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MAY 1951

ON ESTIMATING THE DRAG COEFFICIENT OF MISSILES

H. P. Hitchcock

BALLISTIC RESEARCH LABORATORIES

ABERDEEN PROVING GROUND, MARYLAND

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BALLISTIC RESEARCH LABORATORIES

MEMORANDUM REPORT NO. 545

Hitchcock/kls
Aberdeen Proving Ground, Md.
31 May 1951

ON ESTIMATING THE DRAG COEFFICIENT OF MISSILES

ABSTRACT

A method of estimating the head, base and friction drag coefficients of a missile is outlined. This procedure pertains to rockets and artillery projectiles, with or without fins, and is a combination of theory and empirical data, gathered from numerous sources.

INTRODUCTION

A procedure for estimating the drag coefficient of rockets and artillery projectiles, with or without fins, is stated briefly. It is based partly on theory, partly on empirical data. Since the effect of yaw is neglected, the results apply only to small yaws.

The drag coefficient K_D is assumed to consist of three principal parts: the wave drag coefficient K_{DW}, the base drag coefficient K_{DB}, and the friction drag coefficient K_{DF}. Besides, there are interference effects,[1] which may be represented by an interference drag coefficient K_{DI}. The whole is the sum of its parts:

$$K_D = K_{DW} + K_{DB} + K_{DF} + K_{DI}. \tag{1}$$

If ρ denotes the air density, d the diameter of the cylindrical part of the body (or the caliber) and u the velocity of the missile relative to the air, the drag is

$$D = K_D \rho d^2 u^2. \tag{2}$$

WAVE DRAG COEFFICIENT

a. Conical Head. The wave drag coefficient of a conical head is computed by the theory of Taylor and Maccoll.[2,3] This coefficient is tabulated in Part II of Kopal's "Tables of Supersonic Flow Around Yawing Cones";[4] the values multiplied by $4/\pi$ may also be found in Part II of his "Tables of Supersonic Flow Around Cones".[5] The arguments of these tables are the semi-apex angle θ_s of the cone and the radial velocity u_s along the solid surface. In both tables, the Mach number $M = u/a$ is tabulated; if M is assumed, it is more convenient to find the corresponding value of u_s in Part III of the latter volume. Although the velocity of sound a in the undisturbed air is a function of temperature and varies with humidity, we take its standard value as 1120.27 fps.

In order to obtain u_s in fps, Kopal's values must be multiplied by the velocity of discharge into a vacuum c, which may be computed by the formula

$$c = aM(1 + 4.93827/M^2)^{\frac{1}{2}}. \tag{3}$$

The semi-apex angle of the cone may be found by the formula

$$\tan \theta_s = d/2h, \tag{4}$$

where h is the height of the head.

b. Ogival Head. The wave drag coefficient of a body of revolution can be computed with certain restrictions as a perturbation of the wave drag coefficient of a cone. Van Dyke[6] has derived a second-order theory of supersonic flow, using the particular solution for a cone with the same vertical angle as the principal term and adding other terms which make the flow satisfy the boundary conditions at a finite number of points. Although this theory appears to be quite accurate, it requires more experimental confirmation; besides, its use has the disadvantage of requiring a large amount of computation.

The effect of curvature may be estimated from experimental results. For example, the form factors of British 5-inch Shell with $7.5^{\circ}/0.38$-cal. boattail and three head shapes were determined from the observed ranges at an elevation of 40° and a muzzle velocity of 2500 fps. The heads were all the same height: one was conical, one was a secant ogive with a 16-cal. radius, and one was a tangent ogive with an 8-cal. radius. The results indicate that, at 2500 fps, the drag coefficient of the secant ogive is 0.0043 less than that of the cone, and the drag coefficient of the tangent ogive is 0.0018 less than that of the cone.

Some unpublished data obtained by the Free Flight Aerodynamics Branch for caliber 0.50 bullets with conical and ogival heads 2.92 calibers long, rounded at the tip with a radius of 0.05 caliber, at a Mach number of 2.44, also indicate corrections to be applied for ogives of various radii. The following table gives the drag coefficient for ogival heads less that for a conical head of the same height; R denotes the ogival radius, and R_T the radius of a tangent ogive of the same height.

	R_T/R	ΔK_D
Conical head	0.00	.0000
	0.25	- .0033
	0.50	- .0044
	0.67	- .0031
Tangent ogive	1.00	+ .0055

Miles[7] derived a semi-empirical relation between the wave drag coefficient of an ogival head and that of a conical head of the same apex angle. He obtains the former by multiplying Kopal's tabulated drag coefficient by the factor

$$1 - (98 - 32 \tan^2\theta_s)/(7M + 126). \tag{5}$$

However, this relation does not agree with the results given above, since it yields an increase in K_D for any increase in R_T/R. Its use is not recommended unless it is confirmed by additional experiments.

