

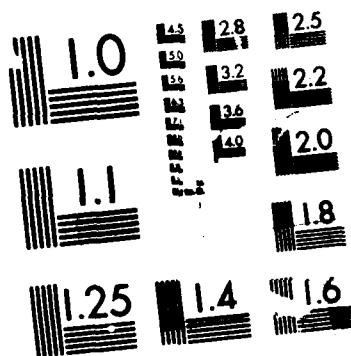
AD-A187 173 120-MM REGENERATIVE LIQUID PROPELLANT GUN: A PARAMETRIC 1/1
INVESTIGATION OF THE 400-ORBITAL-VELOCITY RESEARCH GUN120-MM REGENERATIVE LIQUID PROPELLANT GUN: A PARAMETRIC 1/1
INVESTIGATION OF THE 400-GRAM BULLET REGENERATIVE GUN

1/1

UNCLASSIFIED

BRL-TR-2839
F/G 19/6 NL

NL



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

DTIC FILE COPY

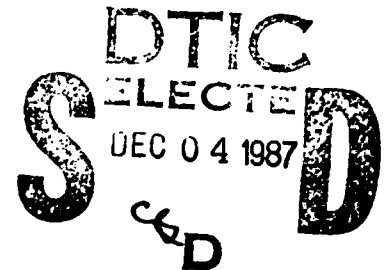
ADF300786

AD



AD-A187 173

TECHNICAL REPORT BRL-TR-2839



120-mm REGENERATIVE LIQUID
PROPELLANT GUN: A PARAMETRIC
INVESTIGATION OF THE INTERIOR
BALLISTICS

GLORIA P. WREN

AUGUST 1987

APPROVED FOR PUBLIC RELEASE, DISTRIBUTION UNLIMITED.

US ARMY BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

87 11 27 220

DESTRUCTION NOTICE

Destroy this report when it is no longer needed. DO NOT return it to the originator.

Additional copies of this report may be obtained from the National Technical Information Service, U.S. Department of Commerce, Springfield, VA 22161.

The findings of this report are not to be construed as an official Department of the Army position, unless so designated by other authorized documents.

The use of trade names or manufacturers' names in this report does not constitute indorsement of any commercial product.

AD-A187173

REPORT DOCUMENTATION PAGE				Form Approved OMB No 0704-0188 Exp Date Jun 30, 1986	
1a REPORT SECURITY CLASSIFICATION Unclassified			1b RESTRICTIVE MARKINGS		
2a SECURITY CLASSIFICATION AUTHORITY			3 DISTRIBUTION/AVAILABILITY OF REPORT		
2b DECLASSIFICATION/DOWNGRADING SCHEDULE					
4 PERFORMING ORGANIZATION REPORT NUMBER(S) BRL-TR-2839			5 MONITORING ORGANIZATION REPORT NUMBER(S)		
6a NAME OF PERFORMING ORGANIZATION US LABCOM/ Ballistic Rsch Lab		6b OFFICE SYMBOL (if applicable) SLCBR-B		7a NAME OF MONITORING ORGANIZATION	
6c ADDRESS (City, State, and ZIP Code) Aberdeen Proving Ground, MD 21005-5066			7b ADDRESS (City, State, and ZIP Code)		
8a NAME OF FUNDING/SPONSORING ORGANIZATION		8b OFFICE SYMBOL (if applicable)		9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER	
8c ADDRESS (City, State, and ZIP Code)			10. SOURCE OF FUNDING NUMBERS		
			PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.
11 TITLE (Include Security Classification) 120-mm Regenerative Liquid Propellant Gun: A Parametric Investigation of the Interior Ballistics					
12 PERSONAL AUTHOR(S) Wren, Gloria P.					
13a TYPE OF REPORT TR		13b TIME COVERED FROM _____ TO _____		14. DATE OF REPORT (Year, Month, Day)	
15. PAGE COUNT					
16 SUPPLEMENTARY NOTATION					
17 COSATI CODES			18 SUBJECT TERMS (Continue on reverse if necessary and identify by block number)		
FIELD	GROUP	SUB-GROUP	regenerative liquid propellant		
19 ABSTRACT (Continue on reverse if necessary and identify by block number) A sensitivity study of a 120-mm regenerative liquid propellant gun was completed to explore the relationships between the variables as expressed in the interior ballistic code developed by T. Coffee at the Ballistic Research Laboratory. Parametric runs were conducted by varying an array of input parameters by +-10% and +-20%, and the effects on performance characteristics were recorded. In the second phase of the study a constraint of maximum liquid pressure equal to 700 MPa was imposed to determine the effect of a parameter change while maintaining gun performance. This report summarizes the major results and examines the interrelationships exhibited.					
20 DISTRIBUTION/AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED UNLIMITED ☐ SAME AS RPT ☐ LIMITS			21 ABSTRACT SECURITY CLASSIFICATION Unclassified		
22a NAME OF RESPONSIBLE INDIVIDUAL Gloria P. Wren			22b TELEPHONE (Include Area Code) 301-278-6199		22c OFFICE SYMBOL SLCBR-TR-B

TABLE OF CONTENTS

	<u>Page</u>
LIST OF FIGURES	v
LIST OF TABLES	
I. INTRODUCTION	1
II. SENSITIVITY STUDY	
1. STANDARD DATA SET	2
2. PROCEDURE OF STUDY	2
III. RESULTS	
1. 120-MM RLP GUN STANDARD CASE RESULTS	4
2. EFFECTS ON MUZZLE VELOCITY	4
3. EFFECTS ON MAXIMUM LIQUID PRESSURE	5
4. EFFECTS ON MAXIMUM COMBUSTION CHAMBER PRESSURE	6
5. SUMMARY VARIATIONS	7
6. OTHER PARAMETERS	8
IV. CONSTRAINT ON MAXIMUM LIQUID PRESSURE	
1. PROCEDURE	9
2. RESULTS	10
V. DIFFERENTIAL COEFFICIENTS	12
VI. CONCLUSIONS	14
VII. FURTHER INVESTIGATIONS	15
REFERENCES	17
APPENDIX A	19
APPENDIX B	25
APPENDIX C	61
DISTRIBUTION LIST	65



ACCEPTED FOR	
NTIS GRANT	✓
DEVELOPER	[]
SPONSOR	[]
DATE	
BY	
DATE	
DATE	
A-1	

LIST OF FIGURES

<u>Figure</u>		<u>Page</u>
1	RLP Gun With Annular Piston	1
2	Percentage Change in Muzzle Velocity	5
3	Percentage Change in Maximum Liquid Pressure	6
4	Percentage Change in Maximum Combustion Chamber Pressure	7
5	Percentage Change in Muzzle Velocity with Constraint Compared to Change in Area	11
6	Percentage Change in Muzzle Velocity with Constraint Compared to Volume and Mass Changes	12
B-1	Percentage change in piston weight vs. percentage changes in maximum liquid pressure, maximum combustion chamber pressure, and maximum base pressure.	27
B-2	Percentage change in piston weight vs. percentage changes in muzzle velocity and maximum piston velocity.	28
B-3	Percentage change in projectile weight vs. percentage changes in maximum liquid pressure, maximum combustion chamber pressure, and maximum base pressure.	29
B-4	Percentage change in projectile weight vs. percentage changes in muzzle velocity and maximum piston velocity.	30
B-5	Percentage change in chamber volume vs. percentage changes in maximum liquid pressure, maximum combustion chamber pressure, and maximum base pressure.	31
B-6	Percentage change in chamber volume vs. percentage changes in muzzle velocity and maximum piston velocity.	32

LIST OF FIGURES (CON'T)

B-7	Percentage change in liquid volume vs. percentage changes in maximum liquid pressure, maximum combustion chamber pressure, and maximum base pressure.	33
B-8	Percentage change in liquid volume vs. percentage changes in muzzle velocity and maximum piston velocity.	34
B-9	Percentage change in area of liquid reservoir vs. percentage changes in maximum liquid pressure, maximum combustion chamber pressure, and maximum base pressure.	35
B-10	Percentage change in area of liquid reservoir vs. percentage changes in muzzle velocity and maximum piston velocity.	36
B-11	Percentage change in area of combustion chamber vs. percentage changes in maximum liquid pressure, maximum combustion chamber pressure, and maximum base pressure.	37
B-12	Percentage change in area of combustion chamber vs. percentage changes in muzzle velocity and maximum piston velocity.	38
B-13	Percentage change in covolume vs. percentage changes in maximum liquid pressure, maximum combustion chamber pressure, and maximum base pressure.	39
B-14	Percentage change in covolume vs. percentage changes in muzzle velocity and maximum piston velocity.	40
B-15	Percentage change in vent area vs. percentage changes in maximum liquid pressure, maximum combustion chamber pressure, and maximum base pressure.	41
B-16	Percentage change in vent area vs. percentage changes in muzzle velocity and maximum piston velocity.	42
B-17	Percentage change in shot start pressure vs. percentage changes in maximum liquid pressure, maximum combustion chamber pressure, and maximum base pressure.	43

LIST OF FIGURES (CON'T)

B-18	Percentage change in shot start pressure vs. percentage changes in muzzle velocity and maximum piston velocity.	44
B-19	Percentage change in molecular weight vs. percentage changes in maximum liquid pressure, maximum combustion chamber pressure, and maximum base pressure.	45
B-20	Percentage change in molecular weight vs. percentage changes in muzzle velocity and maximum piston velocity.	46
B-21	Percentage change in bulk modulus vs. percentage changes in maximum liquid pressure, maximum combustion chamber pressure, and maximum base pressure.	47
B-22	Percentage change in bulk modulus vs. percentage changes in muzzle velocity and maximum piston velocity.	48
B-23	Percentage change in derivative of bulk modulus vs. percentage changes in maximum liquid pressure, maximum combustion chamber pressure, and maximum base pressure.	49
B-24	Percentage change in derivative of bulk modulus vs. percentage changes in muzzle velocity and maximum piston velocity.	50
B-25	Percentage change in chemical energy vs. percentage changes in maximum liquid pressure, maximum combustion chamber pressure, and maximum base pressure.	51
B-26	Percentage change in chemical energy vs. percentage changes in muzzle velocity and maximum piston velocity.	52
B-27	Percentage change in specific heat ratio vs. percentage changes in maximum liquid pressure, maximum combustion chamber pressure, and maximum base pressure.	53
B-28	Percentage change in specific heat ratio vs. percentage changes in muzzle velocity and maximum piston velocity.	54

LIST OF FIGURES (CON'T)

B-29	Percentage change in density vs. percentage changes in maximum liquid pressure, maximum combustion chamber pressure, and maximum base pressure.	55
B-30	Percentage change in density vs. percentage changes in muzzle velocity and maximum piston velocity.	56
B-31	Percentage change in discharge coefficient of liquid vs. percentage changes in maximum liquid pressure, maximum combustion chamber pressure, and maximum base pressure.	57
B-32	Percentage change in discharge coefficient of liquid vs. percentage changes in muzzle velocity and maximum piston velocity.	58
B-33	Percentage change in discharge coefficient of gas vs. percentage changes in maximum liquid pressure, maximum combustion chamber pressure, and maximum base pressure.	59
B-34	Percentage change in discharge coefficient of gas vs. percentage changes in muzzle velocity and maximum piston velocity.	60

LIST OF TABLES

<u>Table</u>		<u>Page</u>
1	120-mm RLP Gun Standard Case Input Data	2
2	120-mm RLP Gun Standard Case Results	4
3	Summary Of Effects	8
4	Adjusted Vent Areas	9
5	Differential Coefficients: Quartic Fit	13
6	Differential Coefficients: Quadratic Fit	14

I. INTRODUCTION

The regenerative liquid propellant gun continues to be of interest to gun designers both for its potential for increased performance and the lower vulnerability of liquid propellants compared to solids. Recent research has indicated increased understanding of the RLP process, and several interior ballistic models are now available. Although mathematical models have been created for the U.S. gun configurations (Bulman,¹ Coffee,² Cushman,³ Gough⁴), the interrelationships between the complex variables associated with the liquid propellant gun continue to be elusive. Thus, this sensitivity study is aimed at exploring the relationships expressed in the mathematical modeling of a hypothetical 120-mm regenerative liquid propellant gun, using the model developed by T. Coffee⁵ at the Ballistic Research Laboratory. The information gained from this study may also aid in the design of regenerative liquid propellant guns other than the 120-mm studied here.

The Coffee code is a lumped parameter model of a regenerative liquid propellant gun, using an annular piston injector as shown in Figure 1.

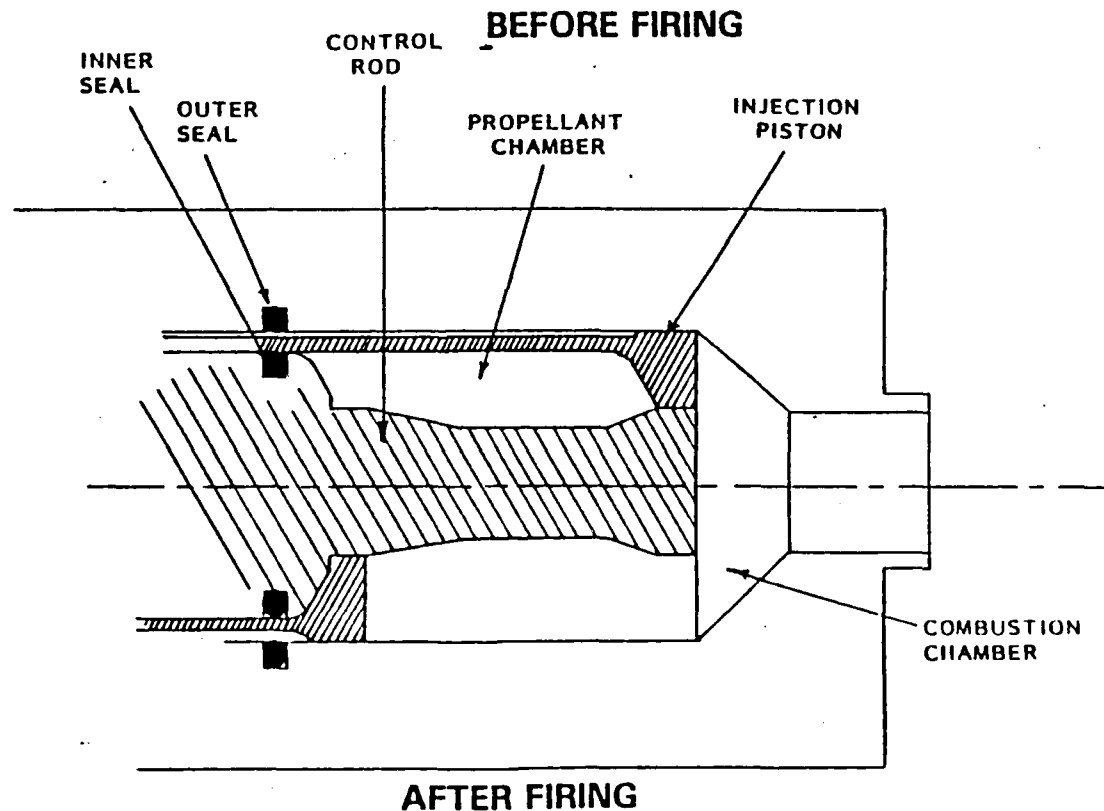


Figure 1. RLP Gun With Annular Piston

The interior ballistic cycle starts with a primer igniting in the combustion chamber pressurizing the chamber, forcing the piston back. The liquid pressure is higher than the combustion chamber pressure due to the piston area differential between the two regions. Liquid propellant is forced through the vent created between the piston and the fixed center bolt into the combustion chamber where it burns, and the resulting pressure pushes the projectile down the gun tube. In this report the piston area on the combustion chamber side is referred to as the chamber area while the piston area on the liquid side is referred to as the liquid area.

II. SENSITIVITY STUDY

1. STANDARD DATA SET

The standard data set for this study was chosen to be the conceptual 120-mm regenerative liquid propellant tank gun with no offset (that is, the base of the projectile is at the entrance to the bore) using a hypothetical JA2 propellant and a projectile mass of 7.12 kg as presented in Table 1.

TABLE 1. 120-mm RLP Gun Standard Case Input Data

VARIABLE	VALUE
Projectile Weight (kg)	7.12
Projectile Travel (m)	6.3
Piston Weight (kg)	76.66
Liquid Chamber Volume (l)	11.7
Combustion Chamber Volume (l)	5.845
Liquid Reservoir Area (cm ²)	719.6
Combustion Chamber Area (cm ²)	916.3
Vent Area (cm ²)	81.
Injector Discharge Coefficient	0.75
Shot-Start Pressure (MPa)	34.
Bore Friction 0 to Muz. (MPa)	5.5
Propellant Type:	Liquid JA2

2. PROCEDURE OF STUDY

The 120-mm gun was chosen partly in response to a study by Woodley⁶ on an English regenerative liquid propellant gun of the same caliber. Although the mechanical configuration of the English version is different from its U.S. counterpart, it was of interest to note the similarities and differences in the models. This study parallels Woodley⁷ by varying parameters by +20%, +10%, -10%, -20%.

The following parameters, including both ballistic parameters and propellant properties, were varied one at a time by -20%, -10%, +10%, +20%.

- Piston Weight
- Projectile Weight
- Combustion Chamber Volume
- Area of Liquid Reservoir (cross-sectional)
- Area of Combustion Chamber (cross-sectional)
- Covolume
- Vent Area
- Shot Start Pressure
- Bulk Modulus
- Derivative of Bulk Modulus with Pressure
- Chemical Energy
- Specific Heat Ratio
- Density
- Discharge Coefficient of Liquid Injector
- Discharge Coefficient Chamber to Barrel

In each case the effects on the following performance characteristics were recorded both absolutely and as percent change.

- Muzzle Velocity
- Maximum Liquid Pressure
- Maximum Combustion Chamber Pressure
- Maximum Base Pressure (base of projectile)
- Maximum Acceleration
- Maximum Piston Travel
- Piston Velocity at Impact
- Time to Ejection of Projectile
- Fraction of Liquid Burned

The complete data appears in Appendix A in table form and in Appendix B as plots of percentage change in performance vs percentage change in input parameters. After viewing the data, it was noticed that the maximum liquid pressure exceeded the stipulated value of 700 MPa in several cases. In an effort to more nearly approximate realistic conditions and to study a high performance situation, each case was recomputed with the condition of a fixed maximum liquid pressure of 700 MPa. The adjustable parameter was taken to be the vent area which controls the influx of liquid fuel into the combustion chamber. The effects on performance characteristics were recorded again both absolutely and as percent change. This data appears in Appendix C.

III. RESULTS

1. 120-MM RLP GUN STANDARD CASE RESULTS

The baseline results for the 120-mm RLP gun described above are presented in Table 2. No piston damping was considered in this model, although damping is routinely included in actual hardware.

TABLE 2. 120-mm RLP Gun Standard Case Results

VARIABLE	VALUE
Muzzle Velocity (m/s)	1925.3
Maximum Liquid Pressure (MPa)	692.8
Maximum Combustion Chamber Pressure (MPa)	494.9
Maximum Base Pressure (MPa)	341.7
Maximum Acceleration (K-G)	54.3
Piston Velocity @ Impact (cm/s)	5140.4

2. EFFECTS ON MUZZLE VELOCITY

The effect of percentage change in piston weight, projectile weight, liquid volume, liquid area, chamber area and vent area on the percentage change in muzzle velocity is illustrated in Figure 2. The ballistic parameter having the greatest impact on muzzle velocity is the chamber area. Although a negative percent change in chamber area is accompanied by a significant decrease in muzzle velocity, the effect is less for a positive percent change in chamber area.

A -20% change in chamber area is associated with a -47% change in muzzle velocity. Since the chamber to reservoir area ratio (the hydraulic ratio or hydraulic difference) is not fixed, lower chamber area results in a lower hydraulic ratio. The effect is a lower reservoir pressure, lower pressure difference between the chamber and reservoir, and, thus, reduced liquid injection and lower chamber pressure. On the other hand, a +20% change in chamber area corresponded to only a 5.69% change in muzzle velocity. Although the larger chamber area results in increased pressure in the liquid, the amount of liquid entering the combustion chamber is also controlled by the vent area which was not changed.

Changes in liquid area mirror results from changes in chamber area inversely. This result is expected since increased liquid area lowers the hydraulic ratio, while decreased liquid area raises the hydraulic ratio. The other major parameters of piston mass, projectile mass, liquid volume, chamber volume, and vent area affected muzzle velocity in the +-10% range.

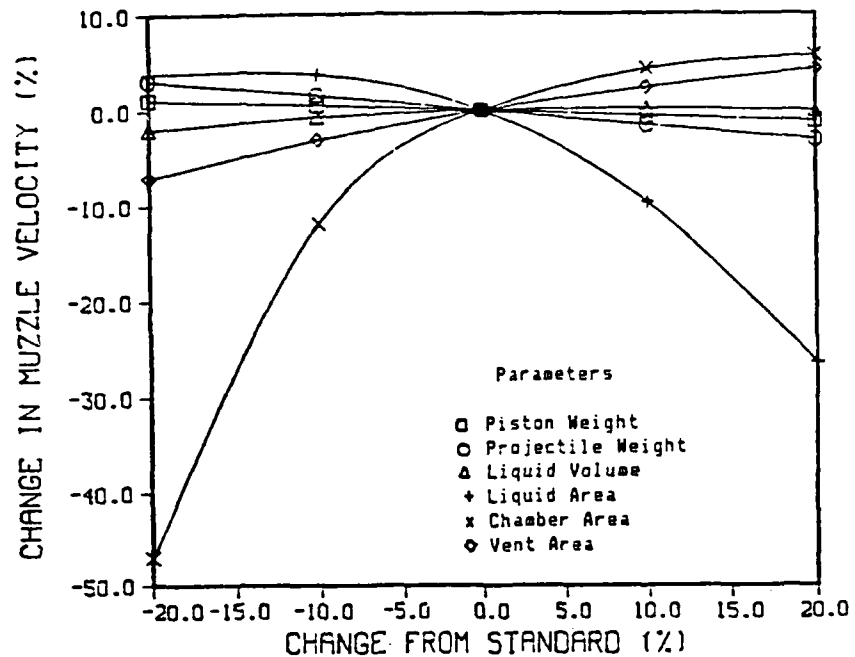


Figure 2. Percentage Change in Muzzle Velocity

3. EFFECTS ON MAXIMUM LIQUID PRESSURE

The effect of percentage change in piston weight, projectile weight, liquid volume, liquid area, chamber area and vent area on the percentage change in maximum liquid pressure is illustrated in Figure 3. The ballistic parameters having the greatest impact on maximum liquid pressure were chamber area and liquid area. This was an expected result since the hydraulic difference controls piston motion. The effect is dramatic; a -20% change in chamber area corresponded to a -86% change in maximum liquid pressure while a +20% change produced a +69% change in maximum liquid pressure. Inversely, a -20% change in liquid area gave a +86% change in maximum liquid pressure while a +20% change is associated with a -66% change in maximum liquid pressure. Other parameters having significant effect were vent area giving changes in the +20% range and projectile mass giving changes in the +10% range.

