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INTRODUCTION:

The interest that arose in new small arms bullets and also in the use of less conventional shapes as small arms projectiles exposed the paucity of exterior ballistic (and other) data on small arms projectiles. It also revealed that the shape spectrum on which there were data was quite polarized: That for the relatively short rifle bullet and that for the high ℓ/d flechette. The Ballistic Research Laboratories (BRL) have been a traditional source of information on artillery projectiles and, as small arms systems began to undergo more critical scrutiny, the BRL was called upon by the Army Material System Analysis Agency (AMSAA), the Army Small Arms Systems Agency (SASA), and others to furnish study inputs. These inputs tended to be peculiar to given systems and any data developed only slowly expanded the data base and altered the polarization of the spectrum. It was apparent that a more general design information base was required.

Hence the BRL proceeded with a plan to expand the data base. The experiences with trying to produce general information on bullet shapes, using actual bullets, led to the following decisions:

(a) Actual bullet tests were so involved with lot-to-lot shape changes and round-to-round deformation differences that an inordinate amount of testing was required to determine the mean aerodynamic properties[1]. This led to a decision to utilize lathe-turned bronze models, or other low deformation projectiles, to reduce the volume of testing needed.

(b) Even using models with predictible shapes the process of extending the data base experimentally would be slow; rapid expansion would require a primary reliance on computation results.

15

(c) The use of aerodynamic computations as a design basis for artillery shell is reasonably well established; however, the information generated had not been on shapes (or in sizes) of obvious interest to the small arms designer nor were the resultant studies in a useful framework for his purposes. Further work was needed to establish a base of confidence in computing the behavior of small arms projectiles and this should be done in bullet sizes and subject to typical small arms systems constraints.

In an effort to provide this more general design basis, several programs were generated within the BRL and later partially supported by other agencies, particularly AMSAA and SASA. These programs had several similarities:

(a) There was interaction between two or more ballistic disciplines; e.g. if certain projectiles were involved in terminal ballistic testing, exterior ballistic tests would be carried out on the same shapes. Thus, the total data base would be expanding in a more uniform and useful manner.

(b) The emphasis was placed on computations, where at all possible, to provide a more rapid expansion of coverage. However for each computational program there was a follow-up phase to prove at least a part of the computational results.

An account of one of these programs is given in BRL Report 1532[2]. This program was an effort to meet the suggestions of AMSAA and SASA that information was needed to span the gap in the ℓ/d spectrum and that it should be in a framework familiar to the small arms designer. The effort was a "Phase I" type; that is, it was based solely on interior and exterior ballistic computations subject to some overall constraints suggested by the interested agencies. Aerodynamic computations were made on some conventional bullet shapes, (CB's), some longer artillery shapes, (AR's), and on shapes with ℓ/d's between those of the AR's and flechettes. The intermediate configurations were selected as simple geometric shapes, such as cone or cone-cylinders. The computations also tried to consider realistically the difference between tracer and ball projectiles. One objective of the latter was to provide a better rationale for the design of matching tracer-ball combinations; the second was a reaction to the use of 100% tracer loading in SEA. The tracer round is usually degraded ballistically to yield a match with the "primary" ball projectile, if the tracer was being used as much as was indicated the possible performance of a tracer round without the match constraint on its design should be looked at.

The aerodynamic data were used with interior ballistic computations, subject to constraints on rifle length, caliber, and recoil momentum, to compute trajectory parameters as a function of range to 1100 meters. The results included trajectory coordinates, velocity, and remaining energy. The study considered permutations of fourteen shapes, three calibers (5.56, 6.5, and 7.62mm), three projectile densities (steel, lead, and tungsten), and three impulse levels (0.8, 1.2, and 2.1 pound-seconds).

The computer study did not really develop any data that were not potentially available to the designer before, but it did present a volume of information in a single context and within the constraints of a rifle class system. Since the information and trends from the Phase I study were contingent on the computed inputs, a Phase II follow-up was conducted involving six of the Phase I configurations and some added types. The exterior ballistic part of the Phase II testing consisted of firing the projectiles through one of the spark shadowgraphic ranges[3] of the BRL. The shapes involved in the Phase I and II programs are shown in Figure 1.

This report will present some samples from the results of the Phase I computations and from the exterior ballistic testing to determine the aerodynamic properties. Since the trends discussed later will be based primarily on the computations, it is perhaps better to reverse the chronology and show that the test results are in adequate agreement with the computed aerodynamic properties on which the trajectory computations were based.

COMPARISONS OF THEORY AND EXPERIMENT:

The first case considered is that of the CB-1. This is an idealized version of the 5.56mm M193 ball projectile. A sketch of the configuration is shown in Figure 2. The test models were pre-engraved bronze projectiles of nominal 5.56mm caliber. The models were fired from Mann barrels through the small 100 meter long spark shadowgraphic range. The positional and attitude measurements made from each flight were then processed and fitted[4] to yield the aerodynamic properties of drag, normal force, static moment, damping moments, and Magnus moment. The computations also furnish the first three above-named properties and comparison can be made.

The computed drag coefficient curve and the measured data points are plotted in Figure 3. Because of its bluntness, the computable range for this shape is only from about Mach 1.4 to 2.3. The agreement is essentially total at the scale of the graph, the maximum discrepancy being about 2% at the lowest computed Mach number. The validity of the assumed drag is the prime requisite for the computed trajectories; however, the static moment coefficient reflects the difficulty of stabilizing the projectile and, hence, is also important. The comparison between the computed and measured values for C_{M_α} is presented in Figure 4, again the agreement is very good. There is a bias of about 5% at the lowest computed point but this is of the same order as the scatter of the test data.

