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Ballistic Range Potential of Scaled Gun Barrels Firing Saboted Dart-Like Barrage Round

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Abstract: Providing the marines expeditionary and amphibious assault forces with long range surface fire support missions is one of the responsibilities of the U.S. Navy. Meeting the U.S. Marine Corps (USMC) Ship-To-Objective Maneuver (STOM) and Operational Maneuver From The Sea (OMFTS) requirements required the prediction of the maximum achievable ballistic ranges for a 100 lbs, 5″ diameter/12 calibers, GPS guided, dart-like barrage round when fired from 5″, 155mm, 8″, 10″, 12″, 14″, 16″, and 18″ bore barrels that are 64 and 200 calibers in length at maximum breech pressures of 448MPa (65Ksi) and 896MPa (130Ksi.)

Keywords: SIMULINK, CONPRES, Interior Ballistics, Exterior Ballistics, Surface Fire Support

1. Nomenclature

A	Projectile Base Area, m^2
BE	Ballistic Efficiency, Equation 12
d	Bore diameter, meter
E_i	Gas Internal Energy, MJ, Equation 7
E_p	Propellant Energy, MJ, Equation 6
ER	Expansion Ratio, Equation 11
I	Propellant Impetus, Joule/kg
K_g	Gas Kinetic Energy, MJ, Equation 5
K_p	Projectile Kinetic Energy, MJ, Equation 4
m_c	Charge Mass, kg
m_p	Projectile mass, kg
P_c	Constant Breech Pressure, MPa
$\overline{P}$	Space Mean Pressure, MPa, Equation 8
P_b	Base Pressure at Muzzle Exit, MPa, Equation 9
PE	Piezometric Efficiency, Equation 13
V_{bf}	Chamber Volume at Propellant Burn-out, m^3, Equation 3
V_c	Chamber Volume, m^3
V_{cf}	Free Chamber Volume accounting for Propellant Covolume, m^3, Equation 1
V_{mf}	Free Gun Volume at Projectile Muzzle Exit, adjusting for Propellant Covolume, m^3, Equation 2
U_m	Projectile Muzzle Exit Velocity, m/sec

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x_b	Projectile Travel at Propellant Burn-out, meter
x_t	Projectile Travel at Muzzle Exit, meter, Equation 10
γ	Ratio of Specific Heats
η	Propellant Covolume, m^3/kg

2. Introduction

The U.S. Navy's Naval Surface Fire Support Systems (NSFS) Program Office PMS 529, which is currently reorganized into the Program Executive Office (PEO) for Integrated Warfare Systems (IWS) Code PEO IWS 3C, has developed visionary objectives for using shipboard gun systems to provide marines expeditionary and amphibious assault forces with long range surface fire support missions that entail suppression of enemy defenses and artillery, execution of quick response call fires, and interdiction of moving counter offensives in addition to executing traditional destruction fires, preparation fires, counter fires, suppression fires, and area neutralization fires. Validation of these objectives and meeting the USMC STOM/OMFTS requirements[1,2], Figure 1, demanded modeling and simulating the range potential of a 100 lbs, 5″ diameter/12 calibers, GPS guided, dart-like barrage round, Figures 2 and 3, when fired from two sets of different caliber guns with barrel lengths of either 64 or 200 calibers, Figure 4, that operate at a maximum breech pressure of 448 MPa (65 Ksi). A future projection of this range potential was also performed when gun technology permitting a maximum breech pressure of 896 MPa (130 Ksi) becomes available.

3. Analysis Methodology

The analysis consisted of the following interior and exterior ballistics tasks and subtasks:

Interior Ballistics

<u>Shipboard Gun and Round Constraints</u>

Establishing values for the following system parameters: (1) maximum breech pressure; (2) maximum round G loading; (3) maximum muzzle exit pressure; (4) propellant composition; and (5) travel at burnout. The table below shows the parameters chosen.

Table 1: Gun, Projectile, and Propellant Constraints

Parameter	Value	Rationale
Maximum Breech Pressure	65 Ksi, 130 Ksi	Customer specified
Maximum G Loading	12.5 KGs	Customer Specified
Max. Muzzle Exit Pressure	Open	Relaxed by Customer
Propellant Composition	EX99	Same as 5″/62 firing ERGM
Travel at Burnout	<64 Calibers <200 Calibers	Efficient use of propellant

<u>Gun System Characteristics</u>

The CONPRESS interior ballistics model, illustrated in Figure 5, is used to compute the maximum muzzle velocity that satisfies the above constraints for each caliber. Additional characteristics needed are: (1) G loading; (2) charge mass, (3) chamber volume; (4) muzzle exit pressure; and (5) travel at propellant burnout.

CONPRESS[3,4] is a constant pressure interior ballistics code that predicts the performance of a gun from its physical parameters, the masses of the propelling charge and projectile, and the thermochemical properties of the propellant. The CONPRESS code is a FORTRAN based computer program. It is described in References [3] and [4]. This code was adapted to Microsoft Excel. A snapshot of this model is shown in Figure 6. Excel's Solver was used to find the maximum muzzle exit velocity, U_m, by changing the charge weight, m_c, and chamber volume, V_c, while ensuring that: (1) the G loading is less than or equal to 12500; (2) the travel at propellant burn-out is less than or equal to the barrel length; and (3) the validation tests for m_c and x_b are passed.

CONPRESS uses the following assumptions to calculate the energy imparted into the projectile by the gun:

- The Lagrange gradient adequately describes the gas pressure and velocities in the gun.
- The propellant burns in an ideal manner. (This means, it is instantaneously converted into gas.)
- The burn rate of the propellant is controlled to provide a constant chamber pressure until burnout.
- After burnout, the gas expands adiabatically.
- The gas is polytropic.
- The Nobel-Able equation of state is valid.
- No energy loss occurs during the ballistic cycle.
- The projectile base area equals the cross-sectional area of the tube.

CONPRESS uses the following equations to compute its parameters. The conventions are explained in the nomenclature section:

$$V_{cf} = V_c - \eta \cdot m_c \tag{1}$$

$$V_{mf} = V_c + A \cdot x_t - \eta \cdot m_c \tag{2}$$

$$V_{bf} = \frac{m_c \cdot I \cdot \left(1 + \frac{m_c}{2 \cdot m_p}\right)}{\gamma \cdot \left(1 + \frac{m_c}{3 \cdot m_p}\right)} + \frac{\gamma - 1}{\gamma} \cdot V_{cf} \tag{3}$$

$$K_p = \frac{P_c}{\left(1 + \frac{m_c}{2 \cdot m_p}\right)} \cdot \left[\frac{\gamma}{\gamma\text{-}1} \cdot V_{bf} - V_{cf} - \frac{V_{mf}}{\gamma - 1} . \left(\frac{V_{bf}}{V_{mf}}\right)^{\gamma}\right] \tag{4}$$

$$K_g = \frac{m_c}{3 \cdot m_p} . K_p \tag{5}$$

$$E_p = \frac{m_c \cdot I}{\gamma - 1} \tag{6}$$

$$E_i = E_p - K_g - K_p \tag{7}$$

$$\overline{P} = \frac{E_i}{V_{mf}} \cdot (\gamma - 1) \tag{8}$$

$$P_b = \frac{\overline{P}}{1 + \frac{m_c}{3 \cdot m_p}} \tag{9}$$

$$x_b = \frac{V_{bf} + \eta \cdot m_c - V_c}{A} \tag{10}$$

$$ER = \frac{V_c + A \cdot x_t}{V_c} \tag{11}$$

$$BE = \frac{K_p}{E_i} \tag{12}$$

$$PE = \frac{K_p}{P_c \cdot A \cdot x_t} \tag{13}$$

Once the maximum muzzle exit velocity is computed for each gun caliber, barrel length, and breech pressure, an exterior ballistics model using the lumped mass approach was developed.