c. Boattail. The Airflow Branch has computed the pressure distribution over cone-cylinders with boattails varying from 4° to 9° at Mach numbers from 1.72 to 5.79. These data are available in graphical form in a report by Carter.[35] The wave drag coefficient is found by the relation

$$K_{DW} = \frac{2\pi}{\gamma M^2 r_c^2} \int_{r_b}^{r_c} (1 - P_r/P1)\, r\, dr, \tag{6}$$

where γ is the ratio of specific heats, r_b the radius of the base, r_c the radius of the cylinder, P_r the pressure at a point where the radius is r, and P_1 the atmospheric pressure. If $\gamma = 1.405$, $2\pi/\gamma = 4.472$. If the variation in P_r is small, an average value may be used, but, if P_r is a linear function of r, the integration is easy to perform.

d. Fins. The wave drag coefficient of a fin depends on its shape. Most aerodynamicists define it by the formula

$$D_W = C_{DW}\rho S u^2/2, \tag{7}$$

where D_W is the wave drag and S is one surface of the fin. The relation between this coefficient and the one based on the missile diameter is

$$K_{DW} = C_{DW} S/2d^2. \tag{8}$$

For a rectangular wing with a single wedge profile of wedge angle β, Graham and Lagerstrom[8] derive the formula

$$C_{DW} = (\beta^2/B)\,(1 - 1/2AB), \tag{9}$$

where A is the aspect ratio and

$$B = (M^2 - 1)^{\frac{1}{2}}. \tag{10}$$

The aspect ratio is, by definition,

$$A = s/c, \tag{11}$$

where s is the span and c the chord.

Graham and Lagerstrom also derive formulas for wings with swept-back leading edges. Since those formulas are long and complicated, they will not be given here.

For a rectangular fin with a double wedge or a biconvex (double circular arc) profile, Bonney[9] derives the formula

$$C_{DW} = K_{\lambda} K_1 \tau^2/B, \tag{12}$$

where τ is the thickness ratio: if $\underline{t}$ is the root thickness,

$$\tau = t/c. \tag{13}$$

If t_2 is the thickness at the tip, the taper in thickness is

$$\lambda = t_2/t \tag{14}$$

and
$$K_\lambda = (1 + \lambda + \lambda^2)/3. \tag{15}$$

If the profile is a symmetrical double wedge, $K_1 = 4$. If the middle third of the profile is constant in thickness and the outer thirds are wedge-shaped, $K_1 = 6$. If the profile is biconvex, $K_1 = 5.33$.

For a delta fin with a triangular planform and a double wedge profile, Puckett[10] derives three expressions which depend on the sweep-back angles of the leading edge and the maximum thickness line. The choice of the applicable expression depends on the magnitude of B relative to the tangents of the two angles. Puckett and Stewart[11] extend this theory to include delta fins with swept-back and swept-forward trailing edges. Beane[12] extends it further to include delta fins with biconvex sections. He presents results pertaining to both profiles in graphical form.

Chapman[13] made a theoretical and experimental investigation of fins with a blunt trailing edge, a rectangular planform, and various modifications of wedge and biconvex profiles. The results are given in graphical form.

BASE DRAG COEFFICIENT

The base drag coefficient is found by the relation

$$K_{DB} = (1 - P_b/P_1)A_b/d^2\gamma M^2, \tag{16}$$

where P_b is the base pressure, P_1 the atmospheric (or free stream) pressure, A_b the base area, $\underline{d}$ the caliber, γ the ratio of specific heats, and M the Mach number. For air, γ is approximately 1.405. For a shell body of base diameter d_b, the base area is

$$A_b = (\pi/4)d_b^2 \tag{17}$$

and the base drag coefficient may be expressed

$$K_{DB} = 0.559\ (1 - P_b/P_1)d_b^2/d^2M^2. \tag{18}$$

a. Square Base. Charters and Turetsky[14] deduced the ratio P_b/P_1 for several cone-cylinder models of different lengths, which were fired in the free-flight range at Mach numbers from 1.2 to 3.8. The total drag was measured, the pressure acting on the cone was computed from Kopal's tables, the skin friction was estimated from a subsonic formula, and the base drag was obtained by subtraction. The plotted results lie close to the curve defined by the quadratic equation

$$1 - P_b/P_1 = 0.3086M - 0.1085 - 0.02411M^2. \qquad (19)$$

This equation should be used only for Mach numbers between 1 and 4. At low subsonic velocities, the base pressure is nearly equal to the atmospheric pressure, and the base drag may be neglected. At very high Mach numbers, experiments indicate that the base pressure decreases with increasing Mach number, approaching the condition of a vacuum at the base. Under certain conditions, therefore, it may be satisfactory to approximate the base pressure with a vacuum for engineering calculations.

