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MEMORANDUM REPORT ARBRL-MR-03020

ALGORITHM FOR ESTIMATING AERODYNAMIC STATIC MOMENTS OF LONG ROD PENETRATORS AT $2<M<5$

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May 1980

US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
BALLISTIC RESEARCH LABORATORY
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Long Rod Projectiles

20. ABSTRACT (Continue on reverse side if necessary and identify by block number) jmk

Estimation of the aerodynamic normal force and static moment of a given class of flight vehicles is demonstrated with reference to AMCP 706-280, which in turn derives from the classic British work "Wings". By means of linearized algebraic reduction, a transmutation permits the designer to quickly evaluate the effects of variation on the flight system.

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LIST OF ILLUSTRATIONS

I. INTRODUCTION

An insight into the influence of aerodynamics on the overall performance of the long rod projectile is obviously necessary to the mechanical analyst and to the terminal ballistician in the concept phase of design consideration. For the unfinned projectile, in the absence of righting moments in the form of gyroscopic reaction or direct aerodynamic contributions of tailfins, the static moment will normally increase the yaw in the plane of the angle of attack and destabilize the flight projectile. Since the gyroscopic correction is bounded by the possibility of dynamic instability[1], a tailfin system is invariably selected to control the flight of long rod projectiles. The designer must then estimate the static moment in compromise with the drag, weight, length/diameter and penetration parameters. For this purpose the projectile is considered as a forebody (total projectile without fins) plus a complete aerodynamic wing plan form. An "interference factor" correction allows the free flight wing characteristic to be coupled to the forebody performance. Reference 2 offers a combined graphical-tabular calculation technique by which C_D, the drag coefficient, $C_{N\alpha}$, the normal force lift coefficient, and $C_{M\alpha}$, the static moment coefficient can be determined over the Mach range from subsonic to $M \approx 5$. In the lower velocity regime, the forebody values are determined from slender body theory wherein second order effects are neglected; while in the true supersonic flow, the data are from open literature reported experimentation. Similarly, the lower Mach number fin performance is based on thin airfoil theory and the higher range data is experimental. Using the graph-tables, however, requires about eight manhours to estimate the aerodynamic performance of one projectile. By restricting the Mach envelope through linearization of critical graphs and by neglecting the effects of wing profile it is possible to simplify the presentation to desk top calculator (HP-97, Appendix B) utility. Linearization consists of the substitution of a straight line for a curved or undulating characteristic.

II. PROCEDURE

Figure 1-a is an outline diagram of a typical fin stablized long rod projectile. In conjunction with Table A-1, the $C_{N\alpha}$, $C_{M\alpha}$, $C_{L\alpha}$, the aerodynamic jump factor and the initial yaw period may be calculated. To use the table it is necessary to separately determine the physical properties of the projectile and C_D. A step-by-step sample calculation, as indicated in Table A-1 will illustrate the procedure for the projectile dimensions of Figure 1-b. The geometric limitations, algebraic specifications, etc., for the column entries are given in Appendix A.

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[1] *C.H. Murphy, "Free Flight Motion of Symmetric Missiles", BRL Report No. 1216, July 1963, (AD 442757).*

[2] *AMCP 706-280, "Design of Aerodynamically Stabilized Free Rockets", 1968.*

A similar, and much more elaborate, procedure based on the same formulation has been published[3] but is not reduced to CDC presentation locally. This current interim report presents the algorithm for determining $C_{N\alpha}$ and $C_{M\alpha}$. From Reference 4, C_D can be estimated and $C_{L\alpha}$ is therefore available. With the known physical properties of the projectile, the aerodynamic jump factor[5] and the inital yaw period[1] are established and, in caliber dimensions, comparison with all other flight vehicles postulated.

III. RESULTS AND CONCLUSIONS

Figures 2-a through 2-d show the comparison performance of the hypothetical projectile with the curve trends in reasonable agreement over the region of interest. An additional example is presented in Appendix E, Figures E-1 through E-4. These plots compare algebraicly determined performance and experimental range data[6] for the XM 110 projectile which has been exhaustively tested at BRL. The data indicate agreement in magnitude as well as direction.

Future work in this area will include:

- Analysis of range data as available.
- A comprehensive Fortran/CDC programming effort to present the results in mapped context.
- Extension of the synthesis to higher Mach numbers.

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[3] *W.D. Washington, "Computer Program, for Estimating Stability Derivatives of Missile Configurations", U.S. Army Missile Command Report RD7625, May 1976, (AD #1473).*

[4] *W.F. Donovan and B.B. Grollman "Procedure for Estimating Zero Yaw Drag Coefficients for Long Rod Projectiles at Mach Numbers from 2 to 5", ARBRL MR 02819, March 1978, (AD #A054326).*

[5] *W.F. Donovan "One Factor Affecting the Dispersion of Long Rod Penetrator", ARBRL MR 02846, June 1978, (AD #A058596).*

[6] *M.J. Piddington, "The Aerodynamic Characteristics of a SPIW Projectile (U)", BRL Memorandum Report 1594, September 1964, (AD #355679).*

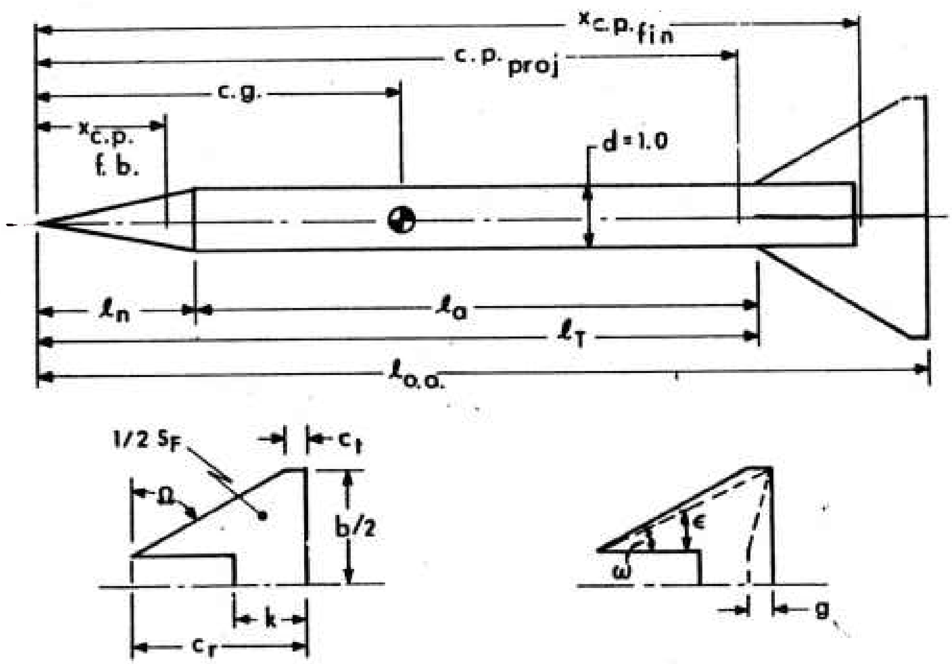
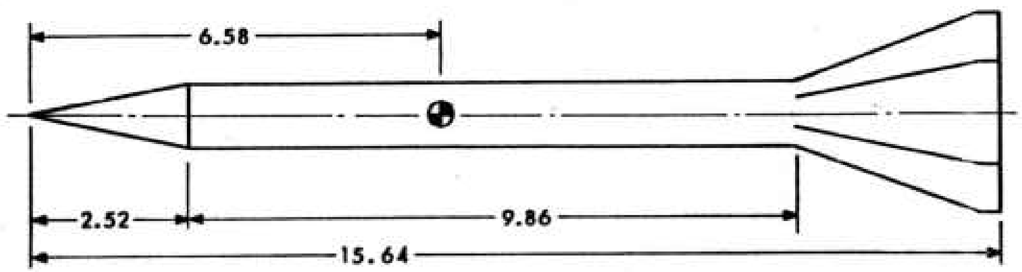