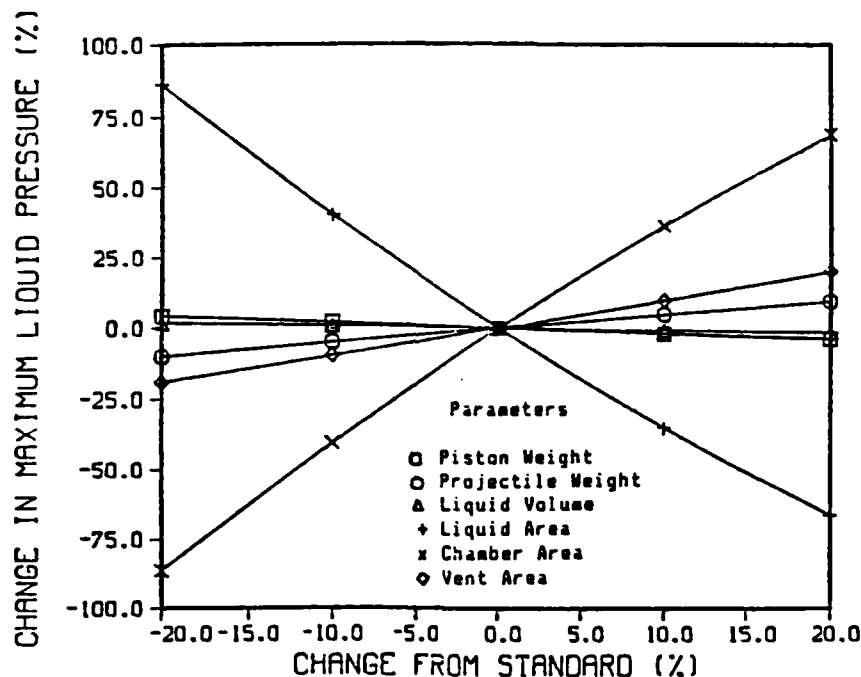


Figure 3. Percentage Change in Maximum Liquid Pressure

4. EFFECTS ON MAXIMUM COMBUSTION CHAMBER PRESSURE

The effect of percentage change in piston weight, projectile weight, liquid volume, liquid area, chamber area and vent area on the percentage change in maximum combustion chamber pressure is illustrated in Figure 4. The ballistic parameters having the greatest impact on maximum combustion chamber pressure were chamber area and liquid area. This was an expected result since these two parameters are recognized to dominate chamber pressure. A significant effect is demonstrated; a -20% change in chamber area corresponded to a -81% change in maximum combustion chamber pressure while a +20% change produced a +34% change in maximum combustion chamber pressure. Inversely, a -20% change in liquid area gave a +33% change in maximum combustion chamber pressure while a +20% change is associated with a -57% change in maximum combustion chamber pressure. Other parameters having significant effect were vent area giving changes in the +-20% range and projectile mass giving changes in the +-10% range.

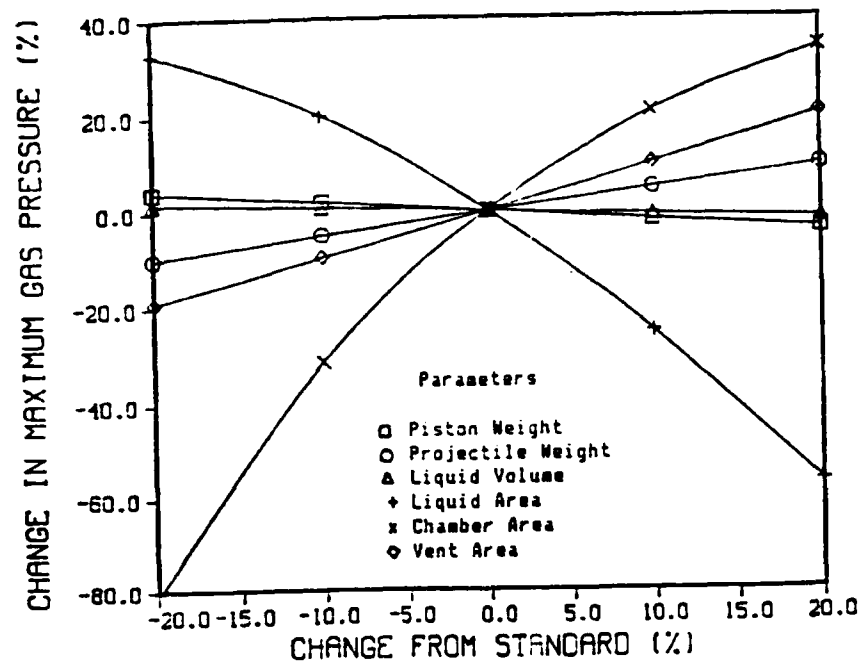


Figure 4. Percentage Change in Maximum Combustion Chamber Pressure

5. SUMMARY VARIATIONS

Table 3 summarizes the major ballistic parameters and the range of corresponding percentage changes in maximum liquid pressure, maximum combustion chamber pressure (gas), and velocity. As already noted, the controlling effect of liquid and chamber areas on maximum liquid and combustion chamber pressures was expected. The hydraulic ratio increases with either increased chamber area or decreased liquid area. Similarly, the hydraulic ratio decreases with decreased chamber area or increased liquid area. Vent area controls the amount of fuel entering the combustion chamber and affects pressures as expected. The volume of liquid propellant has only a minor effect on the system unless there is not enough available to give sufficient impetus to the projectile.

It is, perhaps, more interesting to note the changes in projectile velocity. First, velocity is not substantially affected by projectile (shot) or piston mass in the range $\pm 20\%$, a fact which be suprising at first glance. However,

$$v = \sqrt{\frac{2}{m} \frac{KE}{p}}$$

where KE is the kinetic energy and M_p is the mass of the projectile. Also,

$$KE = A_B \int P_s dx$$

if P_s increases uniformly by 10%, KE increases by 10%. Since M_p is increased by 20%,

$$v' \sim \sqrt{\frac{1.1}{1.2}}$$

or, $v' \sim 0.957v$. That is, the expected change in velocity for a +20% change in shot mass is -4.2% for a uniform increase in P_s . Since P_s does not increase uniformly, the expected change in velocity is less than -4.3%, a value which compares favorably with the results of the study. Secondly, projectile velocity is most affected by chamber and liquid area changes. Again, the dominant effect of the ratio of chamber area to liquid area is illustrated.

6. OTHER PARAMETERS

The other performance characteristics are not addressed in this report since they are of minor interest. Maximum acceleration parallels maximum base pressure; maximum piston travel has an upper limit imposed physically by the gun; projectile ejection time is within a millisecond; the fraction of liquid burned is 1.0 in all but three cases.

TABLE 3. Summary Of Effects

	PMAX LP	PMAX GAS	VEL
-20% / +20%			
CHAMBER AREA	-86/+69	-81/+34	-47/+6
LIQUID AREA	+86/-67	+33/-57	+4/-26
VENT AREA	-19/+20	-19/+20	-7/+4
SHOT MASS	10/+10	-10/+10	+3/-3
PISTON MASS	+4/-4	+4/-4	+1/-1
LP VOLUME	1.6/-1.5	1.7/-1.6	-2/-0.6

A complete listing of all parameters varied recorded both absolutely and as percentage change along with the corresponding absolute and percentage change in performance characteristics for the 120-mm regenerative liquid propellant gun can be found in Appendix A. A visual presentation of the results in the form of percentage change graphs can be found in Appendix B. For each parameter varied two graphs are presented:

1) Percentage change in parameter vs. percentage changes in maximum liquid pressure, maximum combustion chamber pressure, and maximum base pressure.

2) Percentage change in parameter vs. percentage changes in muzzle velocity and maximum piston velocity.

IV. CONSTRAINT ON MAXIMUM LIQUID PRESSURE

1. PROCEDURE

In studies of gun systems a common procedure is to fix chamber pressure and view parameter changes relative to this condition. The analog to the solid propellant case in the regenerative liquid propellant gun is to fix the pressure in the liquid reservoir, essentially the breech pressure, and analyze the effect of parameter changes with a constraint on liquid pressure. Liquid pressure can be controlled by the vent area, analogous to the web in solid propellant. A fixed maximum liquid pressure of 700 MPa was chosen for the 120-mm gun described in this report. This constraint should reflect a high performance regime for the system described. Parameter changes in the $\pm 20\%$ range were then analyzed with the constraint of a fixed maximum liquid pressure of 700 MPa, a value controlled by varying vent area. The vent areas used are given in Table 4.

TABLE 4. Adjusted Vent Areas

PARAMETER	PERCENT CHANGE	VENT AREA (cm ²)
PISTON WEIGHT	-20.0	78.5
PISTON WEIGHT	-10.0	80.0
PISTON WEIGHT	10.0	83.5
PISTON WEIGHT	20.0	85.3
PROJECTILE WEIGHT	-20.0	91.0
PROJECTILE WEIGHT	-10.0	86.2
PROJECTILE WEIGHT	10.0	77.97
PROJECTILE WEIGHT	20.0	74.48

TABLE 4. Adjusted Vent Areas (Con't)

CHAMBER VOLUME	-20.0	77.5
CHAMBER VOLUME	-10.0	80.0
CHAMBER VOLUME	10.0	83.6
CHAMBER VOLUME	20.0	85.3
LIQUID VOLUME	-20.0	80.5
LIQUID VOLUME	-10.0	81.2
LIQUID VOLUME	10.0	82.5
LIQUID VOLUME	20.0	83.1
LIQUID AREA	-20.0	41.22
LIQUID AREA	-10.0	57.45
LIQUID AREA	10.0	127.1
LIQUID AREA	20.0	NONE
CHAMBER AREA	-20.0	NONE
CHAMBER AREA	-10.0	139.9
CHAMBER AREA	10.0	59.4
CHAMBER AREA	20.0	47.18

2. RESULTS

Since controlling vent area controls maximum liquid pressure, the performance characteristic of interest was the muzzle velocity. As pictured in Figure 5, all liquid and chamber area changes resulted in a decrease in muzzle velocity except a -10% change in chamber area (or a +10% increase in liquid area). This may suggest slightly improved performance in the gun system described by decreasing chamber area 10%. It is also noted that it was impossible to reach a maximum liquid pressure of 700 MPa for the -20% chamber area and +20% liquid area cases. Therefore, the graphs reflect the effect utilizing the maximum possible liquid pressure. Statistics can be found in Appendix C.

Changes in chamber volume, liquid volume, piston mass, and projectile mass relate to changes in muzzle velocity in the $\pm 5\%$ range. Now, as expected, lighter projectiles travel faster, and vice versa.

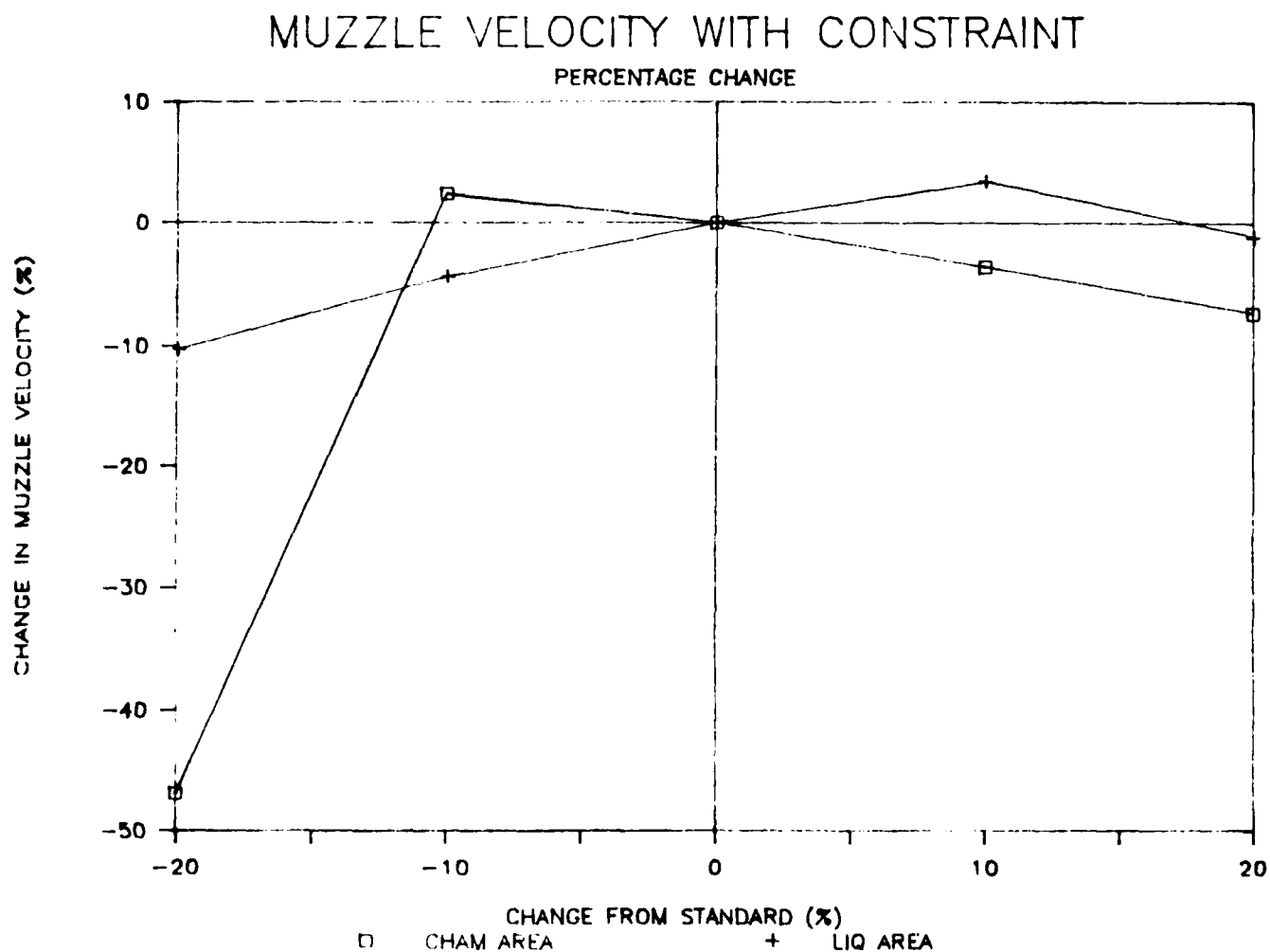


Figure 5. Percentage Change in Muzzle Velocity with Constraint Compared to Change in Area

MUZZLE VELOCITY WITH CONSTRAINT

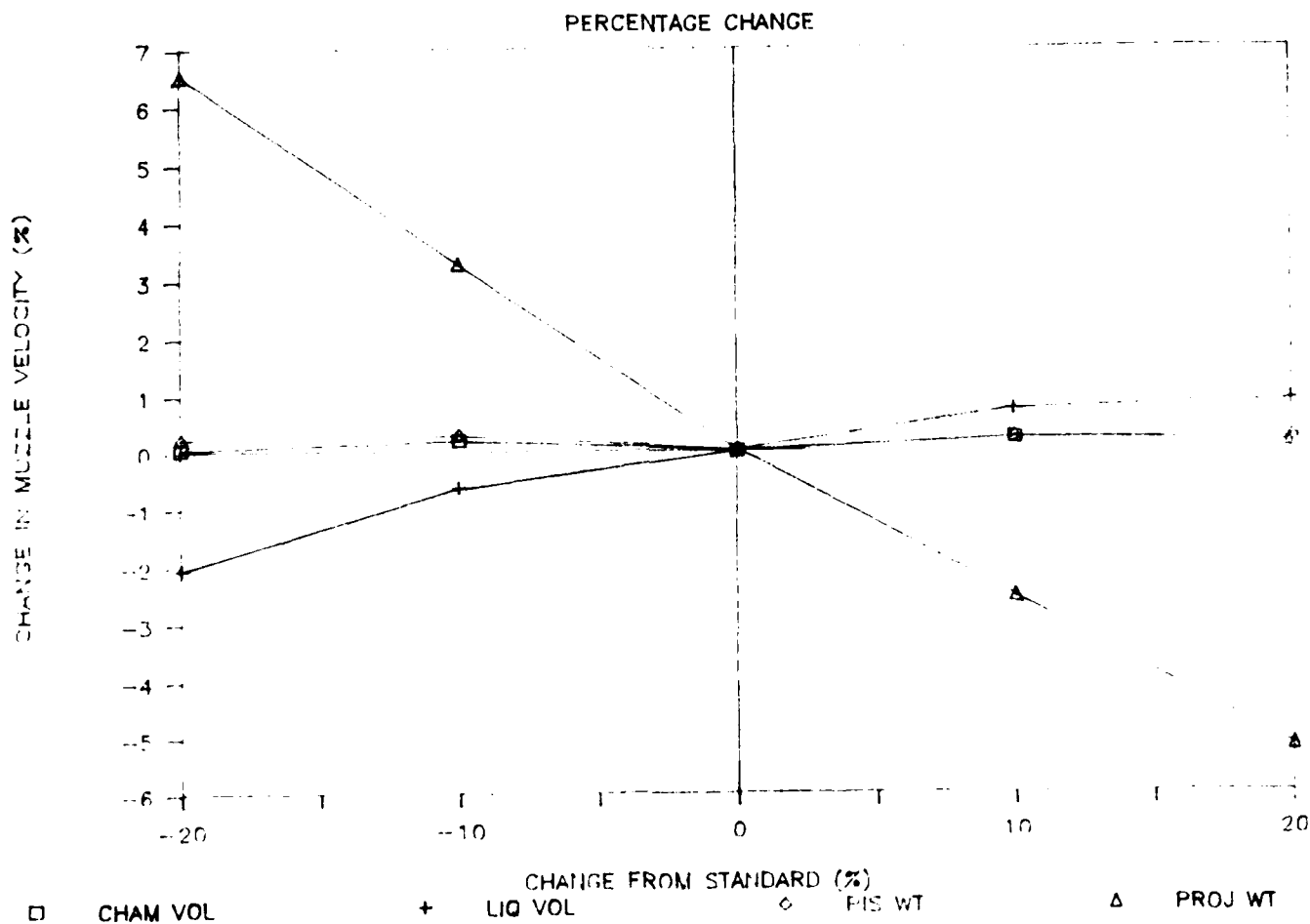


Figure 6. Percentage Change in Muzzle Velocity with Constraint Compared to Volume and Mass Changes

V. DIFFERENTIAL COEFFICIENTS

It may be desirable to approximate expected performance characteristics for percentage changes other than those specifically listed in the appendix. Therefore, the five data points for percentage changes of -20%, -10%, 0%, +10%, +20% were successfully fitted with a fourth degree polynomial to allow for interpolation in the range -20% to +20%. The table below gives the results.

for the coefficients of $Ax^4+Bx^3+Cx^2+Dx+E=0$. In all cases $E=0$ since its value was on the order 10^{-14} .

TABLE 5. Differential Coefficients: Quartic Fit

Variation of:	Ax^4	Bx^3	Cx^2	Dx
Piston Weight with Muzzle Velocity	.84	-.06	-.04	-.05
Piston Weight with Max Liquid Pres	-.12	-.24	.45	-.20
Piston Weight with Max Com Ch Pres	-.08	-.02	.04	-.20
Proj Weight with Muzzle Velocity	.35	.35	-.01	-.15
Proj Weight with Max Liquid Pres	-.60	.01	-.07	.49
Proj Weight with Max Com Ch Pres	.17	.00	-.08	.49
Liquid Vol with Muzzle Velocity	-.04	.09	-.24	.04
Liquid Vol with Max Liquid Pres	.12	-.24	.01	-.08
Liquid Vol with Max Com Ch Pres	.17	.00	.01	-.08
Vent Area with Muzzle Velocity	1.02	.37	-.38	.26
Vent Area with Max Liquid Pres	.60	.12	.12	.97
Vent Area with Max Com Ch Pres	.25	.12	.13	.98

Liquid area and combustion chamber area parameters did not fit well with a fourth degree polynomial. Therefore, the points for -20%, -10%, 0% were fitted with a quadratic function, $Ax^2+Bx+C=0$ while the points for 0%, 10%, 20% were fitted with another quadratic function. In all cases the constant was on the order of 10^{-14} and is considered zero.

TABLE 6. Differential Coefficients: Quadratic Fit

Variation of:	Case of -20%, -10%, 0%		Case of 0%, 10%, 20%	
	Ax^2	Bx	Ax^2	Bx
Liquid Area with Muzzle Velocity	-1.72	-.55	-3.57	-.61
Liquid Area with Max Liquid Pres	2.82	-3.75	1.39	-3.60
Liquid Area with Max Com Ch Pres	-3.62	-2.37	-3.16	-2.21
Chamber Area with Muzzle Velocity	-11.53	.04	-1.47	.58
Chamber Area with Max Liquid Pres	-2.69	3.78	-2.05	3.86
Chamber Area with Max Com Ch Pres	-9.22	2.21	-3.78	2.44

VI. CONCLUSIONS

A sensitivity study has been completed using a hypothetical 120-mm regenerative liquid propellant tank gun. Like its English counterpart, the model has proven quite insensitive to many parameters. Specifically, for parameter changes in the range $\pm 20\%$ the model showed changes of less than 2%, sometimes significantly less, to parameter changes of shot start pressure, bulk modulus, derivative of bulk modulus with pressure. Although piston mass changes gave performance changes of the order of $\pm 5\%$ in pressures, change in muzzle velocity was less than $\pm 1\%$. Projectile mass changes gave $\pm 10\%$ changes in pressures, but only $\pm 3\%$ changes in muzzle velocity. As expected, changes in the cross-sectional area of the liquid reservoir and combustion chamber yielded the greatest changes in both pressures and muzzle velocity, $\pm 60\%$ or more. Thus, the system is driven by the hydraulic difference, the ratio of chamber area to liquid area, which controls the motion of the piston. All other parameters are of secondary consideration.

The second part of the study reflected an analog to some studies of solid propellant gun systems by fixing pressure and viewing parameter changes under this condition. Thus, maximum liquid pressure was taken to be 700 MPa and was controlled by varying vent area. Parameter changes in the $\pm 20\%$ range were analyzed with this constraint. An analysis of the effects on muzzle velocity indicate higher velocity for this system with a -10% change in chamber area or a $+10\%$ change in liquid area. Other parameter changes have little effect.

Although the study considered parameter changes of only $\pm 20\%$ and $\pm 10\%$, a computation of differential coefficients for the changes will enable the researcher to interpolate expected performance characteristics within this range. As with any analysis of differential coefficients, extrapolation outside the $\pm 20\%$ range may not be valid.

In general, results in the $\pm 1\%$ range should always be viewed with some caution since discretization and round-off error may affect small changes. Also, piston velocity at impact was taken from a table of incremental time steps and may not precisely reflect the velocity obtained in the model. Finally, changes in parameters chosen in this study may not at all times be reasonable expectations physically.

VII. FURTHER INVESTIGATIONS

Although the sensitivity study provides insight into the regenerative liquid propellant interior ballistic process gun using the Coffee code, it would be instructive to compare the results to the other existing regenerative liquid propellant gun codes to more clearly understand assumptions and differences in the underlying equations. As data from actual firings of the gun become available, a cross-checking of expected results with actual results will serve to further illuminate the underlying theoretical basis for regenerative liquid propellant guns.