The second case to be considered is that of the AR-2. This is modeled after a prototype 175mm shell that was investigated because of its low drag at supersonic speeds. The test models for the AR-2 differed from those used for the CB-1 because a great many models were needed for other testing also. The AR-2 models were copper plated steel cores; the copper was not pre-engraved but engraved naturally in the firing process. This introduced a degree of realism that increased the data scatter over that of the bronze models, since metal whiskers from the engraving process were apparent on many models.

The AR-2 models accidentally gave an opportunity to check an assumption used in the drag computation[5]. The computations were made assuming a full turbulent boundary layer, although some smooth 5.56mm projectiles could be expected to have a laminar boundary layer. The turbulent assumption was retained because the computations assume a smooth body while the actual projectile is engraved. It was reasoned that thin laminar flow would leave the surface defects due to engraving exposed and added drag would result, while if a turbulent flow occurred its thick nature would tend to blanket the defects and little added drag would occur. Thus it was hoped that the smooth body with turbulent flow computation would represent the real bullet with turbulent flow and, also, adequately represent a bullet with laminar flow since the higher computed skin friction would be in a direction to compensate for the omitted protuberance drag. It would appear that for the AR-2's there is, fortuitously perhaps, a near cancellation since many of the models had laminar flow to the base and the data from these models, as shown in Figure 5, agree with the computed curve. One would not expect this cancellation in the computation for the static moment and the test results for the static moment coefficient of the AR-2 were up to 10% above the computed ones.

The two samples presented represent about the total span of differences observed in the dozen cases checked against test data to date. The agreements in drag coefficient were excellent and the trajectory computations should be very representative; the static moment results agree less well but would appear to be very adequate for preliminary design or evaluation work. It should be pointed out that a significant factor in the agreement is that the flight shape and the computed shape are nearly the same. The differences are much less than those expected between the design drawing shape and the fired shape of lead core bullets, thus use of similar computation on a bullet design would yield less perfect agreement.

The assumptions made for most of the computational aspects were founded either in well understood theory or on experience with larger projectiles. The assumptions made on the effect of an active tracer element on the drag of the bullet were in a different category. There was some guidance from US and UK wind tunnel[6,7] tests on the effect of mass and/or heat addition on the base flow of a projectile, although only the UK results were in a region of interest for shell or bullets. There were also limited results from spark range tests[8,9] at the BRL on bullets and small shell in which the trace elements function well on some shots and not on others. This information suggested the following:

(a) In general, tracer burning decreased the total drag level. Figure 6 shows the drag curve of a ballistic projectile and the traces recorded from the deceleration history when tracer function began in mid-flight.

(b) The nature and magnitude of the measured drag decreases suggested that a base pressure change, rather than a momentum thrust, was involved. If this was the case, base drag component decreases up to 50% were usual and 100% reductions occurred intermittently.

(c) The wind tunnel results suggested that changes in the base pressure to yield more than about one atmosphere were apt to yield external flow changes and increases in the profile drag component. This would imply that changes in the base drag component by much more than 100% might become detrimental.

These led to the assumptions used in the tracer computations: First, that the drag change was due to a base pressure change; second, that the base pressure could be raised to one atmosphere. The question of assuming a magnitude for the change was not bothersome; 50% changes were usual, the conventional tracer element was not designed to produce the drag effect observed and only by accident could the tested element be optimal in this regard. The assumption of the nature of the phenomenon, a base pressure change, was more bothersome since it was foreseen that it would be biased toward square-based projectiles with high base drag components. There were no tracer-on versus tracer-off data for a boat-tailed shell to confirm the assumption for this type.

Frankford Arsenal and the BRL are involved in a long term investigation on the effects of mass and thermal emitting elements on the drag of bullets under the auspices of SASA. However, in order to resolve the question of the behavior of a boat-tailed shape quickly, the BRL engaged in a limited program using bronze models. The models had the same head shape for both the square-based and boat-tailed versions and a base cavity into which a tracer element could be pressed. The 7.62mm size was used to alleviate the problem of loading the element and the projectiles were used with two different sizes of elements; the one used for the 5.56mm tracer M196 and the one used with the 7.62mm M62. All the projectiles loaded with the larger sized element were deformed when the tracer compound was pressed in and could not be fired, therefore, all the following results are for the under-sized element.

The total drag coefficient for the inert projectile, the computed base drag component and the test results with tracer element are shown in Figure 7. Although the experimental loading process led to erratic burning, the trend of the results for both the boat-tail and square-based model results still suggest the base pressure change mechanism more than any other one. The absolute drag reductions were generally larger for the square-based model than for the boat-tail. The boat-tailed model has a smaller base drag component, however, and had larger percentage change; these ranged from 50 to 70% while 50% was the maximum gain observed for the square base. This result is equivalent to the previously measured results, but it was achieved with an under-sized element.

It was not the objective of the Phase I study to investigate the effectiveness of the projectiles in any particular role, rather it was to provide the information essential to such studies. Several trends were so apparent in the results that they are worth commenting on. In the following discussion, the remaining energy, E_R, at various ranges will sometimes be used as a measure of merit. E_R is often the starting point to compute the effectiveness of a bullet against various targets and the discussion will have some of the facades of a terminal effectiveness presentation. However, it must not be so construed, E_R is only one factor in the actual effectiveness.