Figure 1-a Long Rod Penetrator Outline



M	C_D
2.0	.719
2.5	.638
3.0	.559
3.5	.481
4.0	.405
4.5	.329
5.0	.253

	*
Wt	145.1 cal^3
I_x	16.02 cal^5
I_y	1982 cal^5
d	1.0 cal
$S.G._{ave}$	12.96
N	6

*APPENDIX D

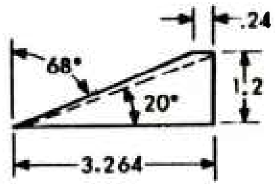


Figure 1-b Input Data for Sample Problem

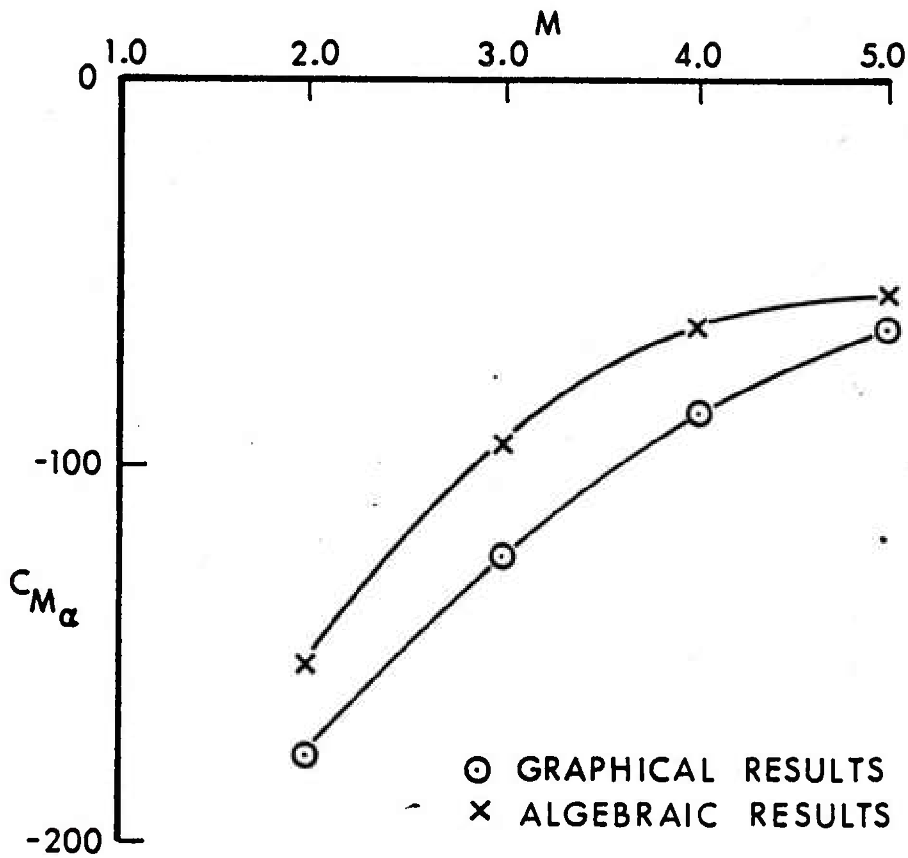


Figure 2-a Static Moment Coefficient for Hypothetical Projectile

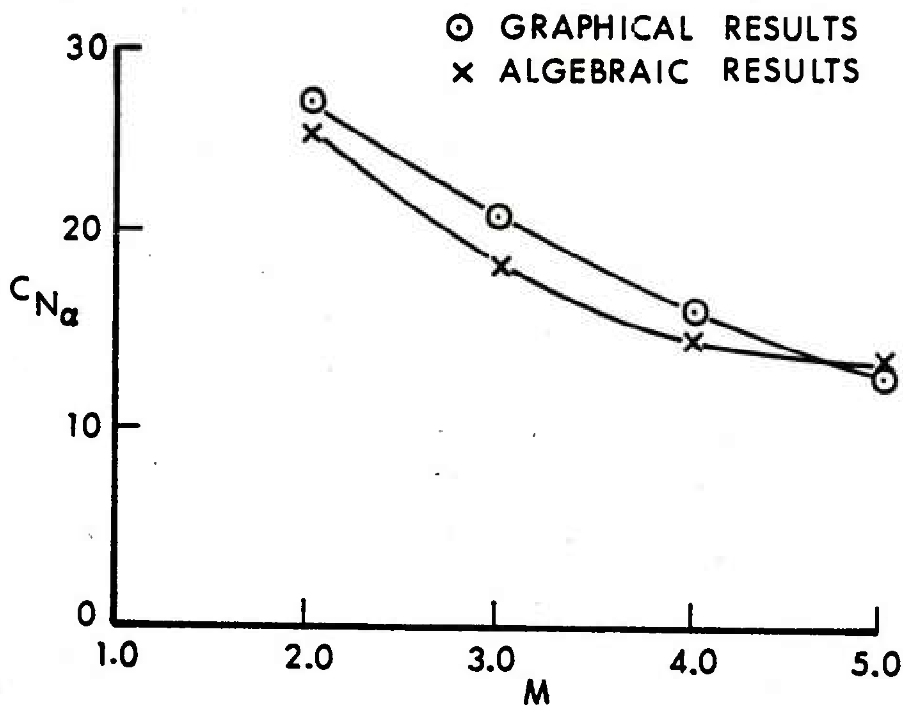


Figure 2-b Normal Force Coefficient for Hypothetical Projectile

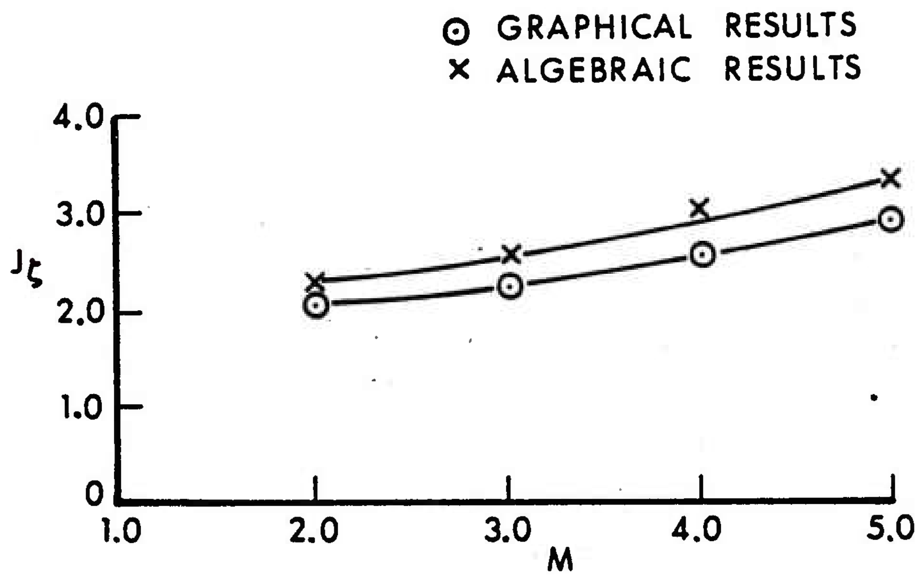


Figure 2-c Aerodynamic Jump Factor for Hypothetical Projectile

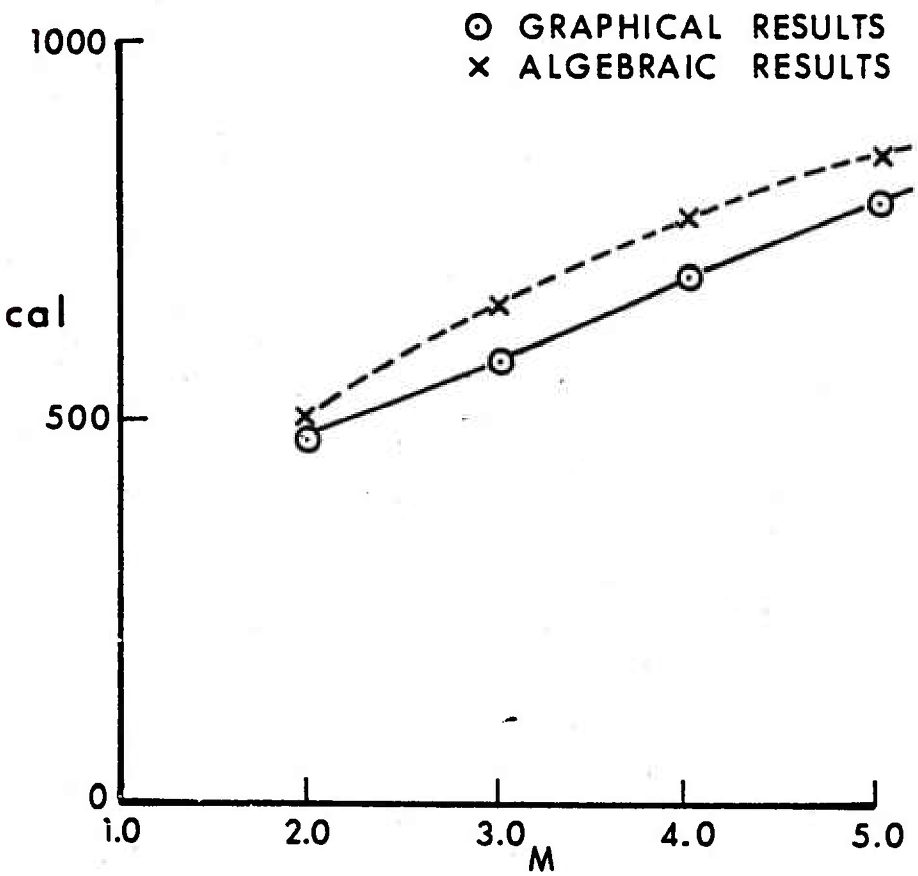


Figure 2-d Initial Yaw Period for Hypothetical Projectile

REFERENCES

1. C.H. Murphy, "Free Flight Motion of Symmetric Missiles", BRL Report No. 1216, July 1963, (AD #442757).

2. AMCP 706-280, "Design of Aerodynamically Stabilized Free Rockets", 1968.

3. W.D. Washington, "Computer Program for Estimating Stability Derivatives of Missile Configurations", U. S. Army Missile Command Report RD-76-25, May 1976, (AD #1473).

4. W.F. Donovan and B.B. Grollman, "Procedure for Estimating Zero Yaw Drag Coefficients for Long Rod Projectiles at Mach Numbers from 2 to 5", ARBRL MR 02819, March 1978, (AD #A054326).

5. W.F. Donovan, "One Factor Affecting the Dispersion of Long Rod Penetrators", ARBRL MR 02846, June 1978, (AD #A058596).

6. M.J. Piddington, "The Aerodynamic Characteristics of a SPIW Projectile (U)", BRL Memorandum Report 1594, September 1964, (AD #355679).

APPENDIX A

TABULATED VALUES

TABLE A-1 FOREBODY

	$\beta = (M^2 - 1)^{1/2}$			②/③	④/②	Fig. 8-4, Ref. 2 or Eq. (1), Appendix A	Fig. 8-5, Ref. 2 or Eq. (2), Appendix A	⑦×⑧	
