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I. Introduction

This report discusses the ramifications of a simple observation of projectile free flight behavior. The observation is that for certain projectile types, when velocity is plotted against range, the data lie in a straight line, as long as the velocity is above Mach 2.5. Examples of this behavior are shown in Figures 1A and 1B. These figures are derived from calculated trajectories based on the standard firing tables data for these rounds. Figure 1A shows three large caliber fin-stabilized projectiles. Figure 1B shows four other projectiles including a spike-nosed high explosive projectile (M831) and a .50 caliber sabot-launched armor piercing projectile (SLAP). The diversity of these projectiles seems to imply that the observation holds true for a variety of projectile types.

II. Implications

There are several implications of this behavior. The first is that the derivative of velocity with respect to range is constant (the slope of the line). If range is expressed in units of the projectile reference length, ℓ , then this derivative is the term dV/ds in the drag equation¹:

$$C_D = -(dV/ds)(1/V)(2m/\rho S\ell) \quad (1)$$

For any given shot of a direct-fire weapon, the only variable term in this equation is the velocity, V . Rewriting V as Ma (Mach number times sound speed) and combining all of the constants into one term, K :

$$K = -(dV/ds)(1/a)(2m/\rho S\ell) \quad (2)$$

Equation (1) becomes:

$$C_D = K/M \quad (3)$$

This is an extremely simple form for the drag equation, with several important implications. One implication is that one test shot can be fired, the factor K can be determined, and drag as a function of Mach number is then known for that projectile type for all Mach numbers above 2.5. Unfortunately, the effects of projectile yaw make things a little more complicated. Drag is assumed to depend on two independent variables: the Mach number, M , and δ^2 , the square of the yaw. The drag equation is thus written as:

$$C_D(M, \delta^2) = C_{D0}(M) + C_{D\delta^2} \delta^2 \quad (4)$$

where C_{D0} is the 'zero-yaw drag coefficient' and $C_{D\delta^2}$ is the 'yaw-drag coefficient'.

Another important result is obtained when Equation (3) for C_D is entered in the drag force equation¹:

$$D = \frac{1}{2} \rho V^2 S C_D$$

$$D = \frac{1}{2} \rho (Ma)^2 S (K/M)$$

$$D = \frac{1}{2} \rho a^2 S K M \quad (5)$$

Again, for a given shot, the only variable is the Mach number. Thus, the drag force is directly proportional to the projectile velocity.

III. Applications

There are several applications with varying levels of usefulness. The first is an alternative method of reducing free-flight spark range data for drag by using the slope of a velocity vs. range plot. However, because the technique is limited to specific projectile types and velocities, the method has limited usefulness when compared with the present data reduction techniques.

A more useful application would be to use the technique to obtain a value of C_D for velocity/range data that consists of sparse measurements (e.g. skyscreens). Since the velocity degradation is a straight line, it is possible to obtain a value of C_D if velocity is only measured at two points (preferably far apart). The technique can also be used to extract C_D from doppler radar data. A FORTRAN program that calculates C_D from an arbitrary set of velocity/range data points is included as Appendix A.

Other applications are based on the fact that what one obtains from the velocity/range data is actually the variation of C_D with Mach number, not just a value of C_D at a particular Mach number. Thus, a C_D curve can be determined from one test round.

This leads to perhaps the most useful application - the more accurate determination of the yaw-drag coefficient and C_{D0} by the elimination of the Mach number variations. For a single shot, the drag will depend on both the zero-yaw drag and the yaw-drag components. The yaw-drag is dependent on the average yaw value for that shot. If the firing is done over a long range, the yaw should damp out and one should get the value of C_{D0} . However, for shorter distances such as the free flight spark ranges, the yaw-drag will have a significant effect.

One common technique for determining C_{D0} and $C_{D\delta^2}$ is to fire groups of shots at different Mach levels (e.g. five shots at $M=3$, five shots at $M=4$, etc.). For each of these groups, the measured value of C_D for each shot is plotted against the average square yaw for that shot. A straight line is then fitted to the data, with the slope of the line being $C_{D\delta^2}$ and the intercept being C_{D0} at that Mach number (see Equation 4). However, if there is some Mach number variation within the group, there is no simple way to eliminate the drag variation with Mach number from the data.

(One method for compensating for Mach number variation, the "Q-function", is described in Reference 2. In order to apply this technique, however, at least two low-yaw data points are required at significantly different Mach numbers. These points are then used to determine the C_{D0} variation with Mach number.)

For the case where the drag function has the form K/M , there is another technique. If one assumes that the yaw-drag coefficient, $C_{D\delta^2}$ is a function of yaw only (independent of Mach number), and that C_{D0} has the form K/M , then it can be shown that for a series of range firings one can plot $(M/M_{REF})C_D$ vs. $(M/M_{REF})\delta^2$, and the intercept of a straight line fitted to the data will be C_{D0} at M_{REF} , and the slope will be $C_{D\delta^2}$. Alternatively, if $M=1$ is used for M_{REF} , the intercept will be the constant, K . A FORTRAN program that does this calculation using a set of (M, C_D, δ^2) data points is included as Appendix B.