REFERENCES

1. Bulman, M.J., General Electric Ordinance Systems Division.
2. Coffee, Terence, "A Lumped Parameter Code for Regenerative Liquid Propellant Guns," BRL-TR-2703, Ballistic Research Laboratory, December, 1985.
3. Cushman, P.G., "Regenerative Liquid Propellant Gun Simulation User's Manual," GE Report 84-POD-004, December, 1983.
4. Gough, P.S., "A Model of the Interior Ballistics of Hybrid Liquid-Propellant Guns," Final Report, Contract DAAK11-82-C-0514, PGA-TR-83-4, September, 1983.
5. Coffee, Terence, Ballistic Research Laboratory, private communication.
6. Woodley, C.R., "A Theoretical Sensitivity Study of a Regenerative Liquid Propellant Gun," Sevenoaks, Kent, England, 1984.
7. Pagan, Harvey, & Izod, "Regenerative Liquid Propellant Gun Modelling," Ministry of Defence, England.
8. Baer, P., Ballistic Research Laboratory, private communication.

Appendix A

The statistics for parameter change vs. change in performance characteristics are presented both absolutely and as percentage change.

120MM REGENERATIVE LIQUID PROPELLANT GUN
SENSITIVITY STUDY
RLGD CODE

Piston Weight	Muzzle	Velocity	Max. Liq. Press.	Max. Comb. Press.	Max. Base Press.	Kgs	Max. Accel.	Max. Pist	Travel Pist.	Vel. Impact	Time Impact	Time Eject	z @ 80					
g	mm/s	m/s	MPa	MPa	MPa	ms	mm/s	mm	mm	mm/s	ms	ms	mm					
61326.4	-20.0	1946.8	1.12	721.6	4.16	515.3	4.12	364.2	6.58	57.9	6.63	20.342	-0.01	5192.2	1.01	6.96	-3.71	1.00
68992.2	-10.0	1935.3	0.52	706.9	2.04	504.9	2.02	352.6	3.19	56.0	3.13	20.361	0.08	5158.7	0.76	7.10	-1.93	1.00
76658.0	0.0	1925.3	0.00	692.8	0.00	494.9	0.00	341.7	0.00	54.3	0.00	20.344	0.00	5140.4	0.00	7.23	0.00	1.00
84333.8	10.0	1914.2	-0.58	679.3	-1.95	485.3	-1.94	331.5	-2.99	52.6	-3.13	20.349	0.02	5106.0	-0.67	7.36	1.71	1.00
91989.6	20.0	1903.3	-1.14	666.2	-3.84	476.0	-3.82	321.7	-5.85	51.0	-6.08	20.352	0.04	5084.3	-1.09	7.48	3.43	1.00
Proj. Weight	Muzzle	Velocity	Max. Liq. Press.	Max. Comb. Press.	Max. Base Press.	Kgs	Max. Accel.	Max. Pist	Travel Pist.	Vel. Impact	Time Impact	Time Eject	z @ 80					
g	mm/s	m/s	MPa	MPa	MPa	ms	mm/s	mm	mm	mm/s	ms	ms	mm					
5696.0	-20.0	1985.2	3.11	622.7	-10.12	444.8	-10.12	290.8	-14.90	57.5	5.89	20.356	0.06	4883.1	-5.01	6.98	-3.54	1.00
6408.0	-10.0	1955.2	1.55	658.3	-4.98	470.2	-4.99	316.7	-7.32	55.8	2.76	20.343	-0.00	5013.9	-2.46	7.11	-1.71	1.00
7120.0	0.0	1925.3	0.00	692.8	0.00	494.9	0.00	341.7	0.00	54.3	0.00	20.344	0.00	5140.4	0.00	7.23	0.00	1.00
7832.0	10.0	1895.1	-1.57	726.2	4.84	518.8	4.83	365.9	7.08	52.9	-2.58	20.350	0.03	5247.8	2.09	7.34	1.55	1.00
8544.0	20.0	1865.8	-3.09	758.8	9.53	542.0	9.52	389.6	14.02	51.7	-4.79	20.354	0.05	5366.9	4.41	7.45	3.04	1.00
Chamber Volume	Muzzle	Velocity	Max. Liq. Press.	Max. Comb. Press.	Max. Base Press.	Kgs	Max. Accel.	Max. Pist	Travel Pist.	Vel. Impact	Time Impact	Time Eject	z @ 80					
cc	mm/s	m/s	MPa	MPa	MPa	ms	mm/s	mm	mm	mm/s	ms	ms	mm					
4676.0	-20.0	1948.9	1.23	726.2	4.82	518.3	4.73	362.7	6.15	57.7	6.26	20.342	-0.01	5177.8	0.73	7.02	-2.88	1.00
5260.5	-10.0	1935.5	0.53	708.7	2.30	506.1	2.26	351.8	2.96	55.9	2.95	20.354	0.05	5168.3	0.54	7.13	-1.44	1.00
5845.0	0.0	1925.3	0.00	692.8	0.00	494.9	0.00	341.7	0.00	54.3	0.00	20.344	0.00	5140.4	0.00	7.23	0.00	1.00
6429.5	10.0	1913.6	-0.61	678.0	-2.14	484.4	-2.12	332.2	-2.78	52.7	-2.95	20.361	0.08	5139.5	-0.02	7.33	1.38	1.00
7014.0	20.0	1903.2	-1.15	664.5	-4.08	474.9	-4.04	323.6	-5.30	51.3	-5.52	20.350	0.03	5084.0	-1.10	7.42	2.65	1.00
Liquid Volume	Muzzle	Velocity	Max. Liq. Press.	Max. Comb. Press.	Max. Base Press.	Kgs	Max. Accel.	Max. Pist	Travel Pist.	Vel. Impact	Time Impact	Time Eject	z @ 80					
cc	mm/s	m/s	MPa	MPa	MPa	ms	mm/s	mm	mm	mm/s	ms	ms	mm					
9360.0	-20.0	1887.8	-1.95	704.0	1.62	503.3	1.70	351.4	2.84	55.8	2.76	16.280	-19.98	5280.1	2.72	7.14	-1.27	1.00
10530.0	-10.0	1911.9	-0.70	698.2	0.78	499.0	0.83	346.4	1.38	55.0	1.29	18.322	-9.94	5210.9	1.37	7.18	-0.72	1.00
11700.0	0.0	1925.3	0.00	692.8	0.00	494.9	0.00	341.7	0.00	54.3	0.00	20.344	0.00	5140.4	0.00	7.23	0.00	1.00
12870.0	10.0	1929.1	0.20	687.6	-0.75	490.9	-0.81	337.2	-1.32	53.5	-1.47	22.386	10.04	5072.2	-1.33	7.28	0.72	1.00
14040.0	20.0	1924.2	-0.06	682.6	-1.47	487.1	-1.58	332.9	-2.58	52.8	-2.76	24.425	20.06	4992.4	-2.88	7.34	1.44	1.00
Liquid Area	Muzzle	Velocity	Max. Liq. Press.	Max. Comb. Press.	Max. Base Press.	Kgs	Max. Accel.	Max. Pist	Travel Pist.	Vel. Impact	Time Impact	Time Eject	z @ 80					
cm ²	mm/s	m/s	MPa	MPa	MPa	ms	mm/s	mm	mm	mm/s	ms	ms	mm					
575.7	-20.0	1999.8	3.87	1290.9	86.33	657.4	32.83	397.4	16.30	63.3	16.57	27.156	33.48	12366.7	140.58	6.84	-5.48	1.00
647.6	-10.0	1996.9	3.72	972.5	40.37	594.1	20.04	382.6	11.97	60.9	12.15	23.256	14.31	8992.7	61.32	6.91	-4.42	1.00
719.6	0.0	1925.3	0.00	692.8	0.00	494.9	0.00	341.7	0.00	54.3	0.00	20.344	0.00	5140.4	0.00	7.23	0.00	1.00
791.6	10.0	1739.0	-9.68	452.6	-34.67	370.0	-25.24	275.2	-19.46	43.5	-19.89	17.802	-12.50	2732.0	-46.85	7.92	9.46	1.00
863.5	20.0	1415.8	-26.46	232.0	-66.51	214.0	-56.76	175.6	-48.61	27.4	-49.54	9.274	-54.41	1098.2	-78.64	9.52	31.69	0.56

120MM REGENERATIVE LIQUID PROPELLANT GUN
SENSITIVITY STUDY
RL6D CODE

Chamber Area cm ²	Z	Muzzle m/s	Velocity Z	Max. Liq. Press. MPa	Max. Comb. Press. MPa	Max. Base Press. MPa	Pres. Z	Max. Accel. Z	Max. Pist cm	Travel Pist. Z	Pist. Vel ² Impact cm/s	Time @ Eject ms	Z @ 80					
732.0	-20.0	1021.1	-46.76	95.0	-86.29	93.2	-81.17	84.6	-75.24	12.7	-76.61	5.829	-71.35	544.9	-69.40	13.12	81.47	0.28
824.7	-10.0	1695.5	-11.93	412.7	-40.43	339.8	-31.34	247.8	-27.48	39.1	-27.99	19.249	-5.38	2968.2	-42.26	8.36	15.60	0.94
916.5	0.0	1925.3	0.00	692.8	0.00	494.9	0.00	341.7	0.00	54.3	0.00	20.344	0.00	5140.4	0.00	7.23	0.00	1.00
1007.9	10.0	2008.4	4.32	946.2	36.58	597.1	20.65	401.4	17.47	63.9	17.68	20.355	0.05	6922.6	34.67	6.69	-7.52	1.00
1099.6	20.0	2034.9	5.69	1171.4	69.08	662.0	33.76	439.0	28.48	70.0	28.91	20.350	0.03	8365.4	62.74	6.39	-11.62	1.00
Co Volume cc/g	Z	Muzzle m/s	Velocity Z	Max. Liq. Press. MPa	Max. Comb. Press. MPa	Max. Base Press. MPa	Pres. Z	Max. Accel. Z	Max. Pist cm	Travel Pist. Z	Pist. Vel ² Impact cm/s	Time @ Eject ms	Z @ 80					
9.7968	-20.0	1870.5	-2.85	641.5	-7.40	459.2	-7.42	319.8	-6.41	50.8	-6.45	20.357	0.06	4975.9	-3.20	7.28	2.10	1.00
0.8964	-10.0	1897.0	-1.47	666.1	-3.85	475.8	-3.86	330.4	-3.31	52.5	-3.31	20.354	0.05	5049.2	-1.77	7.31	1.05	1.00
0.9960	0.0	1925.3	0.00	692.8	0.00	494.9	0.00	341.7	0.00	54.3	0.00	20.344	0.00	5140.4	0.00	7.23	0.00	1.00
1.0956	10.0	1933.8	1.48	721.8	4.19	515.5	4.16	353.8	3.54	56.2	3.50	20.354	0.05	5272.4	1.89	7.15	-1.11	1.00
1.1952	20.0	1984.6	3.08	753.5	8.73	537.9	8.69	366.9	7.37	58.3	7.37	20.354	0.05	5322.0	3.53	7.07	-2.71	1.00
Vent Area cm ²	Z	Muzzle m/s	Velocity Z	Max. Liq. Press. MPa	Max. Comb. Press. MPa	Max. Base Press. MPa	Pres. Z	Max. Accel. Z	Max. Pist cm	Travel Pist. Z	Pist. Vel ² Impact cm/s	Time @ Eject ms	Z @ 80					
64.8	-20.0	1789.9	-7.03	561.1	-19.01	400.0	-19.18	298.6	-12.61	47.3	-12.89	20.937	2.91	3572.8	-30.50	7.61	5.20	1.00
72.9	-10.0	1865.7	-3.10	626.1	-9.63	446.9	-9.70	320.8	-6.12	50.9	-6.26	20.642	1.46	4347.1	-15.43	7.40	2.38	1.00
81.0	0.0	1925.3	0.00	692.8	0.00	494.9	0.00	341.7	0.00	54.3	0.00	20.344	0.00	5140.4	0.00	7.23	0.00	1.00
89.1	10.0	1970.6	2.35	761.2	9.87	544.2	9.96	361.4	5.77	57.5	5.89	20.062	-1.39	5929.9	15.36	7.08	-2.05	1.00
97.2	20.0	2008.2	4.31	832.3	20.14	595.3	20.29	380.3	11.30	60.5	11.42	19.796	-2.69	6716.5	30.66	6.96	-3.76	1.00
Sh-Start Press. MPa	Z	Muzzle m/s	Velocity Z	Max. Liq. Press. MPa	Max. Comb. Press. MPa	Max. Base Press. MPa	Pres. Z	Max. Accel. Z	Max. Pist cm	Travel Pist. Z	Pist. Vel ² Impact cm/s	Time @ Eject ms	Z @ 80					
27.2	-20.0	1920.2	-0.26	687.4	-0.78	491.0	-0.79	337.0	-1.38	53.5	-1.47	20.349	0.02	5132.1	-0.16	7.24	0.11	1.00
30.6	-10.0	1922.0	-0.17	690.0	-0.40	492.9	-0.40	339.2	-0.73	53.9	-0.74	20.359	0.07	5136.2	-0.08	7.24	0.06	1.00
34.0	0.0	1925.3	0.00	692.8	0.00	494.9	0.00	341.7	0.00	54.3	0.00	20.344	0.00	5140.4	0.00	7.23	0.00	1.00
37.4	10.0	1927.1	0.09	695.6	0.40	496.8	0.38	344.1	0.70	54.7	0.74	20.349	0.02	5144.9	0.09	7.22	-0.11	1.00
40.8	20.0	1929.4	0.21	698.5	0.82	498.8	0.79	346.4	1.38	55.0	1.29	20.342	-0.01	5148.8	0.16	7.22	-0.17	1.00
Mol. Weight g/mole	Z	Muzzle m/s	Velocity Z	Max. Liq. Press. MPa	Max. Comb. Press. MPa	Max. Base Press. MPa	Pres. Z	Max. Accel. Z	Max. Pist cm	Travel Pist. Z	Pist. Vel ² Impact cm/s	Time @ Eject ms	Z @ 80					
19.8970	-20.0	1925.7	0.02	693.0	0.03	495.0	0.02	341.8	0.03	54.3	0.00	20.357	0.06	5142.0	0.03	7.23	-0.06	1.00
22.3785	-10.0	1925.2	-0.01	692.9	0.01	495.0	0.02	341.7	0.00	54.3	0.00	20.349	0.02	5141.2	0.02	7.23	-0.06	1.00
24.8650	0.0	1925.3	0.00	692.8	0.00	494.9	0.00	341.7	0.00	54.3	0.00	20.344	0.00	5140.4	0.00	7.23	0.00	1.00
27.3515	10.0	1923.8	-0.08	691.7	-0.16	494.1	-0.16	340.9	-0.23	54.1	-0.37	20.342	-0.01	5138.7	-0.03	7.24	0.06	1.00
29.8380	20.0	1923.5	-0.09	692.6	-0.03	494.8	-0.02	341.5	-0.06	54.3	0.00	20.358	0.07	5139.4	-0.02	7.23	0.00	1.00
Bulk Modulus MPa	Z	Muzzle m/s	Velocity Z	Max. Liq. Press. MPa	Max. Comb. Press. MPa	Max. Base Press. MPa	Pres. Z	Max. Accel. Z	Max. Pist cm	Travel Pist. Z	Pist. Vel ² Impact cm/s	Time @ Eject ms	Z @ 80					
4082.8	-20.0	1925.7	0.02	695.6	0.40	496.8	0.38	339.0	-0.79	53.8	-0.92	20.351	0.03	5124.6	-0.31	7.31	1.05	1.00
4593.2	-10.0	1925.3	0.00	694.1	0.19	495.7	0.16	340.4	-0.38	54.1	-0.37	20.361	0.08	5140.2	-0.00	7.26	0.44	1.00
5103.5	0.0	1925.3	0.00	692.8	0.00	494.9	0.00	341.7	0.00	54.3	0.00	20.344	0.00	5140.4	0.00	7.23	0.00	1.00
5613.9	10.0	1924.7	-0.03	691.9	-0.13	494.2	-0.14	342.9	0.35	54.5	0.37	20.353	0.04	5141.2	0.02	7.20	-0.44	1.00
6124.2	20.0	1923.6	-0.09	691.0	-0.26	493.6	-0.26	343.9	0.64	54.6	0.55	20.354	0.05	5141.0	0.01	7.17	-0.83	1.00

120MM REGENERATIVE LIQUID PROPELLANT GUN
SENSITIVITY STUDY
RLGD CODE

8. Mod. Derv.	Muzzle	Velocity	Max. Liq.	Press.	Max. Comb	Pres.	Max. Base	Pres.	Kgs	Max. Accel.	Max. Pist	Travel	Pist.	Vel	Impact	Time	Eject	z
dBW/dP	z	m/s	MPa	z	MPa	z	MPa	z	z	z	cm	z	cm/s	z	ms	z	z	z
6.574	-20.0	1924.3	-0.02	692.9	0.01	494.8	-0.02	339.7	-0.59	53.9	-0.74	20.351	0.03	5135.9	-0.09	7.24	0.17	1.00
7.376	-10.0	1925.2	-0.01	693.0	0.03	495.0	0.02	340.8	-0.26	54.1	-0.37	20.348	0.02	5138.5	-0.04	7.24	0.06	1.00
8.217	0.0	1925.3	0.00	692.8	0.00	494.9	0.00	341.7	0.00	54.3	0.00	20.344	0.00	5140.4	0.00	7.23	0.00	1.00
9.039	10.0	1924.7	-0.03	692.8	0.00	494.9	0.00	342.6	0.26	54.4	0.18	20.359	0.07	5142.8	0.05	7.22	-0.11	1.00
9.861	20.0	1925.3	0.00	692.7	-0.01	494.9	0.00	343.4	0.50	54.6	0.55	20.342	-0.01	5145.0	0.09	7.22	-0.17	1.00
Chemical Energy	Muzzle	Velocity	Max. Liq.	Press.	Max. Comb	Pres.	Max. Base	Pres.	Kgs	Max. Accel.	Max. Pist	Travel	Pist.	Vel	Impact	Time	Eject	z
Joules	z	m/s	MPa	z	MPa	z	MPa	z	z	z	cm	z	cm/s	z	ms	z	z	z
4053.4	-20.0	1724.4	-10.43	560.4	-19.11	400.3	-19.11	281.9	-17.50	44.6	-17.86	20.342	-0.01	4616.2	-10.20	7.84	8.46	1.00
4560.0	-10.0	1827.7	-5.07	626.6	-9.56	447.5	-9.58	311.9	-8.72	49.5	-8.84	20.350	0.03	4890.2	-4.87	7.51	3.87	1.00
5066.7	0.0	1925.3	0.00	692.8	0.00	494.9	0.00	341.7	0.00	54.3	0.00	20.344	0.00	5140.4	0.00	7.23	0.00	1.00
5573.4	10.0	2017.6	4.79	759.0	9.56	542.1	9.54	371.2	8.63	59.0	8.66	20.347	0.01	5382.1	4.70	6.99	-3.37	1.00
6080.0	20.0	2105.2	9.34	825.7	19.18	589.8	19.18	400.6	17.24	63.8	17.50	20.353	0.04	5600.7	8.96	6.77	-6.36	1.00
Sp. Heat Ratio	Muzzle	Velocity	Max. Liq.	Press.	Max. Comb	Pres.	Max. Base	Pres.	Kgs	Max. Accel.	Max. Pist	Travel	Pist.	Vel	Impact	Time	Eject	z
Cp/Cv	z	m/s	MPa	z	MPa	z	MPa	z	z	z	cm	z	cm/s	z	ms	z	z	z
1.103	-10.0	1390.6	-27.77	362.4	-47.69	259.1	-47.65	184.6	-45.98	28.9	-46.78	20.360	0.08	3772.8	-26.60	9.43	30.37	1.00
1.225	0.0	1925.3	0.00	692.8	0.00	494.9	0.00	341.7	0.00	54.3	0.00	20.344	0.00	5140.4	0.00	7.23	0.00	1.00
1.348	10.0	2260.2	17.39	969.3	39.91	691.8	39.79	477.5	39.74	76.2	40.33	20.352	0.04	5960.9	15.96	6.34	-12.33	1.00
1.470	20.0	2499.1	29.80	1205.1	73.95	859.3	73.63	597.4	74.83	95.6	76.06	20.342	-0.01	6536.9	27.17	5.84	-19.30	1.00
Liquid Density	Muzzle	Velocity	Max. Liq.	Press.	Max. Comb	Pres.	Max. Base	Pres.	Kgs	Max. Accel.	Max. Pist	Travel	Pist.	Vel	Impact	Time	Eject	z
g/cc	z	m/s	MPa	z	MPa	z	MPa	z	z	z	cm	z	cm/s	z	ms	z	z	z
1.144	-20.0	1774.1	-7.85	549.3	-20.71	392.7	-20.65	286.4	-16.18	45.3	-16.57	20.350	0.03	5192.5	1.01	7.76	7.25	1.00
1.287	-10.0	1852.2	-3.80	619.9	-10.52	442.9	-10.51	314.1	-8.08	49.8	-8.29	20.346	0.01	5154.6	0.28	7.47	3.32	1.00
1.430	0.0	1925.3	0.00	692.8	0.00	494.9	0.00	341.7	0.00	54.3	0.00	20.344	0.00	5140.4	0.00	7.23	0.00	1.00
1.573	10.0	1991.8	3.45	768.2	10.88	548.6	10.85	368.9	7.96	58.7	8.10	20.346	0.01	5120.4	-0.39	7.02	-2.93	1.00
1.176	20.0	2056.0	6.79	846.6	22.20	604.4	22.13	395.9	15.86	63.0	16.02	20.345	0.00	5123.8	-0.32	6.84	-5.48	1.00
Disc. Coef.	Muzzle	Velocity	Max. Liq.	Press.	Max. Comb	Pres.	Max. Base	Pres.	Kgs	Max. Accel.	Max. Pist	Travel	Pist.	Vel	Impact	Time	Eject	z
Liq. Inj	z	m/s	MPa	z	MPa	z	MPa	z	z	z	cm	z	cm/s	z	ms	z	z	z
0.600	-20.0	1794.3	-6.80	566.0	-18.30	403.4	-18.49	301.6	-11.74	47.8	-11.97	20.353	0.04	3485.4	-32.20	7.57	4.65	1.00
0.675	-10.0	1867.9	-2.98	628.9	-9.22	448.8	-9.32	322.5	-5.62	51.2	-5.71	20.357	0.06	4287.8	-16.59	7.38	2.10	1.00
0.750	0.0	1925.3	0.00	692.8	0.00	494.9	0.00	341.7	0.00	54.3	0.00	20.344	0.00	5140.4	0.00	7.23	0.00	1.00
0.835	10.0	1972.8	2.47	766.0	10.57	547.5	10.63	361.3	5.74	57.4	5.71	20.346	0.01	6128.0	19.21	7.10	0.98	1.00
0.900	20.0	2002.0	3.98	823.2	18.82	588.8	18.97	375.3	9.83	59.7	9.95	20.361	0.01	6878.5	33.81	7.01	0.97	1.00
Disc. Coef.	Muzzle	Velocity	Max. Liq.	Press.	Max. Comb	Pres.	Max. Base	Pres.	Kgs	Max. Accel.	Max. Pist	Travel	Pist.	Vel	Impact	Time	Eject	z
Ch. Store	z	m/s	MPa	z	MPa	z	MPa	z	z	z	cm	z	cm/s	z	ms	z	z	z
0.800	-20.0	1919.3	-0.31	744.8	7.51	532.4	7.58	332.6	-2.66	52.8	-2.76	20.347	0.01	5411.9	5.28	7.27	0.50	1.00
0.900	-10.0	1922.1	-0.17	714.9	3.19	510.7	3.19	337.6	-1.20	53.6	-1.29	20.343	-0.00	5256.4	2.26	7.25	0.72	1.00
1.000	0.0	1925.3	0.00	692.8	0.00	494.9	0.00	341.7	0.00	54.3	0.00	20.344	0.00	5140.4	0.00	7.23	0.00	1.00

Appendix B

A graphic presentation of the results in Appendix A follows. For each parameter change two graphs are presented:

- 1) Percentage change in parameter vs. percentage changes in maximum liquid pressure, maximum combustion chamber pressure, and maximum base pressure.
- 2) Percentage change in parameter vs. percentage changes in muzzle velocity and maximum piston velocity.