1	2	3	4	5	6	7	8	9	
M	β	ℓ_n	ℓ_a	β/ℓ_n	ℓ_a/β	$C_{N\alpha\,f.b.}$	$x_{c.p.\,f.b.}$	$C_{M\alpha\,f.b.}$	
		cal	cal	1/cal	cal	1/rad	cal	1/rad	
2.	1.732	2.52	9.86	.687	5.690	3.0	2.52	7.56	*
						3.2	1.94	6.24	**
3.	2.828	2.52	9.86	1.122	3.487	3.75	3.06	11.48	
						3.65	2.19	8.04	
4.	3.873	2.52	9.86	1.537	2.546	3.80	3.14	11.93	
						3.99	2.43	9.71	
5.	4.899	2.52	9.86	1.944	2.013	3.70	3.28	12.14	
						4.26	2.65	11.31	

* Graphical values from Ref. 2

** Algebraic values from Appendix B

TABLE A-2 FINS

	$\lambda = c_t/c_r$		②/⑪	⑪/②	b^2 / S_F	⑪ × ⑭
	10	11	12	13	14	15
M	λ	TAN Ω	β/TAN Ω	TAN Ω/β	AR	AR TAN Ω
2.	.074	2.52	.687		1.37	3.45
					1.37	
3.	.074	2.52		.891	1.37	3.45
					1.37	
4.	.074	2.52		.651	1.37	3.45
					1.37	
5.	.074	2.52		.514	1.37	3.45
					1.37	

TABLE A-3 FINS (COMPLETED)

	Fig. 8-13. Ref. 2	Fig. 8-13, Ref. 2	(16)/(11), (17)/(2) or Eq. (3), Appendix A	$\frac{N S_F}{\pi}$ x (18) (based on reference area)	Fig. 8-14, Ref. 2	(19) x (20) (nose fulcrum)
	16	17	18	19	20	21
M	$\beta \tan \Omega$	$\beta C_{N\alpha}$	$C_{N\alpha}$ fin	$C_{N\alpha}$ fin	$x_{c.p.}$ fin	$C_{M\alpha}$ fin
		1/rad	1/rad	1/rad	cal	1/rad
2.	4.56		1.81	14.53	14.4	209
			1.18	9.47		221
3.		3.85	1.36	10.92	14.4	157
			1.10	8.84		133
4.		3.87	1.00	8.03	14.4	115
			1.11	8.88		101
5.		3.90	.80	6.42	14.4	92
			1.14	9.17		84

TABLE A-4 INTERFERENCE FACTOR

		$a = \beta$ TAN ω	$z = \frac{\text{TAN } \omega}{\text{TAN } \epsilon}$	Fig. 8-21, Ref. 2 or Eq. (4), Appendix A
	22	23	24	25
M	d /(1+b)	a	a/z	K
2.	.29	.63	.95	1.69
				1.65
3.	.29	1.03	.95	1.62
				1.58
4.	.29	1.41	.95	1.59
				1.47
5.	.29	1.78	.95	1.55
				1.39

