

COMPUTER SIMULATION OF A PROPELLANT
FEED SYSTEM FOR A LIQUID PROPELLANT GUN

Craig Richard Dampier

DUTLEY KNOX LIBRARY
NAVAL POSTGRADUATE SCHOOL
MONTEREY, CALIFORNIA 93940

NAVAL POSTGRADUATE SCHOOL

Monterey, California



THESIS

COMPUTER SIMULATION OF A PROPELLANT
FEED SYSTEM FOR A LIQUID PROPELLANT GUN

by

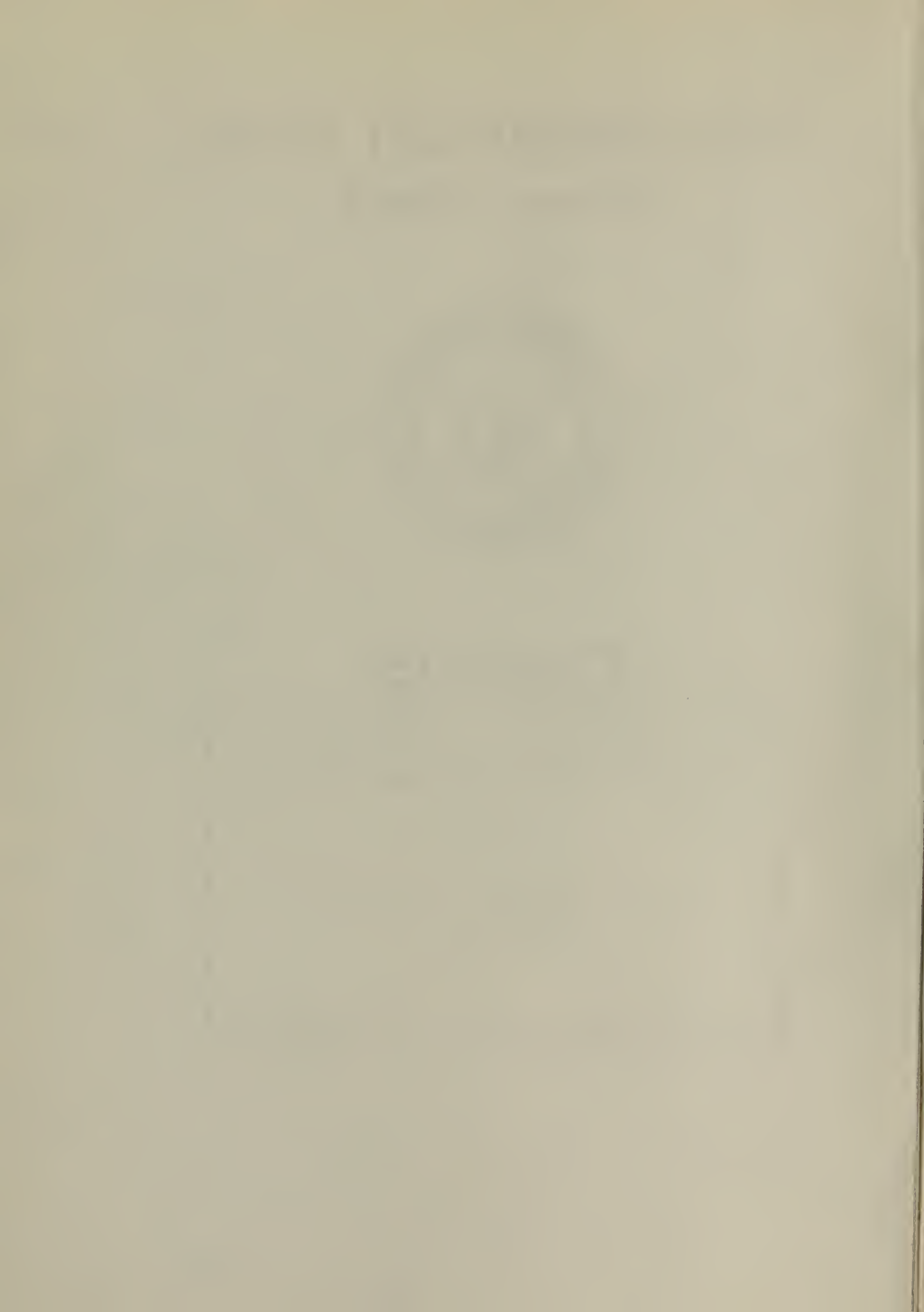
Craig Richard Dampier
June 1976

Thesis Advisor:

T. M. Houlihan

Approved for public release; distribution unlimited.

T175046



REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS
BEFORE COMPLETING FORM

1. REPORT NUMBER		2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Computer Simulation of a Propellant Feed System for a Liquid Propellant Gun			5. TYPE OF REPORT & PERIOD COVERED Master's Thesis June 1976
7. AUTHOR(s) Craig Richard Dampier			6. PERFORMING ORG. REPORT NUMBER
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Postgraduate School Monterey, California 93940			8. CONTRACT OR GRANT NUMBER(s)
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Postgraduate School Monterey, California 93940			10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) Naval Postgraduate School Monterey, California 93940			12. REPORT DATE June 1976
			13. NUMBER OF PAGES 71
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release; distribution unlimited			15. SECURITY CLASS. (of this report) Unclassified
			15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)			
18. SUPPLEMENTARY NOTES			
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Liquid Propellant Gun Computer Simulation Fluid Dynamics Lumped Parameter Approach			
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) A computer model was developed to simulate a projectile ram-propellant feed system for a Liquid Propellant Gun. Using a lumped parameter approach, a set of simultaneous differential equations was derived for the complex interaction of the propellant fluid, the driving injector and the projectile. The computer model was verified against a 20 mm experimental apparatus. Injector displacement, projectile displacement,			

and chamber pressure were compared for a nominal driving pressure of 140 psi. The important system parameters affecting projectile ram time and chamber pressure oscillations were investigated and potential problem areas for testing with actual propellant were identified.