PISTON WEIGHT

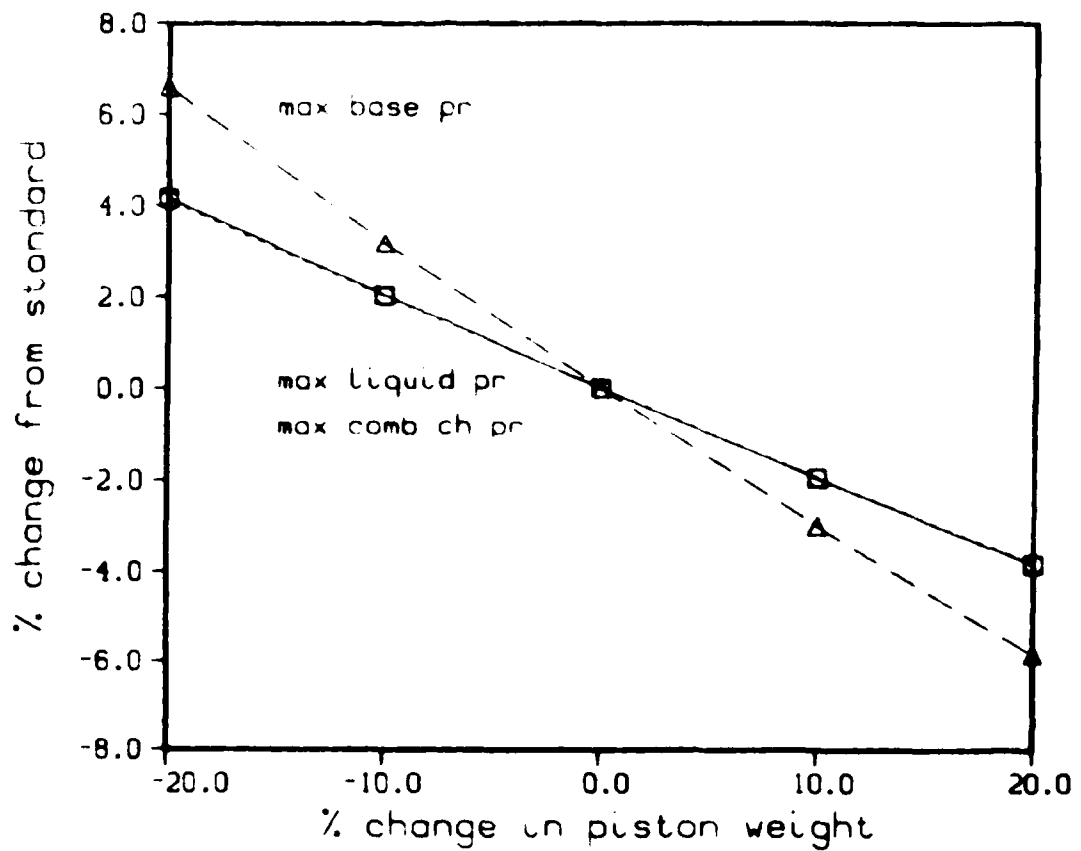


Figure B-1. Percentage change in piston weight vs. percentage changes in maximum liquid pressure, maximum combustion chamber pressure, and maximum base pressure.

PISTON WEIGHT

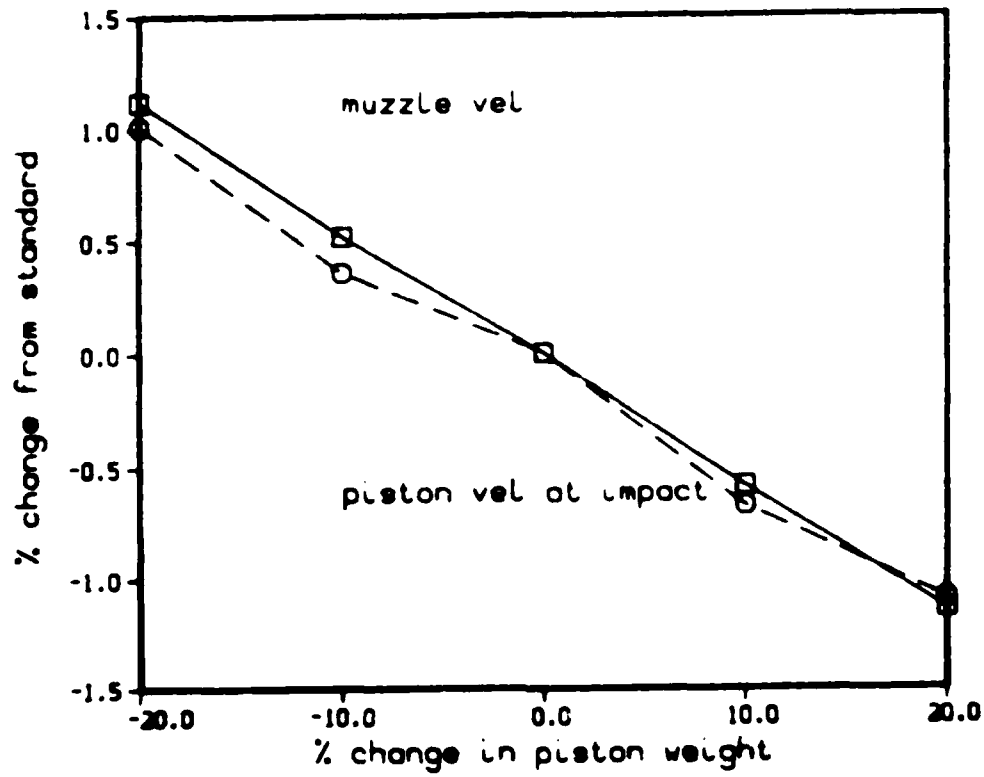


Figure B-2. Percentage change in piston weight vs. percentage changes in muzzle velocity and maximum piston velocity.

PROJECTILE WEIGHT

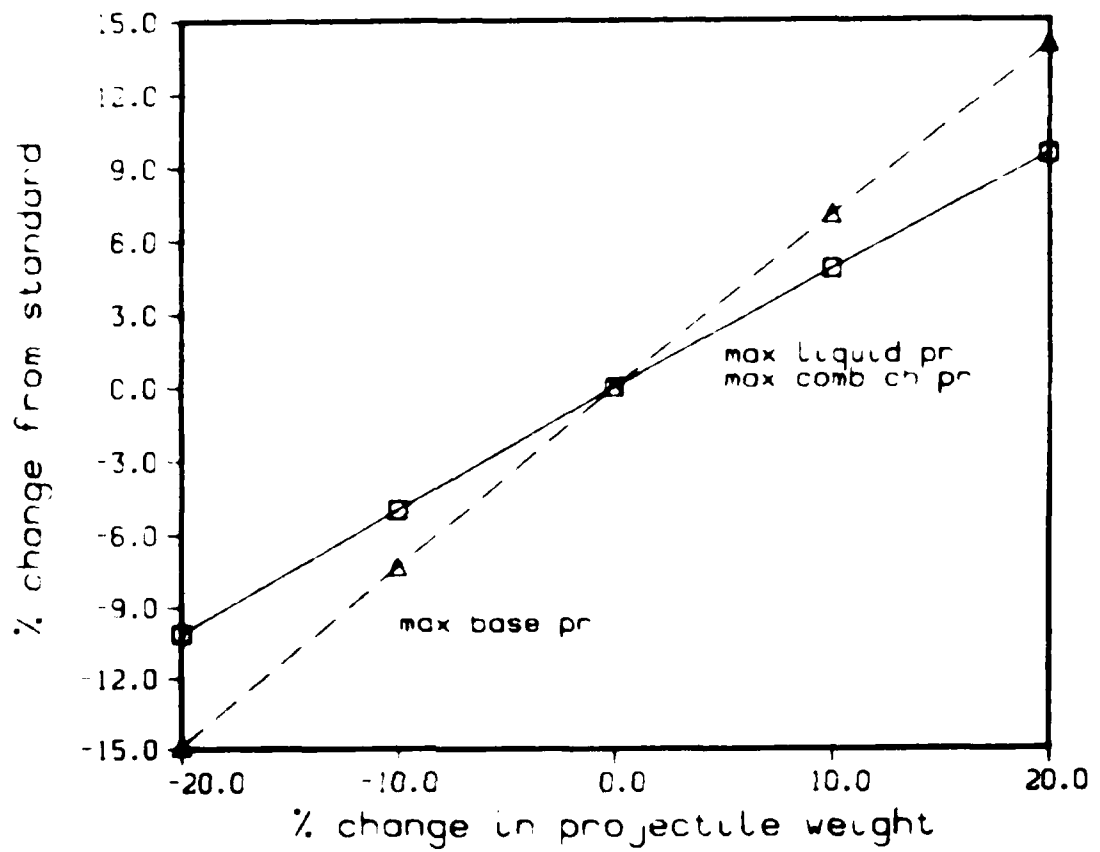


Figure B-3. Percentage change in projectile weight vs. percentage changes in maximum liquid pressure, maximum combustion chamber pressure, and maximum base pressure.

PROJECTILE WEIGHT

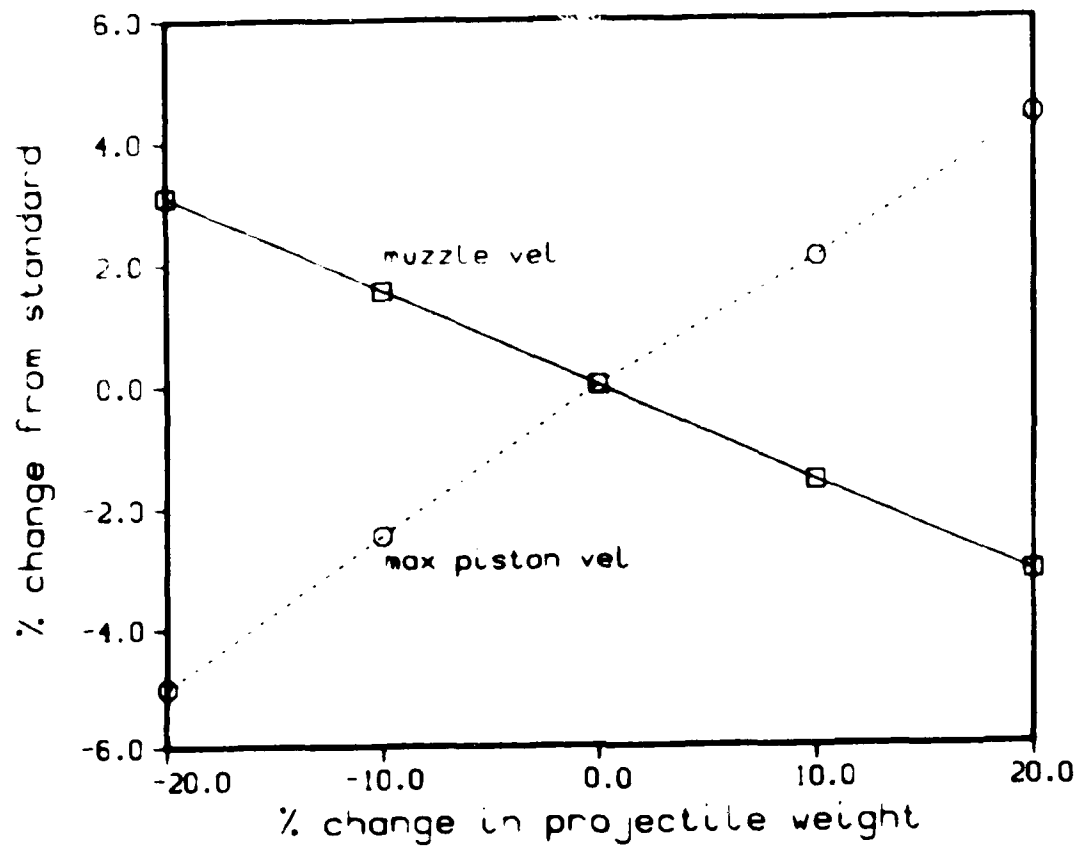


Figure B-4. Percentage change in projectile weight vs. percentage changes in muzzle velocity and maximum piston velocity.

CHAMBER VOLUME.

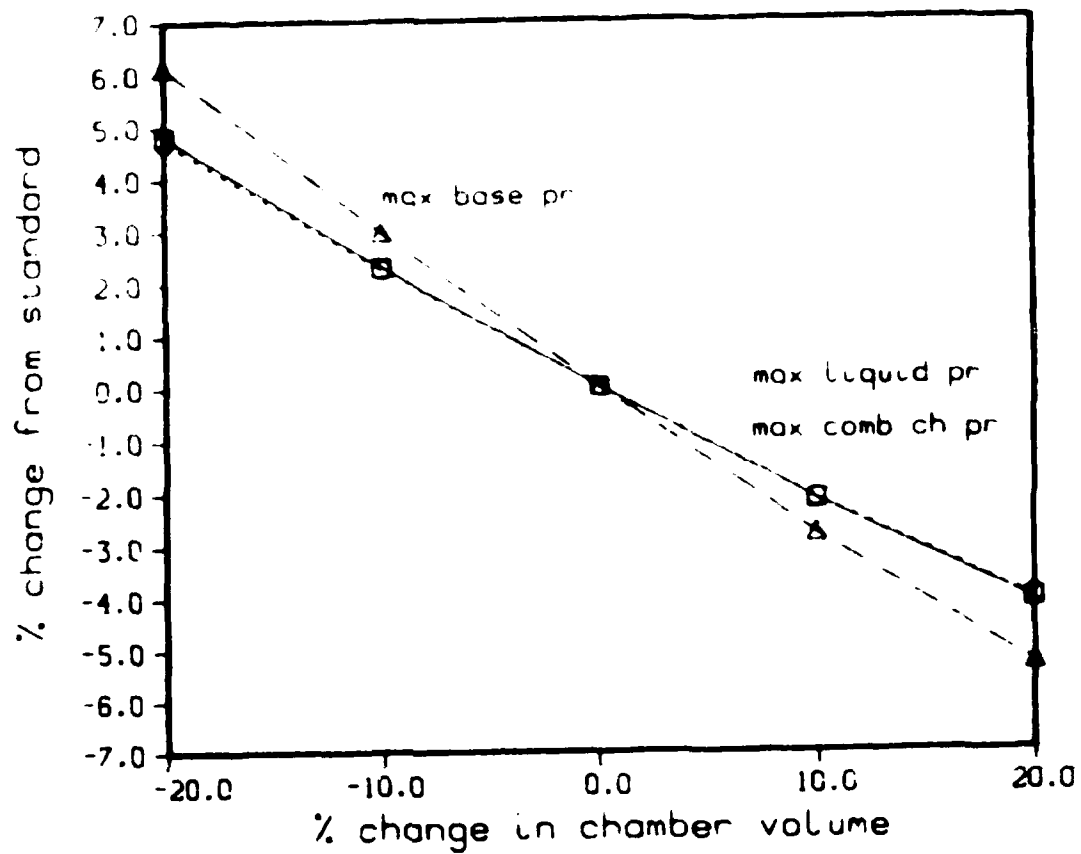


Figure B-5. Percentage change in chamber volume vs. percentage changes in maximum liquid pressure, maximum combustion chamber pressure, and maximum base pressure.

CHAMBER VOLUME

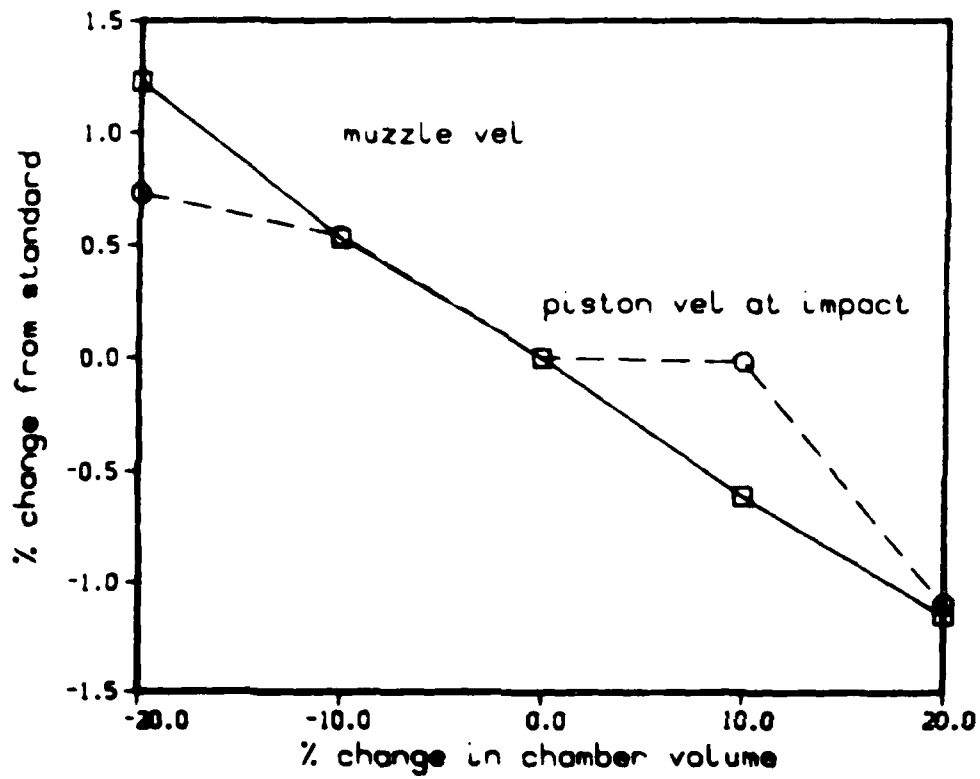


Figure B-6. Percentage change in chamber volume vs. percentage changes in muzzle velocity and maximum piston velocity.

LIQUID VOLUME

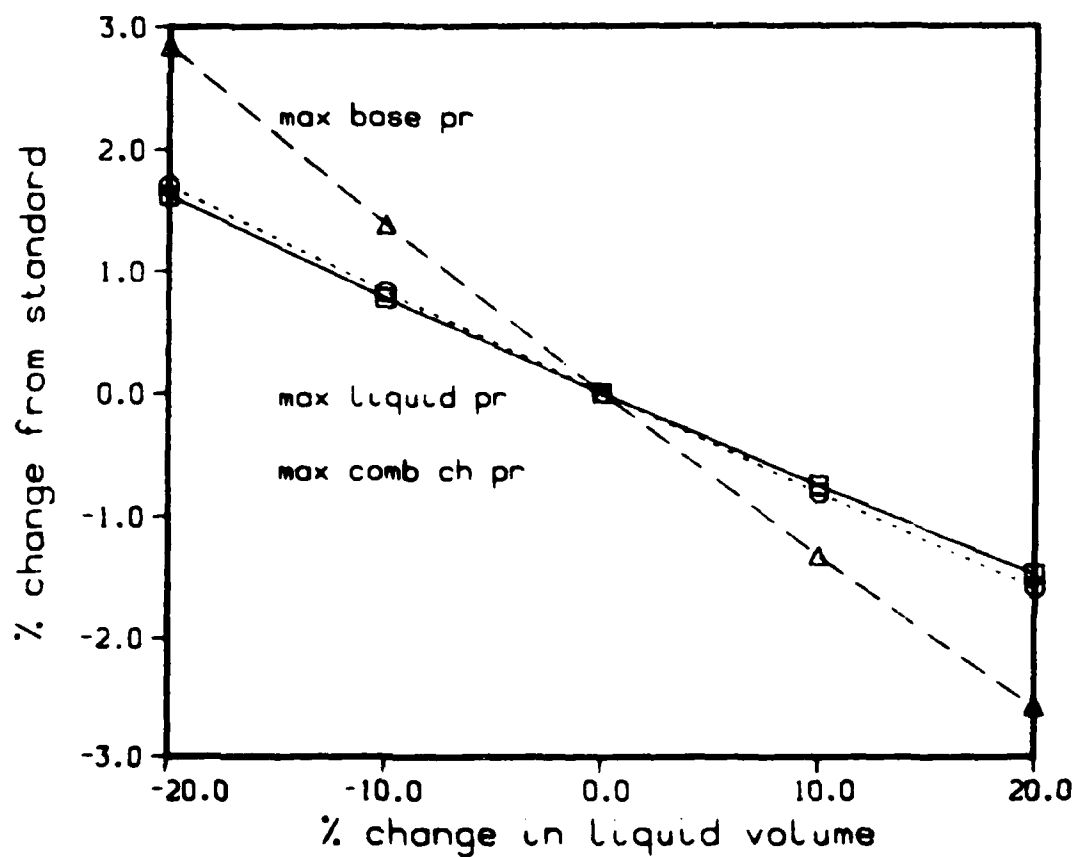


Figure B-1. Percentage change in liquid volume vs. percentage changes in maximum liquid pressure, maximum combustion chamber pressure, and maximum base pressure.

LIQUID VOLUME

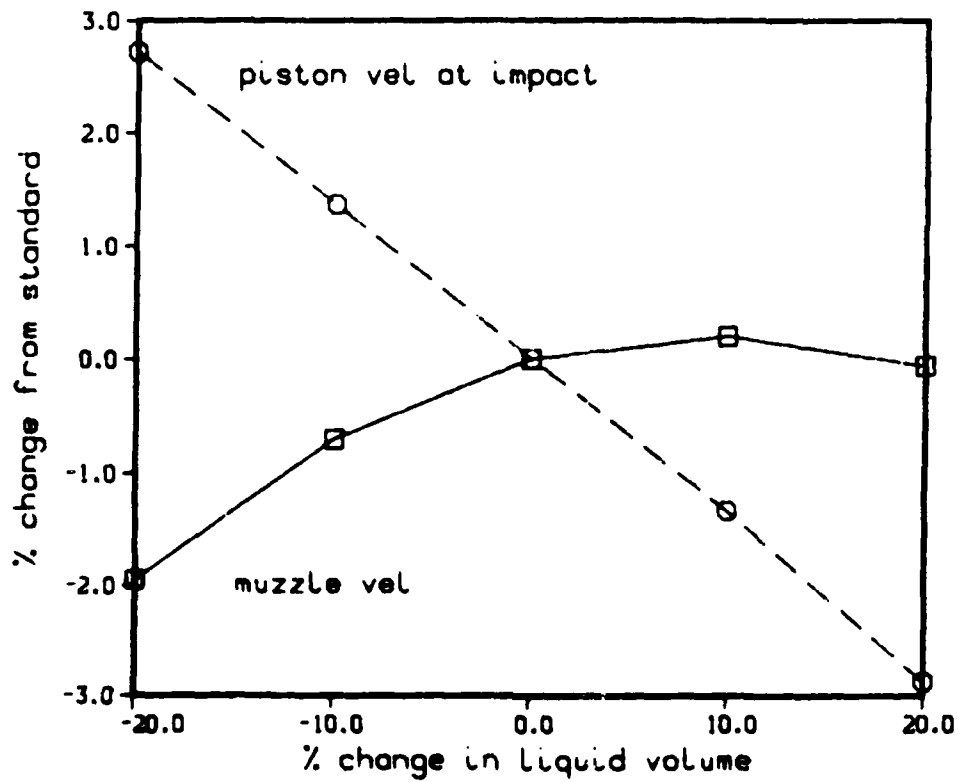


Figure B-8. Percentage change in liquid volume vs. percentage changes in muzzle velocity and maximum piston velocity.

