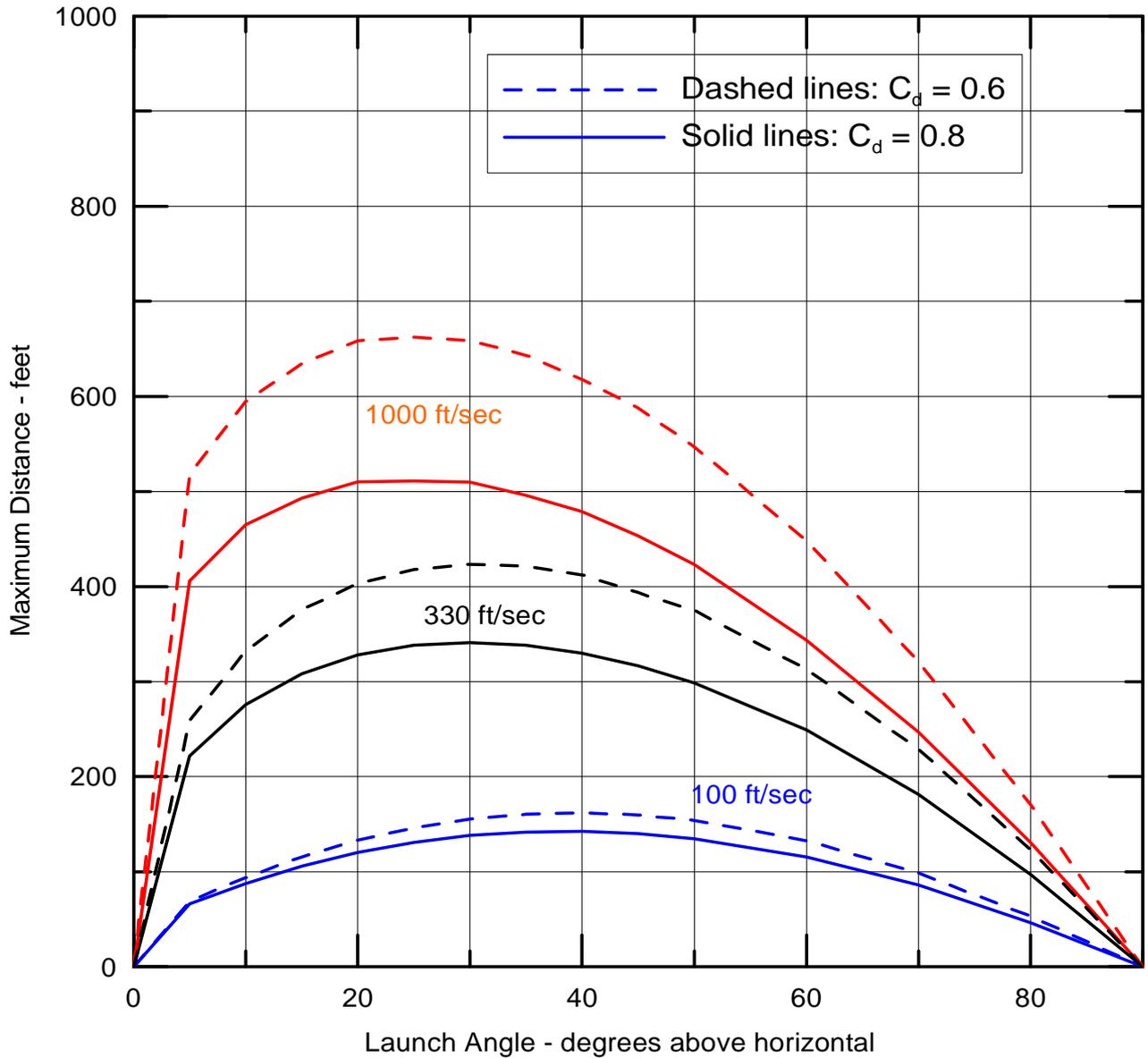


Fig. 1
Maximum Distance vs. Launch Angle and Velocity for $C_d = 0.6$ & $C_d = 0.8$
for a
Rough, stone fragment with an approx. weight of 1 oz and average cross-section of 1 inch