COMPUTER SIMULATION OF A PROPELLANT FEED SYSTEM FOR A
LIQUID PROPELLANT GUN

by

Craig Richard Dampier
Lieutenant, United States Navy
E.S., United States Naval Academy, 1970

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN APPLIED SCIENCE

from the
NAVAL POSTGRADUATE SCHOOL
June, 1976

thesis
D14754
c.1

ABSTRACT

A computer model was developed to simulate a projectile ram-propellant feed system for a Liquid Propellant Gun. Using a lumped parameter approach, a set of simultaneous differential equations was derived for the complex interaction of the propellant fluid, the driving injector and the projectile. The computer model was verified against a 20 mm experimental apparatus. Injector displacement, projectile displacement, and chamber pressure were compared for a nominal driving pressure of 140 psi. The important system parameters affecting projectile ram time and chamber pressure oscillations were investigated and potential problem areas for testing with actual propellant were identified.

TABLE OF CONTENTS

I.	INTRODUCTION.....	8
II.	BACKGROUND.....	9
III.	DERIVATION OF COMPUTER MODEL.....	14
	A. LUMPED PARAMETER APPROACH.....	14
	B. LFG SYSTEM GOVERNING EQUATIONS.....	17
IV.	DESCRIPTION OF EXPERIMENTAL APPARATUS.....	23
V.	COMPARISON OF COMPUTER AND EXPERIMENTAL DATA.....	27
VI.	ANALYSIS OF SYSTEM PERFORMANCE.....	36
	A. PARAMETERS AFFECTING PROJECTILE RAM TIME.....	36
	B. PARAMETERS AFFECTING PRESSURE OSCILLATIONS...	41
VII.	CONCLUSIONS.....	43
	Appendix 1: COMPUTER PROGRAM LISTING.....	46
	LIST OF REFERENCES.....	69
	INITIAL DISTRIBUTION LIST.....	70
	LIST OF FIGURES.....	6

LIST OF FIGURES

1. Basic Geometry.....	11
2. Lumped Parameter Modules.....	16
3. Pneumatic Control System in Ram Position.....	24
4. Comparison of Injector Piston Displacement.....	30
5. Comparison of Breech Chamber Pressure.....	31
6. Simultaneous Pressure Histories.....	32
7. Simultaneous Injector Velocity Histories.....	33
8. Simultaneous Breech Chamber Velocity Histories.....	34
9. Comparison of Injector and Projectile Displacement..	35
10. Resistance Coefficients vs Ram Time.....	39
11. Bulk Modulus vs Ram Time.....	40

ACKNOWLEDGEMENTS

I would like to express my deep appreciation to my thesis advisor, Professor Thomas M. Houlihan, for the many hours he spent keeping me on firm theoretical ground and showing me the "ropes" in the Liquid Propellant Gun business. I would also like to offer my special thanks to my wife, Ingrid, who spent innumerable hours keypunching this thesis into the Naval Postgraduate School's Text Processing system and acting as the "real" first reader.

I. INTRODUCTION

As the state of the art of weapons technology improves, more complex systems are continually being developed. To meet future needs these systems must have improved performance, less weight and volume, less complicated logistics, and at the same time be more cost effective than current systems. One candidate for these future weapon systems is the liquid propellant gun (LPG). Numerous investigations over the past thirty years have demonstrated its potential if the technology can be developed to utilize a liquid propellant in a large caliber gun.

One important area that needs investigation is the aspect of fluid propellant handling. The ordnance designer must know the necessary propellant flow rates and pressure regimes needed to achieve the desired system performance. These parameters must be within allowable safety margins for the handling and use of the explosive propellant. One possible design of an LPG which would allow a very high firing rate utilizes the propellant to ram the loaded projectile. Combining the normally separate propellant load and ram cycles decreases the required movement of mechanical parts. Thus, using this method, it is feasible that firing rates in excess of four to five times present rates could be achieved. This thesis was directed toward identifying the important fluid dynamic parameters involved with such a projectile ram feed system.

II. BACKGROUND

During 1974 and early 1975, an investigation was conducted at the Naval Postgraduate School to study, both analytically and experimentally, the fluid dynamics of a liquid propellant under conditions similar to those which would exist in a rapid-fire LPG feed system. The results of this investigation were to be used to establish such LPG design and performance parameters as time-to-load, injection supply pressure, injection system configuration, ullage, charge-to-mass ratio, caliber size, and projectile mass. It was hoped that this investigation would identify any potential problem areas for further detailed research.

The basic objective of the experimental portion of the investigation was to identify what fluid dynamic characteristics of a liquid propellant feed system would limit loading times and hence rates of fire. A 20 mm experimental model of a basic propellant feed system was designed and built. Data on injector displacement, breech chamber pressure, and ram gas pressure (input driving pressure), were recorded for driving pressures between 50 and 220 psig in 10 psi increments. As reported in Ref. 1, it was found that the instantaneous behavior of the chamber pressure was the result of a complex interaction of inertia forces, viscous forces, and the unsteady motion of the fluid. The experiments demonstrated that frictional and inertial effects were significant during the movements of the injector and the projectile slug. Once the projectile slug stopped, the effect of entrapped gas in the fluid caused large breech chamber pressure oscillations. On several runs, sub-atmospheric pressures were experienced

which suggested the possibility of cavitation and hence vapor-phase ignition. Over all, it was found that the ram time had a quadratic dependence upon ram pressure.

The analytical portion of the investigation was directed toward predicting the pressure and flow rate of the propellant and the projectile slug motion during an LPG loading cycle. The mathematical model which was developed and programmed on an analog computer predicted the position, velocity, and acceleration of the projectile and the pressure at various points in the system as functions of time. The model was tested against experimental results and found to be adequate for the prediction of projectile ram time. An analysis was performed using the model to indicate the areas of system redesign likely to be most profitable and to obtain preliminary predictions of LPG loading system performance under a variety of design conditions. The results of the analytical study, as well as a summary of the experimental work is contained in Ref. 2.

The aforementioned model was the starting point for the present study. To better understand the derivations in the following sections, Figure (1) indicates the geometry of a basic projectile ram propellant feed system. An injector chamber is filled with propellant, which is then pumped into the gun breech by applying ram pressure to the ram side of the injector piston. This can be accomplished by using high pressure gas from an accumulator or by using an hydraulic drive system. The force exerted by the injector piston drives the fluid propellant through the connecting line into the gun breech. The rapidly accelerated propellant drives the already loaded projectile to its seated position ready for firing.