Exterior Ballistics

This model was used to compute the maximum achievable range and optimum launch angle for each gun caliber, barrel length, and breech pressure set. The model entails the following modules;

Drag Function

This function was used to compute the total aerodynamic drag coefficient of the barrage round as a function of its flight Mach number and geometric characteristics using the McDrag[5] model. The core of this model is illustrated in Figure 7.

The Atmosphere

This module uses the U.S. Standard Atmosphere[6] database to calculate the air temperature, pressure, air density, and speed of sound for various geopotential flight altitudes. The database was extended for use at altitudes over 85 km.

4. Analysis Limitations

Sabot Design

The design of different caliber sabots, its volume, and weight calculations have the following limitations:

- Designs were mainly intended to provide ballpark weight estimates of different caliber sabots and were not intended to be in-depth detailed minimum weight designs.
- The lower specific weights of advanced and innovative materials (ceramics, composites, and thermoplastics) were not addressed since cost minimization was a main consideration.

CONPRESS - Constant Breech Pressure Interior Ballistics Model

- Assumes a barrel with no well-defined chamber or transition region.
- Provides an absolute measure of maximum muzzle velocity performance.

McDrag Function and Coefficients

This model assumes:

- Zero degree angle of attack.
- No conning motion.
- Nose first flight.
- Errors in estimating drag coefficients for supersonic, transonic, and subsonic speeds are 3%, 11%, and 6%, respectively.

5. Results

Sabot Design

A sabot was designed for each gun caliber. Each of these sabots, with the exception of the 5″ gun sabot, is composed of three main elements:

- Pusher plate made of carbon steel (density 7.87 gram/cm^3)
- 4-Segment sabot made of aluminum (density 2.7 gram/cm^3). Each segment is reinforced with two-0.25” thick ribs shaped as circular segments.
- Nosecone made of fire retardant nylon (density 1.3 gram/cm^3) that provides an interface to the fuse setter.

The 5″ gun sabot entails the 4 sabot segments and the nosecone, but no pusher plate. The following table summarized the weights of individual elements and the total package weight reflecting weight savings after design refinements for each gun caliber.

Table 2: Sabot Weights

Gun Caliber	Sabot Weight	Pusher Plate Weight	Nose Cone Weight	Package Weight
	[Kg]			
5″	22.11	0.00	3.37	25.48
155 mm	40.77	3.14	3.37	47.27
8″	71.41	5.10	3.37	79.88
10"	93.73	7.70	3.37	104.79
12”	115.05	10.84	3.37	129.26
14”	133.92	14.52	3.37	151.81
16"	149.91	18.74	3.37	172.02
18”	162.46	23.5	3.37	189.33

Interior ballistics

Maximum G loading was constrained to 12.5 KGs and travel at burnout was constrained to occur before muzzle exit. The model was run twice for each gun caliber, for breech pressures of 65 and 130 Ksi. The following tables summarize the main results of the different CONPRESS runs. Figures 8 through 10 depict the major parameters computed from the interior ballistics model.

Table 3: Interior Ballistic Characteristics of 64-Caliber Guns

Gun Caliber		Muzzle Exit Velocity		Kinetic Energy		G Loading		Charge Mass	
		[m/sec]		[MJ]		[Gs]		[kg]	
[inch	[mm]	65 Ksi	130 Ksi	65 Ksi	130 Ksi	65 Ksi	130 Ksi	65 Ksi	130 Ksi
5.0	127.0	999	1296	23	38	6399	11093	39	67
6.1	155.0	1135	1450	29	48	6846	11634	67	111
8.0	203.2	1364	1697	42	65	7748	12500	132	224
10.0	254.0	1597	1918	57	83	8859	12500	222	441
12.0	304.8	1792	2091	73	99	9735	12500	336	717
14.0	355.6	1962	2237	87	113	10532	12500	468	1058
16.0	406.4	2112	2362	101	127	11280	12500	616	1462
18.0	457.2	2248	2473	115	139	12013	12500	780	1931

Table 4: Interior Ballistic Characteristics of 64-Caliber Guns (continued)

Gun Caliber		Muzzle Exit Pressure		Travel at Burnout				Chamber Volume	
		[MPa]		[cm]		[caliber]		[liter]	
[inch	[mm]	65 Ksi	130 Ksi	65 Ksi	130 Ksi	65 Ksi	130 Ksi	65 Ksi	130 Ksi
5.0	127.0	273	406	670	594	52.73	46.81	48	82
6.1	155.0	240	341	777	675	50.11	43.56	81	136
8.0	203.2	188	261	92	820	45.40	40.35	161	273
10.0	254.0	142	216	1026	1088	40.83	42.84	271	538
12.0	304.8	109	169	1103	1270	36.19	41.68	410	875
14.0	355.6	85	131	1152	1410	32.40	39.66	570	1291
16.0	406.4	67	103	1183	1521	29.13	37.41	752	1784
18.0	457.2	53	81	1202	1611	26.29	35.24	951	2356

Table 5: Interior Ballistic Characteristics of 200-Caliber Guns

Gun Caliber		Muzzle Exit Velocity		Kinetic Energy		G Loading		Charge Mass	
		[m/sec]		[MJ]		[Gs]		[kg]	
[inch	[mm]	65 Ksi	130 Ksi	65 Ksi	130 Ksi	65 Ksi	130 Ksi	65 Ksi	130 Ksi
5.0	127.0	1506	1846	51	77	4946	8061	92	146
8.0	203.2	1920	2262	84	116	5567	8820	282	422
10.0	254.0	2161	2494	105	141	6163	9694	451	655
12.0	304.8	2353	2674	126	162	6655	10426	653	930

Table 6: Interior Ballistic Characteristics of 200-Caliber Guns (continued)

Gun Caliber		Muzzle Exit Pressure		Travel at Burnout				Chamber Volume	
		[MPa]		[cm]		[caliber]		[liter]	
[inch	[mm]	65 Ksi	130 Ksi	65 Ksi	130 Ksi	65 Ksi	130 Ksi	65 Ksi	130 Ksi
5.0	127.0	160	202	1684	1386	132.63	109.15	113	178
8.0	203.2	91	104	2116	1648	104.14	81.09	344	514
10.0	254.0	62	68	2231	1680	87.85	66.15	550	799
12.0	304.8	44	47	2291	1686	75.17	55.33	797	1136