TABLE A-5 SUMMARY

	26	27	28	29	30	31	32	33	34	35
	(7)	(19) (interference free)	(25) x (27)	(26) + (28)	(9)	(21) (interference free)	(25) x (31)	(30) + (32) (nose fulcrum)	(33)/(29) (nose datum)	((34) - c.g.) x (29) (c.g. fulcrum)
M	$C_{N\alpha}$ f.b.	$C_{N\alpha}$ fin	$C_{N\alpha}$ fin	$C_{N\alpha T}$ proj.	$C_{M\alpha}$ f.b.	$C_{M\alpha}$ fin	$C_{M\alpha}$ fin	$C_{M\alpha T}$ proj.	c.p. proj.	$C_{M\alpha T}$
	1/rad	1/rad	1/rad	1/rad	1/rad	1/rad	1/rad	1/rad	cal	1/rad
2.	3.00	14.53	24.56	27.56	7.56	209	353	358	12.98	-177
	3.2	9.47	22.75	25.95	6.24	193	318	324	12.49	-153
3.	3.75	10.92	17.69	21.44	11.48	157	254	266	12.40	-125
	3.65	9.84	15.2	18.85	8.04	134	212	220	11.67	-96
4.	3.80	8.03	12.76	16.57	11.93	115	183	195	11.76	-86
	3.99	8.88	11.04	15.03	9.71	104	154	164	10.89	-65
5.	3.70	6.42	9.95	13.65	12.14	92	143	155	11.33	-65
	4.26	9.17	10.0	14.26	11.31	101	140	151	10.61	-58

TABLE A-6 AERODYNAMIC JUMP FACTOR

	Separate schedule	(29) - (36)	(37)/(35)	Separate schedule	(38) x (39)	$144.6\left[I_y/(35)\right]^{1/2}$ Eq. C-1, Appendix C
	36	37	38	39	40	41
M	C_D	$C_{L\alpha}$	$C_{L\alpha}/C_{M\alpha}$	I_y/m	J	s
		1/rad				cal
2.	.72	26.84	.152	13.66	2.08	484
		25.23	.165		2.25	520
3.	.56	20.88	.167	13.66	2.28	576
		18.29	.191		2.60	657
4.	.41	16.16	.188	13.66	2.57	694
		14.62	.224		3.07	798
5.	.25	13.4	.206	13.66	2.82	798
		14.01	.242		3.29	845

NOTES ON COLUMN ENTRIES

Column 1 — The Mach number range is restricted to $2<M<5$ due to linearization of the characteristics.

Column 2 — --

Column 3 — The given example refers to a cone-cylinder forebody. An ogive nose would increase the normal force about 10%; Figures 8-2 and 8-4 of Reference 2. $2<\ell_n<6$.

Column 4 — $5<\ell_a<20$

Column 5 — --

Column 6 — --

Column 7

$$(C_{N\alpha})_{f.b.} = \left(1.9+1.3\,\frac{\beta}{\ell_n} + .0149\,\frac{\ell_a}{\beta}\right)\left(\beta^{-.7}\right)\left(-.0675\ell_T+2.3\right) \qquad (1)$$

This equation is a fitted approximation to the curves of Figure 8-4 of Reference 2. It applies to cone-cylinders only.

Column 8

$$(\chi_{c.p.})_{f.b.} = \left(.69+.65\frac{\beta}{\ell_n} + .5\,\frac{\ell_a}{\beta}\right)\left(\beta^{-.46}\right) \qquad (2)$$

This equation is obtained by fitting Figure 8-5 of Reference 2. It also applies to cone-cylinders only.

Column 9 — Moment is referred to nose.

Column 10 — --

Column 11 — --

Column 12 — --

Column 13 — --

Column 14 — --

Column 15 — --

Column 16 — Figures 8-13, Reference 2.

Column 17 — Figures 8-13 of Reference 2.

Column 18

$$C_{N\alpha} = \frac{1}{\beta}\left[4 + \left(.9\lambda + 1.25\ell_n \frac{AR\,TAN\Omega}{4}\right)\left(\frac{TAN\Omega}{\beta}\right)\right]$$

$$+ \frac{1}{TAN\Omega}\left[\left(.6AR-1\right)\left(1-\frac{\beta}{TAN\Omega}\right)\right]\left(\frac{.541}{M}\right)\left(\beta^{-.58}\right) \quad (3)$$

where the first term is used for $\frac{TAN\Omega}{\beta} < 1$ and both terms are used for $\frac{TAN\Omega}{\beta} > 1$. $C_{N\alpha}$ is based on the plan form area.

This expression is determined by empirical data as fitted from Figures 8-13 (A) through (C) of Reference 2. It includes a term to represent the complete expanse of tip/root ratios, as well as the fin aspect ratio and leading edge sweep angle as affected by Mach number.

Column 19 — $C_{N\alpha}$ is converted to a reference area value (bourrelet).

The effect of the fin solidity is established by Reference 2, p. 8-41.

Column 20 — For the algebraic formulation, the c.p. is taken at the mid point of the total fin length. The error introduced, in comparison with Figures 8-14 of Reference 2, is quite small.

Column 21 — Moment is referred to nose.

Column 22 — --

Column 23 — --

Column 24 — --

Column 25 — $K = (-.167\ a + 1.334)e^{d/d+\ b}$ (4)

The rather minor contribution of "z" has not been included in this equation. This is a sweep angle compensation and would be significant for rectangular fin designs. The equation represents the curves given as Figures 8-21 (C) through (E) of Reference 2.

Column 26 — Transcription of column 7

Column 27 — Interference free $C_{N\alpha}$

Column 28 — Complete empennage

Column 29	--
Column 30	--
Column 31	Interference free fins
Column 32	Complete empennage
	Note that with columns 28 and 32, the capacity of the HP-97 has been exceeded. The table is then completed by individual operations.
Column 33	Complete projectile, nose datum.
Column 34	--
Column 35	c.g. must be separately determined
Column 36	C_D must be separately determined
Column 37	--
Column 38	--
Column 39	--
Column 40	--
Column 41	I_y must be separately determined

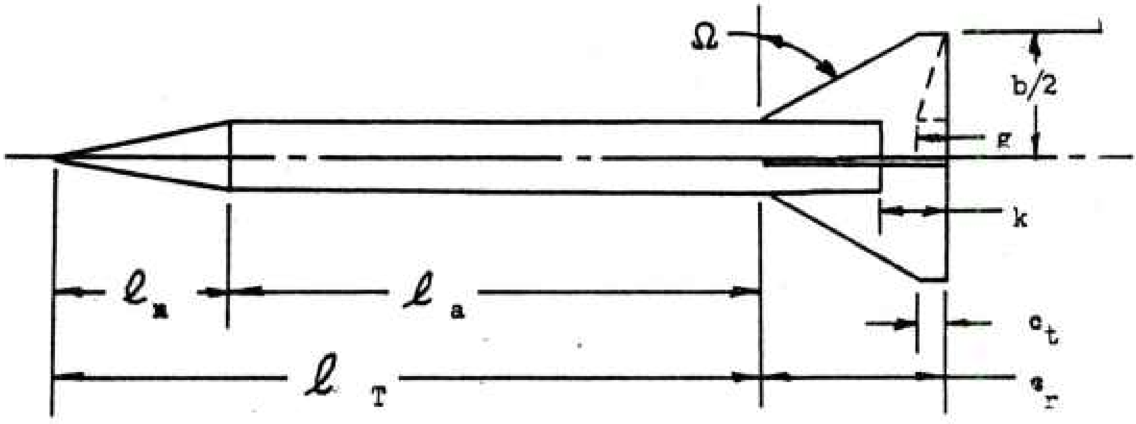
APPENDIX B

DESKTOP CALCULATOR PROGRAMS FOR $C_{N\alpha}$, $C_{M\alpha}$ and C_D

APPENDIX B

DESKTOP CALCULATOR PROGRAMS FOR $C_{N\alpha}$, $C_{M\alpha}$ and C_D

1. HP-97 Listing for $C_{M\alpha}$ and $C_{N\alpha}$.



Listing for Nose/Body $C_{N\alpha}$ and $C_{M\alpha}$

Input Storage Registers

0	ℓ_a	cylindrical body length
9	ℓ_n	nose length
A	M	initial Mach number

Printed Output

Mach number	M
Normal Force coefficient	$C_{N\alpha}$
Static Moment coefficient	$C_{M\alpha}$
Center of pressure (nose datum)	