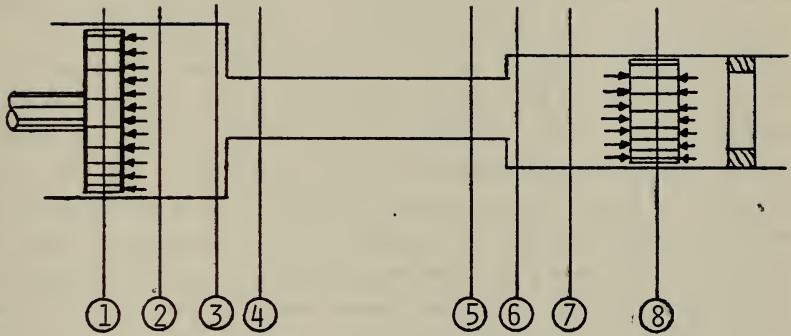


Figure 1 - BASIC GEOMETRY

The complex nature of this dynamic ram process is not easy to describe with mathematical equations. Many researchers have approached the problem using wave mechanics and partial differential equations. These equations were then modified according to the propagation characteristics of the system and the various boundary conditions encountered therein. This usually led to involved finite difference methods of solution on a digital computer.

Another possible approach considers the kinetic energy involved in the ram process. This is the approach that was used to derive the governing equations for the previously described analog computer model. Beginning with the input side, a force balance on the injector piston yielded an equation for the pressure in the injector chamber in terms of the injector motion. Writing Bernoulli's equations for head losses at the expansion to the breech chamber, the contraction to the connecting line, and an orifice in the connecting line resulted in an equation for the pressure drop in the connecting line in terms of the square of the fluid velocity and the fluid acceleration. A force balance on the projectile slug yielded a third equation which described the breech chamber pressure in terms of the slug motion. To solve these equations, some method of relating the motions in the injector, connecting line, and breech chamber had to be established. It was assumed that the fluid was incompressible and therefore these motions were identical. To facilitate the analog simulation it was also assumed that the input ram pressure was a step input. In the process of converting these equations to an integral form for wiring on an analog computer, all variables were normalized to permit scaling.

Despite these limiting assumptions, the analog computer model was able to predict the time to ram the projectile and

the chamber pressures which occur during the time that the injector is in motion. Due to the incompressibility assumption, the model was unable to account for the pressure transients or "water hammer" type pressure oscillations which occurred when the projectile was seated and the propellant fluid was being decelerated. These pressure oscillations are important to the system designer because the peak breech chamber load pressure is experienced during these oscillations. It is also possible that these oscillations could interfere with the uniformity of the ignition and subsequent combustion of the propellant.

A straight forward attempt was made to extend this analog model by first converting it to a digital computer program. This allowed an accurate representation of the input ram pressure and the use of unnormalized variables to be incorporated. These improvements increased the accuracy of the model but the effect of the compressibility of the propellant fluid still was not taken into account. Trying to add compressibility effects to this model by adding time derivatives of the pressure terms to the governing equations unlinked the motions of the injector, the connecting line fluid, and the projectile slug causing a problem with too many unknown variables for the number of equations involved.

It was decided that a new approach should be tried which would adequately describe the system pressure oscillations. The approach would feature an engineering model which would be easy to use, adaptable to any LPG feed system, and not obscure the interaction of system parameters by complicated mathematics.

III. DERIVATION OF COMPUTER MODEL

A. LUMPED PARAMETER APPROACH

The approach that showed the greatest promise for modeling the LPG feed system was that of the fluid transmission line concept. This approach, which has become popular in the last five to ten years, is based on a pressure-voltage and flow velocity-current analogy with Electrical Engineering determinations. It is an outgrowth of the large amount of effort that has been devoted to investigating fluid line transients. Reference 3 is a good survey of this field.

For complex systems this approach is usually simplified by using the approximation of lumped parameters. The effects of fluid inertia, capacitance, and resistance are "lumped" and considered to act only in discreet areas of the system. This results in a reduction of the unknown parameters due to the assumed lack of interaction of the different fluid effects. This approximation, however, results in the necessity of using several empirical constants which must be determined by fitting experimental data. The ordinary differential equations that are derived from this method can be solved either by Laplace transformation or by computer integration.

To consider the effect of fluid inertia it is assumed that only pressure and inertia forces are present and that compressibility effects are negligible in the volume under

consideration. Then,

$$P_1 - P_2 = \rho L \frac{dV}{dT}$$

where ρ is the propellant fluid density, L is a characteristic length and $V_1 = V_2 = V$ because the flow is considered incompressible for this building block (Fig. 2A).

To consider the effect of fluid capacitance, it is assumed that only compressibility effects are important, and that inertia and resistance effects may be neglected in the volume under consideration. Therefore,

$$V_1 - V_2 = \frac{L}{K} \frac{dP}{dT}$$

where K is the effective bulk modulus of the propellant fluid, L is a characteristic length and $P_1 = P_2 = P$ (Fig. 2B).

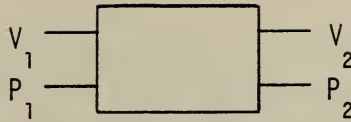
Because fluid resistance can be affected by so many different parameters, it is impossible to write a general equation describing the pressure drop due to fluid resistance. It is best to treat it empirically using an experimentally derived figure. Thus, in the volume under consideration,

$$P_1 - P_2 = Rv V$$

where Rv is a function of fluid velocity and $V_1 = V_2 = V$ (Fig. 2C). Changes in cross sectional area can be accounted for by using appropriate area ratios.

These results specify three building blocks which can be combined in any sequence to model the dynamic characteristics of a system. The complexity of the model can be increased to any degree necessary by including more and more combinations of these three basic building blocks.

A) INERTIA



$$P_1 - P_2 = \rho L \frac{dV}{dT}$$

$$V_1 = V_2 = V$$

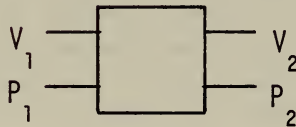
B) CAPACITANCE



$$V_1 - V_2 = \frac{L}{K} \frac{dP}{dT}$$

$$P_1 = P_2 = P$$

C) RESISTANCE



$$P_1 - P_2 = Rv V$$

$$V_1 = V_2 = V$$

Figure 2 - LUMPED PARAMETER MODULES

B. LPG SYSTEM GOVERNING EQUATIONS

Several different combinations of building blocks were tried in attempting to model the experimental LPG system. The experimental results showed that inertial and resistance blocks should be included in the model. The fact that pressure transients occurred in the breech chamber indicated that a capacitance block should also be included. To minimize the use of computer time, it was decided to start with the most simple model thought adequate and work toward more complex models as the quality of the computer results dictated.