The observed trends are primarily due to the interaction of basic ballistic behavior and the momentum constraint conditions that were suggested as a basis for computing the sets of trajectories. The recoil level has a considerable impact on the accuracy of aimed fire and, also, often relates to the weight of the system. Thus, each set of the computations made represents a class of rifle system with about the same aiming errors and weight but firing the different projectiles. The momentum levels used were 0.8, 1.2 and 2.1 pound-seconds, about those for the SPIW, the 5.56mm M16, and a little less than that of the 7.62mm M14 respectively.

The momentum at the gun involves the projectile launch momentum, powder gas momentum, and that of any saboting material. However, many of the trends observed can be explained qualitatively by considering the simple expression for projectile momentum alone, with the understanding that quantitatively the gas momentum term can be quite important for velocities above 1000 meters per second. The momentum constraint, or (mass projected) x (muzzle velocity), implies that high velocities can be achieved by using light projectiles. If the projectile energy is taken as a criteria of usefulness then since;

$$E_o = \frac{m_p V_o^2}{2} = \frac{(m_p V_o)^2}{2m_p} = \frac{K^2}{2m_p}$$

the launch energy can also increase. However, the velocity loss equa-

33

tion for flat fire is,

$$\frac{dV}{dZ}\frac{1}{V} = \frac{-C_D \rho S}{2m_p}$$

where C_D is the drag coefficient, ρ the air density, S the reference area, usually $\pi d^2/4$, m_p the projectile mass, and Z is the range. Assuming the drag coefficient is constant yields the solution,

$$V = V_o \exp\left\{- C_D \rho S/2m_p\right\} Z .$$

One may also write the exponent as $\left(- C_D \rho Sd/2m_p\right)$ (Z/d), where (Z/d) represents the distance traveled in calibers. The retardation coefficient contains the projectile mass term in the denominator and, hence, for a given caliber a lighter projectile will have a more rapid fall off of velocity and energy, although it could have higher initial velocity and energy within the momentum constraint.

Small arms projectiles are usually nearly homogeneous projectiles and with $m_p = (\rho_p)$ x (volume in cubic calibers) x d^3, the retardation coefficient, α, can be written;

$$\alpha = \frac{\rho}{\rho_p}\left[\frac{\pi C_D}{Vol}\frac{1}{d}\right] .$$

That is, the α decreases as 1/d - or larger is better - for physical range (Z), or is constant in terms of caliber range (Z/d). The (C_D/Vol) term can be considered a figure of merit involving only the shape of the projectile. For a given shape family C_D at supersonic speeds tends to decrease with fineness ratio, ℓ/d, increases while the volume increases with ℓ/d; therefore, (C_D/Vol) decreases with ℓ/d. This is shown in Figure 8 for the computed shapes at Mach 3; the relative positioning of the shape families can change with Mach number but the trend with ℓ/d will remain. An important feature of the variation is that it changes rapidly at small ℓ/d's but is relatively flat at the higher ℓ/d's; there can be significant gains, or losses, due to small changes for short projectiles while the penalties, or gains, with ℓ/d changes are small for long projectiles. Turning now to the question of remaining energy, using these simplified models, there results;

$$E_R = E_o \exp\left\{\frac{\rho}{\rho_p}\frac{\pi}{4}\frac{C_D}{Vol}\right\}\frac{Z}{d}$$

$$= \frac{K^2}{2\rho_p\ (Vol)\ d^3}\exp\left\{\frac{\rho}{\rho_p}\frac{\pi}{4}\frac{C_D}{Vol}\right\}\frac{Z}{d}$$

The top curve in Figure 9 shows E_o (5.56mm, steel, 0.8 pound-second) as a function of the (ℓ/d) of the types. As expected, E_o decreases for the longer projectiles - even the use of this heterogeneous collection of projectile shapes does not confuse the general trend. The lower curve shows $E_{R\ 500}$, the remaining energy at 500 meters - this is just the reverse! Projectiles with high E_o have low $E_{R\ 500}$. Patently, there is a range up to which a given lighter projectile will have greater energy and beyond which a heavier, or better (C_D/Vol), projectile has greater energy. It is clear that if one is constrained to a low (ℓ/d) shape, increases in E_R at longer ranges can be obtained by denser projectiles - at the expense of the energy level at shorter ranges. Improvement in (ℓ/d) and clean shapes can permit gains in (C_D/Vol) to a point where the retardation characteristics are comparable even when lighter materials are used. In these cases, the total energy level can be raised over the whole trajectory. For example; three cases for the short CB-1 are plotted in Figure 10, the higher impulse level being used to show another point. The tungsten projectile has less initial energy than the lead one, but more remaining energy beyond 150 meters; this again shows how setting the ranges of consideration specifies a (C_D/ρ_p Vol) class. The steel projectile is an anomaly; it is never really in contention. This is a very high energy case and the increases in velocity within the momentum constraint has led us into a region of ballistic efficiency change and E_o has actually decreased. This warns against extending simplified models too far. The steel AR-2 projectile case, also plotted in Figure 10, can be compared with the lead CB-1. Here the (C_D/Vol) improvements permit a steel projectile which is lighter in weight, hence, higher in initial energy; and superior E_R at all points. Although superior in this sense, the steel AR-2 is a longer projectile and would require a higher twist to stabilize it as well as other features that may be good or bad when considering a particular system. The exhibited trends point out that given a single range specification, e.g. the ability to penetrate a helmet at 1000 meters with a particular weapon, the minimum value of (C_D/ρ_p Vol) is specified when terminal ballistic considerations are taken into account. This assists the designer but it should also be pointed out that there is a danger if such a specific requirement is poorly considered. It is often easy to rationalize that if a projectile can achieve a given result at long range, the weapons system will be desirable in other respects and at shorter ranges. It is not too difficult to couple longer range, hard target criteria with other desirable weapon constraints to yield "rifles" firing short tungsten projectiles at relatively low velocities on arcing trajectories as the "only" solutions. Needless to say, the specifier probably did not have such a weapon in mind.