Since Mach number variation is effectively removed from the data, the data points do not have to be at the same Mach number in order to do the fit. Also, since the only fit being done is a straight line, the drag coefficient can be completely defined (both C_{D0} as a function of Mach number and $C_{D\delta^2}$) with just two well-determined data points, providing they are at different yaw levels.

IV. Examples

An example of each of the applications listed previously will be given. The examples use the data from BRL Transonic Range firings of untraced, ambient temperature, DM13 projectiles. The DM13 is a fin-stabilized KE penetrator with a tungsten core, fired from a 120 mm smoothbore gun tube.

1. Determination of C_D From Velocity vs. Range Data

Figure 2 is a plot of velocity vs. range for Transonic Range round number 17682. The range measures position and time, so the velocity was calculated between each two successive timing stations by dividing the difference in distance by the difference in time between the two stations. The resulting average velocity was said to have occurred midway between the two stations because of the assumed linear behavior of velocity with range. Table 1A lists the position, time, and velocity data. A least-squares linear fit was performed on the velocity-range data. The slope of this fit, together with the measured physical properties and meteorological data at the time of the test (Table 1B) were used to determine K, using Equation 2. The value of K for this shot was found to be 1.402.

The values of C_D and M from the standard range reduction for this round number are 0.2904 and 4.823, respectively. At this Mach number, the calculated C_D using Equation 3 is:

$$C_D = K/M = 1.402 / 4.823 = 0.2907$$

2. Extrapolation of C_D to Other Mach Numbers

The previous example showed how to determine K and, subsequently, C_D from velocity vs. range data. If one were to start with a value of C_D from a standard range reduction, K can be calculated by:

$$K = C_D M \quad (6)$$

For round 17682, this yields:

$$K = 0.2904 (4.823) = 1.401$$

Table 2 contains a round-by-round listing of measured drag data from the BRL Transonic Range. Figure 3 is a plot of C_D vs. M including the measured values from Table 2, as well as the curve $C_D = 1.401/M$. The measured value for round 17682 is the solid symbol. The extrapolated drag curve from this one data point is in excellent agreement with the other data. Note that round 17682 had very low yaw, so the curve should be a good approximation of C_{D0} . For this reason, most of the other data lie somewhat above the curve.

3. Calculation of the Drag Force

Equation 5 can be used to calculate the actual drag force experienced by a projectile. Using values from the previous examples:

$$D = K(\frac{1}{2}\rho a^2 S)M = 1.4[\frac{1}{2}(1.23)(339.6)^2(0.001137)]M = 112.9 M$$

At the launch Mach number of 4.86, the drag force is:

$$D = (112.9)(4.86) = 548.7 \text{ N} \quad (123.4 \text{ lbf})$$

4. Determination of C_{D0} and $C_{D\delta^2}$

Figure 4 is a plot of C_D vs. δ^2 for all of the measured data. Most of the scatter in the data is due to Mach number variations (in this case, from $M=3.27$ to $M=4.83$). Figure 5 shows $(M/M_{REF})C_D$ plotted against $(M/M_{REF})\delta^2$, using $M_{REF}=4.7$. In this case, the scatter has been greatly reduced because the Mach number variation has been eliminated. A linear least-squares fit of the data gives the slope, or $C_{D\delta^2}$, as 13.212, and the intercept, or C_{D0} at $M=4.7$, as 0.298. Using Equation 6, the constant K can be calculated as being 1.401. Thus, the drag equation is:

$$C_D(M, \delta^2) = 1.401/M + 13.212 \delta^2$$

The advantage of this method, however, is that these coefficients can be determined from very limited data. The previous calculation can be repeated using only the three dark data points in Figures 4 and 5. These points are from rounds 17683, 26417, and 17691, which had the highest Mach number, largest yaw, and lowest Mach number, respectively. In this case, the calculated values are: $C_{D\delta^2}=9.976$, $C_{D0}=0.297$, and $K=1.397$. The drag equation is then:

$$C_D(M, \delta^2) = 1.397/M + 9.976 \delta^2$$

which is a good approximation, considering only three data points were used.

V. Restrictions

So far, it has not been possible to completely define restrictions on the use of these equations. The restrictions that have been identified are: the projectile velocity must be above Mach 2.5 and the ambient conditions cannot change significantly over the flight path. These restrictions are met by most large- and medium-caliber direct-fire weapons.

One problem with defining restrictions is that it has been difficult to find projectiles that do not obey the equations. In fact, the only projectile found so far that does not exhibit this behavior is the 25 mm M910 training round, which simulates some of the characteristics of the M791.