The first attempt considered that compressibility effects would dominate in the injector chamber as the accelerating piston interacted with the propellant fluid. The resistance effects of changes in the feedline cross sectional diameter and associated orifices were modeled as one resistance block at the beginning of the connecting line. Inertial effects were thought to dominate in the connecting line. This would be particularly true in large scale models where the length of the connecting line would be very large. It was thought that compressibility effects should again dominate in the breech chamber as the accelerating propellant fluid drove the projectile down the breech chamber. Results in this case were governed by inertial effects because the calculated connecting line velocity was too great. This led to a decrease in the chamber pressure as the projectile accelerated until a large negative chamber pressure existed. In addition to this deficiency, the computed system pressure oscillations were not sufficiently damped.

To try to adjust the connecting line velocity, another

resistance block was added. As will be seen in the section discussing the parameters which affect the pressure oscillations, the value of this resistance coefficient is proportional to the amount of damping in the pressure oscillations. Even with a value which gave the proper damping, the breech chamber pressure was dominated by the pressure loss due to the accelerating fluid in the connecting line.

To reduce the dominance of the fluid inertia effects, it was decided to restructure the model. To model the injector chamber it was decided to consider the effect of fluid capacitance and inertia. The connecting line was modeled by two resistance blocks separated by a fluid capacitance block. The breech chamber was modeled using a fluid capacitance and a fluid inertia block, as was done for the injector chamber. This model gave the final results described in the section comparing computer and experimental data. By combining these building blocks, the governing equations became: (See Fig. (1) for notation)

For the injector:

$$1. P_R A_1 - P_1 \dot{A}_1 = M P \dot{V}_1 + K F S V_1 + P D I A_1$$

$$2. V_1 - V_2 = \frac{L_1}{K} \dot{P}_1$$

$$3. P_2 - P_3 = \rho L_1 \dot{V}_2$$

For the connecting line:

$$4. P_3 - P_4 = Rv_1 V_4$$

$$5. V_4 - V_5 = \frac{L_2}{K} \dot{P}_4$$

$$6. P_5 - P_6 = Rv_2 V_5$$

For the breech chamber:

$$7. P_6 - P_7 = \rho L_3 \dot{V}_6$$

$$8. V_7 - V_8 = \frac{L_3}{K} \dot{P}_8$$

$$9. P_8 A_3 - PDS A_3 = Ms \dot{V}_8 + KFS V_8$$

These equations were subsequently modified to account for changes in cross-sectional area and changing geometry as the injector chamber decreased in volume and the breech chamber increased. Once the projectile reached the end of the breech chamber, the force balance equation was no longer considered applicable. At this time, it was noted that the remaining equations for the connecting line and the breech chamber could be combined to form a second order differential equation for the breech chamber pressure which described the "water hammer" type pressure oscillations displayed by the experimental data. Thus,

$$10. \ddot{P}_8 + \frac{A_3}{A_2} \frac{Rv_2}{\rho L_3} \dot{P}_8 + \frac{K}{\rho L_3 L_3} P_8 = \frac{K}{\rho L_3 L_3} P_4$$

Once the injector piston reached the end of its travel, the injector chamber no longer existed and the governing equations were considered as no longer applicable. Ultimately, the injector chamber pressure was propagated down the connecting line as the propellant fluid came to rest. Throughout these analyses, input ram pressure was modeled using exponential terms to fit experimental data.

The equations from the lumped parameter approach for the propellant fluid were combined with the force balance equations for the injector piston and the projectile using State Variable methods. Subsequently, a computer program was constructed to solve these state variable relations using a fourth order Runge-Kutta integration routine for simultaneous first order differential equations which was developed at the Naval Postgraduate School. A brief description of the state variable method and a listing of the computer program can be found in Appendix A.

The following is a listing of the nomenclature and the values of constants used in the derivation of the governing equations and the computer program:

A1	Injector Cross-Sectional Area	1.77	in ²	11.42	cm ²
A2	Connecting Line Cross-Sectional Area	.255	in ²	1.65	cm ²
A3	Breech Chamber Cross-Sectional Area	.49	in ²	3.16	cm ²
AR	Ram Piston Cross-Sectional Area	1.77	in ²	11.42	cm ²
I1	Injector Length	1.60	in	4.22	cm

L2	Connecting Line Length	16.0	in	40.6	cm
L3	Breech Chamber Length	5.0	in	12.7	cm
MF	Injector Piston Mass	.0052	$\frac{\text{lb-sec}^2}{\text{in}}$	913.8	gm
MS	Projectile Mass	.00053	$\frac{\text{lb-sec}^2}{\text{in}}$	93.1	gm
KFP	Injector Friction Factor	.001	$\frac{\text{lb-sec}}{\text{in}}$	175.7	gm/sec
KFS	Projectile Friction Factor	.001	$\frac{\text{lb-sec}}{\text{in}}$	175.7	gm/sec
EDI	Injector Back Pressure	24.0	PSI	163.3	kPa
EDS	Projectile Back Pressure	.50	PSI	3.4	kPa
K	Effective Bulk Modulus	3200	PSI	6808	kPa
RHC	Propellant Density	.000093	$\frac{\text{lb-sec}^2}{\text{in}^4}$.994	gm/cm ³
PR	Ram Pressure			Computed	
P1	Injector Chamber Pressure			Computed	
V1	Injector Piston Velocity			Computed	
V2	Injector Chamber Exit Velocity			Computed	
P4	Connecting Line Pressure			Computed	
V6	Breech Chamber Entrance Velocity			Computed	
P8	Breech Chamber Pressure			Computed	
V8	Projectile Velocity			Computed	

The treatment of several areas of the computer model continually reappeared as requiring refinement. The governing differential equations worked well during the dynamic portion of the feed cycle but experienced difficulties during the initial and final static periods. The handling of static friction and back pressure as a constant value created the possibility of negative velocities until the driving ram pressure overcame the system back pressure. These negative values never occurred

in the real system due to the geometric restraints on the injector piston and projectile; therefore, the computer model had to be manipulated to maintain this condition. Unfortunately the need for simultaneous solution of the governing equations made it difficult to manipulate the initial conditions without greatly increasing the complexity of the computer model. After the projectile stopped, the transition from the force balance equation on the projectile to an equation describing the fluid velocity in response to the pressure transients was awkward. No simple differential equation describes the complexity of the wave mechanics involved with the reflection of the pressure waves in the system. In this regard several alternate approaches involving sequential alterations of the governing equations were tried with varying degrees of success.