The limited Phase II tests indicate that the previously measured reductions of 50% in the base drag component occur for both square-based and boat-tailed bullets with a standard tracer and suggest higher percentages are possible with acceptable compounds. The latter possibility is still being investigated, although whether the 100% base drag reduction assumed in BRL Report 1532 can be achieved with acceptable materials is not clear.

The position of a drag-reducing tracer within the previous discussion is that of a design feature reducing C_D. Thus, other things being equal, the tracer projectile will have a lower (C_D/Vol) value than an inert projectile of the same shape. The major question that the Phase I study tried to answer was how great were the changes and under what conditions.

In figure 11, the velocities for a series of projectile shapes with and without the tracer assumption are plotted. All projectiles show gains with the tracer operative; the low drag, square-based ones with large base-drag components show the most, the low drag, highly boat-tailed configurations show the least. This pattern holds for all the cases computed or tested. The impact on tracer-ball matching is fairly straight-forward; the job can be achieved with the least modification if the ball projectile has a long boat-tail and the tracer projectile has one also, but a blunter nose, or higher weight in some cases. Conversely, it would be very difficult to develop a matching ball round for a low-drag, square-based projectile with tracer. The latter type of projectile could, of course, be a prime candidate for an efficient basic round.

The experimental and computed comparisons permit conclusions for typical supersonic bullet designs:

(a) Trajectory computations based on computed aerodynamics of the flight shape are more than adequate.

(b) Computations of the gyroscopic stability properties based on the flight shape are at least adequate.

(c) Conventional trace elements reduce the <u>base drag component</u> by about 50%.

More speculatively, because the relative meaning of the term "range" is involved:

(a) A recoil momentum constraint means that the short range behavior is dominated by the possibility of higher initial energy for light projectiles.

(b) At longer ranges the retardation term $(C_D/\rho_p\ \mathrm{Vol})$ dominates because it governs the velocity fall-off. Projectiles with higher densities or inherently good values of drag-to-volume are favored.

(c) Since the effect of a drag reducing element is primarily on the drag-to-volume term it influences primarily the longer range behavior. The potential effect is high enough so that reliability of the element will be an important factor in acceptable behavior.

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[10]"Addendum to BRL Report 1532; Part I - Exterior Ballistic Tests and Comparison, Part II - Additional Trajectory Cases," Ballistic Research Laboratories Report in preparation.