VI. Summary

A technique has been described that can be used to completely determine the drag coefficient using very limited drag data. The technique assumes C_{D0} has the form K/M . The overall findings of this report can be summarized as follows:

1. Almost all ammunition examined so far slows down at a rate such that a plot of velocity vs. range will yield a straight line, as long as the velocity is above Mach 2.5.
2. This type of behavior dictates that C_D has the form K/M .
3. The slope of the straight line in a plot of velocity vs. range can be used to determine the value K and, consequently, C_D as a function of Mach number.
4. If C_{D0} has the form K/M and C_D has been determined at (at least) two different yaw levels, C_D as a function of both M and δ^2 can be completely defined.
5. If C_D has the form K/M , the drag force is directly proportional to the projectile velocity.

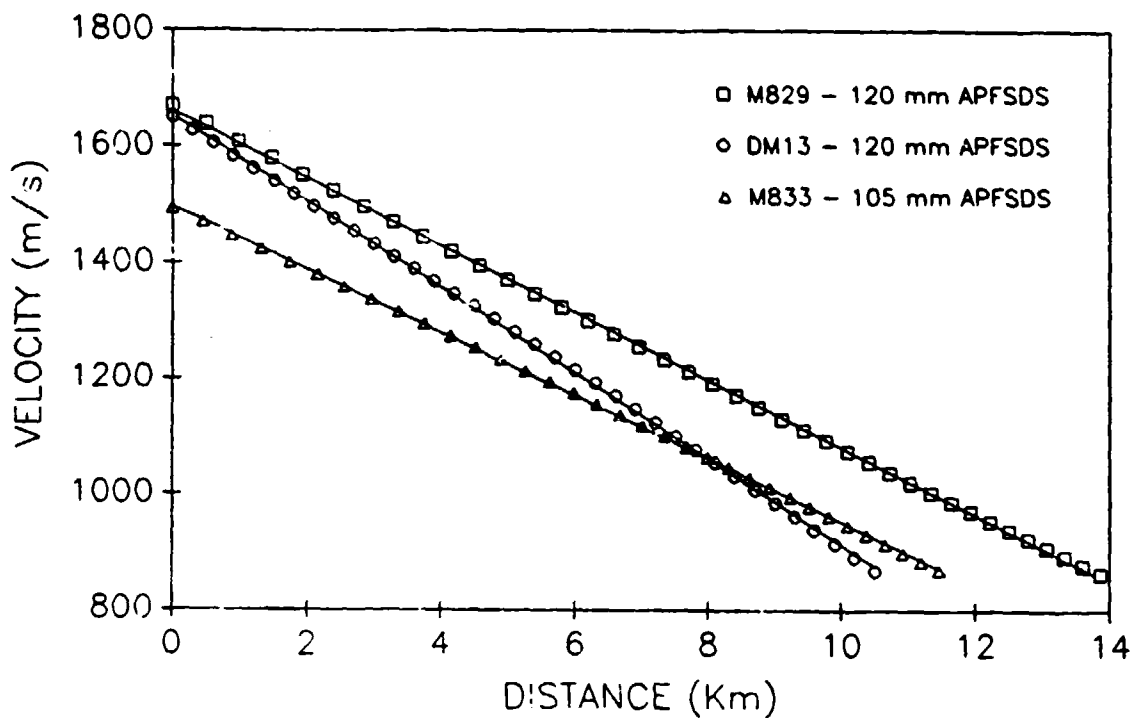


Figure 1A. Velocity vs. Range, Large Caliber Fin-Stabilized Projectiles.