IV. DESCRIPTION OF EXPERIMENTAL APPARATUS

In order that the comparison of the experimental and computer generated data can be fully understood, a brief description of the NPS experimental apparatus and the conduct of the associated experiments is included (See Ref. 1, pages 17-27).

The test chamber was fabricated from a three-inch O.D. Lucite cylinder, 18 inches long, bored to a 20 mm inside diameter and fitted with aluminum end caps. The chamber was loaded with a brass slug weighing 93 grams which rode on two graphite filled Teflon sealing rings. The brass slug, which simulated the projectile, was cycled from the breech end of the chamber to the barrel end and returned to the breech end, completing one hypothetical firing cycle.

Because of the desire to vary the charge to mass ratio, a variable chamber velocity was necessary. To accomplish this with one chamber, a volume control retaining rod was designed into the system. This brass rod, bored to allow gas to pass its length, was threaded through a plate which was attached to the barrel end cap holding the rod in the chamber. The rod, which has a Teflon disc on the end, not only established the volume of the test chamber, but provided a buffer stop for the slug at the end of its forward motion. Another Teflon buffer was affixed to the breech end cap to cushion the slug in return motion.

The IEG simulator started a simulated firing cycle with the slug at the breech end of the empty chamber, as shown in Fig. (3).

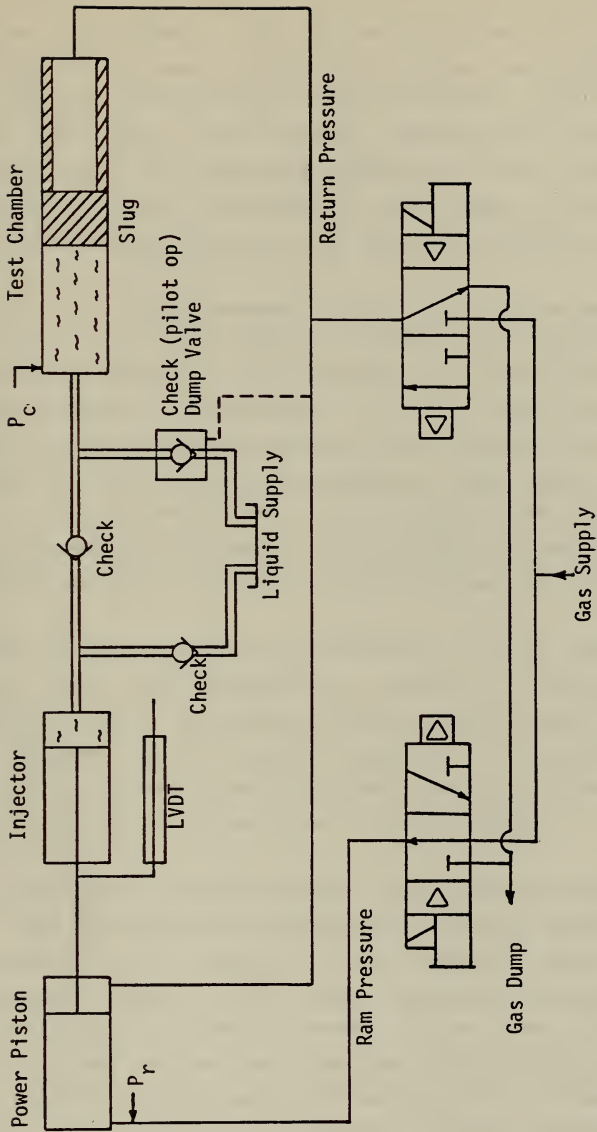


Figure 3 - PNEUMATIC CONTROL SYSTEM IN RAM POSITION

This is the ready-to-ram position. The simulated propellant, distilled water, was then introduced, ramming the slug to the opposite (barrel) end of the chamber as the chamber was filled. This was accomplished by applying gas pressure to a power piston which drove the injector piston. The injector piston forced the propellant past a flow check valve and into the chamber. This placed the slug in the ready-to-fire or in-battery position. In an actual gun, the propellant would be ignited at this time in the cycle. Due to laboratory constraints, an expulsion system was used.

An LVDT displacement transducer was manufactured and mounted next to the injector piston. The LVDT was attached to the connecting rod, between the power piston and the injector piston. The volume of the liquid being placed under pressure during each shot was measured by filling the system in the ready-to-ram position and then draining it into a graduated beaker. By measuring the displacement of the injector piston head with the LVDT, the volumetric rate of fluid injection during the ram stroke was obtained.

Two pressure taps were drilled in the test chamber. These taps were located as close to the breech end as possible, one at 20 degrees from top center and the other at 20 degrees from bottom center in a counterclockwise direction, as seen from the breech end of the chamber. Only the bottom location was used to record data.

A 4-channel Hewlett-Packard 3960 Magnetic Tape Recorder was used to FM record desired data during system operation. For each data run signals were recorded from two Kaman diaphragm type (1000 psi) pressure transducers, one connected to the breech pressure tap on the test chamber, and the other to the gas injection side of the power piston. The pressure signals were processed with a Kaman Digi-Vit Readout Unit which also provided a visual (digital) display.

Data from the LVDT displacement transducer was also recorded on the tape.

A Brush Recorder (Mark 280) was used to obtain a visual display of the recorded data. By transcribing the desired signals on the Magnetic Tape Recorder at a tape speed of 15 feet per minute and playing them back into the Brush Recorder at $3\text{-}3/4$ feet per minute, the time scale of the output was expanded by a factor of four on the Brush recordings (viz., from a real-time maximum of 200 mm/sec to a delayed time maximum of 800 mm/sec.)