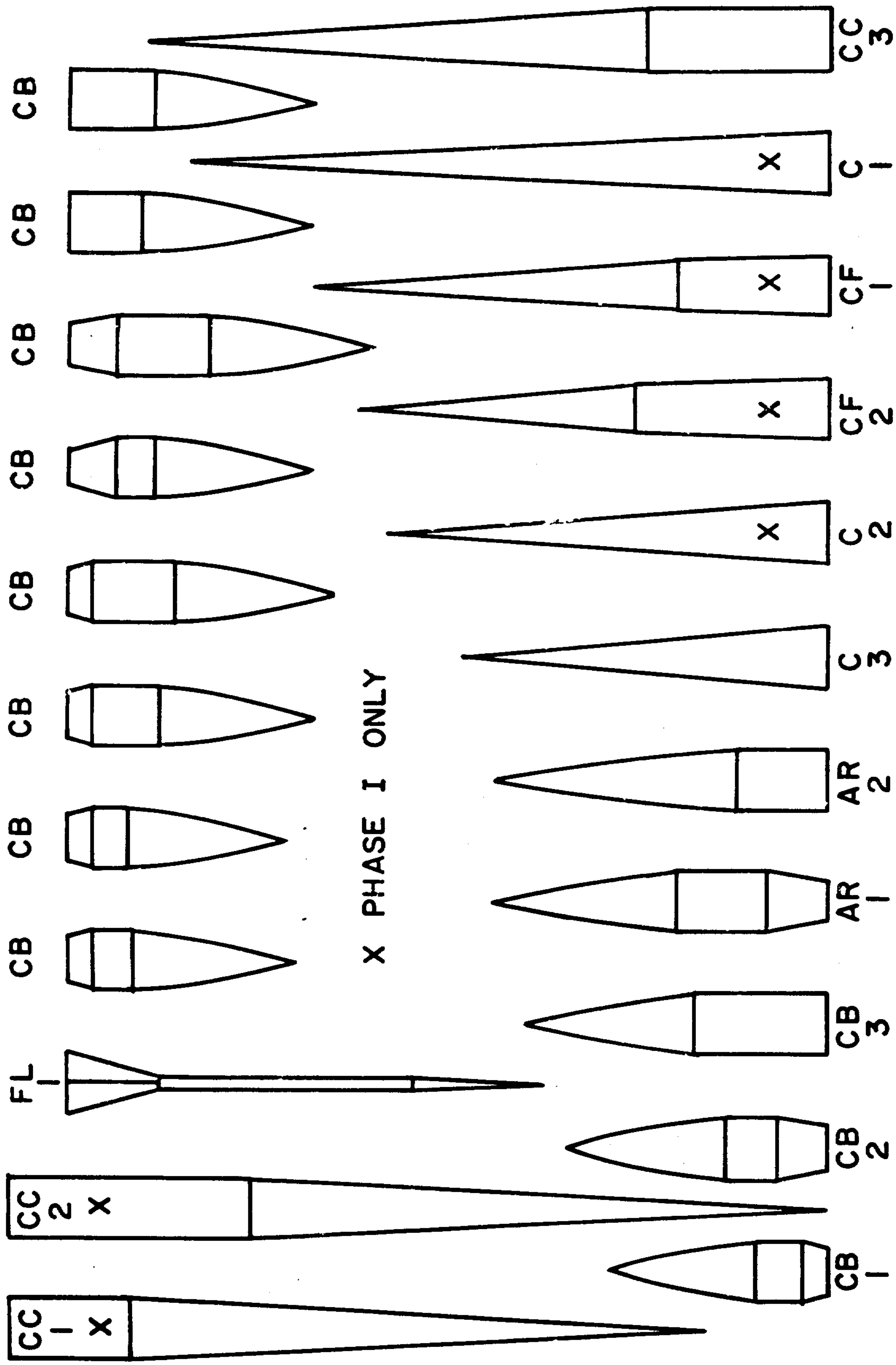

Figure 1 Configurations

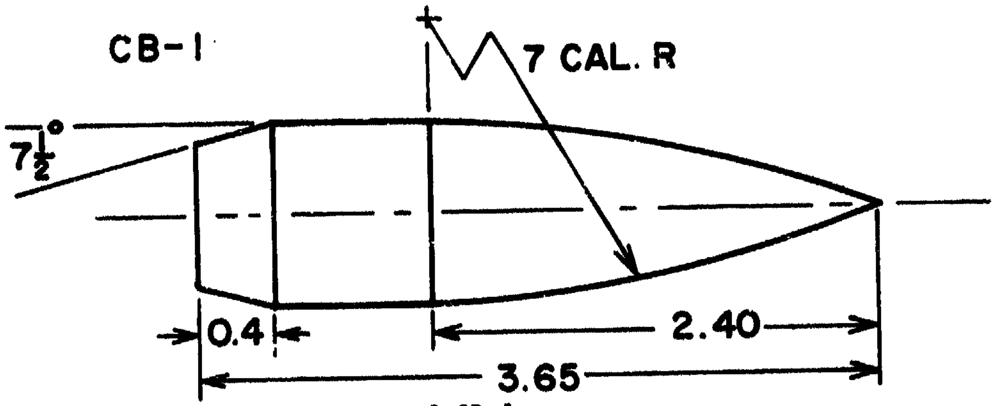

Figure 2 Configuration of CB-1

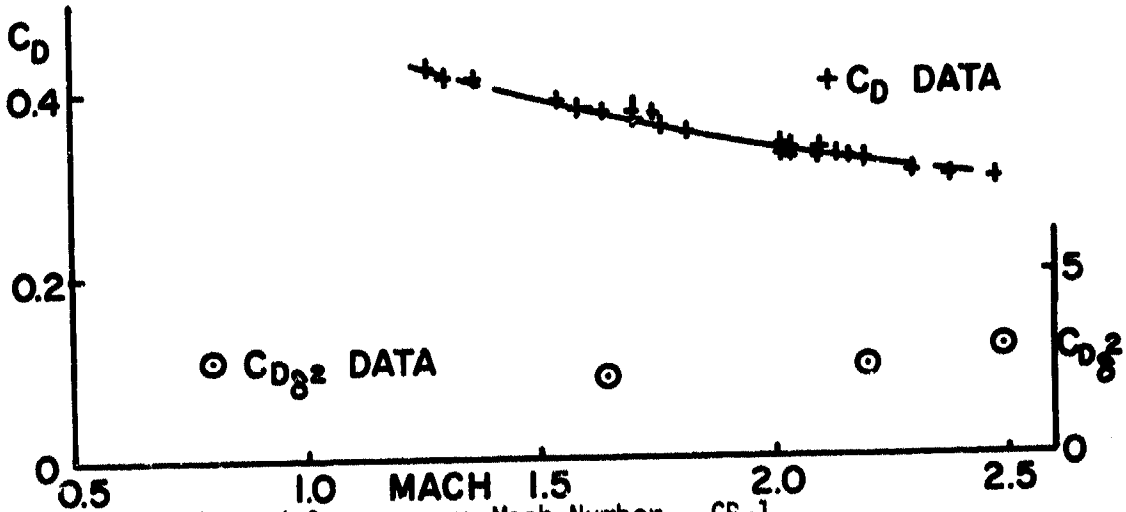

Figure 3 C_D and $C_{D_{\delta^2}}$ versus Mach Number - CB-1