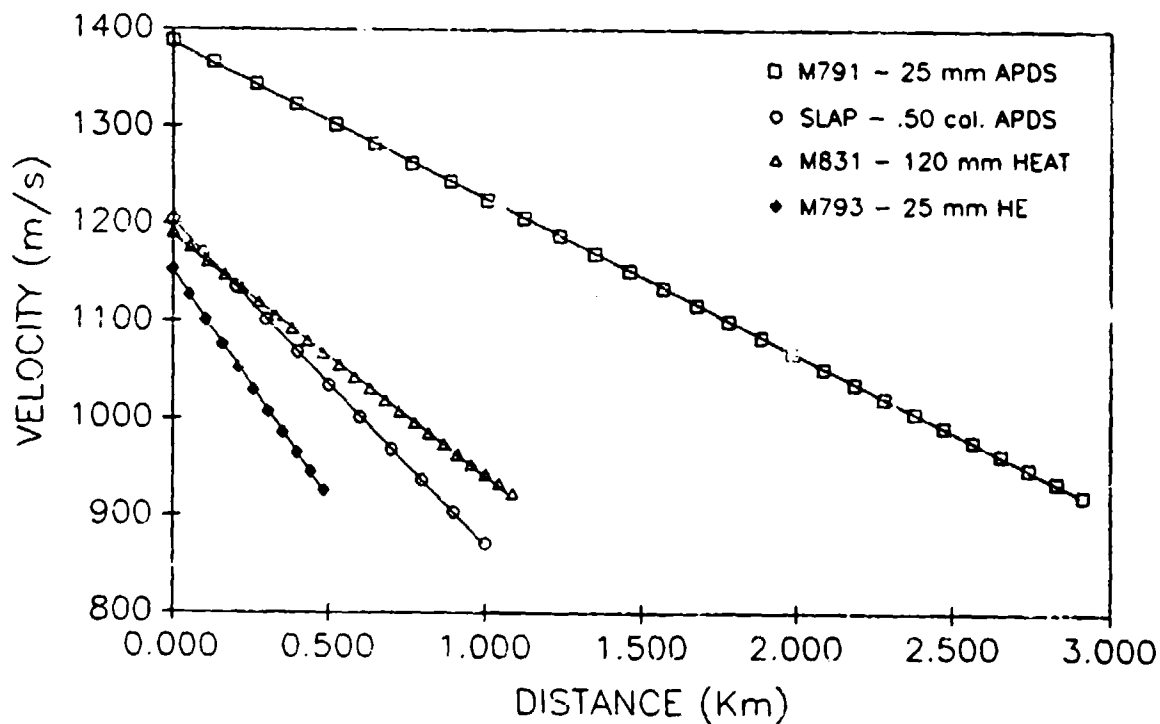


Figure 1B. Velocity vs. Range, Miscellaneous Projectiles.

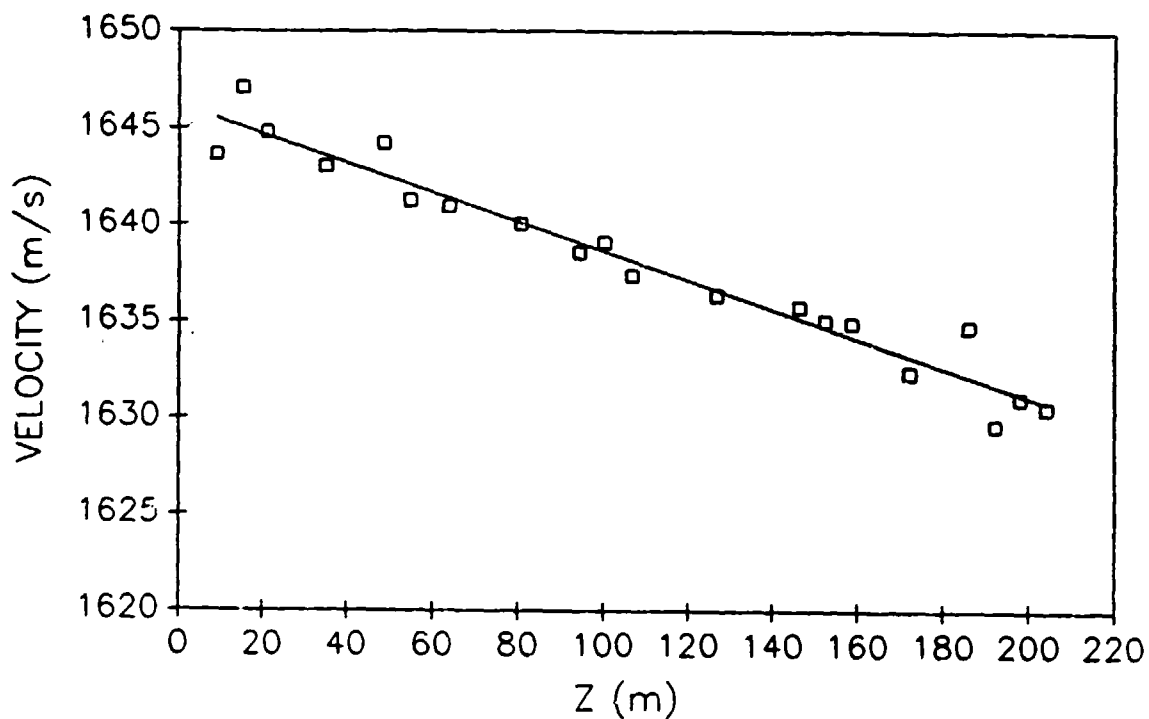


Figure 2. Velocity vs. Range, Transonic Range Round 17682.