Exterior Ballistics

The following tables summarize the main results of the different runs of the exterior ballistics model. Figures 11 through 16 illustrate these results versus the gun caliber for the two barrel lengths and breech pressures:

Table 7: Exterior Ballistic Performance of 64-Caliber Guns

Gun Caliber		Max Range		Firing Angle		Range Increase	
		[mile]		[degree]		[mile]	%
[inch]	[mm]	65 Ksi	130 Ksi	65 Ksi	130 Ksi		
5.0	127.0	32	67	52	51	35	108.23
6.1	155.0	46	91	52	50	45	98.04
8.0	203.2	77	137	51	49	60	77.16
10.0	254.0	118	185	49	48	67	57.07
12.0	304.8	157	227	49	48	70	44.30
14.0	355.6	195	265	48	47	69	35.52
16.0	406.4	232	300	48	47	68	29.09
18.0	457.2	268	332	47	47	64	23.97

Table 8: Exterior Ballistic Performance of 200-Caliber Guns

Gun Caliber		Max Range [mile]		Firing Angle [degree]		Range Increase	
[inch]	[mm]	65 Ksi	130 Ksi	65 Ksi	130 Ksi	[mile]	%
5.0	127.0	101	169	50	48	68	67.09
8.0	203.2	185	271	48	47	86	46.43
10.0	254.0	245	338	48	47	93	38.20
12.0	304.8	297	395	47	47	97	32.80

6. Conclusions

The 200-caliber gun barrels offer definite advantages over the 64-caliber barrels in terms of its: (1) longer range potential; (2) efficient propellant usage and economy for the smaller bore diameters; (3) lower projectile G loads, and (4) lower muzzle exit pressures. This analysis focused only on the range potential of a ballistic round fired from different gun calibers with different barrel lengths and breech pressures. Cancellation of Raytheon's rocket-assisted EX171 Extended Range Guided Munition (ERGM) program, the vague destiny of Zona's (Zona Technology Inc.) Arizona Glider (AG) gliding projectile, and the very expensive cost of the cruise missile left us with no other options to analyze for meeting the USMC STOM/OPFTS requirements.

7. References

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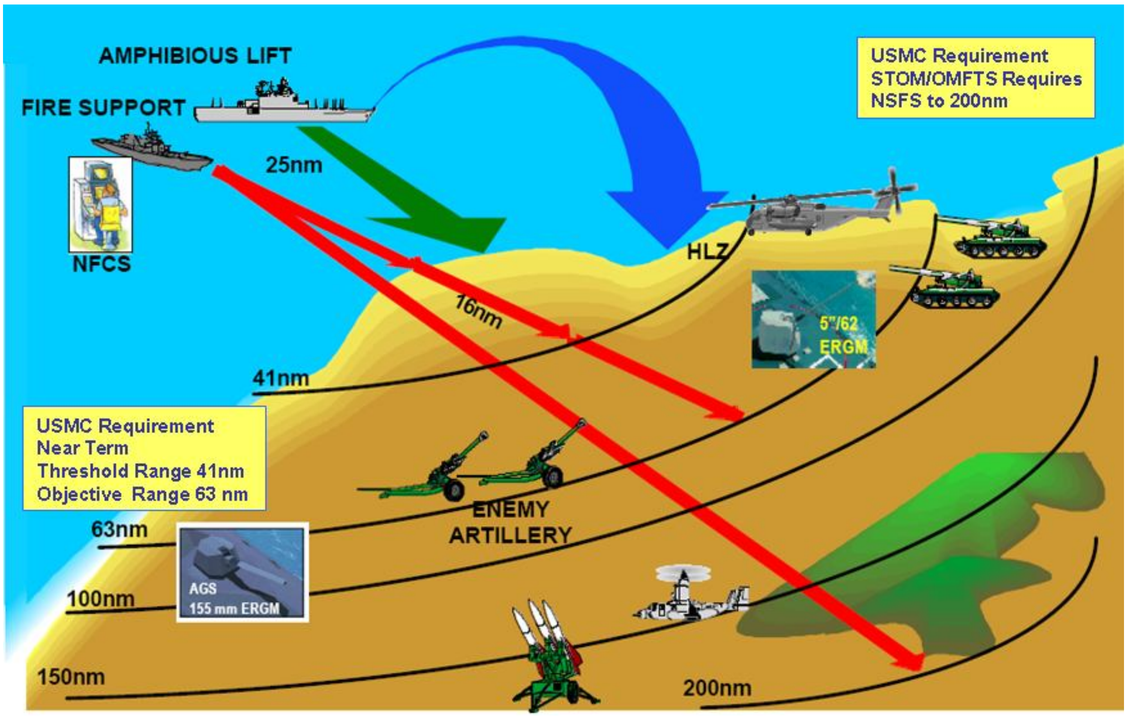

Figure 1: The USMC Requirements for Naval Surface Fire Support

Figure 2: The 5"/12 Calibers, 100 lbs, Dart-Like Barrage Round

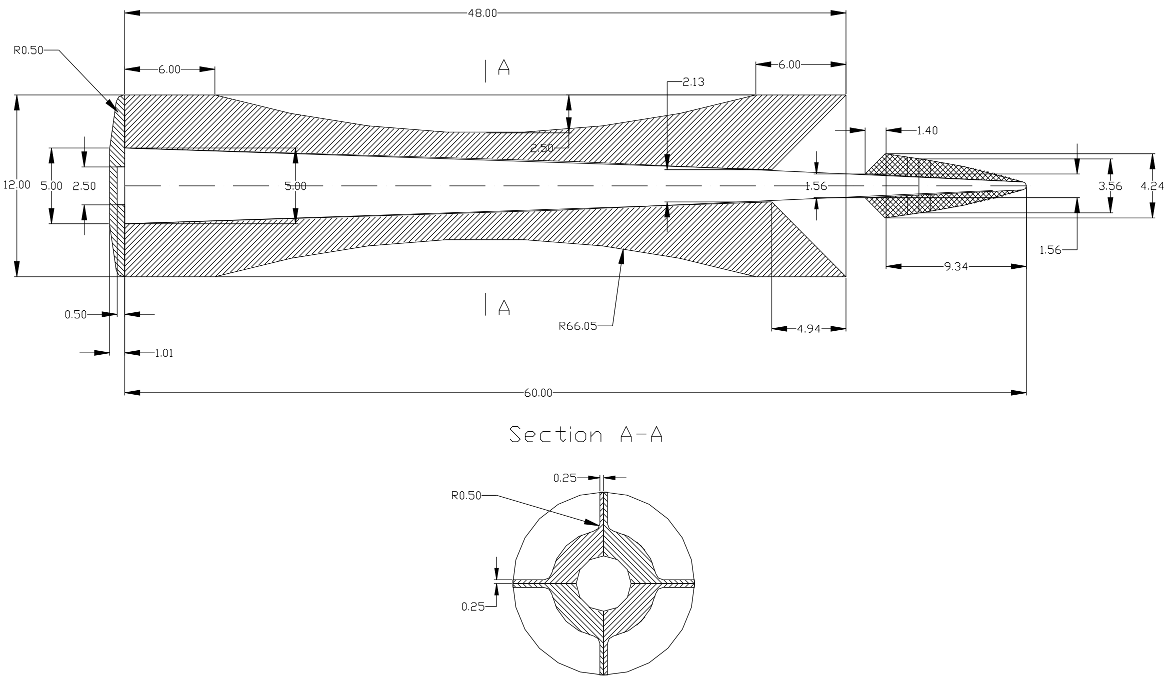

Figure 3: Design Drawing for the 12" Caliber Sabot

Figure 4: The Applied Ordnance Technology AOT or XLR Gun[7,8]; AOT Claims It Is Capable of Developing 200 Caliber Barrels