V. COMPARISON OF COMPUTER AND EXPERIMENTAL DATA

As mentioned previously, experimental data was taken for raw gas pressures ranging from 50 to 220 psig. From this collection of data, one run at 140 psig was selected as representative of system performance. It was felt that any model which would adequately describe system operation at this intermediate pressure would be valid for the entire range of expected LPG driving pressures.

Figure (4) is a comparison of computed and recorded data for injector piston displacement. As can be seen, the agreement is very good. This is not very significant in that all models tried, as well as the original analog computer model, were able to correctly predict injector piston motion.

Figure (5) is a comparison of analytical results and experimental data for breech chamber pressure. The computer model follows the shape of the experimental curve for the duration of the time that the projectile is in motion (0-30 msec). It oscillates very rapidly but does not fall off to a zero value at the end of the projectile motion. The frequency of these initial oscillations is approximately 1.0 khz which is within the frequency range of the Kaman pressure transducers used in testing. However, the mounting of these transducers within a connecting cavity instead of flush with the chamber wall could have led to them experiencing a reduced, lagging frequency response. It is felt that some, if not all, of the computed pressure oscillations must exist as evidenced by the close correspondence of the first two peaks in Fig. (5). The

accuracy of the experimental pressure reading could also be considered as being reduced by the location of the pressure transducer in the test setup. It is possible that the monitoring pressure tap was too close to the end of the breech chamber and may not have sensed the full chamber pressure during the latter part of the projectile's travel when the fluid velocity is greatest. It is felt that to adequately describe the pressure decrease toward zero, it would be necessary to completely account for exact changes in system geometry. To do this would require using a distributed parameter approach featuring variable lengths for the injector chamber and breech chamber.

The pressure transients which occur after the projectile stops are complex interference phenomena which are not fully described by the model. However, the peak pressure and the natural frequency of oscillation of the computer model compare favorably with the experimental data. Unfortunately, the damping characteristics of the model do not follow the experimental data well. The system parameters which determine these values will be discussed in the next section.

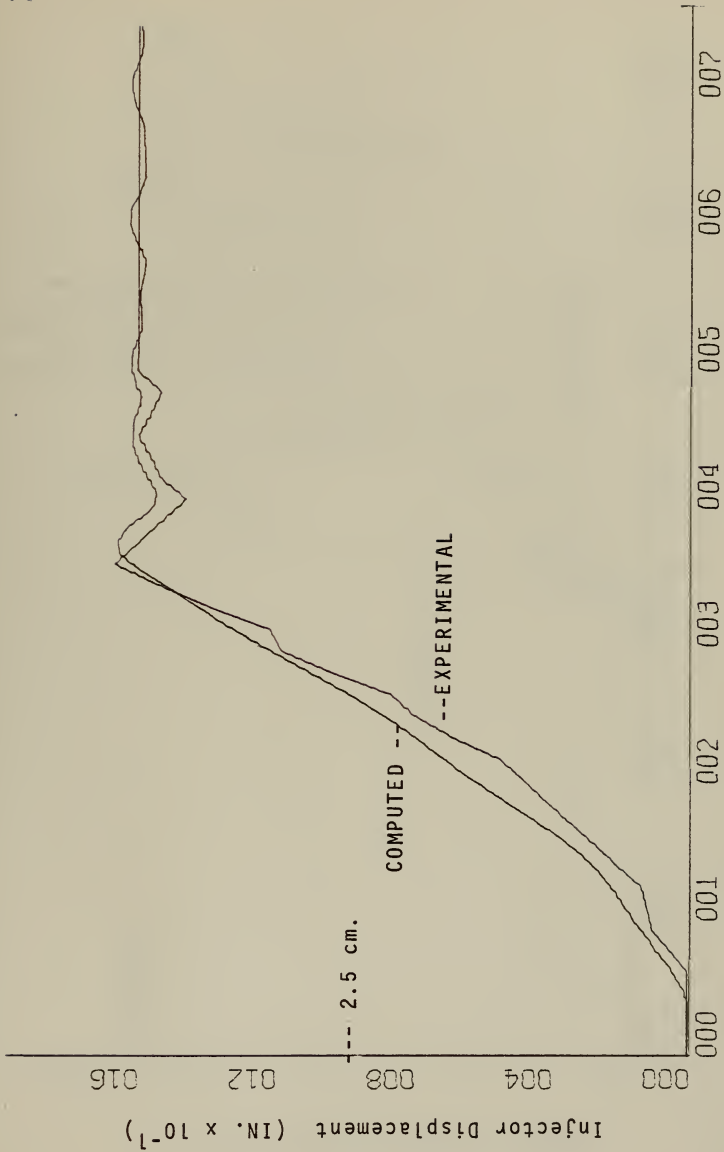
It should be reiterated that the lumped parameter approach is an approximation. In a distributed parameter approach, pressure and velocity would vary continuously with distance within the system as well as with time. In the lumped parameter approach, these changes are assumed to occur only at the input and output of a building block; therefore, pressure and velocity are considered constant within the building block. This will always lead to some discrepancies when comparing model data to experimental data taken at at a fixed point.

Figure (6) shows the simultaneous pressure history for several areas of the LPG feed system. The input ram

pressure, injector chamber pressure, connecting line pressure, and breech chamber pressure are graphed as functions of time.

Figures (7) and (8) show the simultaneous velocities at several points as predicted by the computer model. The injector piston velocity, fluid propellant velocities at the beginning and end of the connecting line, and projectile velocity are plotted as functions of time.

The injector and projectile displacements as functions of time are included as Figure (9). As can be seen from Figures (7), (8), and (9), the movement of the injector piston is much more rapid than that of the projectile. It is felt that this velocity difference is very much a function of system geometry and should not be considered as a generalization for all LPG feed systems. The NPS experimental apparatus being modeled had only small pressure drops between injector and breech chambers. In addition, the projectile slug was an order of magnitude lighter than the injector piston. In large scale systems, with significant pressure drops and very massive projectiles, it is quite possible that the injector piston's full stroke will occur significantly before the projectile has seated.