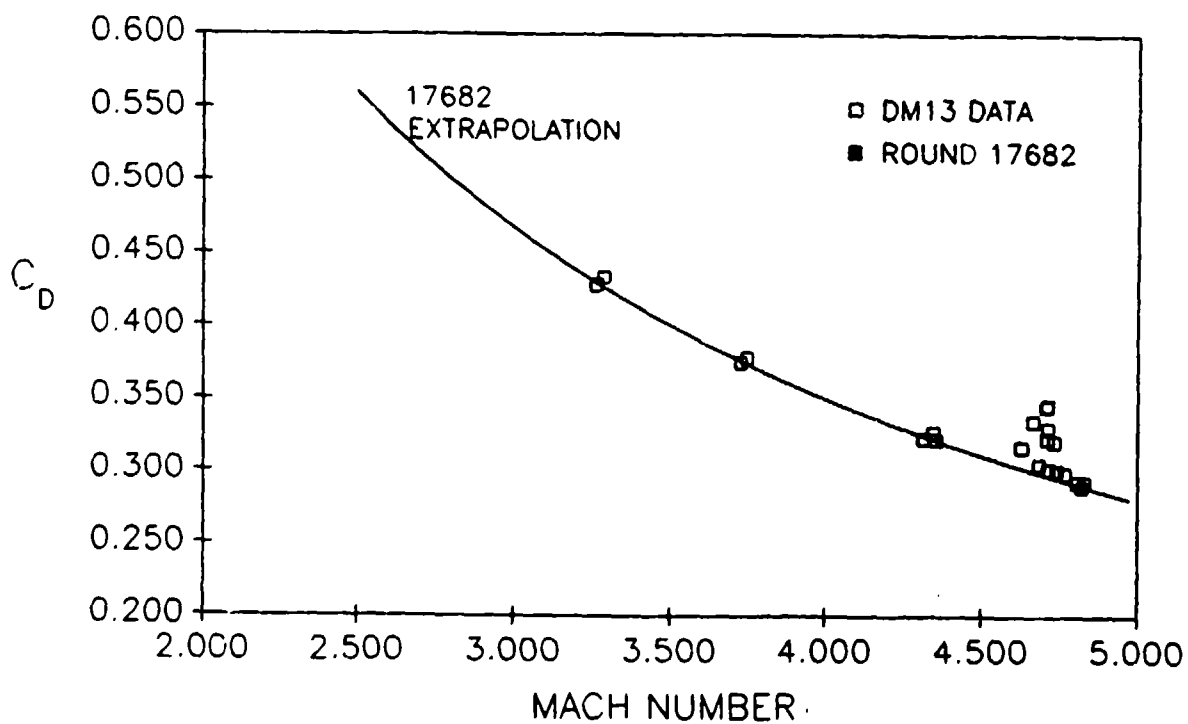


Figure 3. Coefficient of Drag vs. Mach Number.

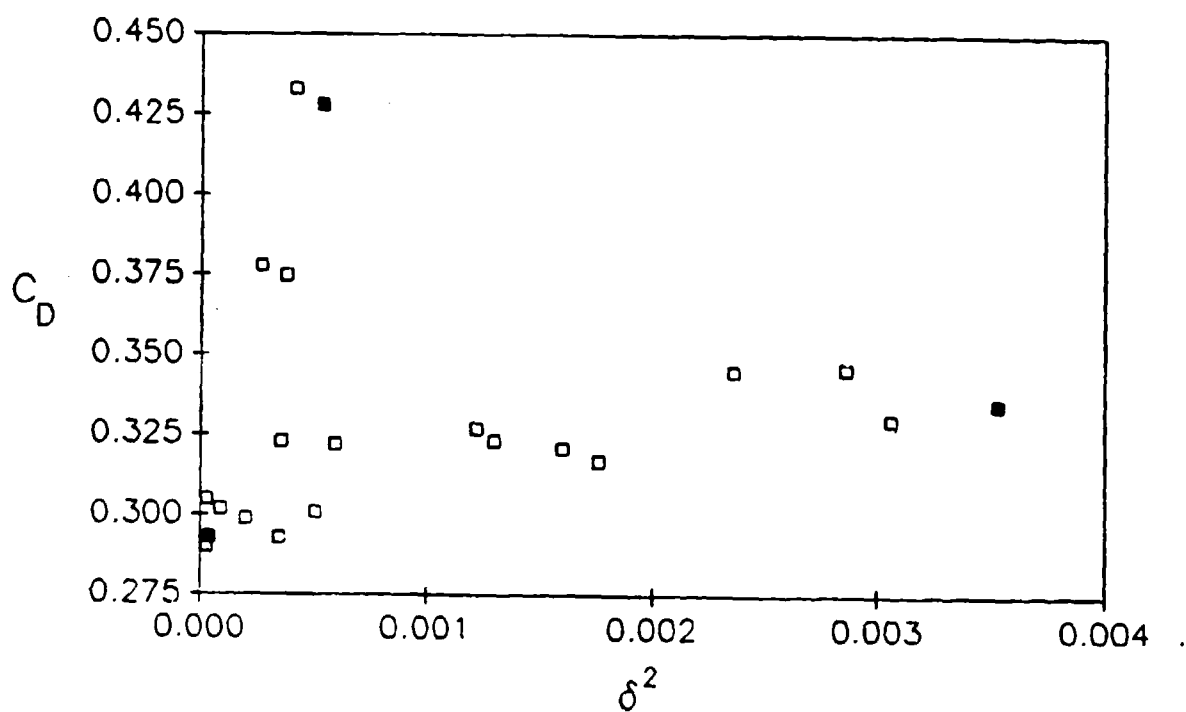


Figure 4. Coefficient of Drag vs. Delta Squared, Raw Data.