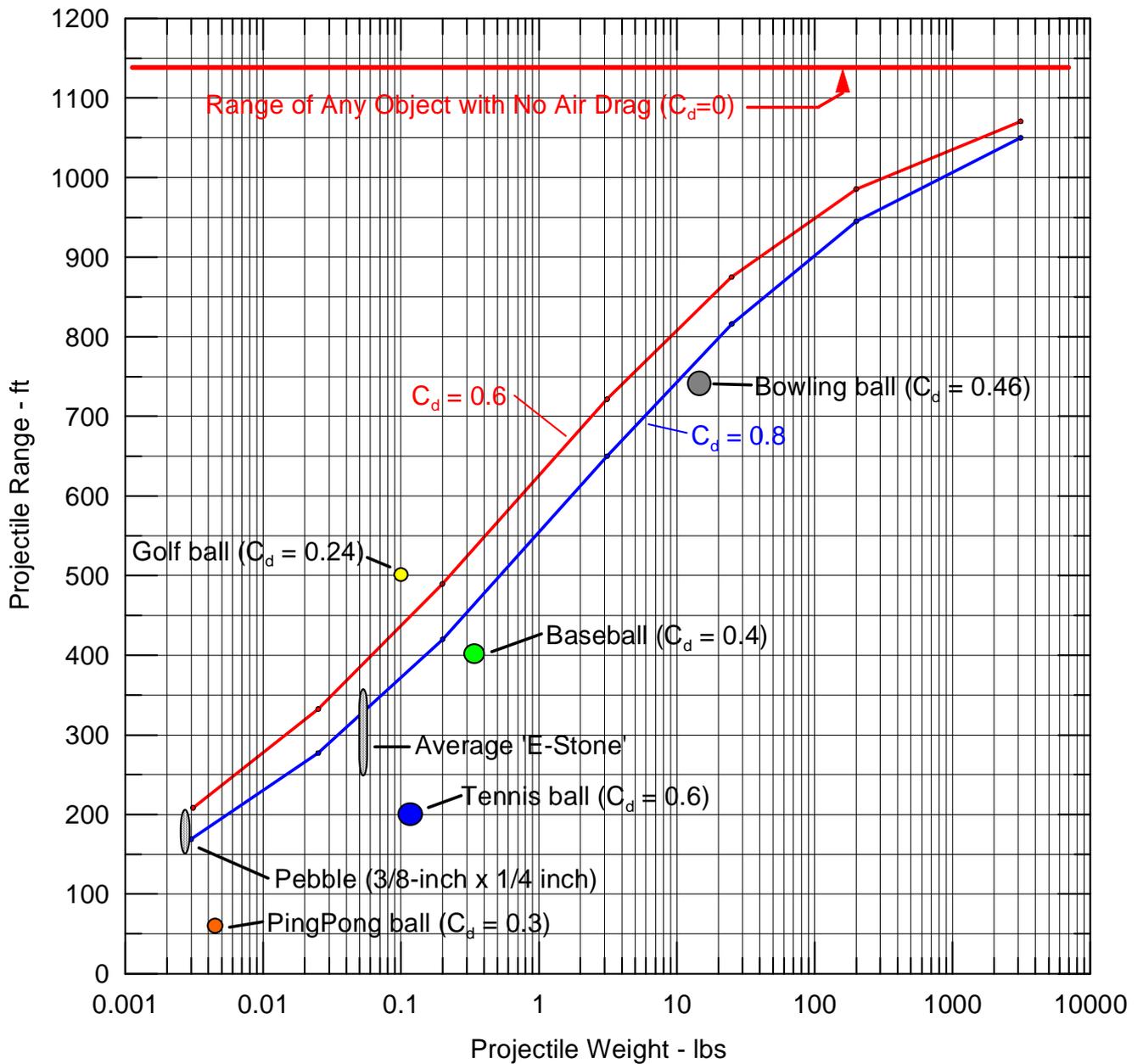


Fig. 2
Projectile Ranges as a Function of Weight and Air Drag
 for
 Initial Velocity = 200 ft/sec and Optimum Launch Angle of 35 degrees
 with
 Density = 2.7 gm/cm³ (granite), $C_d = 0.6$ and $C_d = 0.8$, and altitude = 1500 ft