Chapman[15,16] derived two semi-empirical formulas for the base pressure on cone-cylinders and ogive-cylinders, which fit Charters and Turetsky's free-flight data and some wind-tunnel measurements. His base drag coefficient consists of two terms: one calculated from the pressure just upstream of the base, which depends only on the body shape; and another, which depends on viscosity. If the boundary layer just upstream of the base is laminar, viscosity has a large effect on the base pressure; but, if this boundary layer is turbulent, the effect of viscosity is small. On a long missile, with a cylindrical body, the pressure just upstream of the base is nearly atmospheric and the boundary layer is turbulent; therefore, the given free-flight data should be applicable.

b. Boattailed base. Chapman[16] showed that his theory could be applied to boattailed bodies providing the boundary layer on the boattail is laminar, but not if it is turbulent. Unless appropriate experimental data are available, however, formula (19) should be used to obtain a rough approximation of the pressure on the base of a boattailed body.

c. Fins. Chapman and Summers[17] found that the base pressure on the blunt trailing edge of a fin is not appreciably affected by Reynolds number, providing the boundary layer approaching the base is turbulent and thin compared to the base thickness. They give a base pressure curve which approximately fits data obtained from wind-tunnel and free-flight measurements on wings of rectangular planform and various profiles and aspect ratios at Mach numbers from 1.5 to 4 and Reynolds numbers from 2 to 9 million.

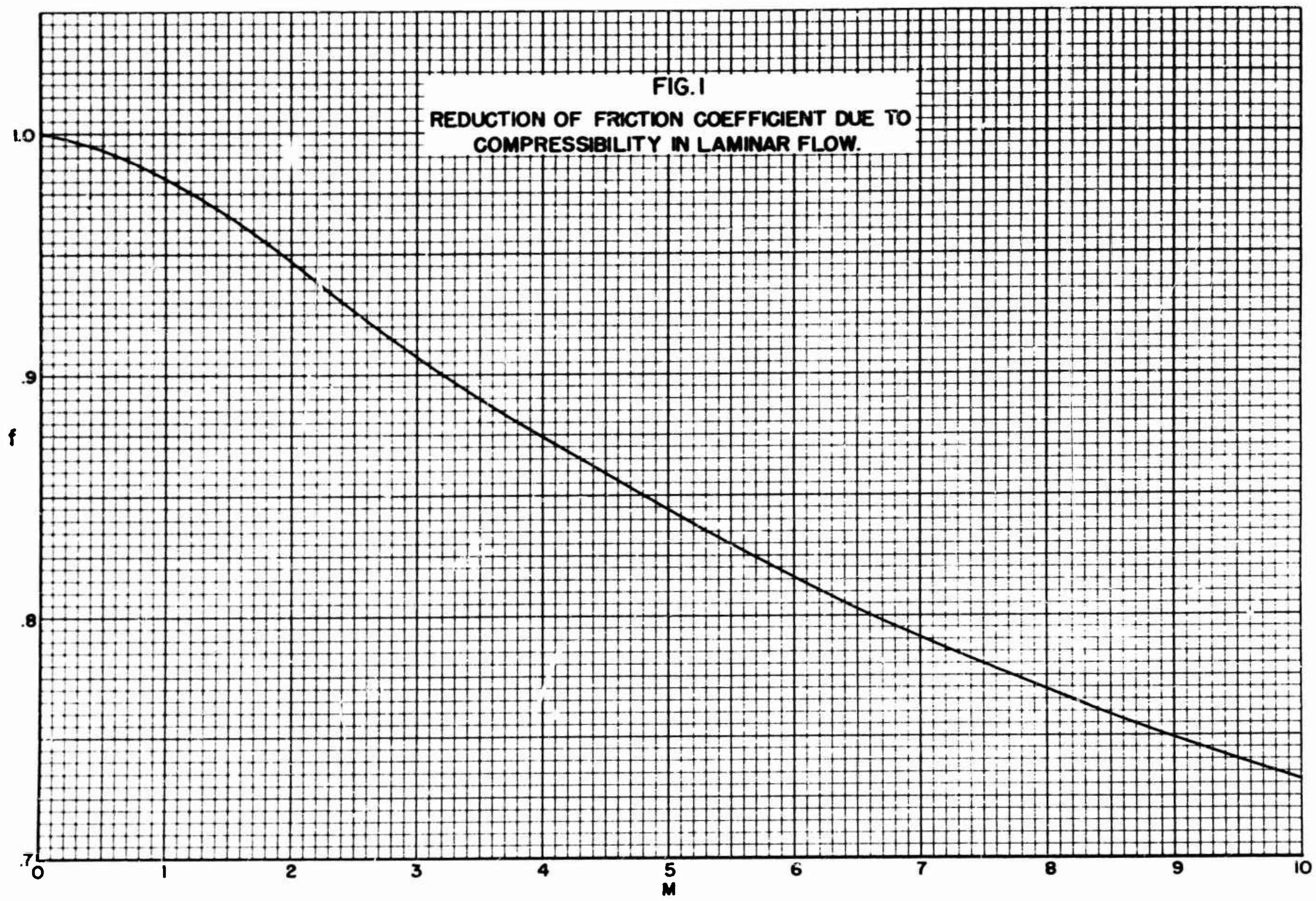
FIG. I
REDUCTION OF FRICTION COEFFICIENT DUE TO COMPRESSIBILITY IN LAMINAR FLOW.
1.0
.9
.8
.7
f
0
1
2
3
4
5
6
7
8
9
10
M

For estimating the base pressure on wedge type fins with square bases, Poor* suggests taking 0.35 as a mean value of P_b/P_1. This is based on the limited data that is available over a range of Mach number, aspect ratio, and Reynolds number.