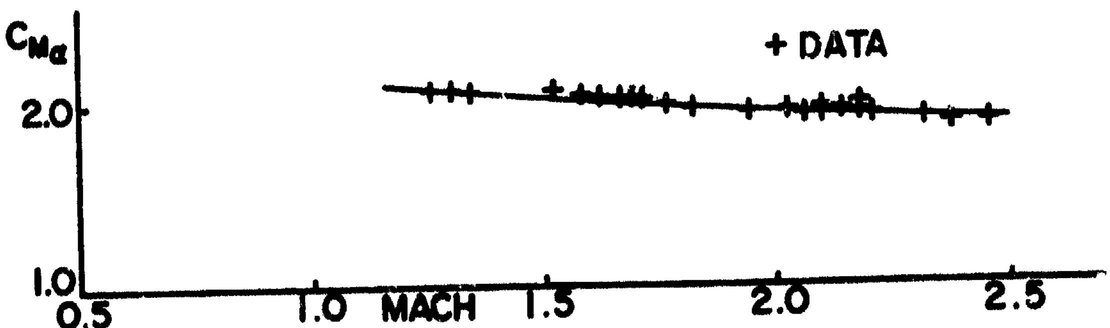

Figure 4 Static Moment Coefficient, CB-1

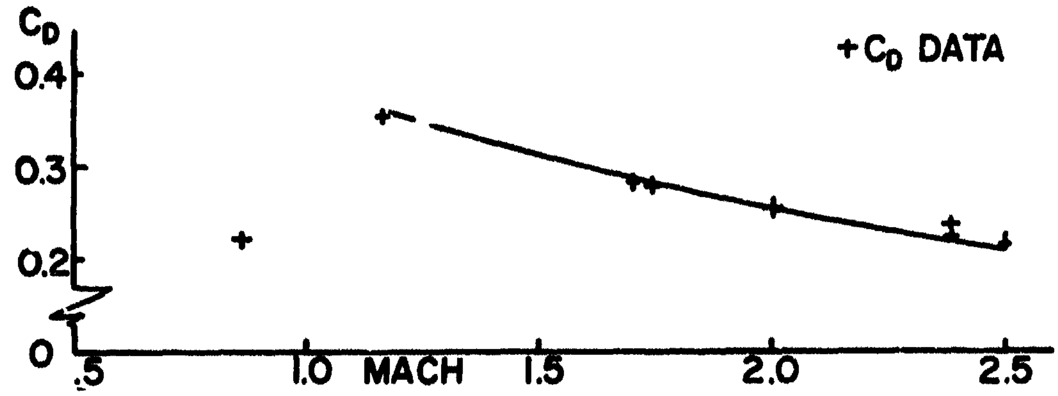

Figure 5 Drag Coefficient versus Mach Number, AR-2

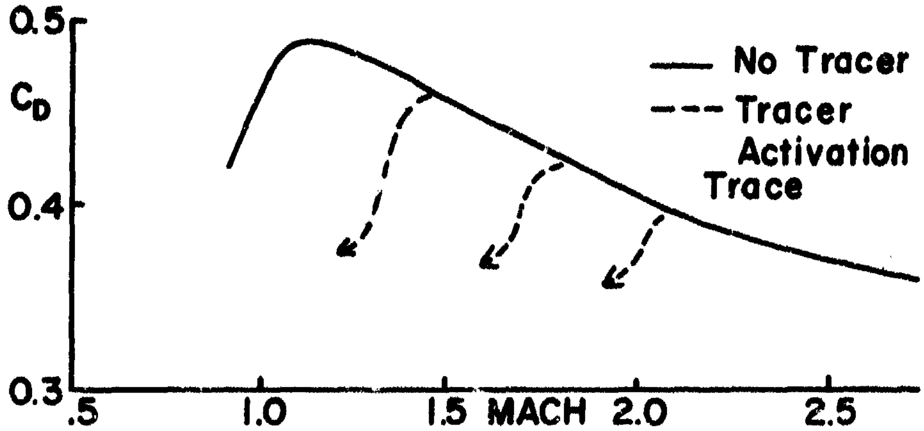

Figure 6 Effect of Onset of Tracer Burning, 20mm Shell