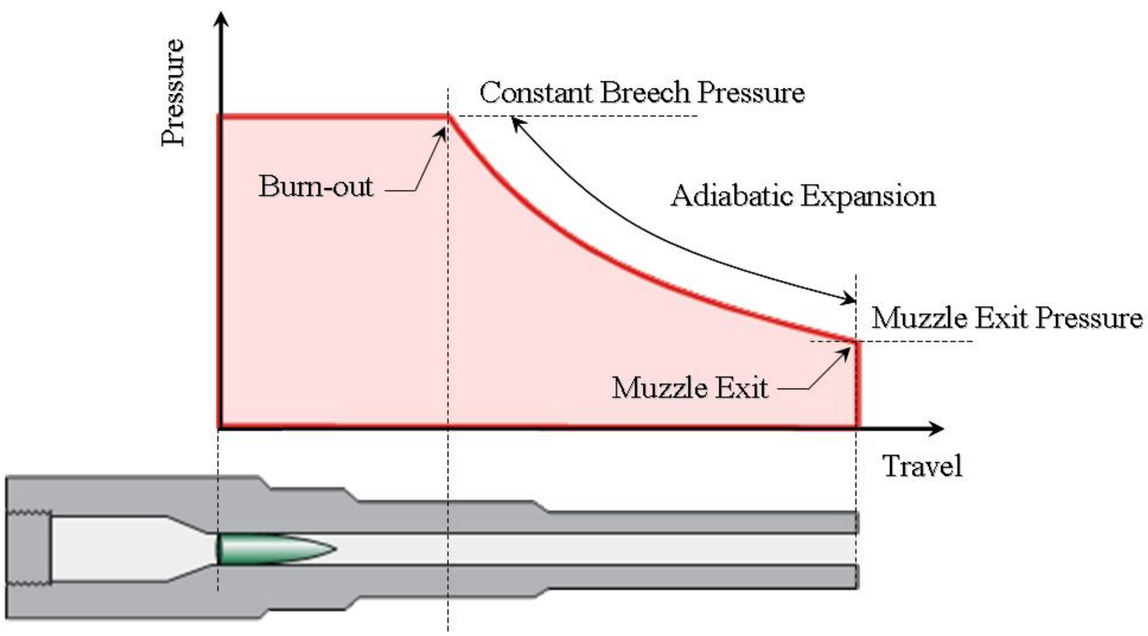

Figure 5: Schematic of the CONPRESS Model and the Pressure versus Travel Chart

HVP-18"-L-64				Model Results										
Charge Weight	Muzzle Velocity	Travel at Burnout	Muzzle Exit Press	Expansion Ratio	Peizo-metric Effeciency	Ballistic Effeciency	Porpellant Energy	Projectile Kinetic Energy	Gas Kinetic Energy	Gas Internal Energy	Kp Ep	Kg Ep	Ei Ep	Check
Kg	m/sec	cm	Mpa	1	%	%	MJ	MJ	MJ	MJ	%	%	%	%
230.595	1642.83	0.00	20.00	6.05	14.71	63.19	921.58	316.70	103.72	501.16	34.37	11.26	54.38	100.00
779.684	2248.03	1202.20	53.46	6.05	27.54	31.78	3116.05	593.03	656.71	1866.31	19.03	21.08	59.89	100.00
1523.945	2078.54	2926.00	105.53	6.05	23.55	11.30	6090.52	506.97	1097.32	4486.23	8.32	18.02	73.66	100.00

Propellant/Gun Parameters				
Pc	448.175	Mpa	448175000	Pa
mp	235	kg		
γ	1.29			
η	1.22	cm^3/g	0.00122	m^3/kg
I	1159	J/g	1159000	J/kg
Vc	951.215	L	0.951215287	m^3
d	457	mm	0.4572	m
xt	2926	cm	29.2608	m
A	164173.22	mm^2	0.16	m^2
γ-1	0.29			
(γ-1)/γ	0.224806202			
G Load	1.20E+04			
mp/mc	3.322			
Pc	65	Ksi		
BL	64	calibers		
FALSE	3	TRUE		
TRUE	TRUE	100		

Validation Tests			
mc	779.68	TRUE	1
Pc	930503671.99	TRUE	1
xb	1202.20	TRUE	1
Pb	168.42	TRUE	1
(Pbm)max	53.46	TRUE	1
			5

Scratch Area								
mc/mp	(1+mc/2mp)	(1+mc/3mp)	mc*I/γ*Pc	Vcf	Vmf	Vbf	(Vbf/Vmf)^γ	V multiplyer
1	1	1	m^3	m^3	m^3	m^3	1	m^3
0.98	1.49	1.33	0.46	0.6699	5.4737	0.6699	0.066551609	1.053806718
3.32	2.66	2.11	1.56	0.0000	4.8038	1.9737	0.31743863	3.521143963
6.49	4.25	3.16	3.06	-0.9080	3.8958	3.8957	0.999956511	4.803839847