FRICTION DRAG COEFFICIENT

The friction drag coefficient is expressed by the formula

$$K_{DF} = C_f S'/2d^2, \tag{20}$$

where C_f is the skin friction coefficient for smooth flat plates, S' the superficial area exclusive of the base (the 'wetted area'), and $\underline{d}$ the diameter of the body.

a. Laminar Flow. For laminar flow in the boundary layer, Blasius' formula[18,19] for C_f as a function of Reynolds number R is

$$C_f = 1.328\ R^{-\frac{1}{2}}. \tag{21}$$

To take account of compressibility, this value should be reduced by a factor $\bar{f}$ which is a function of Mach number. Van Driest[20] derives the factor

$$\bar{f} = (1 + 0.3\ \overline{\gamma - 1}\ M^2)^{-0.12}, \tag{22}$$

which is a close approximation to Kármán and Tsien's exact solution.[21] Here, γ is the ratio of specific heats (1.405 for air). This factor may be obtained from Figure 1.

Crocco[22] shows that the effect of compressibility depends on the ratio of the enthalpy on the surface of the plate to that in the free stream and also on the enthalpy ratio corresponding to the characteristic temperature of Sutherland's formula for viscosity, as well as on Mach number. He gives these effects in graphical form.

b. Turbulent Flow. For turbulent flow in the boundary layer, Prandtl's empirical formula for C_f is[19]

$$C_f = 0.455\ (\log_{10} R)^{-2.58}. \tag{23}$$

For $\log_{10} R$ between 5 and 9, this agrees closely with von Kármán's formula for an incompressible fluid:[23]

$$\log_{10} R = 0.242\ C_f^{-\frac{1}{2}} - \log_{10} C_f. \tag{24}$$

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* Memo from C. L. Poor, 3d, to R. H. Kent on "Base Pressure Measurements", 18 Jan 50.