AREA OF LIQUID RESEVOIR

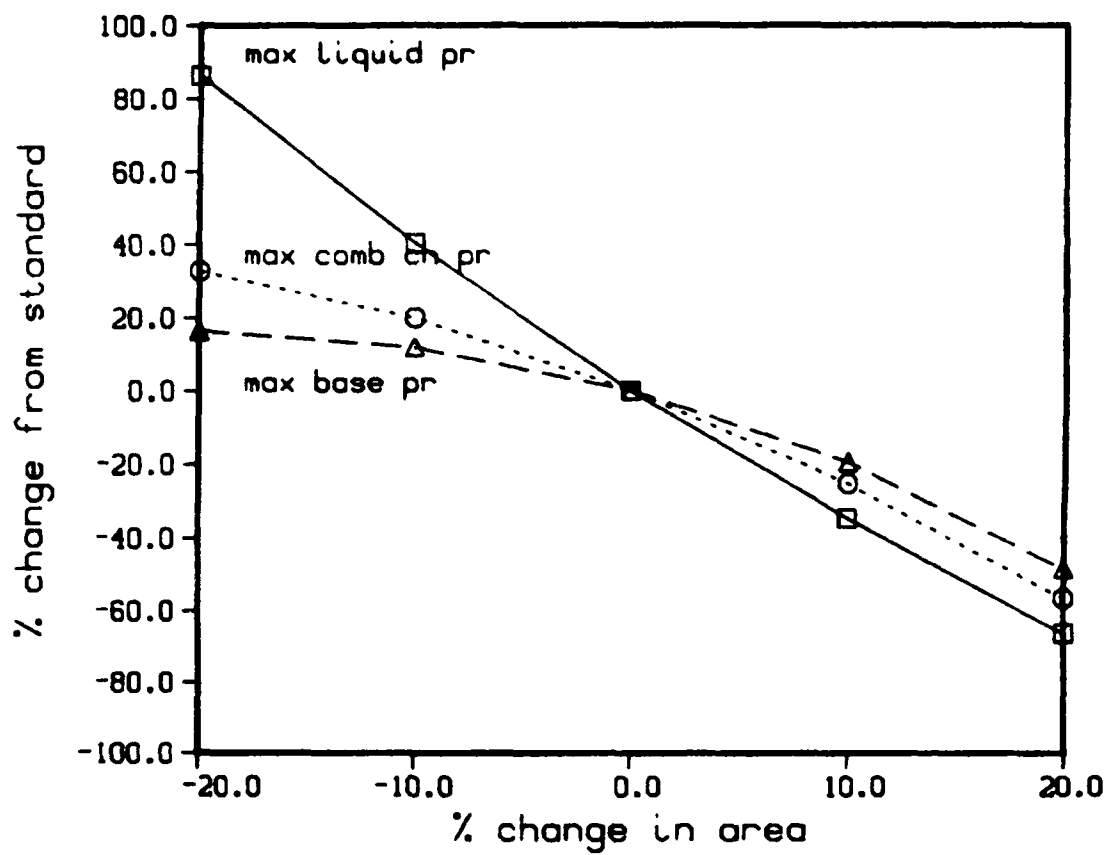


Figure B-9. Percentage change in area of liquid reservoir vs. percentage changes in maximum liquid pressure, maximum combustion chamber pressure, and maximum base pressure.

AREA OF LIQUID RESEVOIR

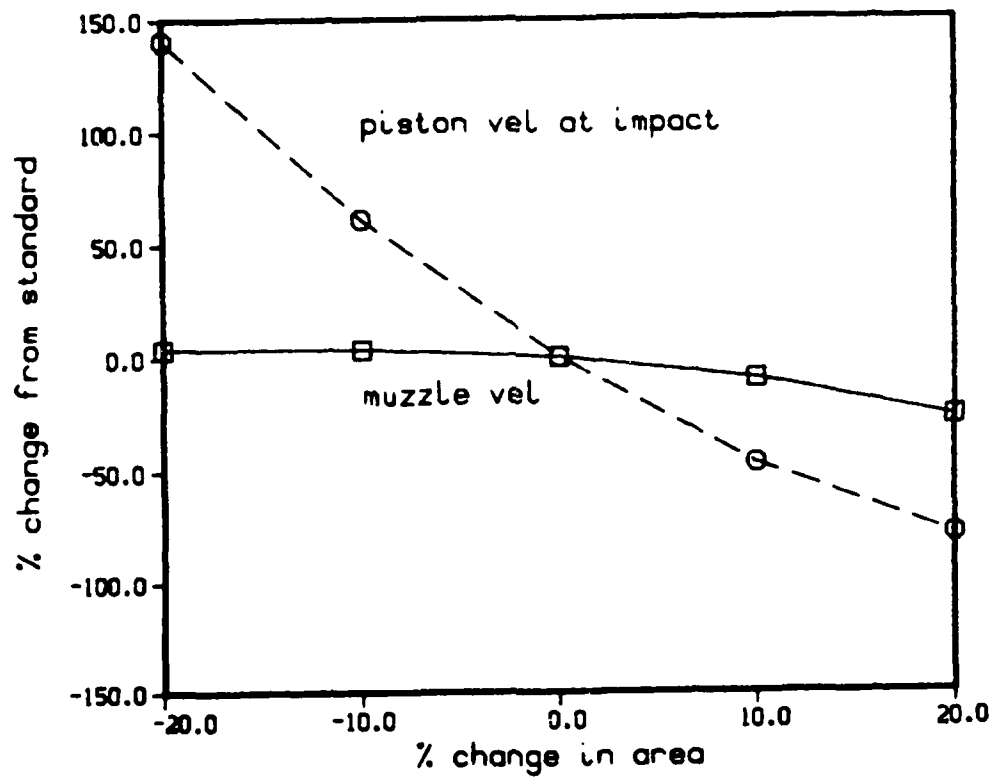


Figure B-10. Percentage change in area of liquid reservoir vs. percentage changes in muzzle velocity and maximum piston velocity.

AREA OF COMBUSTION CHAMBER

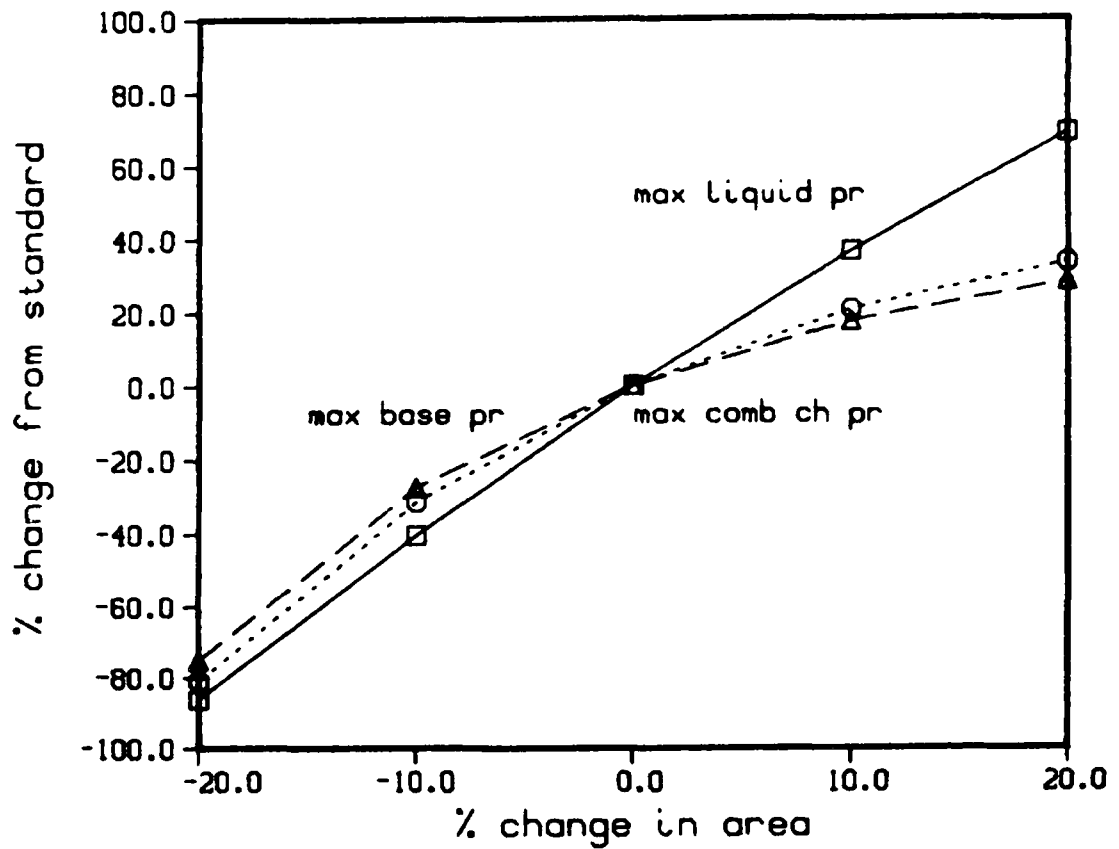


Figure B-11. Percentage change in area of combustion chamber vs. percentage changes in maximum liquid pressure, maximum combustion chamber pressure, and maximum base pressure.

AREA OF COMBUSTION CHAMBER

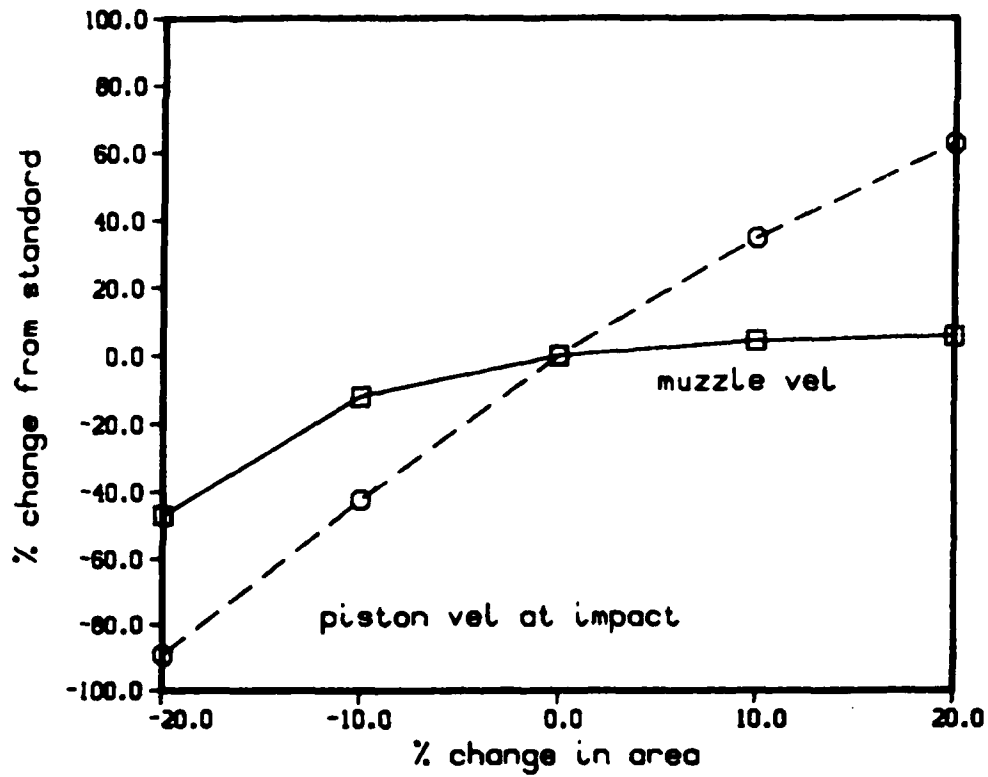


Figure B-12. Percentage change in area of combustion chamber vs. percentage changes in muzzle velocity and maximum piston velocity.

COVOLUME

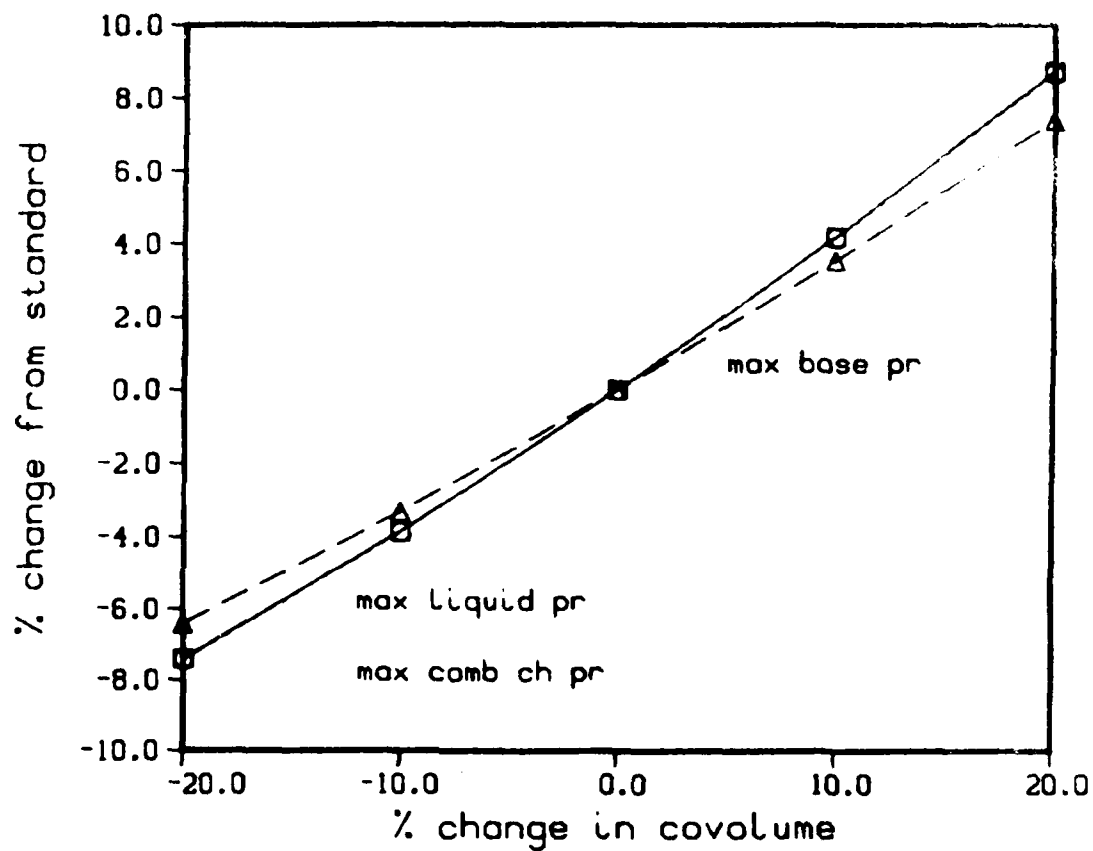


Figure B-13. Percentage change in covolume vs. percentage changes in maximum liquid pressure, maximum combustion chamber pressure, and maximum base pressure.

COVOLUME

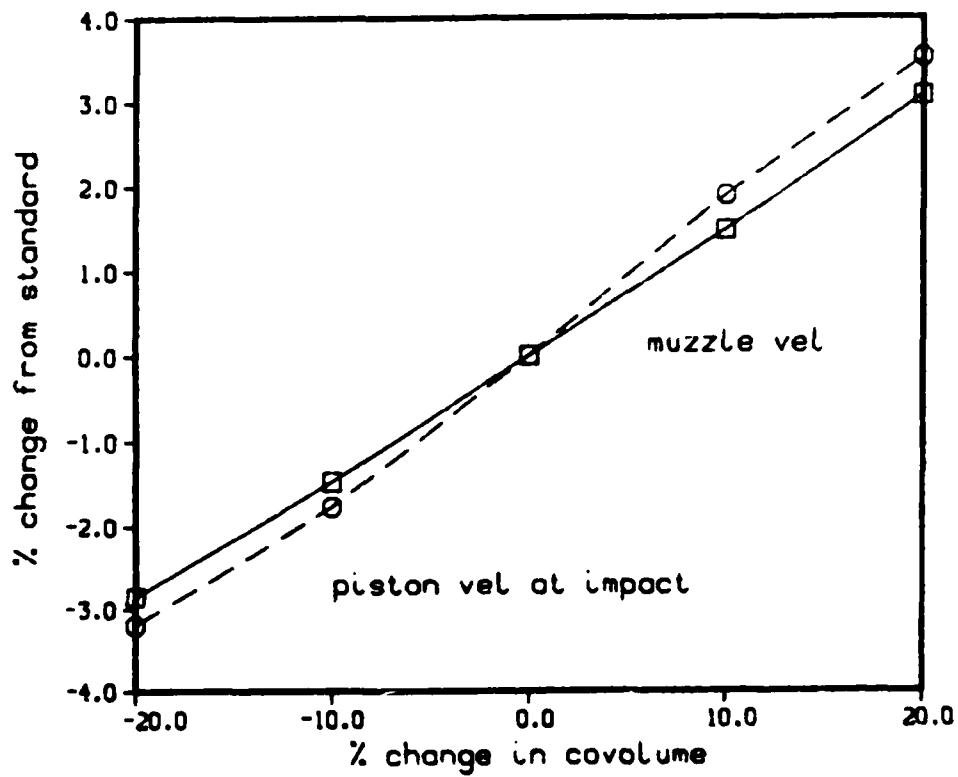


Figure B-14. Percentage change in covolume vs. percentage changes in muzzle velocity and maximum piston velocity.

VENT AREA

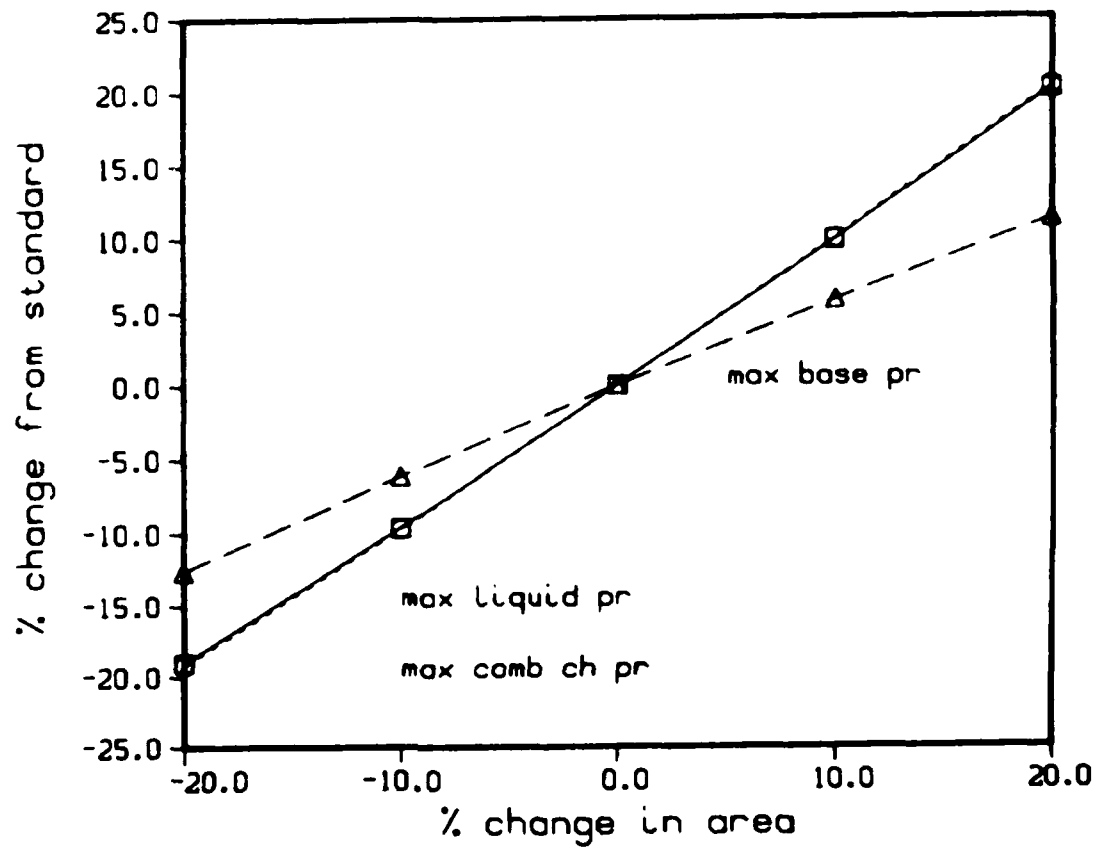


Figure B-15. Percentage change in vent area vs. percentage changes in maximum liquid pressure, maximum combustion chamber pressure, and maximum base pressure.

VENT AREA

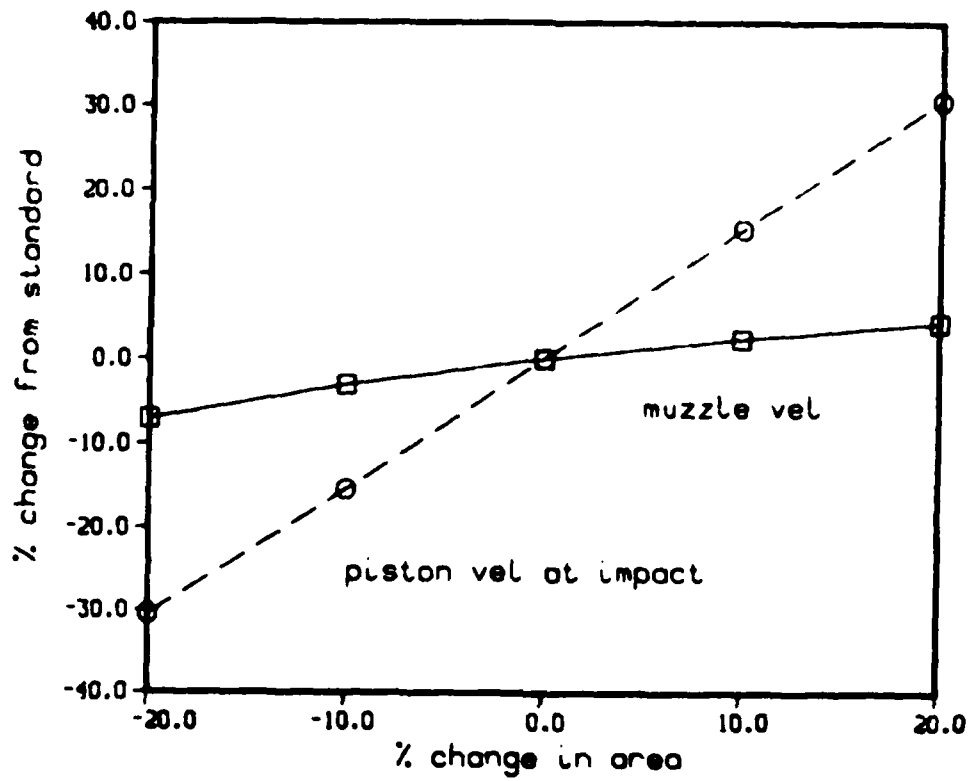


Figure B-16. Percentage change in vent area vs. percentage changes in muzzle velocity and maximum piston velocity.