Figure 6: The Microsoft Excel Implementation of the FORTRAN Based CONPRESS Model

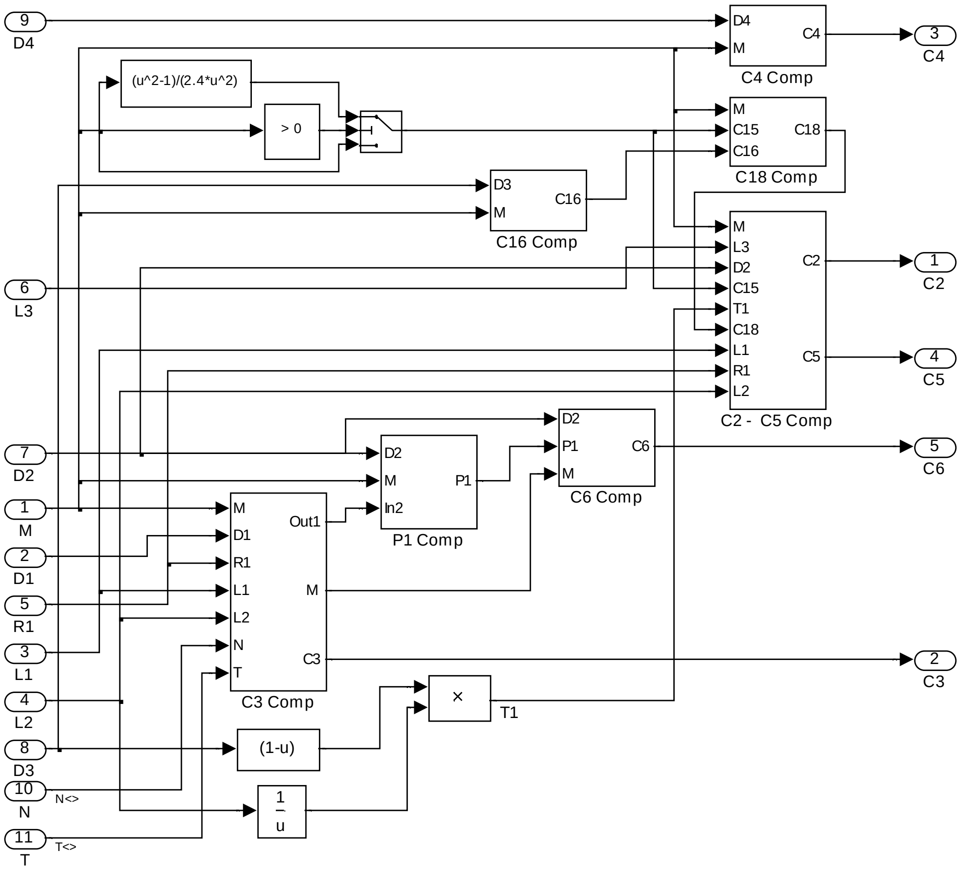

Figure 7: The McDrag Model Core

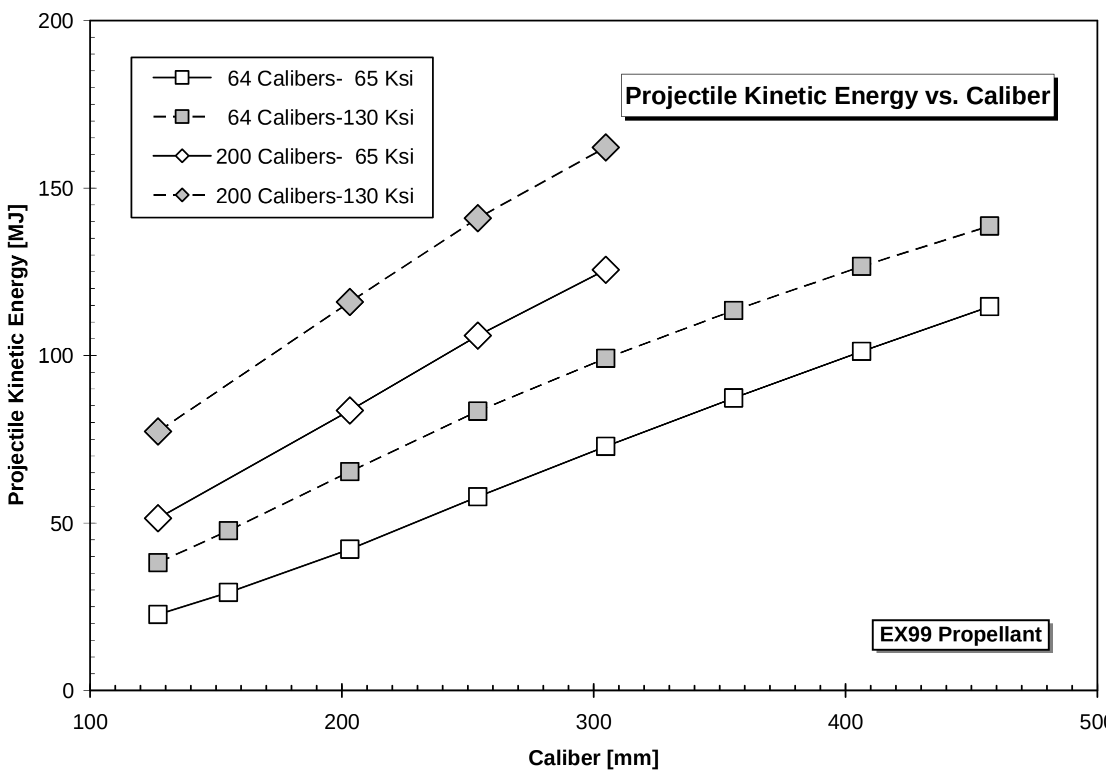

Figure 8: Projectile Kinetic Energy versus Gun Caliber for the Two Barrel Lengths and Breech Pressures

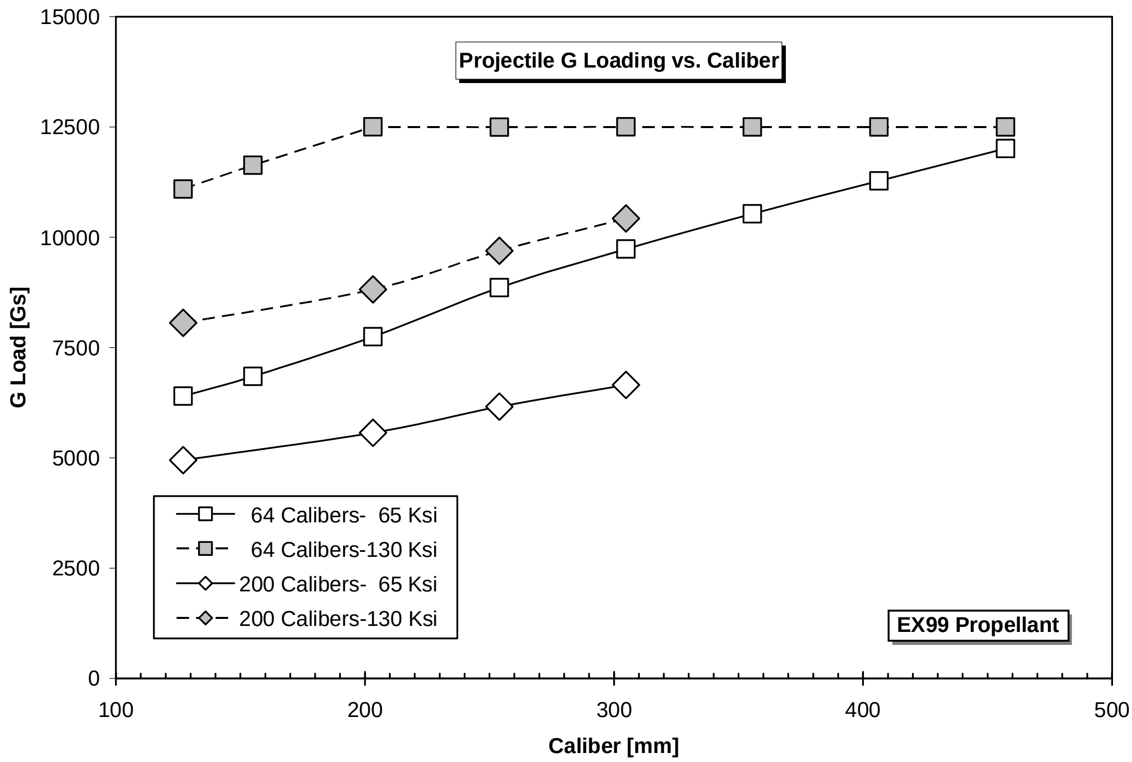

Figure 9: Projectile G Loading versus Gun Caliber for the Two Barrel Lengths and Breech Pressures