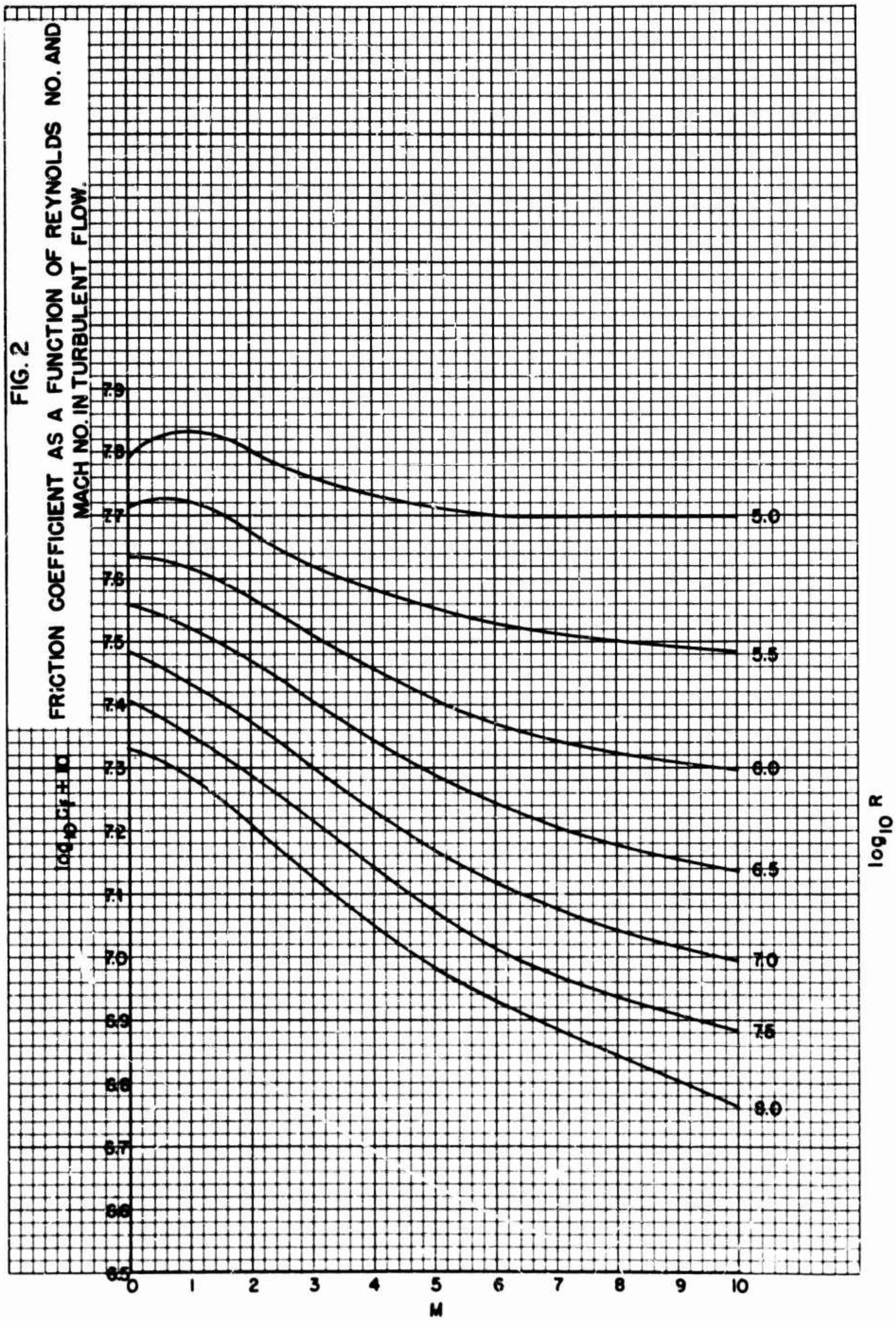

FIG. 2

FRICTION COEFFICIENT AS A FUNCTION OF REYNOLDS NO. AND MACH NO. IN TURBULENT FLOW.

Taking account of compressibility, von Kármán derived the formula:

$$\log_{10}R = 0.242\, C_f^{-\frac{1}{2}} \left(1 + \frac{\gamma - 1}{2} M^2\right)^{-\frac{1}{2}} - \log_{10}C_f$$

$$+ \log_{10}\left(1 + \frac{\gamma - 1}{2} M^2\right). \qquad (25)$$

Van Driest[20] obtained closer agreement with experimental data with the following modification of von Kármán's formula, which takes account of a variation of density across the boundary layer:

$$\log_{10}R = 0.242\, C_f^{-\frac{1}{2}}(1 - \lambda^2)^{\frac{1}{2}} \lambda^{-1}\sin^{-1} \lambda - \log_{10}C_f$$

$$- 1.26 \log_{10}(1 - \lambda^2), \qquad (26)$$

$$\lambda^2 = \frac{\frac{\gamma - 1}{2} M^2}{1 + \frac{\gamma - 1}{2} M^2}. \qquad (27)$$

The value of C_f, calculated by (26), may be obtained from Figure 2; for a given value of M, $\log_{10}C_f$ may be interpolated linearly between curves of constant $\log_{10}R$.

c. Reynolds Number. Charters[24] applies the formulas for C_f to projectiles by taking

$$R = u\ell\rho/\mu, \qquad (28)$$

where u is the velocity of the projectile relative to the air, ℓ the length of the projectile, ρ the density of the air, and μ the viscosity of the air. For this purpose, the length of the surface of revolution should be its axis and the length of the fins, their average actual chord. The standard air density is 0.07513 lb/ft^3.[25] The viscosity corresponding to the standard temperature of 15°C is 1.199×10^{-5} lb/ft.-sec.[26] Hence the kinematic viscosity is

$$\mu/\rho = 1.596 \times 10^{-4} \text{ ft}^2/\text{sec}$$

and $$\log_{10}(\rho/\mu) = 3.7970.$$

d. Surfaces. The surface whose areas S is required may be divided into regions. The surface of revolution consists of cylinders, cones, and ogives. The nose may also have a circular méplat. The surface of the fins consists of rectangles and triangles.

Formulas for computing the area of most of these shapes are well known, but not for an ogive. The area of a curved ogival surface is

$$S = 2\pi R(h + b\theta_1 - b\theta_2), \tag{29}$$

where R is the radius of the ogival arc, h the height of the ogive, b the distance from the center of the arc to the axis of the ogive, θ_1 and θ_2 the angles (in radians) between the axis and the tangent to the element at the base and the nose of the ogive. If d_s is the swell diameter,

$$b = R - d_s/2. \tag{30}$$

If the origin 0 is on the axis at the base of the complete ogive (of diameter d_s) and z_1 and z_2 are the distances from 0 to the base and nose of the actual ogive,

$$h = z_2 - z_1, \tag{31}$$

$$\sin \theta_1 = z_1/R, \tag{32}$$

$$\sin \theta_2 = z_2/R. \tag{33}$$

e. Average. The friction drag coefficient should be computed for both laminar and turbulent flow, and a weighted average taken. The weight for the laminar flow on the surface of revolution is that proportion of the length that is in front of the transition point, which may be at the base of the ogive or some rough place on the surface; this weight should probably be not more than 1/3. On the fins, the weight for the laminar flow is the fraction of the surface in front of a line from the intersection of the leading edge and the shell body, going back and away from the axis at an angle of 10°.[27] In either case, the weight for the turbulent flow is the complement of the weight for the laminar flow.