Time (Sec. x 10²)

Figure 4 - COMPARISON OF INJECTOR PISTON DISPLACEMENT

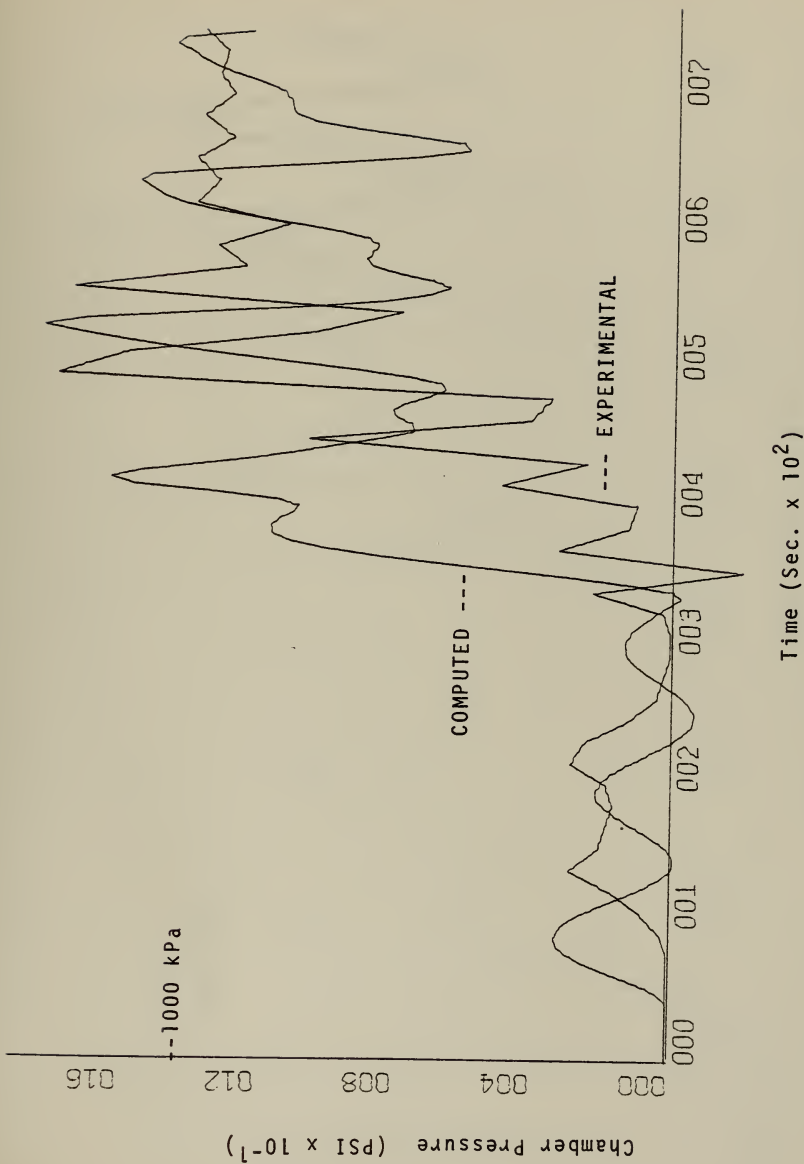


Figure 5 - COMPARISON OF BREECH CHAMBER PRESSURE

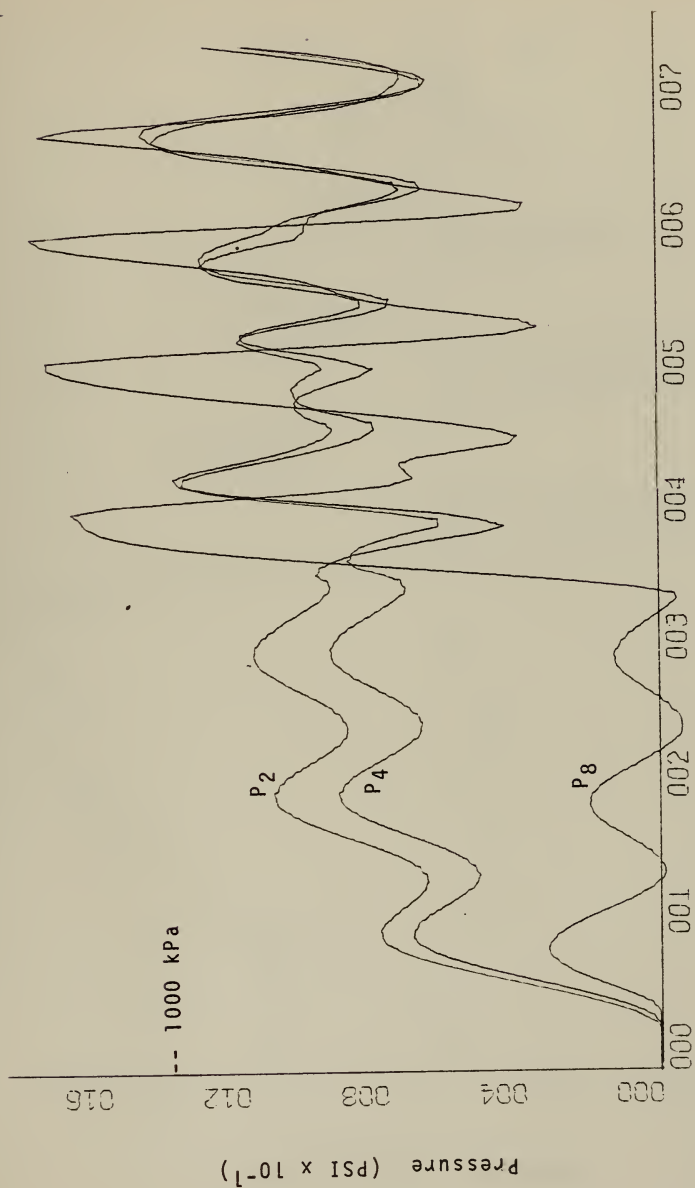