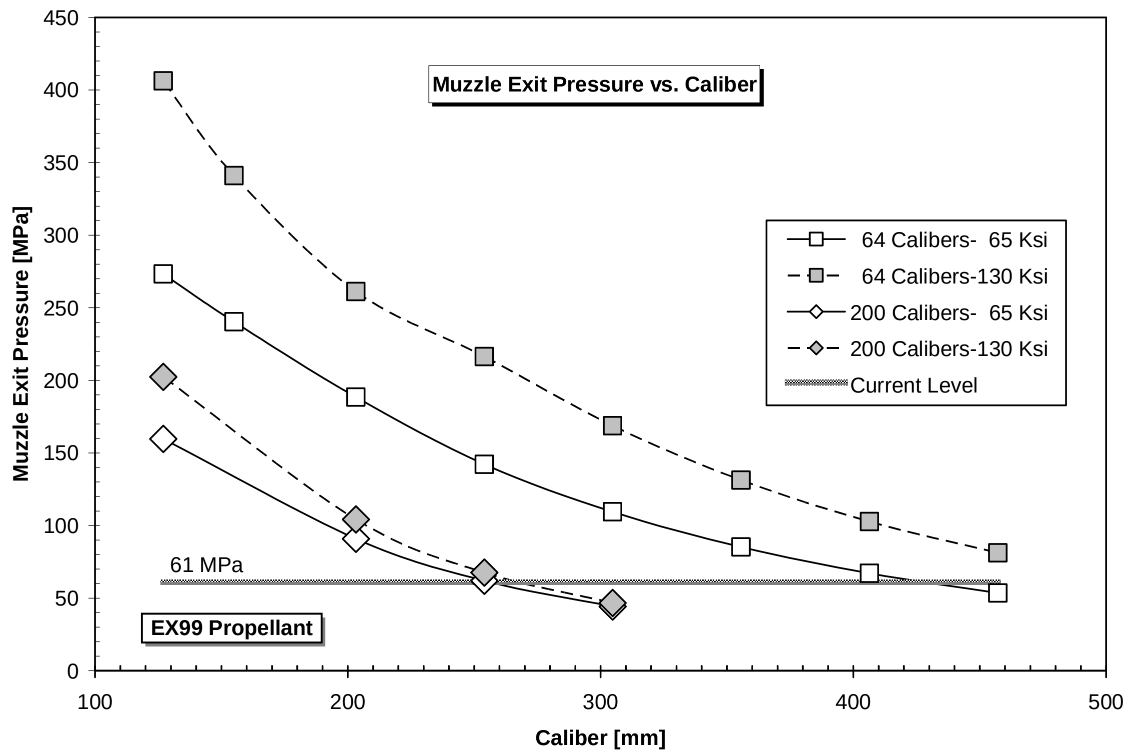

Figure 10: Muzzle Exit Pressure versus Gun Caliber for the Two Barrel Lengths and Breech Pressures

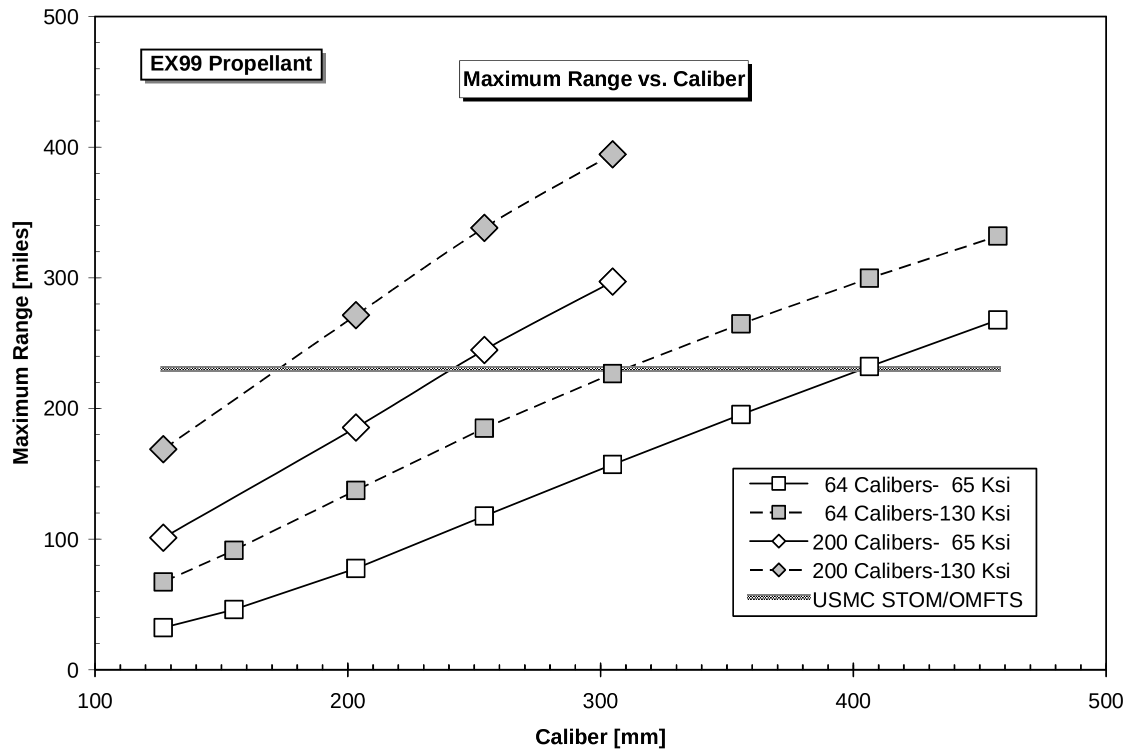

Figure 11: Maximum Range versus Gun Caliber for the Two Barrel Lengths and Breech Pressures