SHOT START PRESSURE

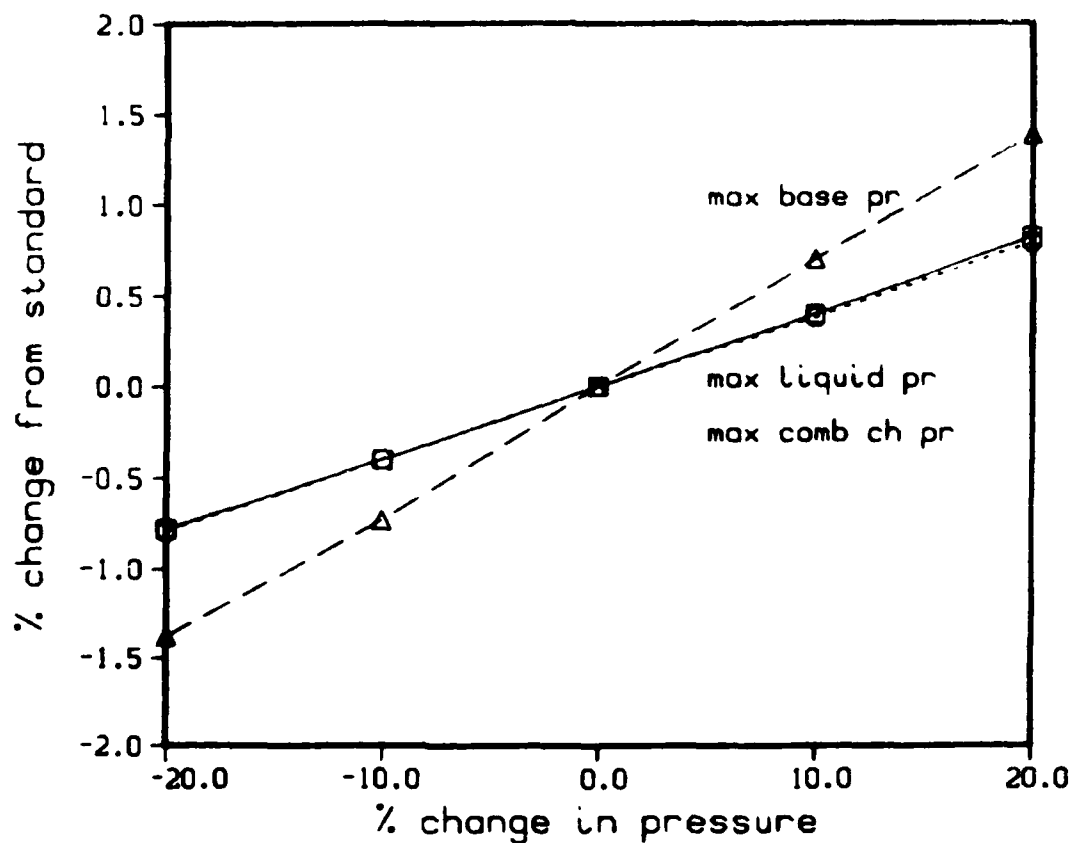


Figure B-17. Percentage change in shot start pressure vs. percentage changes in maximum liquid pressure, maximum combustion chamber pressure, and maximum base pressure.

SHOT START PRESSURE

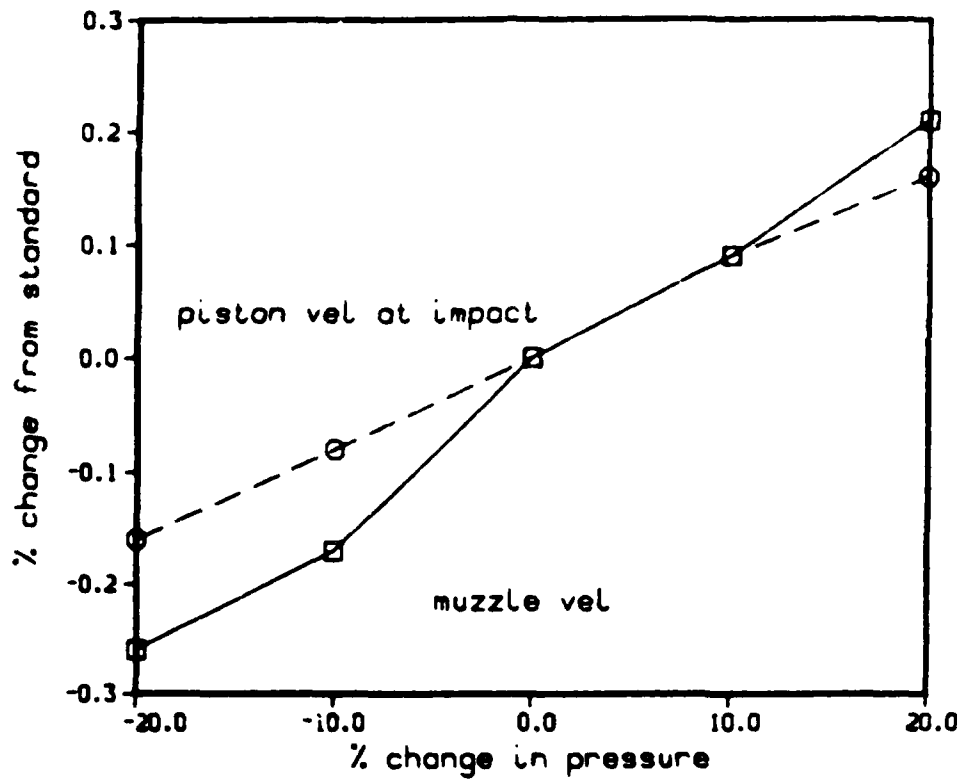


Figure B-18. Percentage change in shot start pressure vs. percentage changes in muzzle velocity and maximum piston velocity.

MOLECULAR WEIGHT

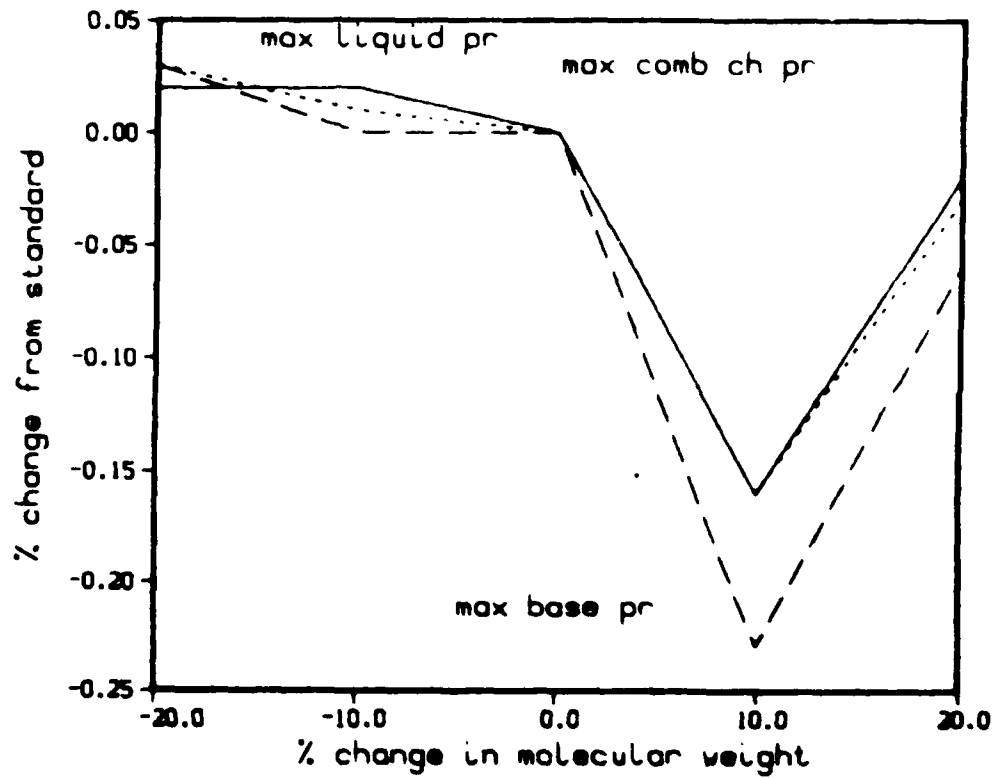


Figure B-19. Percentage change in molecular weight vs. percentage changes in maximum liquid pressure, maximum combustion chamber pressure, and maximum base pressure.

MOLECULAR WEIGHT

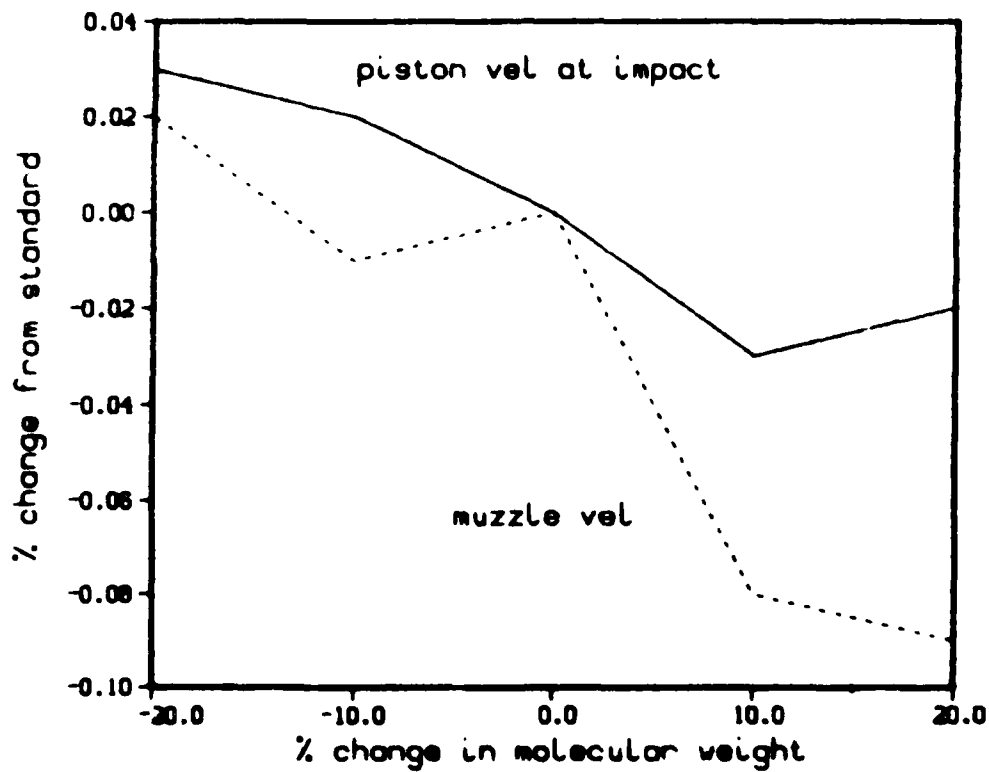


Figure B-20. Percentage change in molecular weight vs. percentage changes in muzzle velocity and maximum piston velocity.

BULK MODULUS

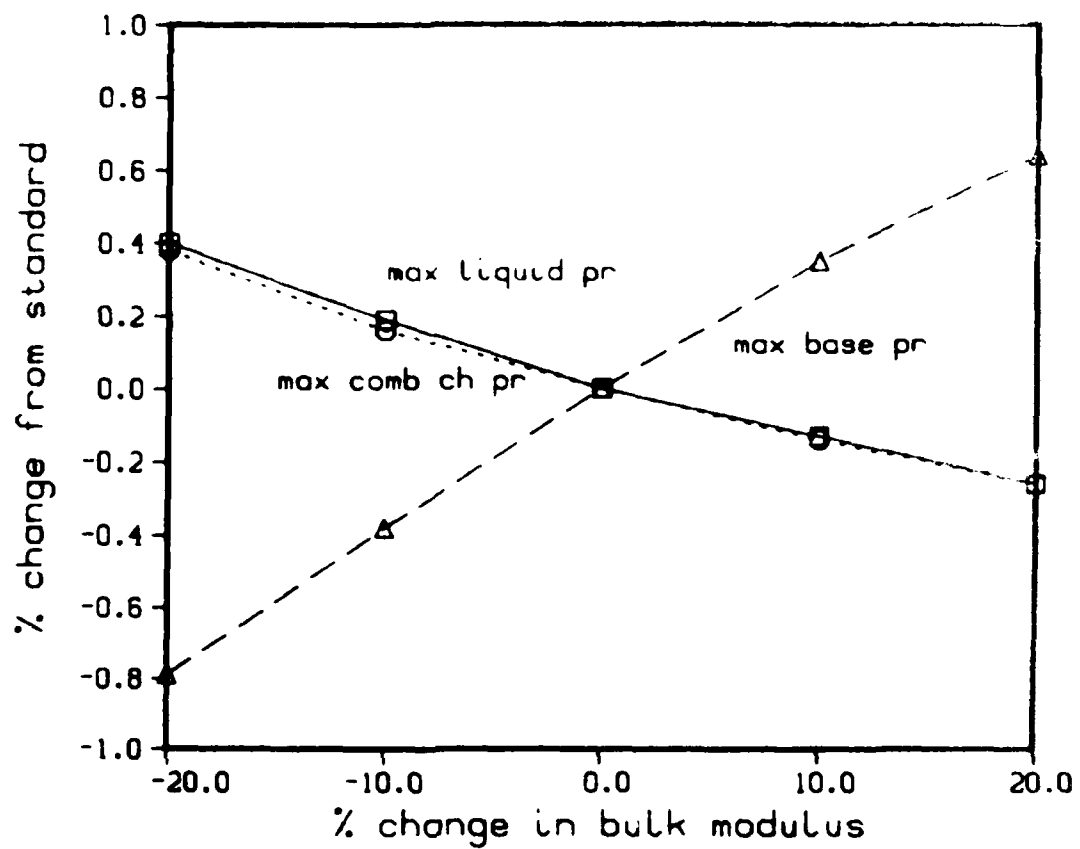


Figure B-21. Percentage change in bulk modulus vs. percentage changes in maximum liquid pressure, maximum combustion chamber pressure, and maximum base pressure.

BULK MODULUS

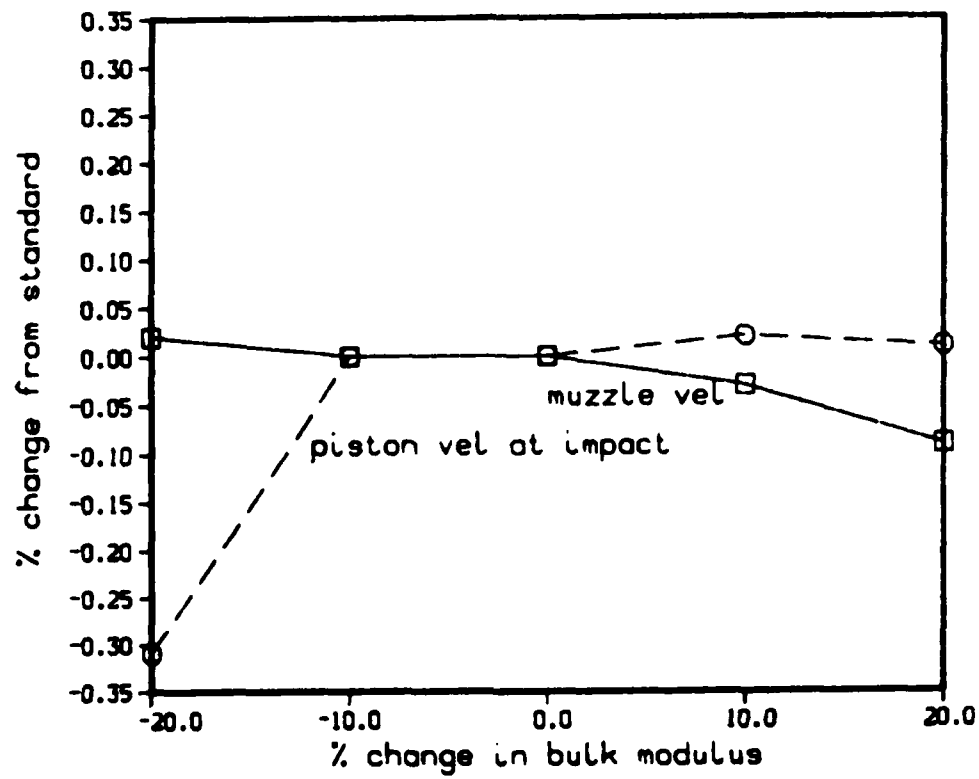


Figure B-22. Percentage change in bulk modulus vs. percentage changes in muzzle velocity and maximum piston velocity.

DERIVATIVE OF BULK MODULUS WITH PRESSURE

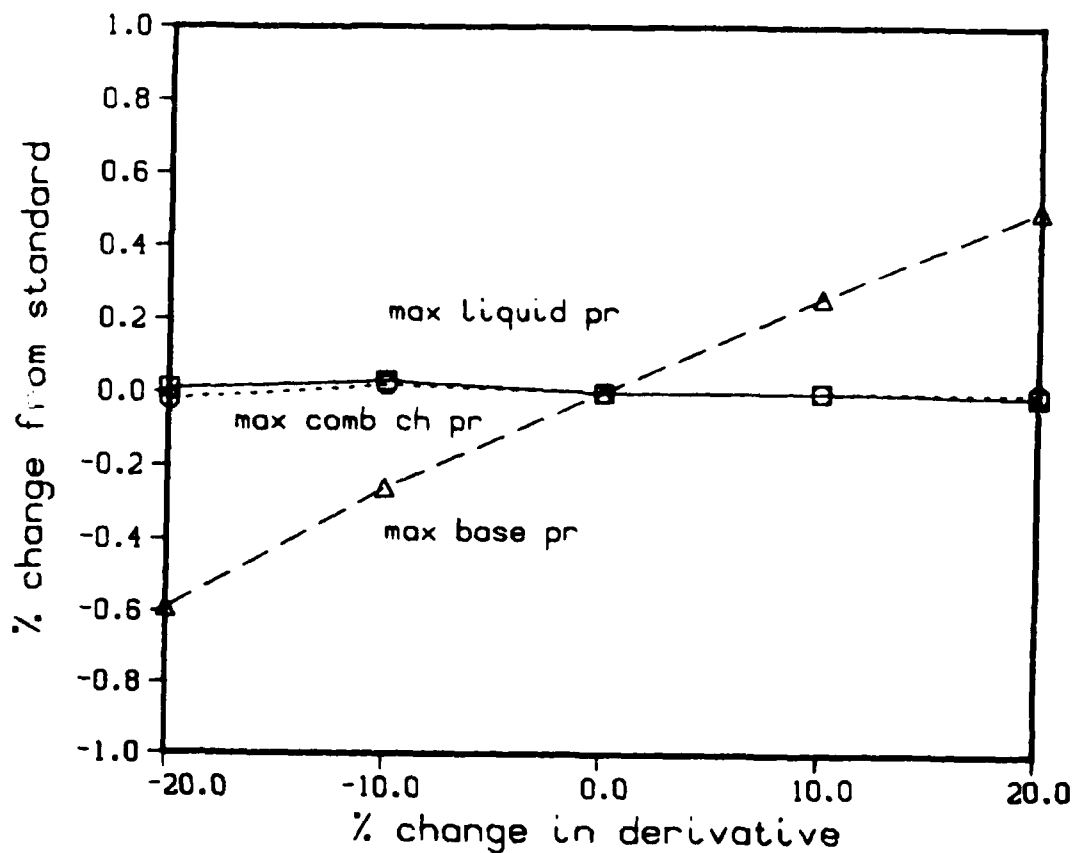


Figure B-23. Percentage change in derivative of bulk modulus with pressure vs. percentage changes in maximum liquid pressure, maximum combustion chamber pressure, and maximum base pressure.

DERIVATIVE OF BULK MODULUS WITH PRESSURE

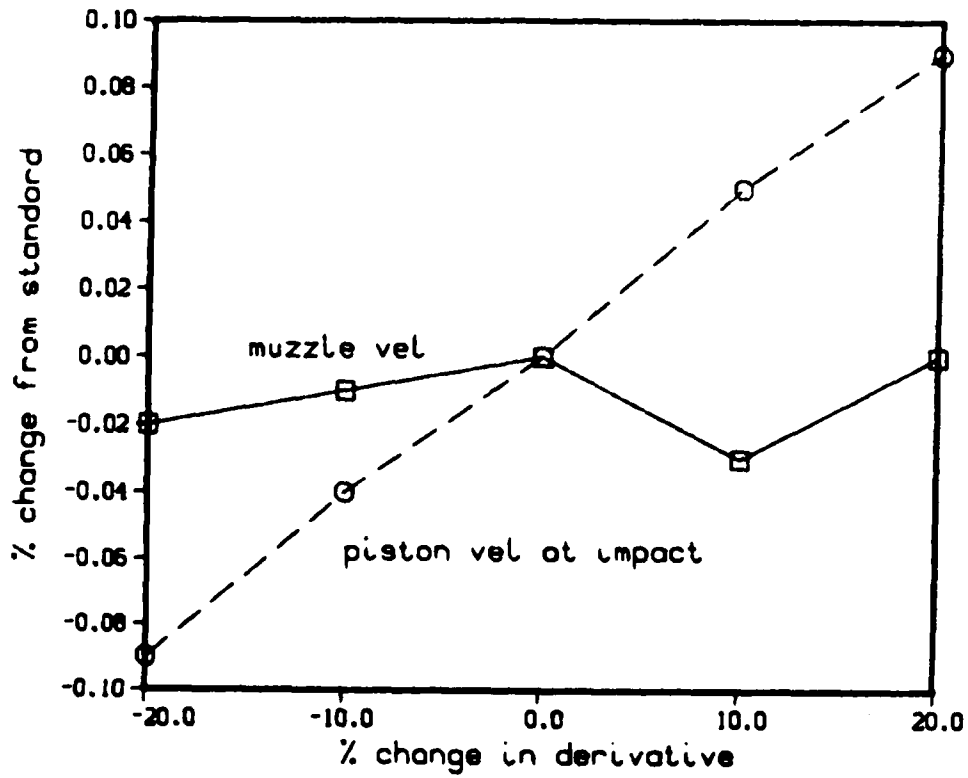


Figure B-24. Percentage change in derivative of bulk modulus with pressure vs. percentage changes in muzzle velocity and maximum piston velocity.