INTERFERENCE DRAG COEFFICIENT

a. Body-fin Interference. The flow of air over a body with fins attached is different from that over the body alone, and consequently the drag coefficient is different from that of the body alone plus that of the fins. The flow of air over the fins is different after passing around the fore part of the body than it would be in the undeflected stream. These effects could be determined for particular shapes by wind tunnel measurements, but at present no data appear to be available for such a determination.

b. Fin Interference. The flow of air over one pair of fins may also be influenced by the presence of other fins. The resulting variation in drag coefficient can be determined by wind tunnel measurements. One set of such measurements[28] indicates that 1/3 of the increase in K_D due to 6 fins is more than the increase due to 2 fins at $M = 2.48$ and at $M = 3.25$. No interference was evident with 6 fins at $M = 1.57$, or with 4 fins at any of the three Mach numbers.

DRAG COEFFICIENT

The drag coefficient is a function of M and R. For a given missile in air of constant density and temperature, R is a function of M alone. Therefore, for a given projectile, K_D may be treated as a function of M alone. Thomas[36] has discovered a convenient form for this function in the case of a spinning projectile at supersonic velocities: in this region, the parameter

$$Q = (1 + K_D M^2)^{\frac{1}{2}} \tag{34}$$

may be closely approximated by a linear function of M, which requires only two empirical coefficients.

The ratio of the drag coefficient of a missile to that of a typical projectile is called its form factor relative to the typical projectile and denoted by i_t, where $\underline{t}$ represents the type of projectile. If there is a typical projectile on which i_t is nearly constant, its tabulated drag coefficient multiplied by the average i_t may be used as the estimated drag coefficient of the missile.

Wherever possible, the results should be checked by comparison with experimental data. For spinning projectiles of moderate length, some semi-empirical formulas have been derived from range firing data:[29] these show the dependence of the form factor on length of head. A large number of form factors determined from resistance firings are listed in another report.[30] The contribution of fins to the drag coefficient of rockets and guided missiles has been determined from wind tunnel measurements.[28, 31, 32, 33]

Some time-of-flight firings of caliber 0.50 bullets have indicated that the increase in drag due to méplat is proportional to the area of the méplat:[34] the form factors of bullets with the same head length approximately satisfied the relation

$$i_2 = 1.25(1 + 0.375\, d_n^2) \tag{35}$$

where d_n is the nose diameter expressed in calibers, valid up to 0.36 caliber. Hence, if the nose diameter is less than 0.16 caliber, the increase in drag is less than 1%. Stein[37] has determined the effect of nose diameter on the drag of conical-head bullets at supersonic velocities from firings in the spark range, and gives the results in his report.

In this report, the drag coefficient has been defined by formula (2) in terms of the square of the caliber. Sometimes it is denoted by the symbol C_D and defined by the formula

$$D = C_D A \rho u^2/2 \tag{36}$$

where A is the cross-sectional area. The relation between K_D and C_D is

$$K_D = 0.3927\, C_D. \tag{37}$$

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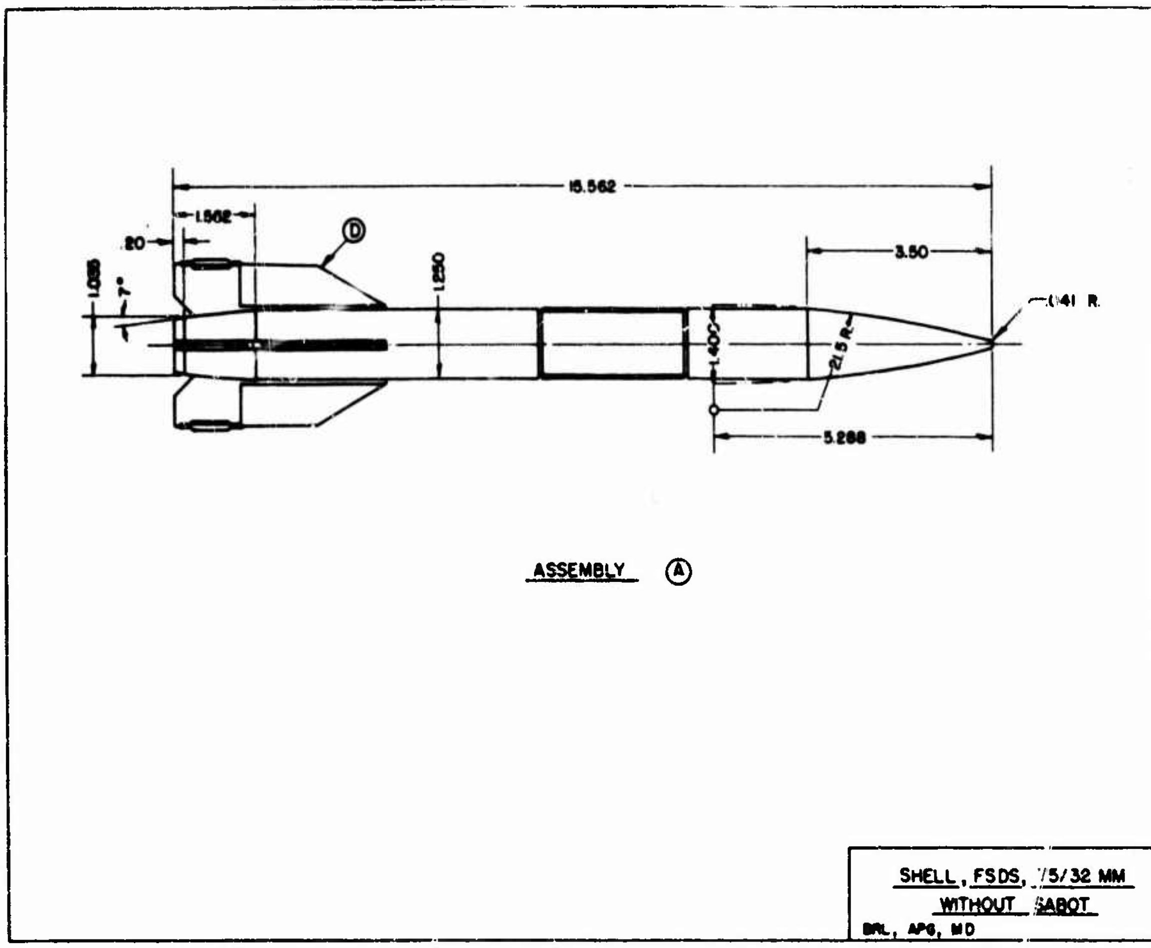
15.562
1.562
.20
1.085
7°
1.250
3.50
.041 R.
1.400
21.5 R.
5.288
ASSEMBLY (A)
SHELL, FSDS, 75/32 MM
WITHOUT SABOT
BRL, APG, MD