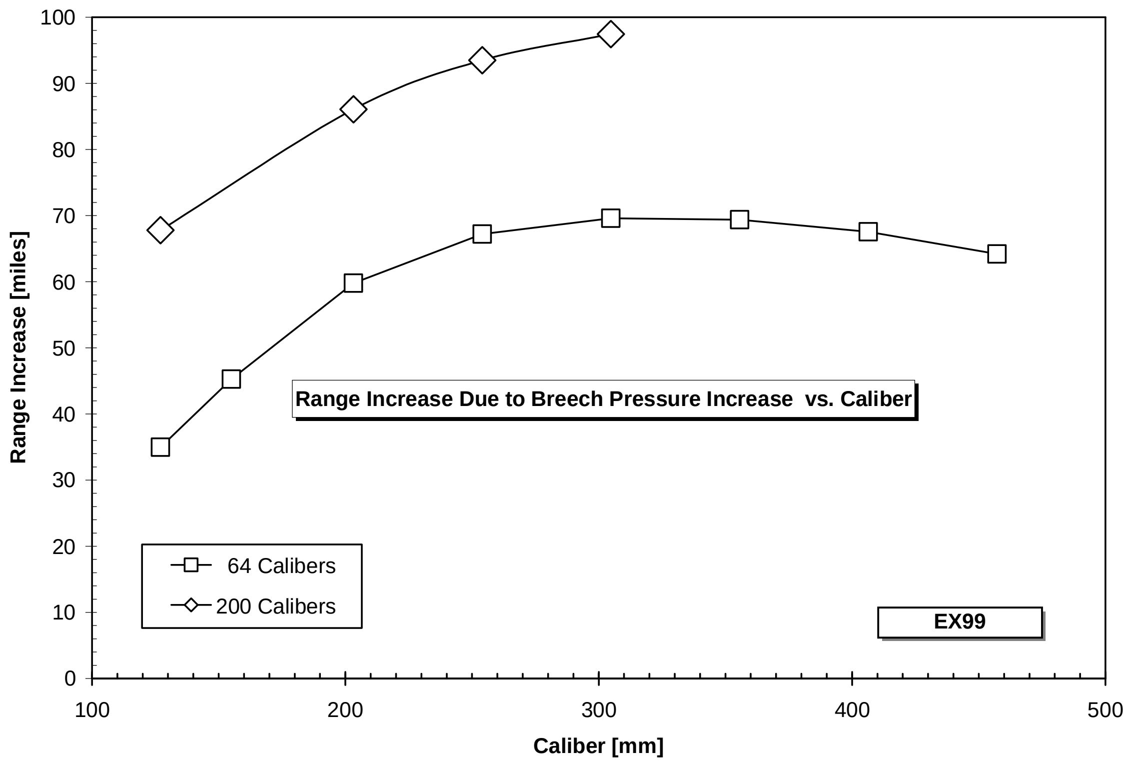

Figure 12: Range Increase Due to Breech Pressure Increase versus Gun Caliber for the Two Barrel Lengths

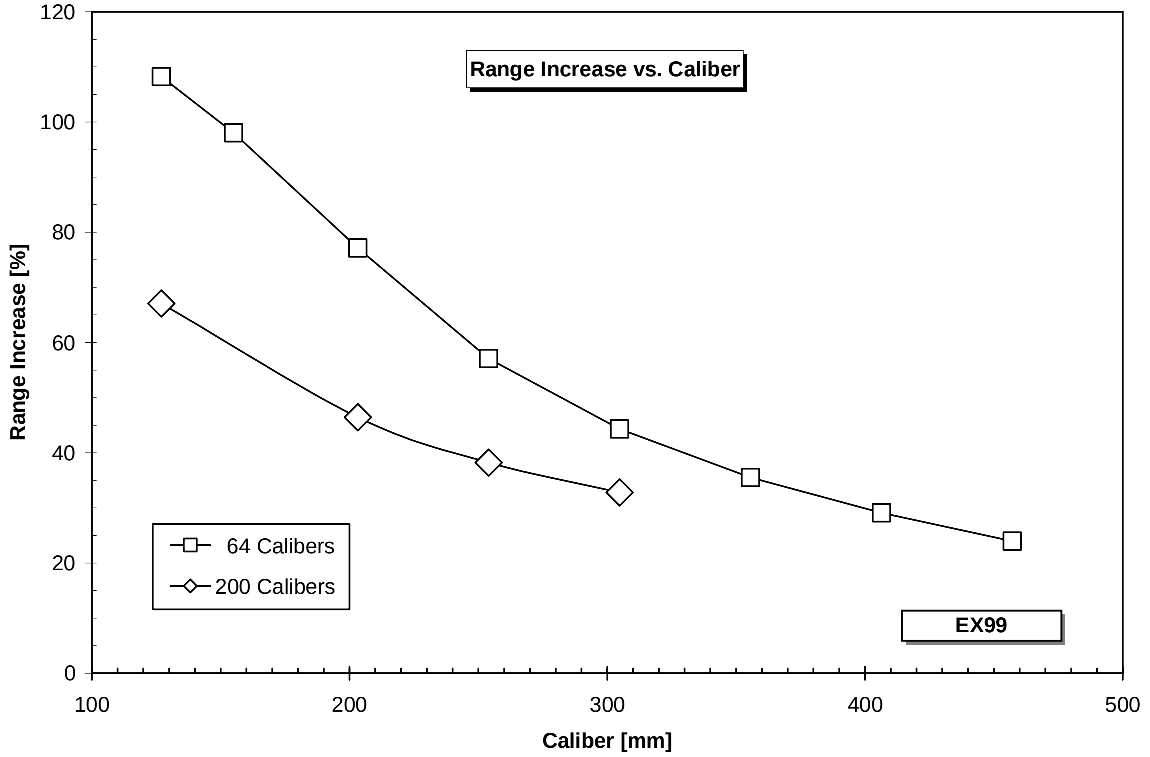

Figure 13: Percentage Range Increase Due to Increase in Breech Pressure versus Gun Caliber for the Two Barrel Lengths