001	*LBLA	21 11
002	RCLA	36 11
003	PRTX	-14
004	X²	53
005	1	01
006	-	-45
007	√X	54
008	STO1	35 01
009	CLX	-51
010	RCL1	36 01
011	RCL9	36 09
012	÷	-24
013	1	01
014	.	-62
015	3	03
016	×	-35
017	STOE	35 15
018	CLX	-51
019	RCL0	36 00
020	8	08
021	÷	-24
022	RCL1	36 01
023	×	-35
024	STOB	35 12
025	.	-62
026	1	01
027	1	01
028	9	09
029	+	-55
030	RCLE	36 15
031	+	-55
032	RCL1	36 01
033	LN	32
034	.	-62
035	7	07
036	×	-35
037	eˣ	33
038	÷	-24
039	STOD	35 14
040	CLX	-51
041	RCL0	36 00
042	RCL9	36 09
043	+	-55
044	.	-62
045	0	00
046	6	06
047	5	05
048	CHS	-22
049	×	-35
050	2	02
051	.	-62
052	3	03
053	+	-55
054	STO2	35 02
055	RCLD	36 14
056	×	-35
057	PRTX	-14
058	STOD	35 14
059	CLX	-51
060	RCLE	36 15
061	2	02
062	÷	-24
063	STOC	35 13
064	RCLB	36 12
065	.	-62
066	4	04
067	×	-35
068	RCLC	36 13
069	+	-55
070	.	-62
071	6	06
072	9	09
073	+	-55
074	2	02
075	÷	-24
076	RCL9	36 09
077	×	-35
078	RCLD	36 14
079	×	-35
080	RCL1	36 01
081	LN	32
082	.	-62
083	4	04
084	6	06
085	×	-35
086	eˣ	33
087	÷	-24
088	PRTX	-14
089	RCLD	36 14
090	÷	-24
091	PRTX	-14
092	CLX	-51
093	SPC	16-11
094	.	-62
095	5	05
096	RCLA	36 11
097	+	-55
098	STOA	35 11
099	GSBA	23 11
100	RTN	24
101	PRTX	-14
102	R/S	51

Listing for Fin/Empennage $C_{N\alpha}$ and $C_{M\alpha}$

Input Primary Storage Registers

0	$b/2$	fin blade height
1	c_r	fin blade length at root
2	$\tan \Omega$	tangent of fin sweepback angle
3	g	fin dimension
4	k	fin dimension
5	c_t	fin blade length at tip
6	ΔM	Mach number increment
7	N	number of fin blades

Secondary Storage

1	ℓ_T	complete body length
2	ℓ_a	body length
3	ℓ_n	nose length
6	c.g.	center of mass (nose datum)
I	M	initial Mach number

Printed Output

Mach number	M
Static Moment coefficient	$C_{M\alpha}$
Normal Force coefficient	$C_{N\alpha}$

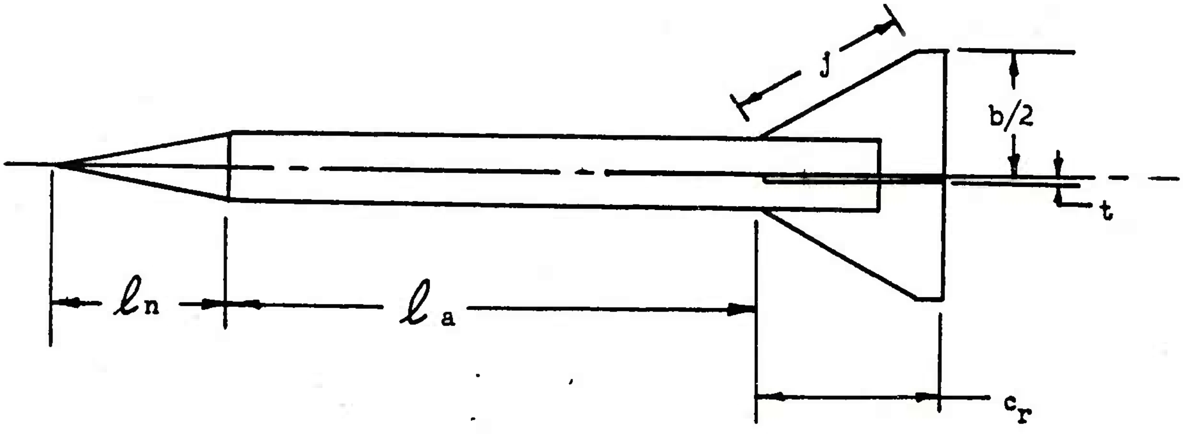
001	*LBLE	21 15
002	RCL0	36 00
003	2	02
004	×	-35
005	X²	53
006	STOA	35 11
007	CLX	-51
008	RCL0	36 00
009	RCL1	36 01
010	×	-35
011	STOB	35 12
012	CLX	-51
013	RCL2	36 02
014	RCL0	36 00
015	X²	53
016	×	-35
017	2	02
018	÷	-24
019	RCLB	36 12
020	-	-45
021	CHS	-22
022	STOB	35 12
023	CLX	-51
024	RCL0	36 00
025	RCL3	36 03
026	×	-35
027	2	02
028	÷	-24
029	RCLB	36 12
030	-	-45
031	CHS	-22
032	STOB	35 12
033	CLX	-51
034	RCL4	36 04
035	.	-62
036	5	05
037	×	-35
038	RCLB	36 12
039	+	-55
040	2	02
041	×	-35
042	RCLA	36 11
043	X⇄Y	-41
044	÷	-24
045	STOB	35 12
046	CLX	-51
047	RCLI	36 46
048	RCL6	36 06
049	+	-55
050	PRTX	-14
051	STOI	35 46
052	X²	53
053	1	01
054	-	-45
055	√X	54
056	STOA	35 11
057	CLX	-51
058	RCL2	36 02
059	RCLB	36 12
060	×	-35
061	4	04
062	÷	-24
063	LN	32
064	5	05
065	×	-35
066	4	04
067	÷	-24
068	X⇄Y	-41
069	RCL5	36 05
070	RCL1	36 01
071	÷	-24
072	.	-62
073	9	09
074	×	-35
075	+	-55
076	X⇄Y	-41
077	RCL2	36 02
078	×	-35
079	RCLA	36 11
080	÷	-24
081	STO8	35 08
082	4	04
083	+	-55
084	RCLA	36 11
085	÷	-24
086	STOC	35 13
087	CLX	-51
088	RCLA	36 11
089	RCL2	36 02
090	÷	-24
091	1	01
092	-	-45
093	CHS	-22
094	STOD	35 14
095	CLX	-51
096	RCLB	36 12
097	.	-62
098	6	06
099	×	-35
100	1	01

```
151      .       -62
152      5        05
153      8        08
154      ×       -35
155      eˣ       33
156      ÷       -24
157   STOD     35 14
158   STOE     35 15
159   RCL1     36 01
160      .       -62
161      5        05
162      ×       -35
163    P⇄S     16-51
164   RCL1     36 01
165      +       -55
166   RCLE     36 15
167    P⇄S     16-51
168      ×       -35
169   STOE     35 15
170    CLX       -51
171   RCLE     36 15
172   STOE     35 15
173   RCL0     36 00
174   RCL1     36 01
175      ÷       -24
176   RCLA     36 11
177      ×       -35
178      .       -62
179      1        01
180      6        06
181      7        07
182    CHS       -22
183      ×       -35
184      1        01
185      .       -62
186      3        03
187      3        03
188      4        04
189      +       -55
190   RCL0     36 00
191      2        02
192      ×       -35
193      1        01
194      +       -55
195    1/X        52
196      eˣ       33
197    X⇄Y       -41
198      ×       -35
199   STO9     35 09
200   RCLE     36 15
```

```
101      -       -45
102   RCLD     36 14
103      ×       -35
104   RCL2     36 02
105      ÷       -24
106   STOD     35 14
107    CLX       -51
108      1        01
109    X⇄Y       -41
110   RCLA     36 11
111      ÷       -24
112   STO9     35 09
113   X≤Y?     16-35
114  *LBLD     21 14
115   RCL8     36 08
116   RCL9     36 09
117      ×       -35
118      4        04
119      +       -55
120   RCLA     36 11
121      ÷       -24
122   STOC     35 13
123    CLX       -51
124   RCLC     36 13
125   RCLD     36 14
126      +       -55
127   RCLI     36 46
128      3        03
129      .       -62
130      7        07
131      ÷       -24
132      ×       -35
133   STOE     35 15
134    CLX       -51
135   RCL0     36 00
136      2        02
137      ×       -35
138     X²        53
139   RCLB     36 12
140      ÷       -24
141     Pi     16-24
142      ÷       -24
143   RCL7     36 07
144      ×       -35
145   RCLE     36 15
146      ×       -35
147      2        02
148      ×       -35
149   RCLA     36 11
150     LN        32
```

```
201      ×       -35
202   PRTX       -14
203    CLX       -51
204   RCLD     36 14
205   RCL9     36 09
206      ×       -35
207   PRTX       -14
208    CLX       -51
209    X⇄Y       -41
210    CLX       -51
211    SPC     16-11
212   GTOE     22 15
213    RTN        24
214    R/S        51
```