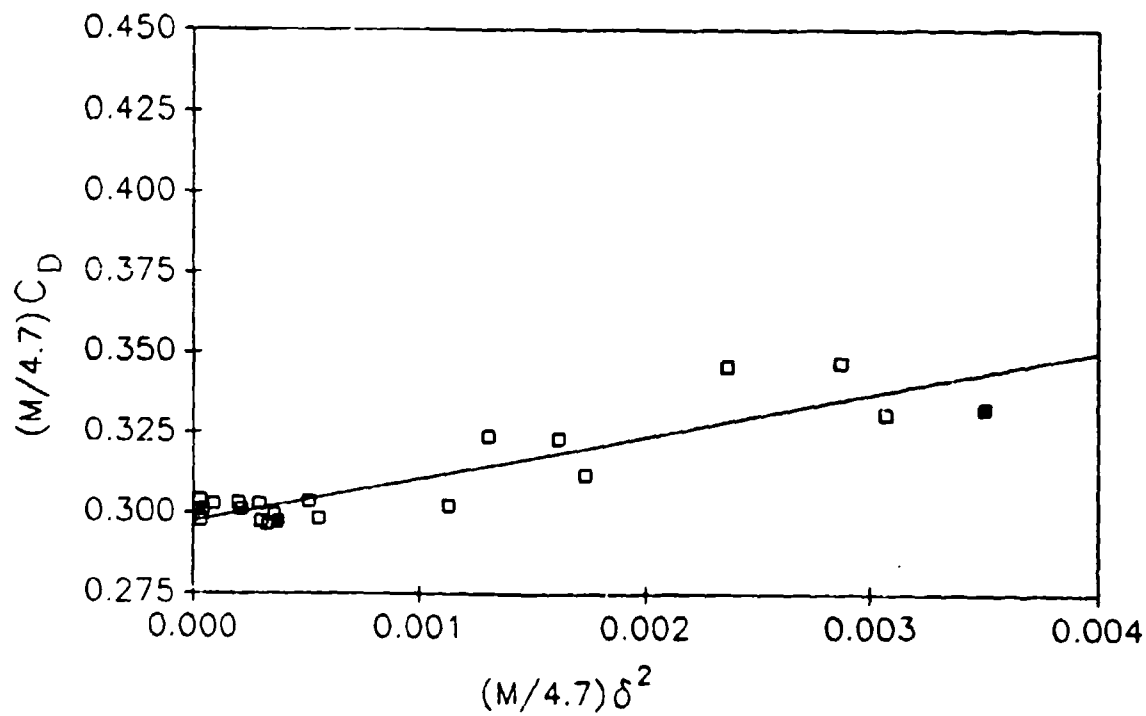


Figure 5. Coefficient of Drag vs. Delta Squared, Corrected for Mach Number

Table 1A. Time, Position, and Velocity for Transonic Range Round 17682.

Time (millisec.)	Measured Range (meters)	Calculated Range (meters)	Velocity (meters/sec.)
292.6346	5.772	8.937	1643.617
296.4863	12.103	15.089	1647.069
300.1130	18.076	21.100	1644.795
303.7899	24.124	34.919	1643.029
316.9303	45.714	48.698	1644.226
320.5601	51.682	54.809	1641.255
324.3706	57.936	63.872	1640.940
331.6055	69.808	80.653	1640.045
344.8312	91.499	94.277	1638.571
348.2219	97.056	100.265	1639.088
352.1388	103.475	106.816	1637.364
356.2205	110.158	126.686	1636.366
376.4219	143.215	146.268	1635.766
380.1552	149.322	152.334	1635.065
383.8402	155.347	158.588	1634.923
387.8047	161.828	172.141	1632.375
400.4403	182.454	185.959	1634.753
404.7283	189.464	192.208	1629.679
408.0961	194.953	198.013	1631.065
411.8493	201.074	204.124	1630.585
415.5895	207.173		

Table 1B. Projectile Physical Properties and Ambient Conditions.

$l = .03805 \text{ m}$	reference length, projectile body diameter
$S = 0.001137 \text{ m}^2$	reference area
$m = 4.4282 \text{ Kg}$	projectile mass
$\rho = 1.234 \text{ Kg/m}^3$	air density
$a = 339.63 \text{ m/s}$	sound speed

Table 2. Transonic Range Data for DM13 Projectiles.

Round No.	Mach No.	C_D	δ^2
17683	4.832	0.293	0.00004
17682	4.823	0.290	0.00003
17681	4.807	0.293	0.00035
17692	4.767	0.299	0.00020
26443	4.743	0.301	0.00051
26390	4.735	0.321	0.00160
26442	4.715	0.302	0.00009
26391	4.714	0.330	0.00306
26289	4.714	0.346	0.00286
26288	4.713	0.323	0.00130
26417	4.711	0.345	0.00236
26444	4.687	0.305	0.00003
30691	4.666	0.335	0.00353
30687	4.630	0.317	0.00176
17685	4.357	0.322	0.00060
17686	4.347	0.327	0.00122
17687	4.317	0.323	0.00036
17688	3.748	0.378	0.00027
17689	3.728	0.375	0.00038
17690	3.288	0.433	0.00042
17691	3.265	0.428	0.00054