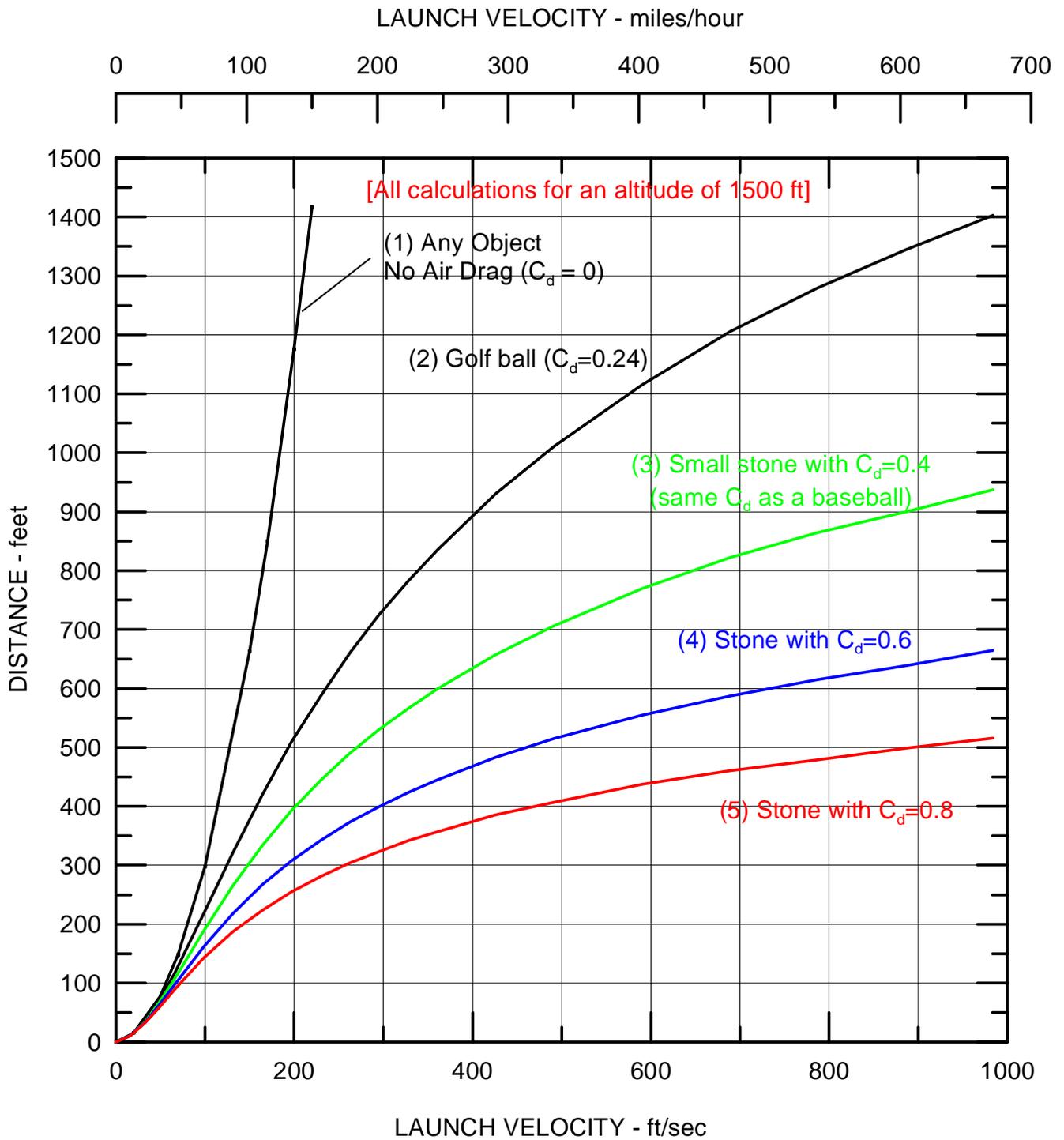


Fig. 3
Maximum Flyrock Distance vs. Launch Velocity at Optimum Launch Angle
 for (1) Any object with no air drag, i.e., $C_d = 0$
 (2) A golf ball with $C_d = 0.24$, a weight of 1.6 oz and a diameter of 1.7 inch
 (3) A small stone with $C_d = 0.4$, a weight of approx. 1 oz and a diameter of approx. 1 in
 (4) Same stone as in (3) above with $C_d = 0.6$, and (5) Same stone as in (3) above with $C_d = 0.8$