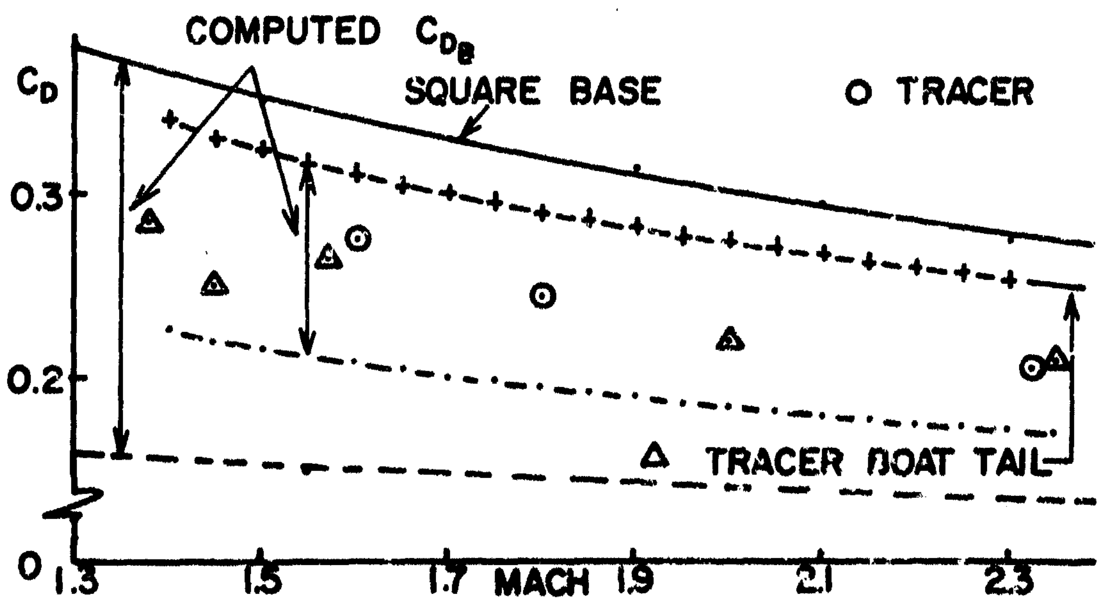

Figure 7 Effect of Tracer on C_D, 7.62mm

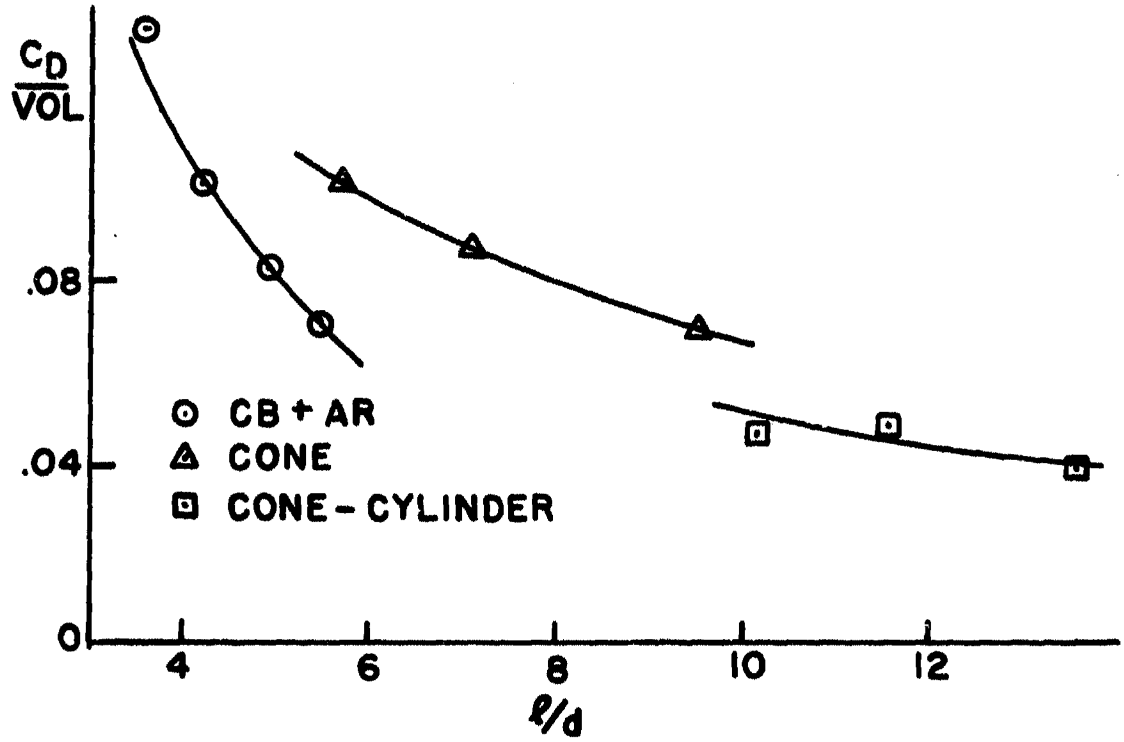

Figure 8 Trend of C_D/Vol with Length-to-Diameter Ratio

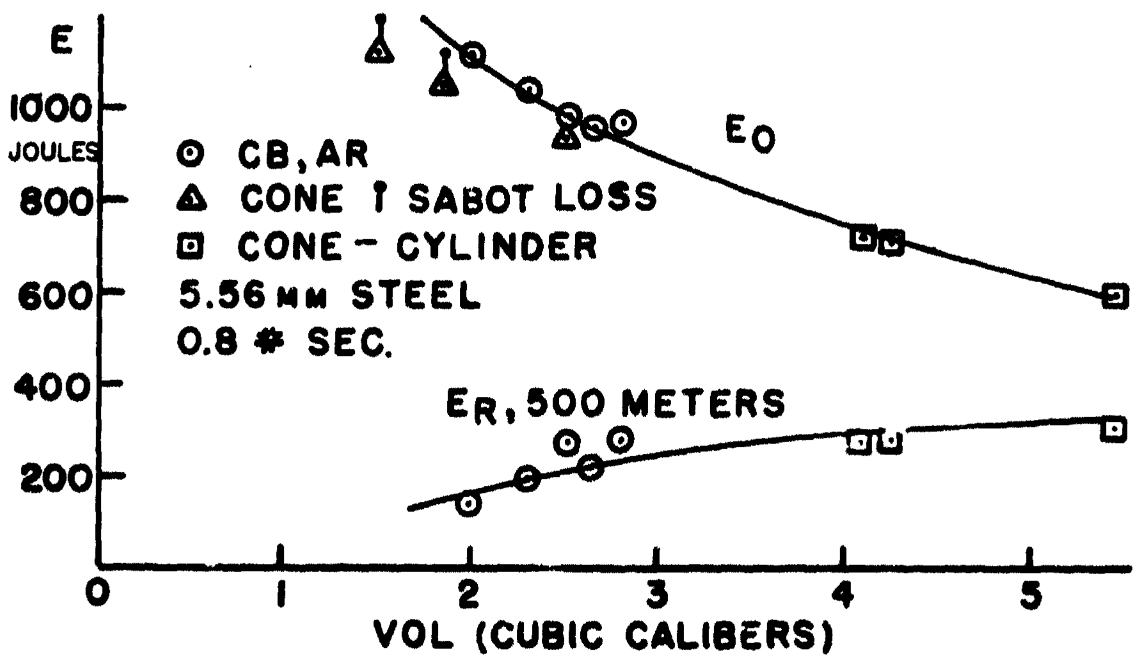