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References

- 1.) **Murphy, C.H., "Free Flight Motion of Symmetric Missiles," US Army Ballistic Research Laboratory, Aberdeen Proving Ground, Maryland, BRL Report No. 1216, July 1963. (AD 442757)**
- 2.) **Thomas, R.N., "Some Comments on the Form of the Drag Coefficient at Supersonic Velocity," BRL Report No. 542, April 1945. (AD 494220)**

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List of Symbols

Symbol	Description	Equation
a	= speed of sound	
C _D	= coefficient of drag	$-(dV/ds)(1/V)(2m/\rho S\ell)$
C _{D0}	= zero-yaw drag coefficient	
C _{Dδ²}	= quadratic yaw drag coefficient	
D	= drag force	$\frac{1}{2}\rho V^2 S C_D$
K	= drag constant	C _D M
ℓ	= projectile reference length, usually body diameter	
m	= projectile mass	
M	= Mach number	
s	= dimensionless arc length along the trajectory	
S	= reference area	$\pi\ell^2/4$
V	= projectile velocity	
δ²	= effective squared yaw	
ρ	= air density	

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Appendix A: FORTRAN Code that Calculates C_D from Position and Velocity Data.

```

C *****
C  CALC_CD.FOR
C  THIS PROGRAM CALCULATES CD FROM Z-V DATA
C  *****

      PARAMETER(MAX = 100)          I MAXIMUM NUMBER OF POINTS
      CHARACTER*50 FWIN, FWRITE, STRING, FWRITE2
      CHARACTER RND*20
      DIMENSION Z(MAX), V(MAX), C(2)

100  FORMAT(A)

C *****
C  GET ROUND DESIGNATION. INPUT DATA MUST BE IN A FILE CALLED
C  "ROUND"_ZV.DAT WHERE "ROUND" CAN BE EITHER A ROUND TYPE OR
C  A ROUND NUMBER
C  *****
      WRITE(6,*)
      WRITE(6,*)'ENTER ROUND DESIGNATION'
      READ(5,100)RND

      FWIN = RND//'_ZV.DAT'
      FWRITE = RND//'.CD'

C *****
C  READ Z-V PAIRS FROM FILE AND CALCULATE AVERAGE VELOCITY
C  *****
      SUM = 0.
      OPEN( UNIT=1, FILE=FWIN, STATUS='OLD', READONLY )
      DO 10 I=1,MAX
         READ(1,*,END=11)Z(I),V(I)
         SUM = SUM + V(I)
10     CONTINUE
11  CLOSE(1)
      N = I - 1
      AVG_V = SUM / FLOAT(N)

C *****
C  ENTER PHYSICAL PROPERTIES AND ATMOSPHERIC DATA
C  *****
      WRITE(6,*)
      WRITE(6,*)'ENTER PROJECTILE DIAMETER, I (M)'
      READ(5,*)XL
      WRITE(6,*)
      WRITE(6,*)'ENTER PROJECTILE MASS, m (KG)'
      READ(5,*)XMASS
      WRITE(6,*)

```

```

WRITE(6,*)'ENTER AIR DENSITY, rho (KG/M**3)'
READ(5,*)RHO
WRITE(6,*)
WRITE(6,*)'ENTER VELOCITY OF SOUND, a (M/S)'
READ(5,*)A
WRITE(6,*)
AVG_M = AVG_V / A
WRITE(6,*)'ENTER REFERENCE MACH NUMBER, M*'
WRITE(6,*)' (AVERAGE MACH NUMBER IS ',AVG_M,' )'
READ(5,*)XMSTAR

C *****
C CALCULATE THE FACTOR K AND CD AT THE REFERENCE MACH NUMBER
C *****
PI = 3.1415927
S = (PI/4.) * XL**2          ! REFERENCE AREA
RDF = (RHO*S*XL) / (2.*XMSTAR) ! RELATIVE DENSITY FACTOR

CALL LSQ1( Z, V, M, C )

DRAGDOWN = C(2)
DVDS = C(2) * XL

XK = -DVDS / (RDF*A)
CDREF = XK / XMSTAR

WRITE(6,*)
WRITE(6,*)'CD(M) = K/M,    K = ',XK
WRITE(6,*)'CD(MREF) = ',CDREF
WRITE(6,*)

C *****
C SAVE CD vs. M AS PLOTTABLE FILE
C *****
XMIN = 2.5
XMAX = 5.0
XSTEP = (XMAX-XMIN) / FLOAT(MAX)
XM = XMIN + XSTEP
OPEN(UNIT=2,FILE=FNOUT,STATUS='NEW')
DO 20 J=1,MAX
    XM = XM + XSTEP
    CD = XK / XM
    WRITE(2,*)XM,CD
20  CONTINUE
CLOSE(2)

STOP
END