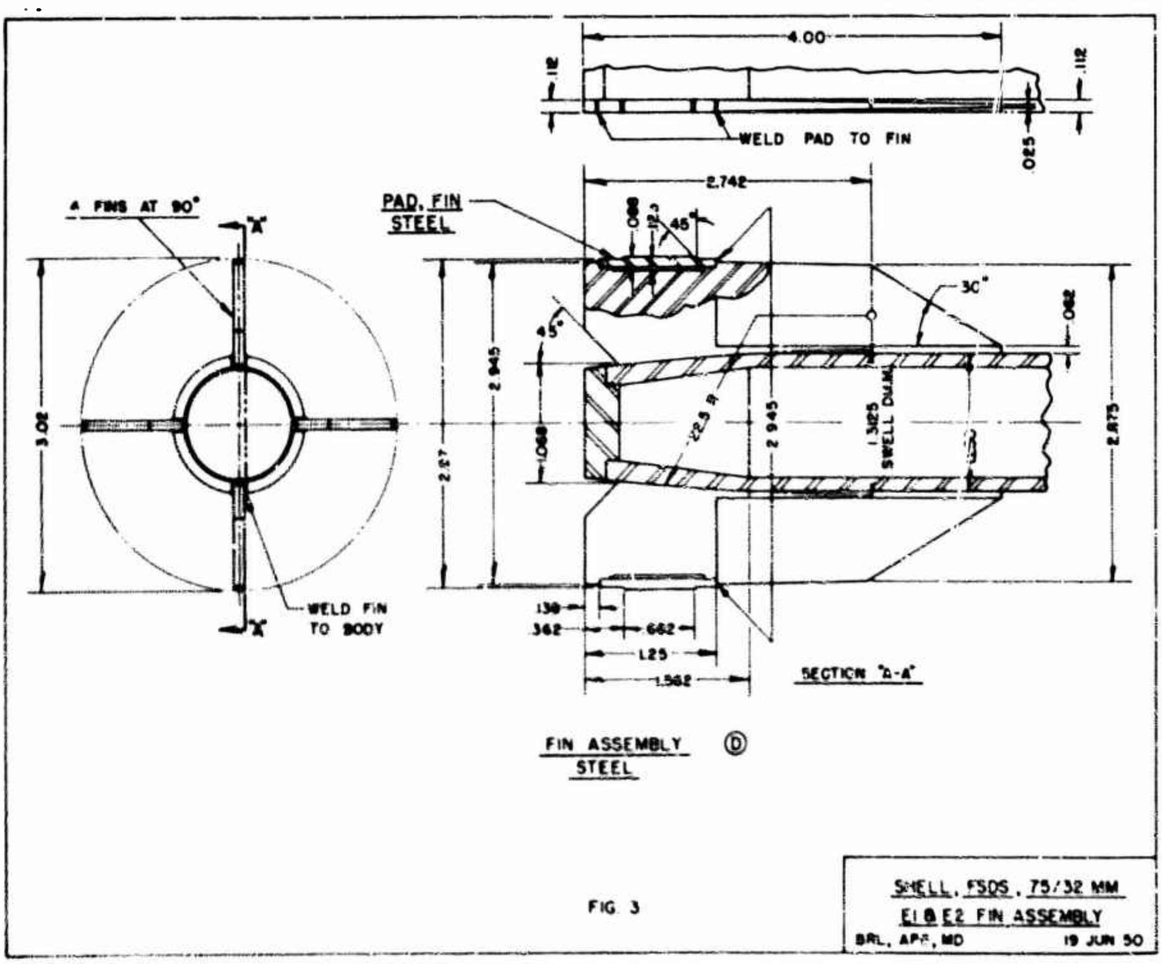
4.00
.112
.112
WELD PAD TO FIN
.025
2.742
4 FINS AT 90°
PAD, FIN
STEEL
45°
30°
.062
3.02
2.945
2.87
2.945
22.5 R
1.325
SWELL DIAM.
2.875
WELD FIN
TO BODY
.138
.362
.662
1.25
1.562
SECTION "A-A"
FIN ASSEMBLY (D)
STEEL
SHELL, FSDS, 75/32 MM
E1 & E2 FIN ASSEMBLY
BRL, APG, MD 19 JUN 50