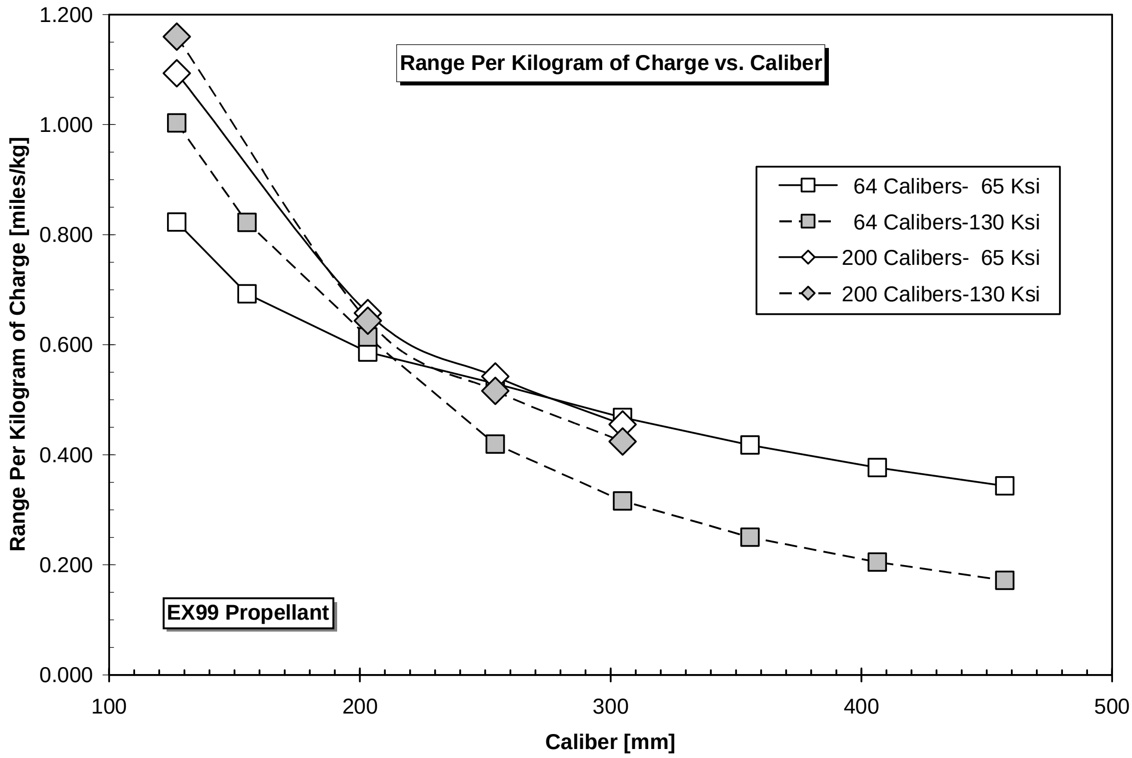

Figure 14: Range per Kilogram of Charge versus Gun Caliber for the Two Barrel Lengths and Breech Pressures

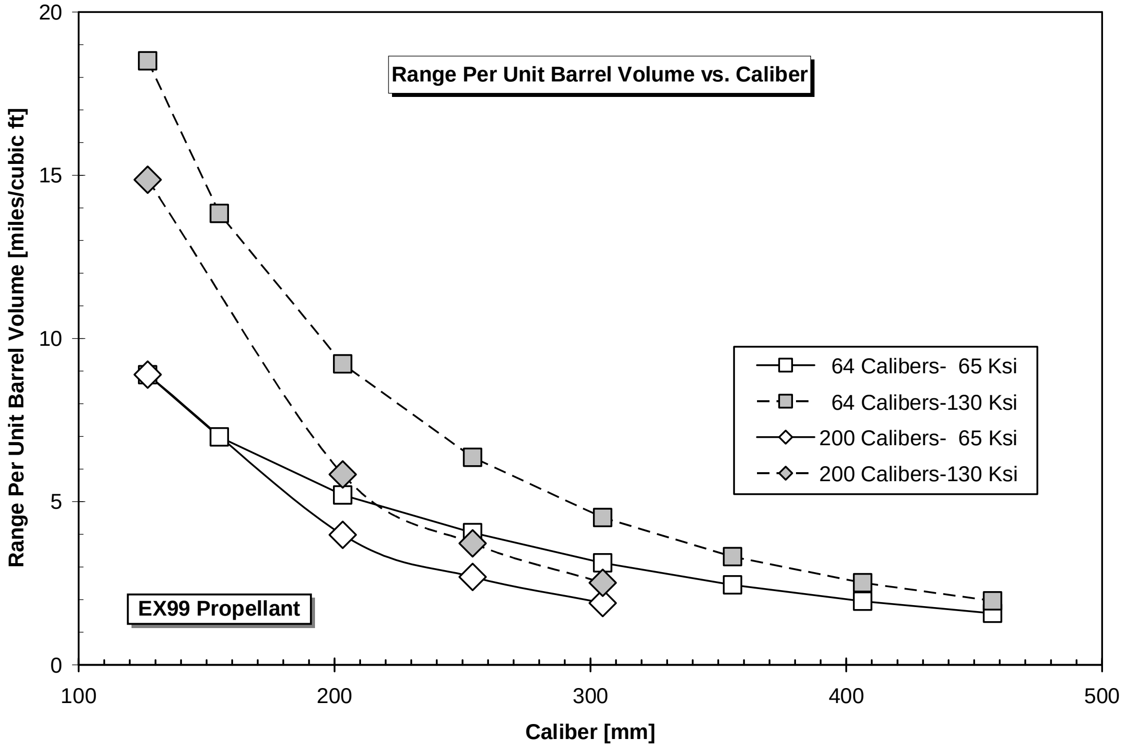

Figure 15: Range per Unit Barrel Volume versus Gun Caliber for the Two Barrel Lengths and Breech Pressures

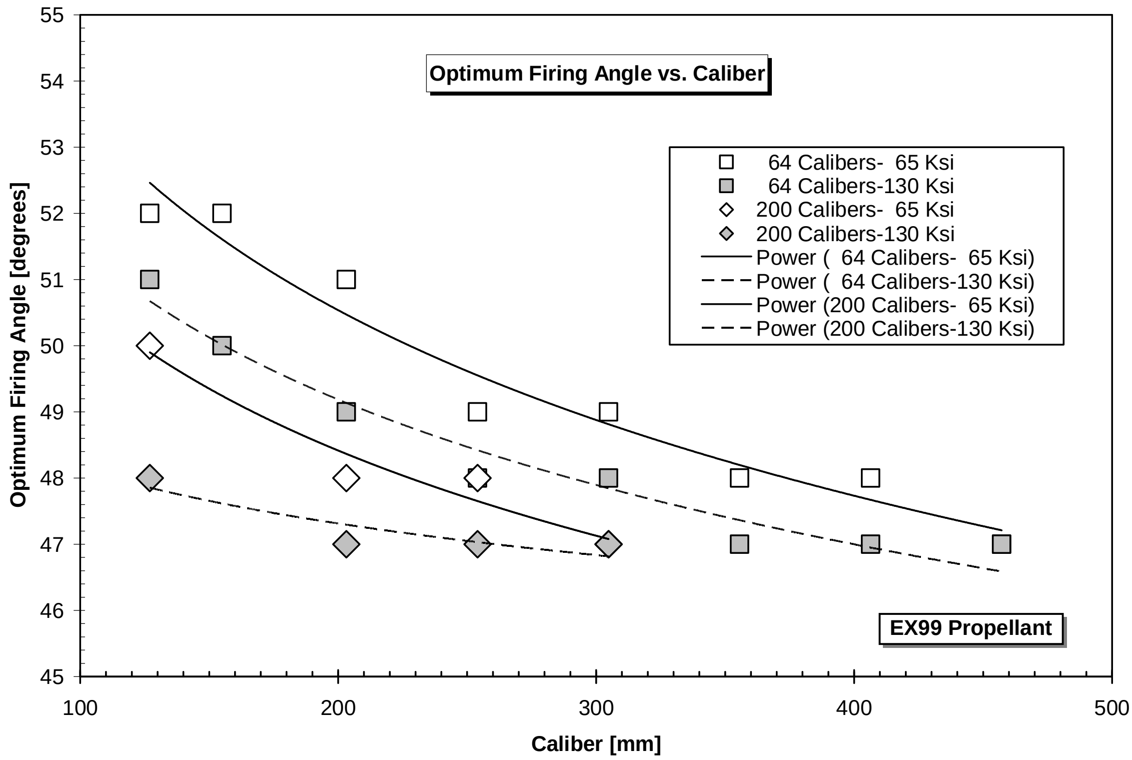

Figure 16: Optimum Firing Angle Curves versus Gun Caliber for the Two Barrel Lengths and Breech Pressures