```

```

C .....
C SUBROUTINE TO CALCULATE LINEAR LEAST SQUARES FIT
C .....
SUBROUTINE L991(X,Y,N,C)
PARAMETER ( MAX=100 )
IMPLICIT DOUBLE PRECISION (A-H, O-Z)
REAL*4 X(MAX),Y(MAX),C(2),SUM,ERROR
RN=FLOAT(N)
SUMX=0.0
SUMY=0.0
SUMXY=0.0
SUMX2=0.0
DO 10 J=1,N
    DUBX = X(J)          I DOUBLE PRECISION X
    DUBY = Y(J)
    SUMX = SUMX + DUBX
    SUMY = SUMY + DUBY
    SUMXY = SUMXY + DUBX*DUBY
    SUMX2 = SUMX2 + DUBX**2
10 CONTINUE
DUBC2 = (RN*SUMXY-SUMX*SUMY) / (RN*SUMX2-SUMX**2)
DUBC1 = (SUMY/RN) - (DUBC2*SUMX/RN)
C(2) = DUBC2
C(1) = DUBC1
RETURN
END

```

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Appendix B: FORTRAN Code that Calculates C_{D0} and $C_{D0.2}$ from (M, C_D, σ^2) Data.

```

C *****
C CD_DELSQ.FOR
C THIS PROGRAM CALCULATES CD0 AND CD-DELSQ
C FROM RAW M, DELSQ, CD DATA
C *****

      PARAMETER(MAX = 100)          ! MAXIMUM NUMBER OF POINTS
      CHARACTER FNAME*50
      DIMENSION XM(MAX), CD(MAX), DELSQ(MAX), NR(MAX)
      DIMENSION DELSQ2(MAX), CD2(MAX), CD0(MAX), C(2)

100  FORMAT(A)

C *****
C READ DATA FROM FILE AND CALCULATE AVERAGE MACH NUMBER
C *****
      WRITE(6,*)
      WRITE(6,*)'ENTER INPUT FILENAME'
      READ(5,100)FNAME
      SUM = 0.
      OPEN( UNIT=1, FILE=FNAME, STATUS='OLD' )
      DO 10 I=1,MAX
         READ(1,*,END=11)XM(I),CD(I),DELSQ(I)
         SUM = SUM + XM(I)
10    CONTINUE
11  CLOSE(1)
      N = I - 1
      AVG_M = SUM / FLOAT(N)

C *****
C GET REFERENCE MACH NUMBER AND SHIFT ALL DATA TO THAT MACH NO.
C *****
      WRITE(6,*)
      WRITE(6,*)'ENTER REFERENCE MACH NUMBER'
      WRITE(6,*)' (AVERAGE MACH NUMBER IS ',AVG_M,')'
      READ(5,*)XMREF

      DO 20 I=1,N
         RATIO = XM(I) / XMREF
         CD2(I) = CD(I) * RATIO
         DELSQ2(I) = DELSQ(I) * RATIO
20  CONTINUE

```

```

C *****
C CALCULATE CD0 AND CD-DELSQ AT REFERENCE MACH NUMBER, WITH AND
C WITHOUT MACH NUMBER CORRECTION
C *****
CALL LSQ1( DELSQ, CD, N, C, ERROR )
WRITE(6,*)
WRITE(6,*)'WITHOUT MACH NUMBER CORRECTION'
WRITE(6,*)'CD0 = ',C(1)
WRITE(6,*)'CD DELSQ = ',C(2)
WRITE(6,*)'ERROR = ',ERROR

CALL LSQ1( DELSQ2, CD2, N, C, ERROR )
WRITE(6,*)
WRITE(6,*)'WITH MACH NUMBER CORRECTION'
WRITE(6,*)'CD0 = ',C(1)
WRITE(6,*)'CD DELSQ = ',C(2)
WRITE(6,*)'ERROR = ',ERROR
WRITE(6,*)
CD_DELSQ = C(2)

STOP
END

C .....
C SUBROUTINE TO CALCULATE LINEAR LEAST SQUARES FIT
C .....
SUBROUTINE LSQ1(X,Y,N,C,ERROR)
PARAMETER ( MAX=100 )
IMPLICIT DOUBLE PRECISION (A-H, O-Z)
REAL*4 X(MAX),Y(MAX),YF(MAX),C(2),SUM,ERROR
RN=FLOAT(N)
SUMX=0.0
SUMY=0.0
SUMXY=0.0
SUMX2=0.0
DO 10 J=1,N
    DUBX = X(J)          I DOUBLE PRECISION X
    DUBY = Y(J)
    SUMX = SUMX + DUBX
    SUMY = SUMY + DUBY
    SUMXY = SUMXY + DUBX*DUBY
    SUMX2 = SUMX2 + DUBX**2
10 CONTINUE
DUBC2 = (RN*SUMXY-SUMX*SUMY) / (RN*SUMX2-SUMX**2)
DUBC1 = (SUMY/RN) - (DUBC2*SUMX/RN)
C(2) = DUBC2
C(1) = DUBC1
SUM = 0.
DO 20 J=1,N
    YF(J)=C(2)*X(J)+C(1)
    SUM = SUM + (YF(J) - Y(J))**2
20 CONTINUE
ERROR = SUM / FLOAT(N-2)
RETURN
END

```

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