FIG. 3

APPENDIX

Computation of Drag Coefficient of 75/32mm Fin-Stabilized Shell (Fig.3)

Mach Number (assumed)	$M = 3.00$	
Diameter of body	$d = 1.25$ in.	
Height of ogival head	$h = 3.50$ in.	
By Eq. (4)	$\tan\theta_s = 0.17357$	
Semi-apex angle of inscribed cone	$\theta_s = 10.125^\circ$	
Radial velocity (from Part III of Kopal's Tech Rep 1)	$u_s = 0.7725$	
Wave drag coefficient of the cone (from Part II of Kopal's Tech Rep 3)	$K_D(\text{cone}) = 0.0351$	
Correction for ogival head ($R_T/R = 10.1/21.5 = 0.47$)	$K_D = \underline{-0.0044}$	
Wave drag coefficient of body K_{DW}(body)		.0307
Wave drag on boattail is neglected. Carter's report has no data for projectiles longer than seven (7) calibers.		
Span of fins	$s = 2.93$ in.	
Chord of fins	$c = 3.33$ in.	
Aspect ratio	$A = 0.88$	
Wedge angle	$\beta = 1.8^\circ$	
Sweep-back angle	60°	
Wave drag coefficient of fins (from Graham and Lagerstrom's report) K_{DW}(fins)		.0095
By Eq. (19) for base of body	$1 - P_b/P_1 = 0.600$	
Base diameter	$d_b = 0.974$ in.	

By Eq. (18) Base drag coefficient of body K_{DB} (body) .0226

Poor's estimate for base of fins $1 - P_b/P_1 = 0.650$

Base area of fins $A_b = 0.4331 \text{ in}^2$

By Eq. (16)
Base drag coefficient of fins $K_{DB}(\text{fins}) =$ .0142

Velocity (1120 M) $u = 3360$ fps

Length of body $\ell(\text{body}) = 1.297$ ft.

Length (chord) of fins $\ell(\text{fins}) = 0.2775$ ft.

By (28), Reynolds No. is given by $\log R(\text{body}) = 7.4362$
$\log R(\text{fins}) = 6.7966$

By Fig. 1, Compressibility Factor $\bar{f}$ $= 0.9075$

By Fig. 2, Skin friction coefficient for turbulent flow is given by $\log C_{ft}(\text{body}) = 7.207$
$\log C_{ft}(\text{fins}) = 7.346$

The surface of the body consists of a truncated cone, a cylinder, and an ogive; the area of the ogive is given by Eq.(20) $S'/2d^2(\text{body}) = 13.195$

The surface of the fins consists of triangles and trapezoids $S'/2d^2(\text{fins}) = 7.553$

By Eq. (20), with the help of Eq.(21) for laminar flow,
Friction drag coefficient
of body in laminar flow $K_{DF\ell}(\text{body}) = 0.0029$

of body in turbulent flow $K_{Dft}(\text{body}) = 0.0213$

of fins in laminar flow $K_{Df\ell}(\text{fins}) = 0.0036$

of fins in turbulent flow $K_{Dft}(\text{fins}) = 0.0168$

Since the distance from the nose to the threads is more than 1/3 the length of the body, the weight for the laminar flow on the body is $w_\ell(\text{body}) = 0.33$

Since the transition line on each fin surface intersects the body at the leading edge and makes an angle of 10° with the axis, it intersects the trailing edge 1.33 in. from the axis, the flow is laminar in front of this line (neglecting the effect of the fin pad) and the weight for the laminar flow on the fins is w_ℓ (fin)= 0.50

The weight for the turbulent flow on the body is	w_t (body)= 0.67	
The weight for the turbulent flow on the fins is	w_t (fins)= 0.50	
Friction drag coefficient of body	K_{D_F} (body)	.0152
Friction drag coefficient of fins	K_{D_F} (fins)	.0102
Total drag coefficient	K_D	.1024

The estimated drag coefficient of other fin-stabilized shell at several Mach numbers greater than 1 is approximately proportional to $K_{D2.2}$, the second revision of the drag coefficient for projectile type 2. At M = 3, $K_{D2.2}=$ .0868

Form factor	$i_{2.2}$	1.18

In this calculation, the fin-body interference is neglected. Since there are only four fins, the interference between fins is probably negligible. This result applies to 0 yaw; the effect of yaw is not considered in this report