CHEMICAL ENERGY

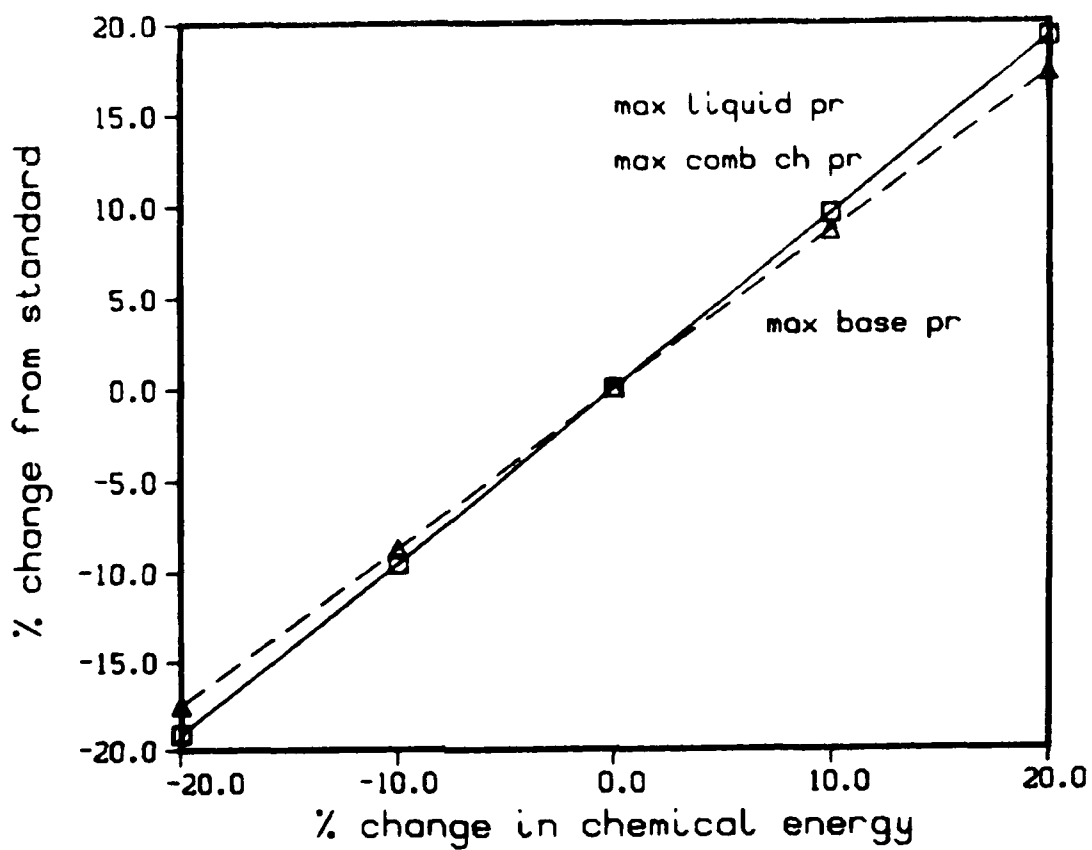


Figure B-25. Percentage change in chemical energy vs. percentage changes in maximum liquid pressure, maximum combustion chamber pressure, and maximum base pressure.

CHEMICAL ENERGY

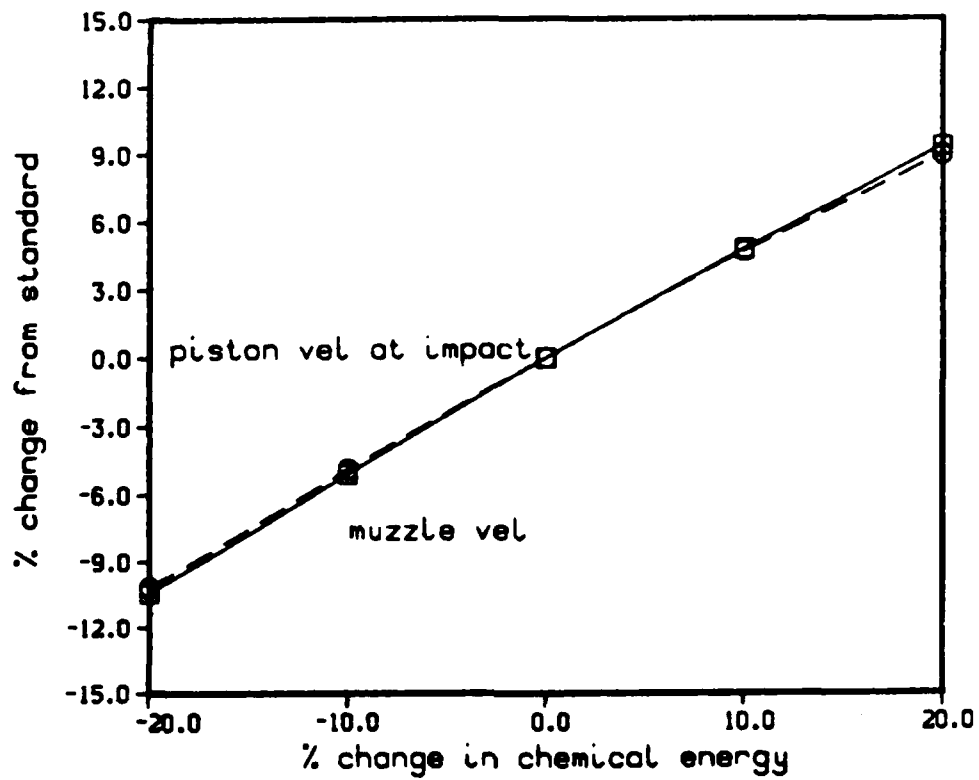


Figure B-26. Percentage change in chemical energy vs. percentage changes in muzzle velocity and maximum piston velocity.

SPECIFIC HEAT RATIO

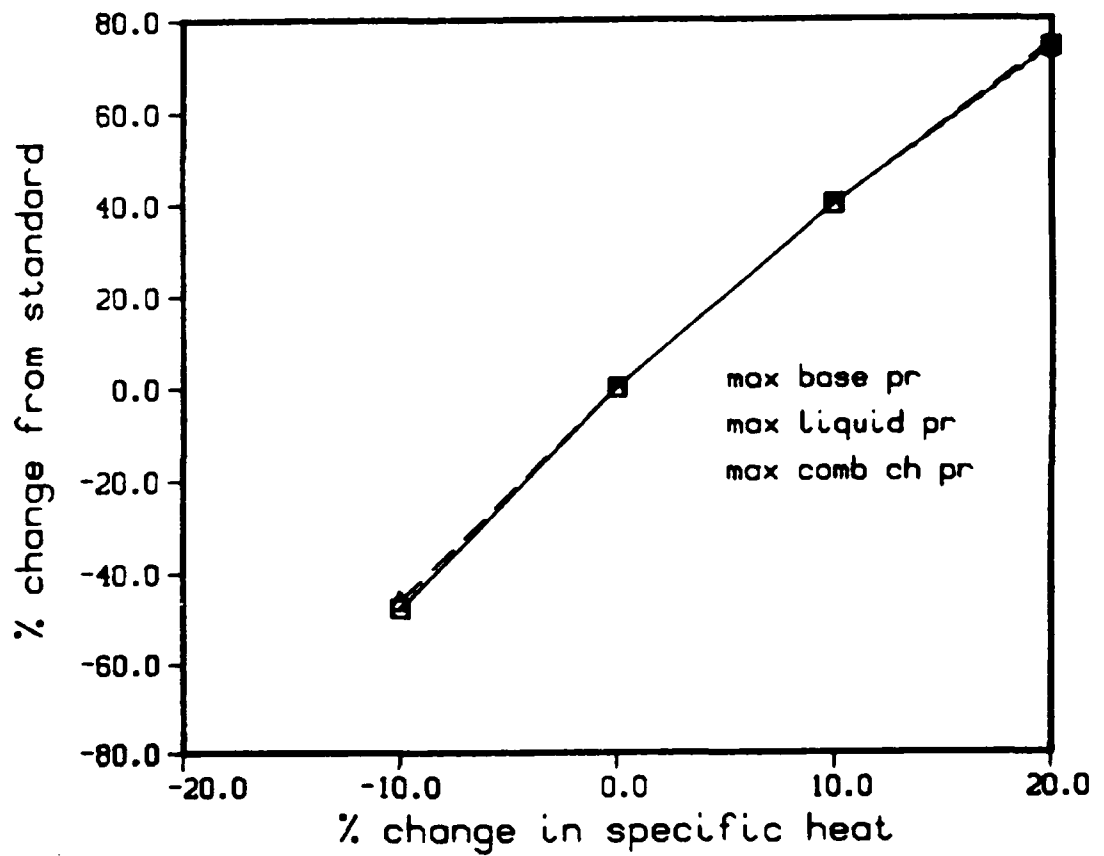


Figure B-27. Percentage change in specific heat ratio vs. percentage changes in maximum liquid pressure, maximum combustion chamber pressure, and maximum base pressure.

SPECIFIC HEAT RATIO

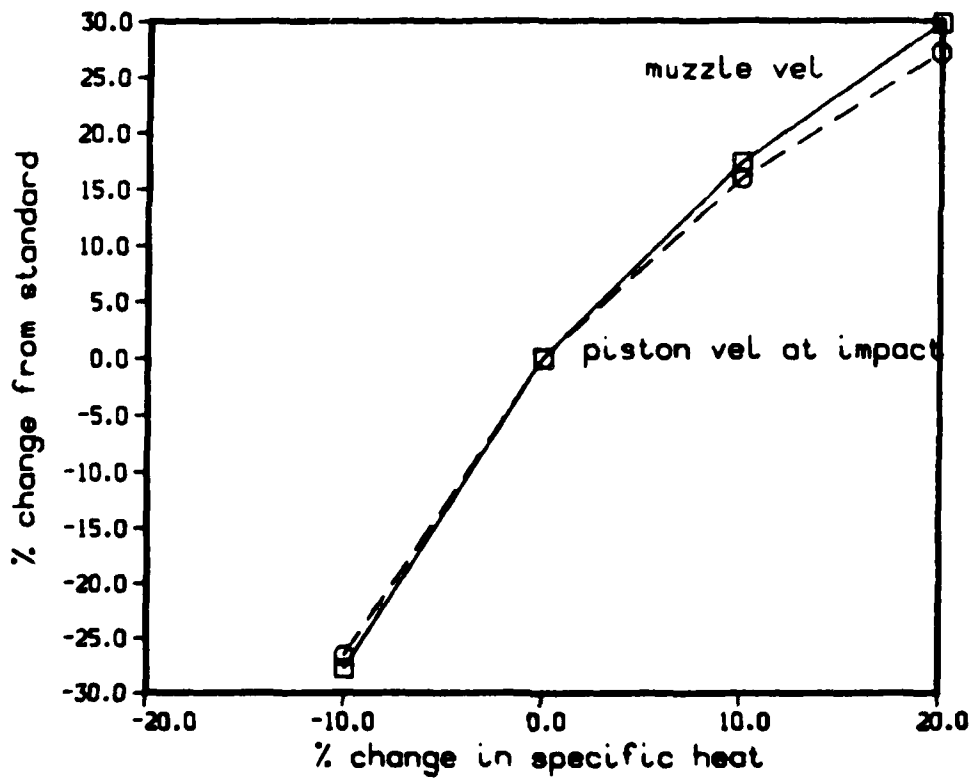


Figure B-28. Percentage change in specific heat ratio vs. percentage changes in muzzle velocity and maximum piston velocity.

DENSITY

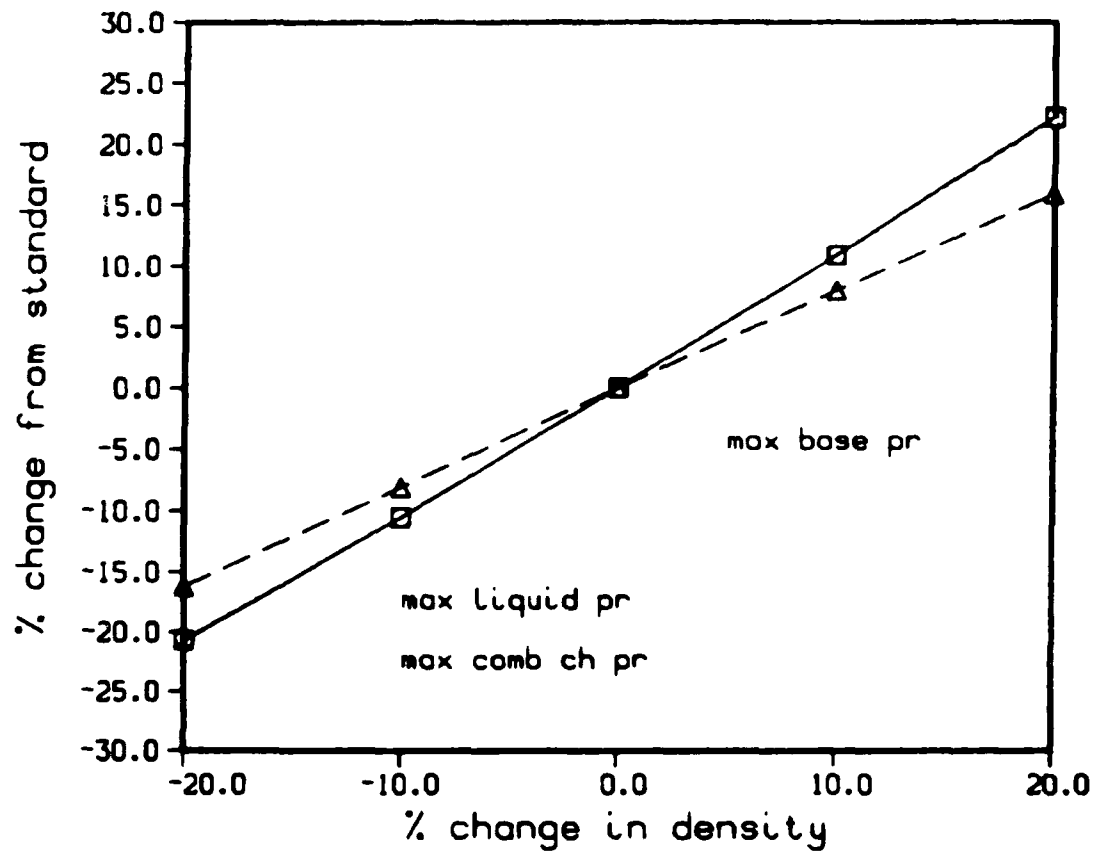


Figure B-29. Percentage change in density vs. percentage changes in maximum liquid pressure, maximum combustion chamber pressure, and maximum base pressure.

DENSITY

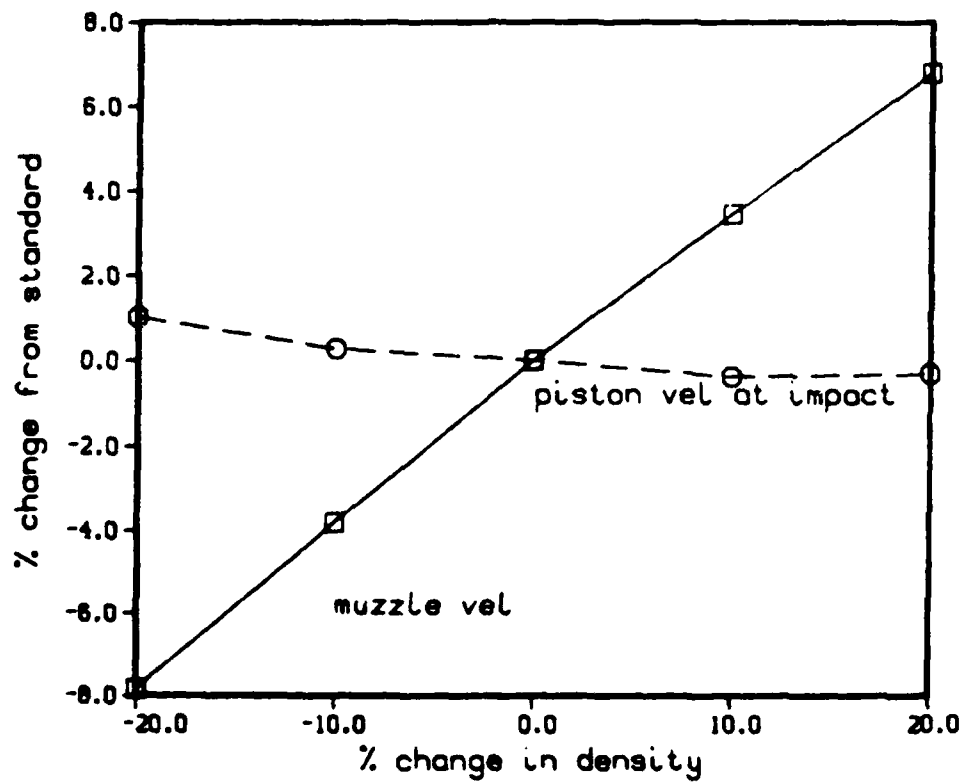


Figure B-30. Percentage change in density vs. percentage changes in muzzle velocity and maximum piston velocity.

DISCHARGE COEFFICIENT OF LIQUID

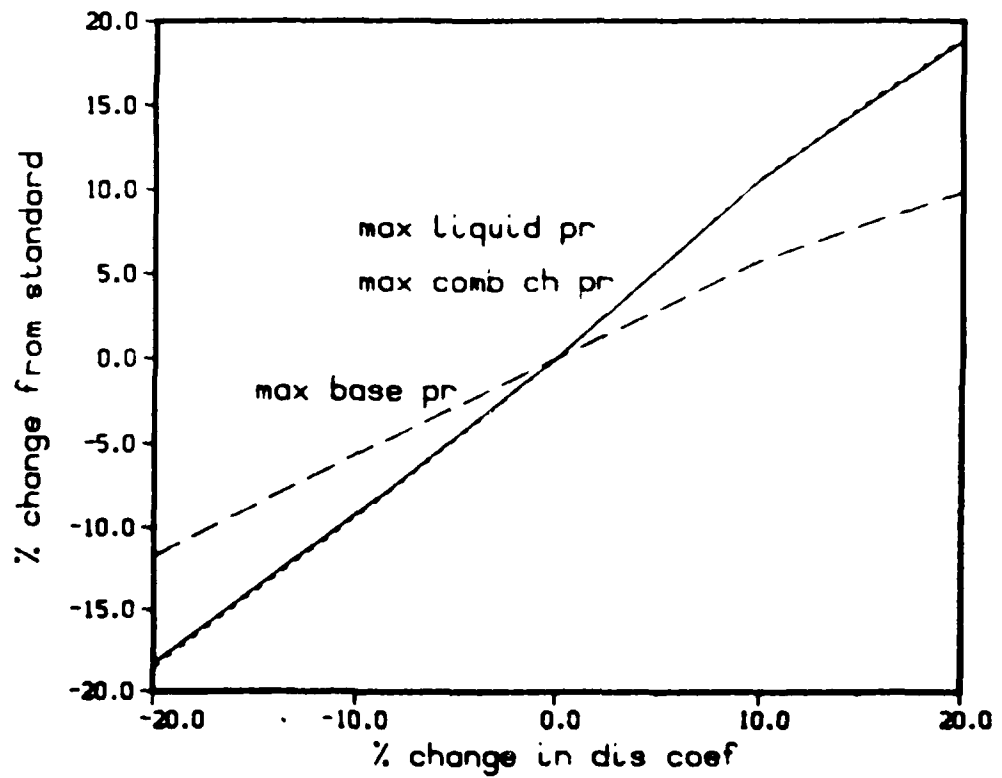


Figure B-31. Percentage change in discharge coefficient of liquid vs. percentage changes in maximum liquid pressure, maximum combustion chamber pressure, and maximum base pressure.

DISCHARGE COEFFICIENT OF LIQUID

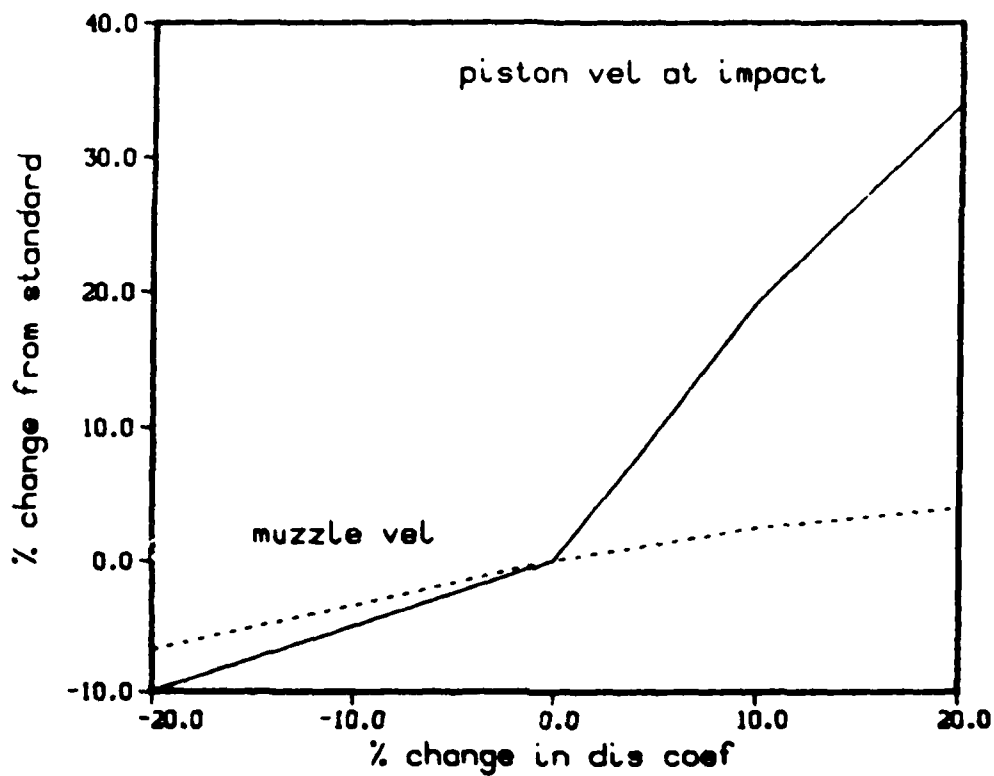


Figure B-32. Percentage change in discharge coefficient of liquid vs. percentage changes in muzzle velocity and maximum piston velocity.