Figure 9 Initial and 500 Meter Energy versus Projectile Volume

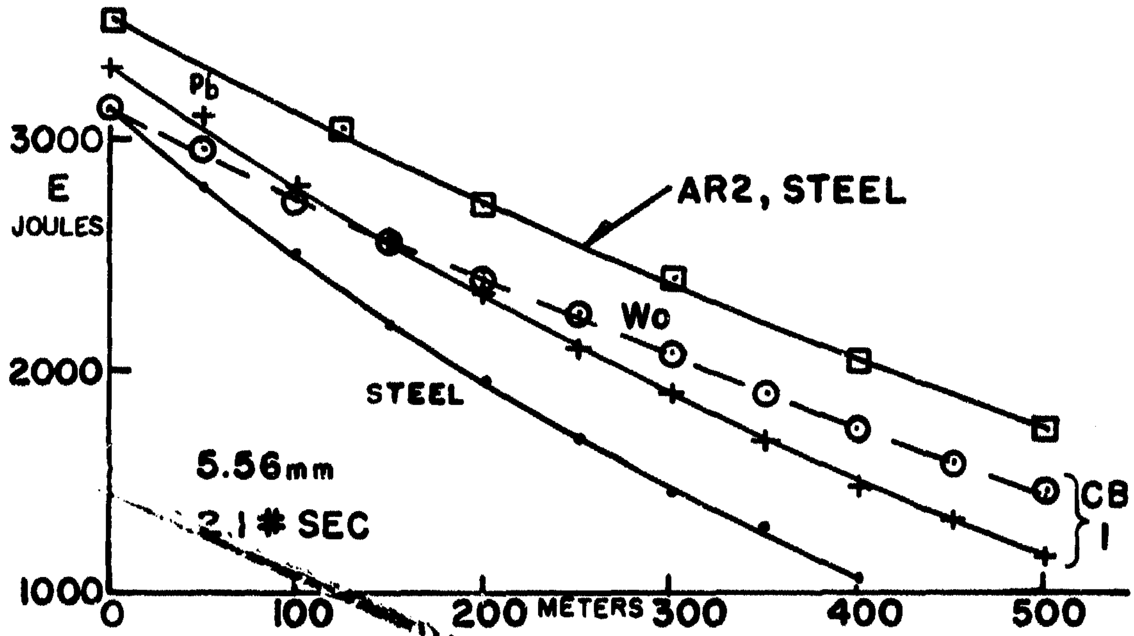

Figure 10 Energy versus Range, 3 Weights CB-1 and Steel AR-2

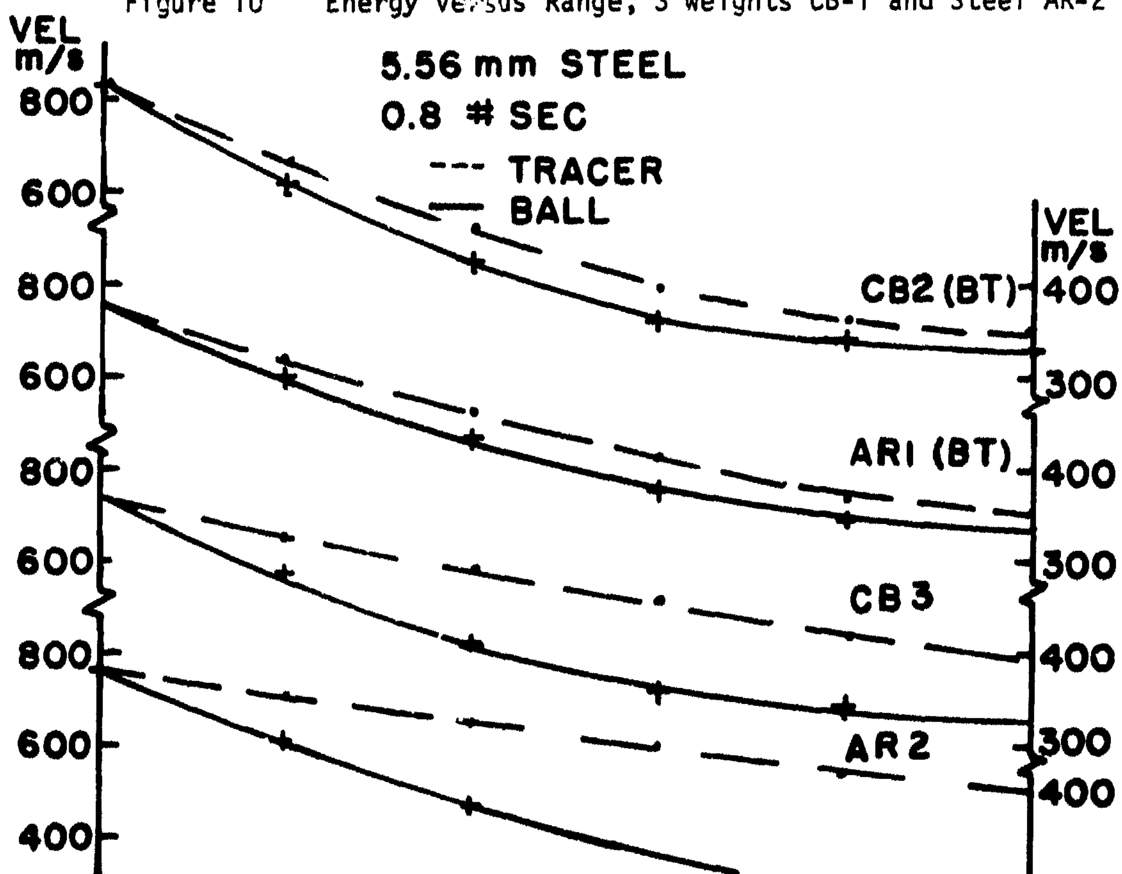

Figure 11 Velocity versus Range - Tracer and Ball