Program for C_D



Input Storage Registers

1	ℓ_n	nose length
2	ℓ_a	cylindrical body length
3	b/2	fin blade height at trailing edge
4	t	fin thickness
5	c_r	fin blade length at root
6	j	fin leading edge length
7	N	number of fin blades
I	M	Mach number

Printed Output

Mach number M
Body wave C_D
Body base C_D
Body viscous C_D
  Body total C_D
Fin wave C_D
Fin base C_D
Fin viscous C_D
  Fin total C_D
Combined C_D

```
001  *LBLC   21 13
002  RCLI    36 46
003  PRTX      -14
004  LN         32
005  .         -62
006  2          02
007  3          03
008  CHS       -22
009  x         -35
010  eˣ         33
011  STOA    35 11
012  CLX       -51
013  RCL1    36 01
014  LN         32
015  1          01
016  .         -62
017  7          07
018  3          03
019  CHS       -22
020  x         -35
021  eˣ         33
022  RCLA    36 11
023  x         -35
024  .         -62
025  7          07
026  x         -35
027  PRTX      -14
028  STOA    35 11
029  CLX       -51
030  RCLI    36 46
031  .         -62
032  0          00
033  4          04
034  8          08
035  CHS       -22
036  x         -35
037  .         -62
038  2          02
039  6          06
040  5          05
041  +         -55
042  PRTX      -14
043  STOB    35 12
044  CLX       -51
045  RCL1    36 01
046  X²         53
047  .         -62
048  5          05
049  X²         53
050  +         -55
051  √X         54
052  .         -62
053  5          05
054  x         -35
055  RCL2    36 02
056  +         -55
057  Pi      16-24
058  x         -35
059  STO9    35 09
060  Pi      16-24
061  ÷         -24
062  4          04
063  x         -35
064  .         -62
065  0          00
066  0          00
067  0          00
068  1          01
069  7          07
070  3          03
071  x         -35
072  STOC    35 13
073  CLX       -51
074  RCLI    36 46
075  4          04
076  .         -62
077  1          01
078  6          06
079  5          05
080  CHS       -22
081  x         -35
082  2          02
083  8          08
084  .         -62
085  7          07
086  5          05
087  +         -55
088  RCLC    36 13
089  x         -35
090  PRTX      -14
091  STOC    35 13
092  RCLA    36 11
093  +          55
094  RCLB    36 12
```

```
095      +        -55
096   PRTX        -14
097   STO8      35 08
098    CLX        -51
099   RCL3      36 03
100   RCL6      36 06
101      ÷        -24
102  SIN⁻¹      16 41
103    TAN         43
104   STOE      35 15
105   RCL3      36 03
106     X²         53
107   RCLE      36 15
108      ÷        -24
109      2         02
110      ÷        -24
111   STOE      35 15
112   RCL3      36 03
113      ÷        -24
114      2         02
115      x        -35
116    CHS        -22
117   RCL5      36 05
118      +        -55
119   RCL3      36 03
120      x        -35
121   RCLE      36 15
122      +        -55
123   STOA      35 11
124     Pi      16-24
125      ÷        -24
126      4         04
127      x        -35
128   STOE      35 15
129   RCL4      36 04
130   RCL6      36 06
131      ÷        -24
132     X²         53
133   RCLE      36 15
134      x        -35
135   RCL7      36 07
136      x        -35
137   STOE      35 15
138    CLX        -51
139   RCLI      36 46
140     X²         53
141      1         01
142      -        -45
143     √X         54
144   RCLE      36 15
145      ÷        -24
146    1/X         52
147   PRTX        -14
148   STOD      35 14
149   RCLB      36 12
150   RCL7      36 07
151      x        -35
152   RCL3      36 03
153      x        -35
154   RCL4      36 04
155      x        -35
156     Pi      16-24
157      ÷        -24
158      4         04
159      x        -35
160   PRTX        -14
161   STOE      35 15
162    CLX        -51
163   RCLA      36 11
164      2         02
165      x        -35
166   RCL9      36 09
167      ÷        -24
168   RCLC      36 13
169      x        -35
170   RCL7      36 07
171      x        -35
172      1         01
173      .        -62
174      1         01
175      5         05
176      ÷        -24
177   PRTX        -14
178   RCLE      36 15
179      +        -55
180   RCLD      36 14
181      +        -55
182   PRTX        -14
183   RCL8      36 08
184      +        -55
185   PRTX        -14
186    SPC      16-11
187   DSZI   16 25 46
188   GTOC      22 13
189    RTN         24
190    SPC      16-11
191   GTOC      22 13
192    RTN         24
193   GSBC      23 13
194   RCLE      36 15
195      6         06
196      .        -62
197      5         05
198   STOI      35 46
199      +        -55
200   RCLD      36 14
201      +        -55
202   PRTX        -14
203   RCL8      36 08
204      +        -55
205   PRTX        -14
206      x        -35
207     eˣ         33
208   STO8      35 08
209    CLX        -51
210   RCLA      36 11
211      2         02
212      x        -35
213   RCL9      36 09
214      ÷        -24
215   RCLC      36 13
216      x        -35
217   RCL7      36 07
218      x        -35
219      1         01
220      .        -62
221      1         01
222      5         05
223      ÷        -24
224   PRTX        -14
```