DISCHARGE COEFFICIENT OF GAS

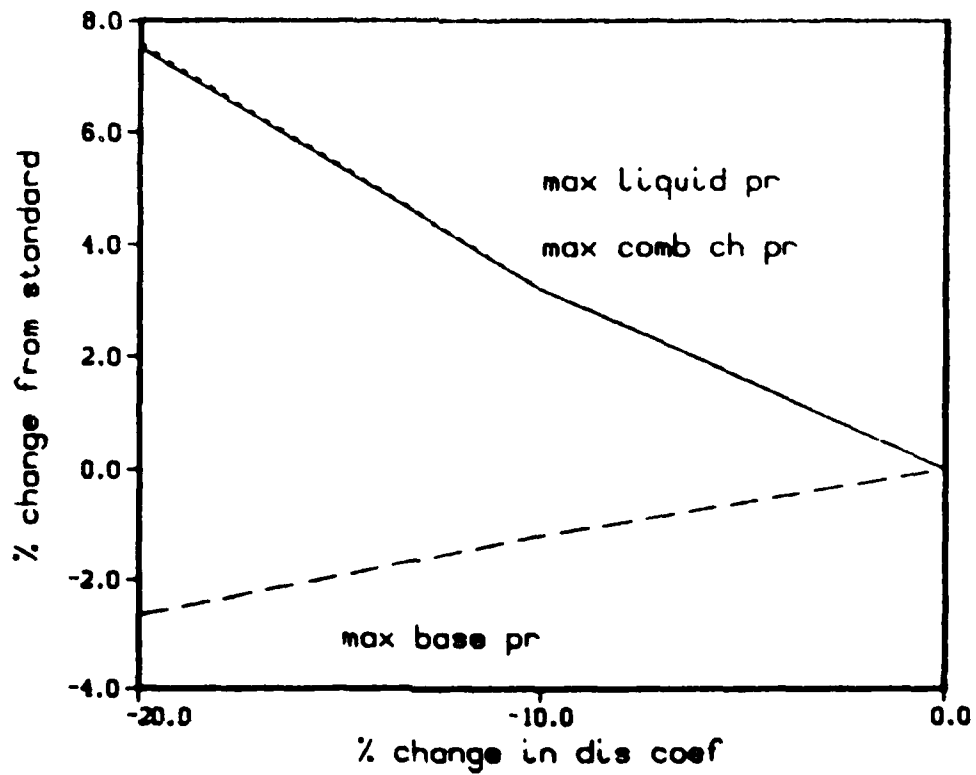


Figure B-33. Percentage change in discharge coefficient of gas vs. percentage changes in maximum liquid pressure, maximum combustion chamber pressure, and maximum base pressure.

DISCHARGE COEFFICIENT OF GAS

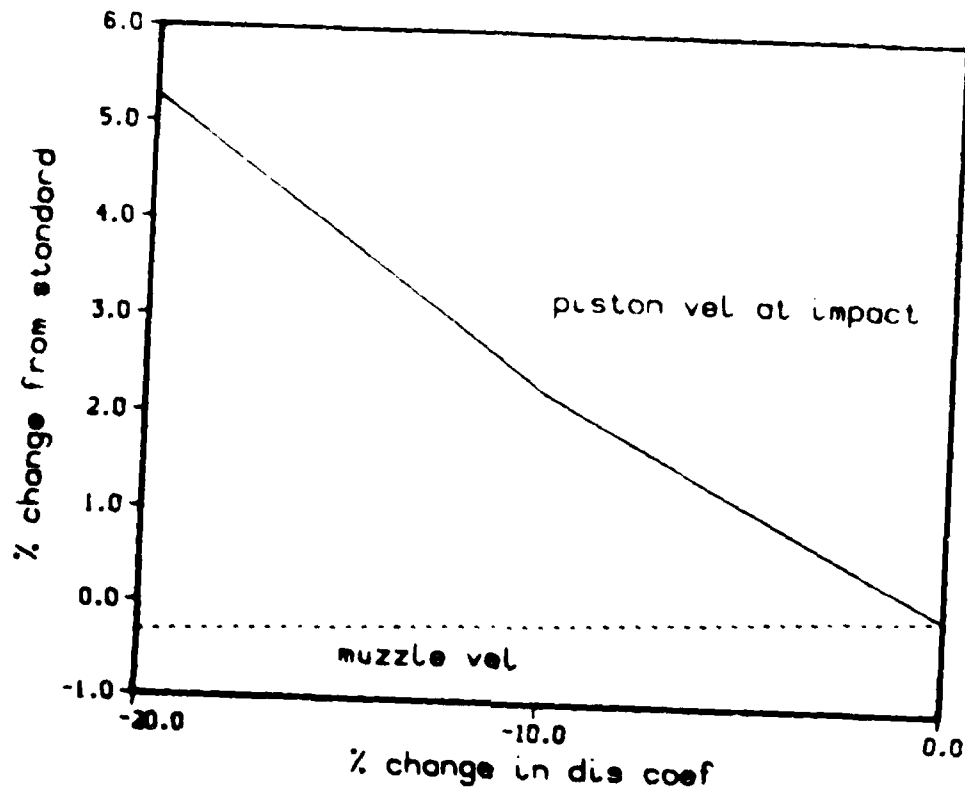


Figure B-34. Percentage change in discharge coefficient of gas vs. percentage changes in muzzle velocity and maximum piston velocity.

Appendix C

The statistics for parameter change with a constraint of 700 MPa on maximum liquid pressure vs. change in performance characteristics are presented both absolutely and as percentage change.

120MM REGENERATIVE LIQUID PROPELLANT GUN
SENSITIVITY STUDY
RLSG CODE

CONSTRAINT: MAX LIQUID PM = 700 MPa

Piston Weight g	Nozzle m/s	Velocity m/s	Max. Liq. MPa	Press. MPa	Max. Comb. MPa	Press. MPa	Max. Base MPa	Pres. MPa	Max. Accel. g	Max. Pist. Ca	Travel Pist. Vel. Ca/s	Impact m/s	Time to Impact ms	z @ 80
61725.4	-20.0	1929.7	0.23	699.6	0.98	499.5	0.93	334.8	4.42	4.42	20.440	-4.02	7.00	1.00
68992.2	-10.0	1930.9	0.29	700.2	1.07	500.0	1.03	330.4	2.55	2.58	20.286	-1.03	7.12	1.00
76458.0	0.0	1925.1	0.00	699.4	0.95	499.9	0.90	341.7	0.00	34.3	20.344	0.00	7.22	1.00
84223.8	10.0	1929.4	0.21	699.5	0.97	499.9	1.01	337.2	-1.22	-1.47	20.239	-0.42	7.21	1.00
91991.6	20.0	1928.7	0.18	700.3	1.08	500.7	1.17	331.0	-3.12	-3.31	20.252	6.75	7.40	1.00
Proj. Weight g	Nozzle m/s	Velocity m/s	Max. Liq. MPa	Press. MPa	Max. Comb. MPa	Press. MPa	Max. Base MPa	Pres. MPa	Max. Accel. g	Max. Pist. Ca	Travel Pist. Vel. Ca/s	Impact m/s	Time to Impact ms	z @ 80
5896.0	-20.0	2051.0	6.55	699.6	0.98	500.2	1.07	309.3	-4.48	61.3	12.89	13.34	6.32	1.00
6408.0	-10.0	1988.1	3.26	700.1	1.05	500.3	1.09	328.0	-4.01	37.8	6.45	7.23	7.02	1.00
7120.0	0.0	1925.3	0.00	697.8	0.90	499.9	0.90	341.7	0.00	34.3	0.00	0.00	7.22	1.00
7832.0	10.0	1876.0	-2.56	699.9	1.02	499.8	0.99	337.4	4.59	51.7	-4.79	-5.52	7.41	1.00
8544.0	20.0	1825.1	-5.20	699.9	1.02	499.6	0.95	349.1	8.02	48.9	-8.94	-8.29	7.60	1.00
Chamber Volume cc	Nozzle m/s	Velocity m/s	Max. Liq. MPa	Press. MPa	Max. Comb. MPa	Press. MPa	Max. Base MPa	Pres. MPa	Max. Accel. g	Max. Pist. Ca	Travel Pist. Vel. Ca/s	Impact m/s	Time to Impact ms	z @ 80
4436.0	-20.0	1926.3	0.05	699.8	1.01	499.3	0.89	334.5	3.25	34.3	1.48	-5.24	7.08	1.00
5260.5	-10.0	1929.2	0.20	700.3	1.06	500.0	1.03	349.1	2.17	35.3	2.21	-1.31	7.15	1.00
5895.0	0.0	1925.3	0.00	697.8	0.90	499.9	0.90	341.7	0.00	34.3	0.00	0.00	7.23	1.00
6479.5	10.0	1929.4	0.21	699.7	1.00	500.0	1.03	338.7	-0.88	53.8	-0.92	4.21	7.28	1.00
7014.0	20.0	1927.7	0.12	699.9	1.02	500.3	1.09	333.8	-2.31	53.0	-2.39	7.00	7.34	1.00
Liquid Volume cc	Nozzle m/s	Velocity m/s	Max. Liq. MPa	Press. MPa	Max. Comb. MPa	Press. MPa	Max. Base MPa	Pres. MPa	Max. Accel. g	Max. Pist. Ca	Travel Pist. Vel. Ca/s	Impact m/s	Time to Impact ms	z @ 80
9360.0	-20.0	1882.9	-2.06	699.7	1.00	500.2	1.07	330.0	2.43	35.4	2.29	16.293	7.15	1.00
10330.0	-10.0	1912.8	-0.45	699.8	1.01	500.2	1.07	344.9	1.52	35.1	1.47	18.315	7.18	1.00
11700.0	0.0	1925.3	0.00	697.8	0.90	499.9	0.90	341.7	0.00	34.3	0.00	0.00	7.23	1.00
12870.0	10.0	1939.1	0.72	700.0	1.04	499.8	0.99	340.8	-4.26	54.3	-4.27	22.328	7.24	1.00
14040.0	20.0	1941.8	0.86	700.0	1.04	499.7	0.97	337.8	-1.16	53.6	-1.29	24.330	7.20	1.00
Liquid Area cm ²	Nozzle m/s	Velocity m/s	Max. Liq. MPa	Press. MPa	Max. Comb. MPa	Press. MPa	Max. Base MPa	Pres. MPa	Max. Accel. g	Max. Pist. Ca	Travel Pist. Vel. Ca/s	Impact m/s	Time to Impact ms	z @ 80
575.7	-20.0	1727.1	-10.29	700.0	1.04	500.2	1.07	330.0	-20.84	42.8	-21.12	29.923	7.85	1.00
647.4	-10.0	1840.2	-4.42	699.4	0.98	499.6	1.01	342.0	-8.49	49.5	-8.84	24.407	7.44	1.00
719.4	0.0	1925.3	0.00	697.8	0.90	499.9	0.90	341.7	0.00	34.3	0.00	0.00	7.23	1.00
791.4	10.0	1949.4	3.38	699.5	0.97	500.3	1.04	332.8	3.25	54.0	3.13	16.875	7.22	1.00
863.5	20.0	1901.7	-1.23	567.5	-18.09	520.3	0.94	272.3	-20.31	43.0	-20.81	13.333	7.99	1.00
Chamber Area cm ²	Nozzle m/s	Velocity m/s	Max. Liq. MPa	Press. MPa	Max. Comb. MPa	Press. MPa	Max. Base MPa	Pres. MPa	Max. Accel. g	Max. Pist. Ca	Travel Pist. Vel. Ca/s	Impact m/s	Time to Impact ms	z @ 80
733.0	-20.0	1621.1	-44.96	95.0	-46.29	93.2	-81.17	94.6	-75.24	12.7	-76.61	3.879	13.12	0.28
874.7	-10.0	1971.3	2.39	700.1	1.05	578.6	16.91	323.3	-5.38	51.3	-5.35	18.447	7.37	1.00
916.3	0.0	1925.3	0.00	697.8	0.90	499.9	0.90	341.7	0.00	34.3	0.00	0.00	7.23	1.00
1007.9	10.0	1855.5	-3.63	700.0	1.04	440.7	-10.95	379.1	-3.46	54.3	-3.46	21.148	7.19	1.00
1099.6	20.0	1783.1	-7.39	699.2	0.92	393.7	-20.45	391.2	-10.37	48.7	-10.31	21.019	7.29	1.00

DISTRIBUTION LIST

<u>No. of Copies</u>	<u>Organization</u>	<u>No. of Copies</u>	<u>Organization</u>
12	Commander Defense Technical Info Center ATTN: DTIC-DDA Cameron Station Alexandria, VA 22304-6145	3	Director Benet Weapons Laboratory Armament R&D Center US Army AMCCOM ATTN: SMCAR-LCB-TL E. Conroy A. Graham Watervliet, NY 12189
1	Director Defense Advanced Research Projects Agency ATTN: H. Fair 1400 Wilson Boulevard Arlington, VA 22209	1	Commander US Army Armament, Munitions and Chemical Command ATTN: SMCAR-ESP-L Rock Island, IL 61299-7300
1	HQDA DAMA-ART-M Washington, DC 20310	1	Commander US Army Aviation Research and Development Command ATTN: AMSAV-E 4300 Goodfellow Blvd. St. Louis, MO 63120
1	Commander US Army Materiel Command ATTN: AMCDRA-ST 5001 Eisenhower Avenue Alexandria, VA 22333-0001	1	Commander Materials Technology Lab US Army Laboratory Cmd ATTN: SLCMT-MCM-SB M. Levy Watertown, MA 02172-0001
13	Commander Armament R&D Center US Army AMCCOM ATTN: SMCAR-TSS SMCAR-TDC SMCAR-SCA, B. Brodman R. Yalamanchili SMCAR-AEE-B, D. Downs A. Beardell SMCAR-LCE, N. Slagg SMCAR-LCS, W. Quine A. Bracuti J. Lannon SMCAR-FSS-A, R. Price L. Frauen SMCAR-FSA-S, H. Liberman Picatinny Arsenal, NJ 07806-5000	1	Director US Army Air Mobility Rsch. and Development Lab. Ames Research Center Moffett Field, CA 94035
		1	Commander US Army Communications Electronics Command ATTN: AMSEL-ED Fort Monmouth, NJ 07703
		1	Commander ERADCOM Technical Library ATTN: STET-L Ft. Monmouth, NJ 07703-5301

DISTRIBUTION LIST

<u>No. of Copies</u>	<u>Organization</u>	<u>No. of Copies</u>	<u>Organization</u>
1	Commander US Army Harry Diamond Labs ATTN: DELHD-TA-L 2800 Powder Mill Rd Adelphi, MD 20783	1	Commander Armament Rsch & Dev Ctr US Army Armament, Munitions and Chemical Command ATTN: SMCAR-CCS-C, T Hung Picatinny Arsenal, NJ 07806-5000
1	Commander US Army Missile Command Rsch, Dev, & Engr Ctr ATTN: AMSMI-RD Redstone Arsenal, AL 35898	1	Commandant US Army Field Artillery School ATTN: ATSF-CMW Ft Sill, OK 73503
1	Commander US Army Missile & Space Intelligence Center ATTN: AIAMS-YDL Redstone Arsenal, AL 35898-5500	1	Commandant US Army Armor Center ATTN: ATSB-CD-MLD Ft Knox, KY 40121
1	Commander US Army Belvoir R&D Ctr ATTN: STRBE-WC Tech Library (Vault) B-315 Fort Belvoir, VA 22060-5606	1	Commander US Army Development and Employment Agency ATTN: MODE-TED-SAB Fort Lewis, WA 98433
1	Commander US Army Tank Automotive Cmd ATTN: AMSTA-TSL Warren, MI 48397-5000	1	Commander Naval Surface Weapons Center ATTN: D.A. Wilson, Code G31 Dahlgren, VA 22448-5000
1	Commander US Army Research Office ATTN: Tech Library P.O. Box 12211 Research Triangle Park, NC 27709-2211	1	Commander Naval Surface Weapons Center ATTN: Code G33, J. East Dahlgren, VA 22448-5000
1	Director US Army TRADOC Systems Analysis Activity ATTN: ATAA-SL White Sands Missile Range NM 88002	2	Commander US Naval Surface Weapons Ctr. ATTN: O. Dengel K. Thorsted Silver Spring, MD 20902-5000
1	Commandant US Army Infantry School ATTN: ATSH-CD-CSO-OR Fort Benning, GA 31905	1	Commander Naval Weapons Center China Lake, CA 93555-6001
		1	Commander Naval Ordnance Station ATTN: C. Dale Code 5251 Indian Head, MD 20640

DISTRIBUTION LIST

<u>No. of Copies</u>	<u>Organization</u>	<u>No. of Copies</u>	<u>Organization</u>
1	Superintendent Naval Postgraduate School Dept of Mechanical Eng. ATTN: Code 1424, Library Monterey, CA 93943	10	Central Intelligence Agency Office of Central Reference Dissemination Branch Room GE-47 HQS Washington, DC 20502
1	AFWL/SUL Kirtland AFB, NW 87117	1	Central Intelligence Agency ATTN: Joseph E. Backofen HQ Room 5F22 Washington, DC 20505
1	Air Force Armament Lab ATTN: AFATL/DLODL Eglin, AFB, FL 32542-5000	4	Bell Aerospace Textron ATTN: F. Boorady K. Berman A.J. Friona J. Rockenfeller Post Office Box One Buffalo, NY 14240
1	AFOSR/NA (L. Caveny) Bldg. 410 Bolling AFB, DC 20332	1	Calspan Corporation ATTN: Tech Library P.O. Box 400 Buffalo, NY 14225
1	Commandant USAFAS ATTN: ATSF-TSM-CN Ft Sill, OK 73503-5600	7	General Electric Ord. Sys Dpt ATTN: J. Mandzy, OP43-220 R.E. Mayer H. West M. Bulman R. Pate I. Magoon J. Scudiere 100 Plastics Avenue Pittsfield, MA 01201-3698
1	US Bureau of Mines ATTN: R.A. Watson 4800 Forbes Street Pittsburgh, PA 15213	1	General Electric Company Armanent Systems Department ATTN: D. Maher Burlington, VT 05401
1	Director Jet Propulsion Lab ATTN: Tech Libr 4800 Oak Grove Drive Pasadena, CA 91109	1	IITRI ATTN: Library 10 W. 35th St. Chicago, IL 60616
2	Director National Aeronautics and Space Administration ATTN: MS-603, Tech Lib MS-86, Dr. Povinelli 21000 Brookpark Road Lewis Research Center Cleveland, OH 44135	1	Olin Chemicals Research ATTN: David Gavin P.O. Box 586 Cheshire, CT 06410-0586
1	Director National Aeronautics and Space Administration Manned Spacecraft Center Houston, TX 77058		

DISTRIBUTION LIST

<u>No. of Copies</u>	<u>Organization</u>	<u>No. of Copies</u>	<u>Organization</u>
2	Olin Corporation ATTN: Victor A. Corso Dr. Ronald L. Dotson P.O. Box 30-9644 New Haven, CT 06536	2	University of Delaware Department of Chemistry ATTN: Mr. James Cronin Professor Thomas Brill Newark, DE 19711
1	Paul Gough Associates ATTN: Paul Gough PO Box 1614 Portsmouth, NH 03801	1	U. of ILLinois at Chicago ATTN: Professor Sohail Murad Dept of Chemical Eng Box 4348 Chicago, IL 60680
1	Safety Consulting Engr ATTN: Mr. C. James Dahn 5240 Pearl St. Rosemont, IL 60018	1	U. of Maryland at College Park ATTN: Professor Franz Kasler Department of Chemistry College Park, MD 20742
1	Science Applications, Inc. ATTN: R. Edelman 23146 Cumorah Crest Woodland Hills, CA 91364	1	U. of Missouri at Columbia ATTN: Professor R. Thompson Department of Chemistry Columbia, MO 65211
1	Sunstrand Aviation Operations ATTN: Dr. Owen Briles P.O. Box 7002 Rockford, IL 61125	1	U. of Michigan ATTN: Prof. Gerard M. Faeth Department of Aerospace Engineering Ann Arbor, MI 48109-3796
1	Veritay Technology, Inc. ATTN: E. B. Fisher 4845 Millersport Highway, P.O. Box 305 East Amherst, NY 14051-0305	1	U. of Missouri at Columbia ATTN: Professor F. K. Ross Research Reactor Columbia, MO 65211
1	Director Applied Physics Laboratory The Johns Hopkins Univ. Johns Hopkins Road Laurel, Md 20707	1	U. of Missouri at Kansas City Department of Physics ATTN: Prof. R.D. Murphy 1110 East 48th Street Kansas City, MO 64110-2499
2	Director Chemical Propulsion Info Agency The Johns Hopkins Univ. ATTN: T. Christian Tech Lib Johns Hopkins Road Laurel, MD 20707	1	Pennsylvania State University Dept. of Mechanical Eng ATTN: K. Kuo University Park, PA 16802

DISTRIBUTION LIST

<u>No. of Copies</u>	<u>Organization</u>	<u>No. of Copies</u>	<u>Organization</u>
2	Princeton Combustion Rsch Laboratories, Inc. ATTN: N.A. Messina M. Summerfield 475 US Highway One North Monmouth Junction, NJ 08852		
1	University of Arkansas Department of Chemical Engineering ATTN: J. Havens 227 Engineering Building Fayetteville, AR 72701		

Aberdeen Proving Ground

Dir, USAMSAA
ATTN: AMXSY-D
AMXSY-MP, H. Cohen

Cdr, USATECOM
ATTN: AMSTE-TO-F

CDR, CRDEC, AMCCOM
ATTN: SMCCR-RSP-A
SMCCR-MU
SMCCR-SPS-IL

USER EVALUATION SHEET/CHANGE OF ADDRESS

This Laboratory undertakes a continuing effort to improve the quality of the reports it publishes. Your comments/answers to the items/questions below will aid us in our efforts.

1. BRL Report Number _____ Date of Report _____
2. Date Report Received _____
3. Does this report satisfy a need? (Comment on purpose, related project, or other area of interest for which the report will be used.) _____

4. How specifically, is the report being used? (Information source, design data, procedure, source of ideas, etc.) _____

5. Has the information in this report led to any quantitative savings as far as man-hours or dollars saved, operating costs avoided or efficiencies achieved, etc? If so, please elaborate. _____

6. General Comments. What do you think should be changed to improve future reports? (Indicate changes to organization, technical content, format, etc.) _____

CURRENT ADDRESS

Name _____

Organization _____

Address _____

City, State, Zip _____

7. If indicating a Change of Address or Address Correction, please provide the New or Correct Address in Block 6 above and the Old or Incorrect address below.

OLD ADDRESS

Name _____

Organization _____

Address _____

City, State, Zip _____

(Remove this sheet, fold as indicated, staple or tape closed, and mail.)

----- FOLD HERE -----

Director
US Army Ballistic Research Laboratory
ATTN: DRXBR-OD-ST
Aberdeen Proving Ground, MD 21005-5066

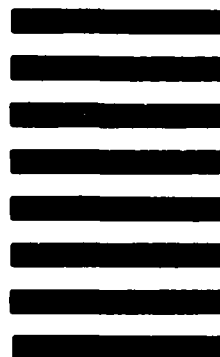


NO POSTAGE
NECESSARY
IF MAILED
IN THE
UNITED STATES

OFFICIAL BUSINESS
PENALTY FOR PRIVATE USE: \$300

BUSINESS REPLY MAIL
FIRST CLASS PERMIT NO 12062 WASHINGTON, DC
POSTAGE WILL BE PAID BY DEPARTMENT OF THE ARMY

Director
US Army Ballistic Research Laboratory
ATTN: DRXBR-OD-ST
Aberdeen Proving Ground, MD 21005-9989



----- FOLD HERE -----

END

FEB.

1988

DTic