APPENDIX C

DETERMINATION OF INITIAL YAWING PERIOD

APPENDIX C

DETERMINATION OF INITIAL YAWING PERIOD

The initial yawing period for a fin stabilized missile where the epicyclic arm rates are self compensating may be approximated as

$$s = \pi \left(\frac{2 I_y}{\rho S \, d \, C_{M\alpha}} \right)^{1/2} \qquad \text{(C-1)}$$

where

s = yaw distance between successive maxima or between successive minima, cal

ρ = Air density, .075/62.4 = .00120

S = Reference area, $\pi/4$ cal^2

d = 1.0 cal

I_y = 1982 cal^5, Figure 1-a.

Thus:

$$s = \pi \left(\frac{2 \times 1982}{.00120 \times .7854 \times 1.0} \right)^{1/2} \left(C_{M\alpha} \right)^{-1/2}$$

APPENDIX D

CALIBER NOMENCLATURE

APPENDIX D

CALIBER NOMENCLATURE

Caliber nomenclature is widely used in aerodynamic expression as a dimensional convenience to compare performance parameters of geometrically similar models. It is usually referred to a linear scale representing the arithmetic ratio of a linear dimension to an arbitrary standard - most often the body diameter at the forward bourrelet - but has been employed to identify volumes*. Only a simple extension of the reasoning is required then to simultaneously de-dimensionalize the "mass" factor in a given expression and deduce a normalized system of mechanical units which permits a rational comparison of the dynamic properties of even geometrically dissimilar elements of machinery. Usually the context of discussion identifies the quantities as "mass cal", "inertia cal" "length cal", etc., although a complete lexicon of explicit and descriptive terms is available for this purpose.

For this report, the following correlation is employed:

$$\text{Length (cal)} = \frac{\text{linear dimension}}{\text{diametral dimension}}$$

$$\text{Weight (cal}^3\text{)} = \frac{\text{weight}}{\text{weight of unit volume of water}}$$

$$= \text{S.G.N.}$$

$$\text{Mass (cal}^2\ \text{sec}^2\text{)} = \frac{\text{S.G.N.}}{\text{gravity acceleration}}$$

Thus, with force equal to mass times acceleration:

$$(\text{cal}^3) = (\text{cal}^2\ \text{sec}^2)\left(\frac{\text{cal}}{\text{sec}^2}\right)$$

---

* *MacAllister, et al., "A Compendium of Ballistic Properties of Projectiles of Possible Interest in Small Arms", BRL Report No. 1532, February 1971, (AD #882117).*

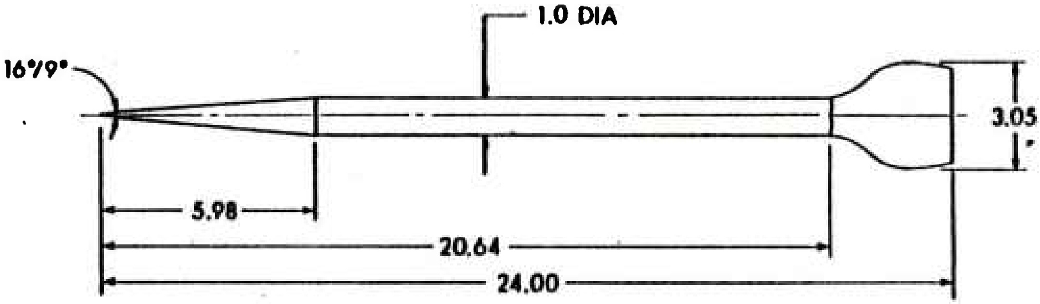
APPENDIX E

ANALYSIS OF THE XM-110 PROJECTILE

APPENDIX E

ANALYSIS OF THE XM-110 PROJECTILE

The static moment and normal force coefficients for the XM-110 projectile, a flechette (Figures E-1 and E-2), were determined by the techniques described in this report and compared with range test data as shown on Figures E-3 and E-4. Agreement is satisfactory, the algebraic values being roughly 15% low for the normal force coefficient and within 10% for the static moment coefficient over the velocity range $2<M<5$.

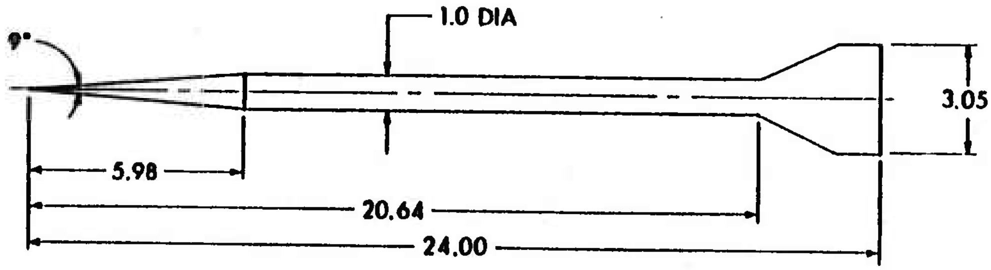


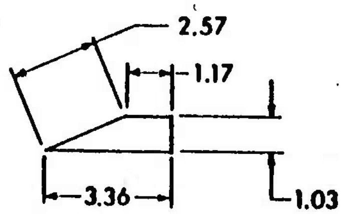
**

WT.	115 CAL^3
I_X	CAL^5
I_Y	2452 CAL^5
DIA	1.0 CAL
ρ	7.86

** APPENDIX D

Figure E-1. Outline of XM-110 Projectile





**

WT.	115 CAL^3
I_X	CAL^5
I_Y	2452 CAL^5
DIA	1.0 CAL
ρ	7.86

** APPENDIX D

Figure E-2. Outline of Idealized Model of XM-110 Projectile

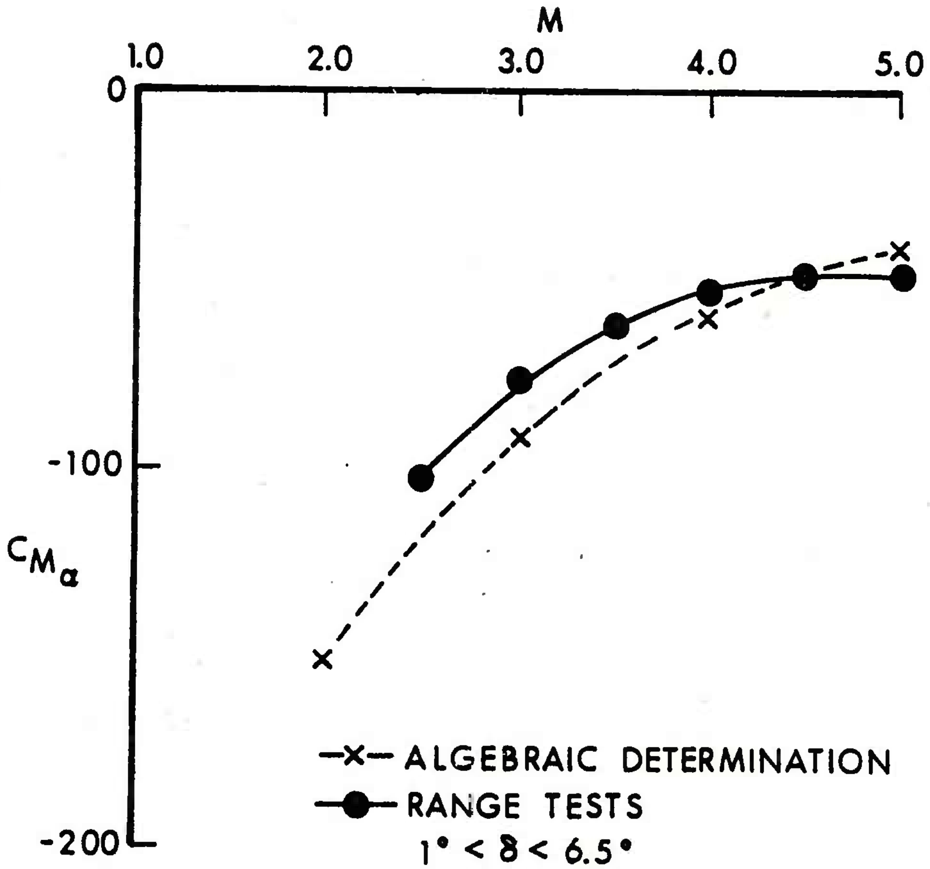


Figure E-3 Static Moment Coefficient of the XM-110 Projectile

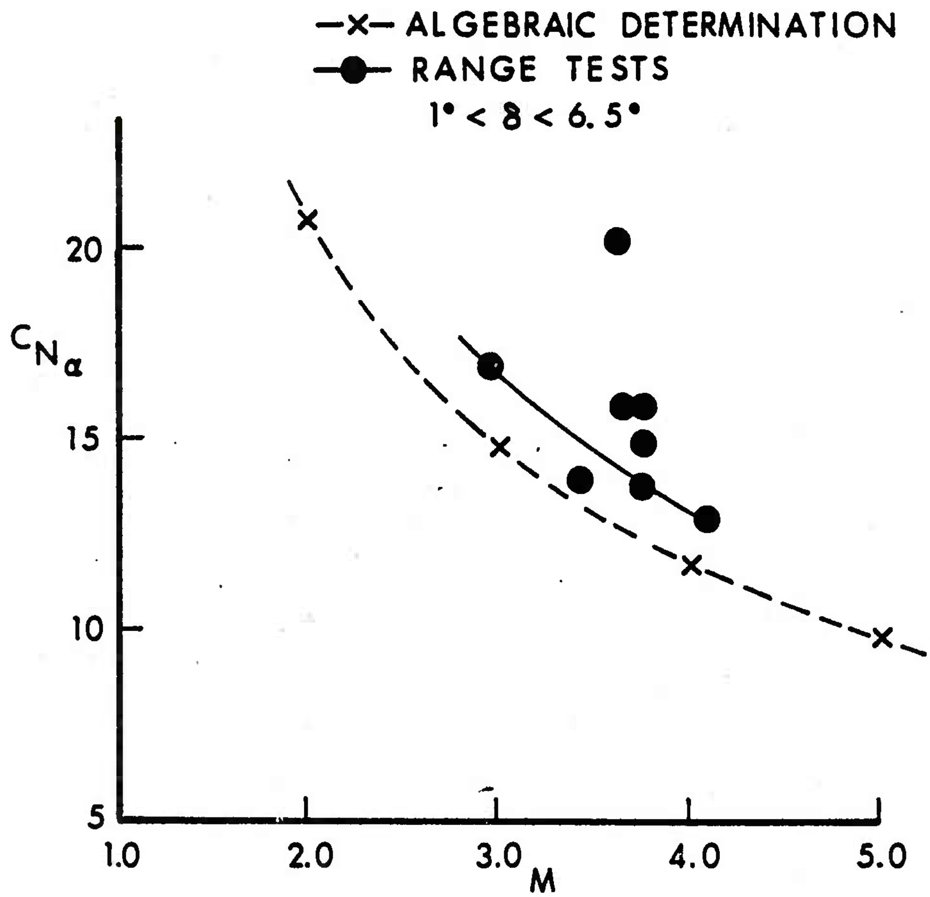


Figure E-4 Normal Force Coefficient of the XM-110 Projectile

LIST OF SYMBOLS

a	$= \beta \tan \omega$, operational parameter
$b/2$	Fin blade height
c_r	Fin blade length at root
c_t	Fin blade length at tip
c.g.	Center of gravity of projectile, nose datum
c.p.	Center of pressure of normal force
d	= 1.0 cal , reference diameter
g	Fin dimension
k	Fin dimension
ℓ_a	Cylindrical body length
ℓ_n	Nose length
$\ell_{o.a.}$	Overall length of projectile
ℓ_T	$= \ell_a + \ell_n$
m	Mass of projectile
s	Length of initial yaw period
v	Velocity of projectile
x	Distance along projectile, nose datum
z	Operational parameter
α, γ	Angle of attack, sideslip
α_T	$= (\alpha^2+\gamma^2)^{\frac{1}{2}} = \arcsin \delta$, total angle of attack
β	$= (M^2-1)^{\frac{1}{2}}$, operational parameter
δ	$= \sin \alpha_T$, operational parameter
δ'	Initial yawing rate
ε	$= \arctan (b/2)/(C_r+g)$, fin shade angle
λ	$= C_t/C_r$, fin tip ratio

Ω Fin sweep back angle

ρ Density of air

ω $= \frac{\Pi}{2} - \Omega$, fin leading edge angle taken from axis of rotation.

AR $= b^2/S_F$, Aspect ratio of fin planform

C_D $= \frac{\text{Drag Force}}{\frac{1}{2}\rho v^2 S}$, zero-yaw drag coefficient

$C_{L\alpha}$ $= \frac{\text{Lift Force}}{\frac{1}{2}\rho v^2 S \delta}$, aerodynamic lift slope coefficient, $\delta = \sin \alpha_T$

$C_{M\alpha}$ $= \frac{\text{Static Moment}}{\frac{1}{2}\rho v^2 Sd \delta}$, aerodynamic moment slope coefficient

$C_{N\alpha}$ $= \frac{\text{Normal Force}}{\frac{1}{2}\rho v^2 S \delta}$, aerodynamic normal force slope coefficient

I_x Axial moment of inertia

I_y Transverse moment of inertia

J $= J_\zeta \delta'$, aerodynamic jump term

J_ζ $= \frac{I_y}{md^2} \frac{C_{L\alpha}}{C_{M\alpha}}$, aerodynamic jump factor

K Interference factor

M Mach number

N Number of fin blades

S $= \frac{\Pi}{4} d^2$, reference area

$S.G.N._{ave.}$ Specific gravity of projectile as normalized

S_F Fin planform area

Supernumerary Subscripts

f.b.	Forebody
T	Total quantity

Abbreviations

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CDC	Computer Development Corporation
HP-97	Hewlett-Packard - 97

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