Figure 6 - SIMULTANEOUS PRESSURE HISTORIES

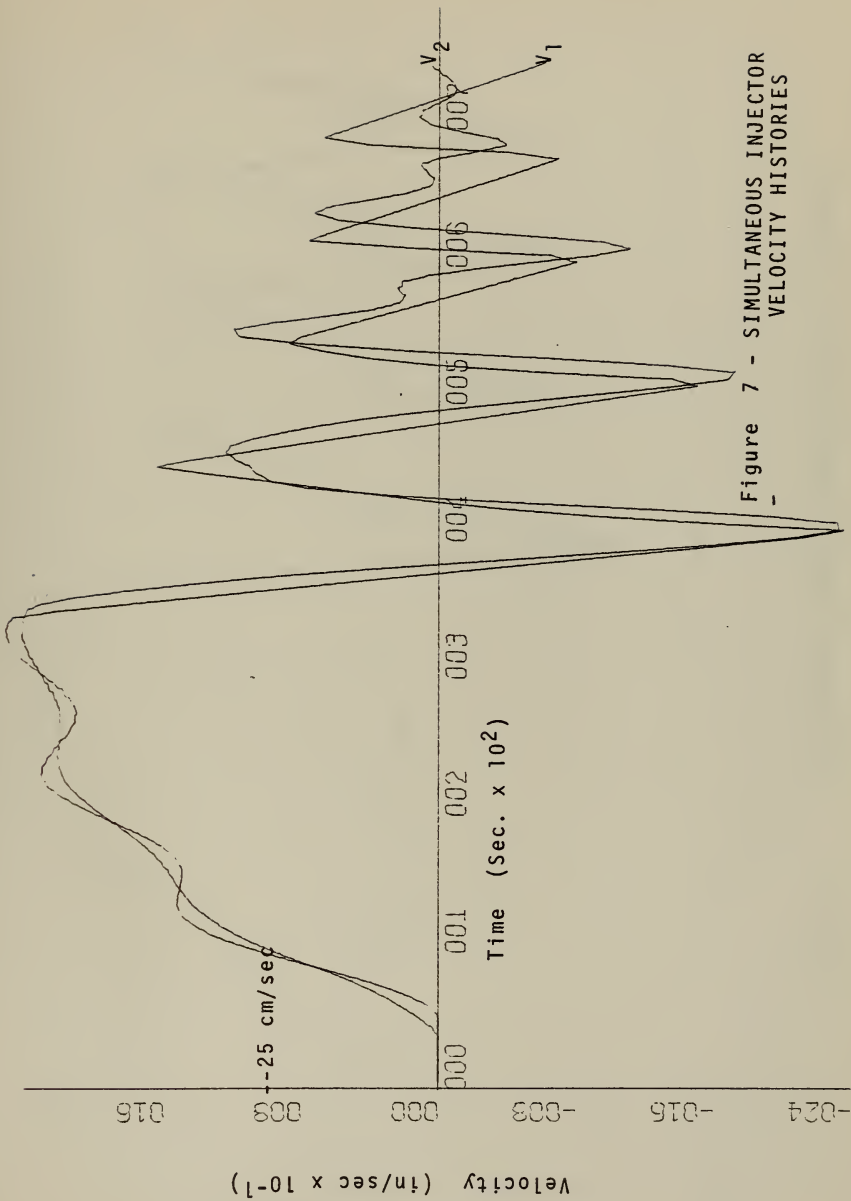


Figure 7 - SIMULTANEOUS INJECTOR VELOCITY HISTORIES

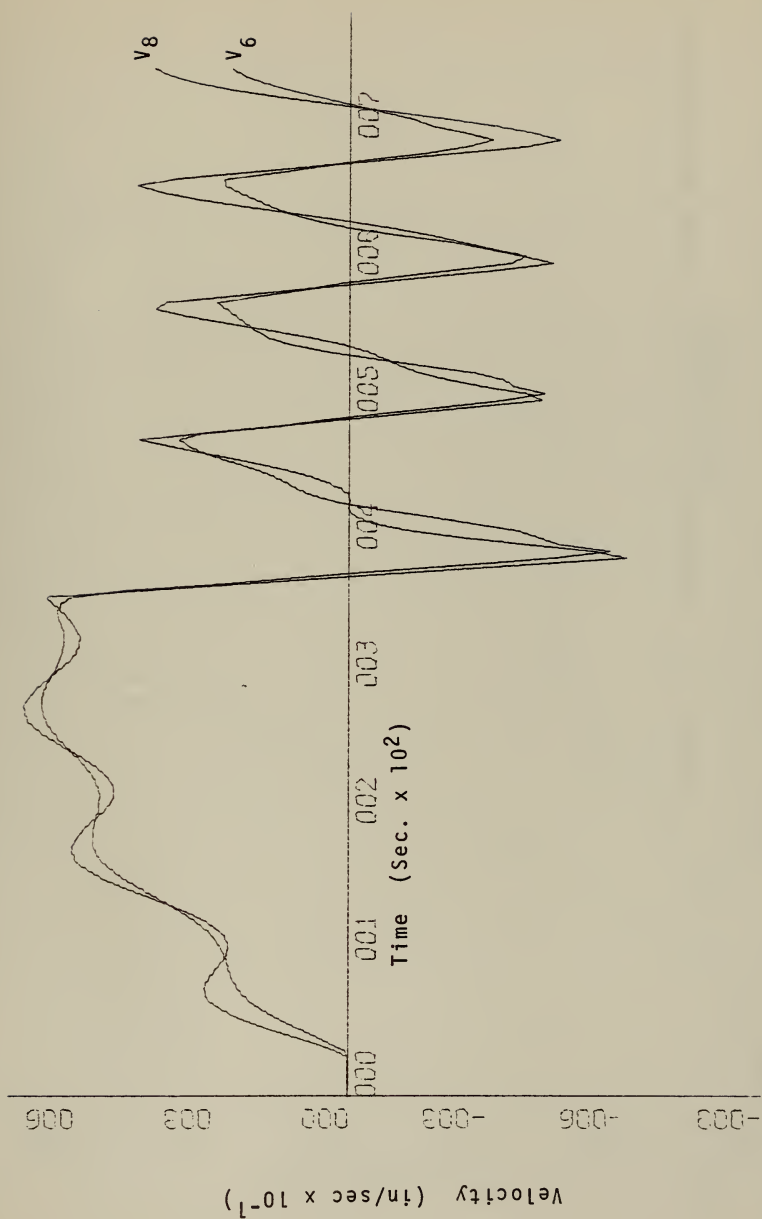


Figure 8 - SIMULTANEOUS BREECH CHAMBER VELOCITY HISTORIES

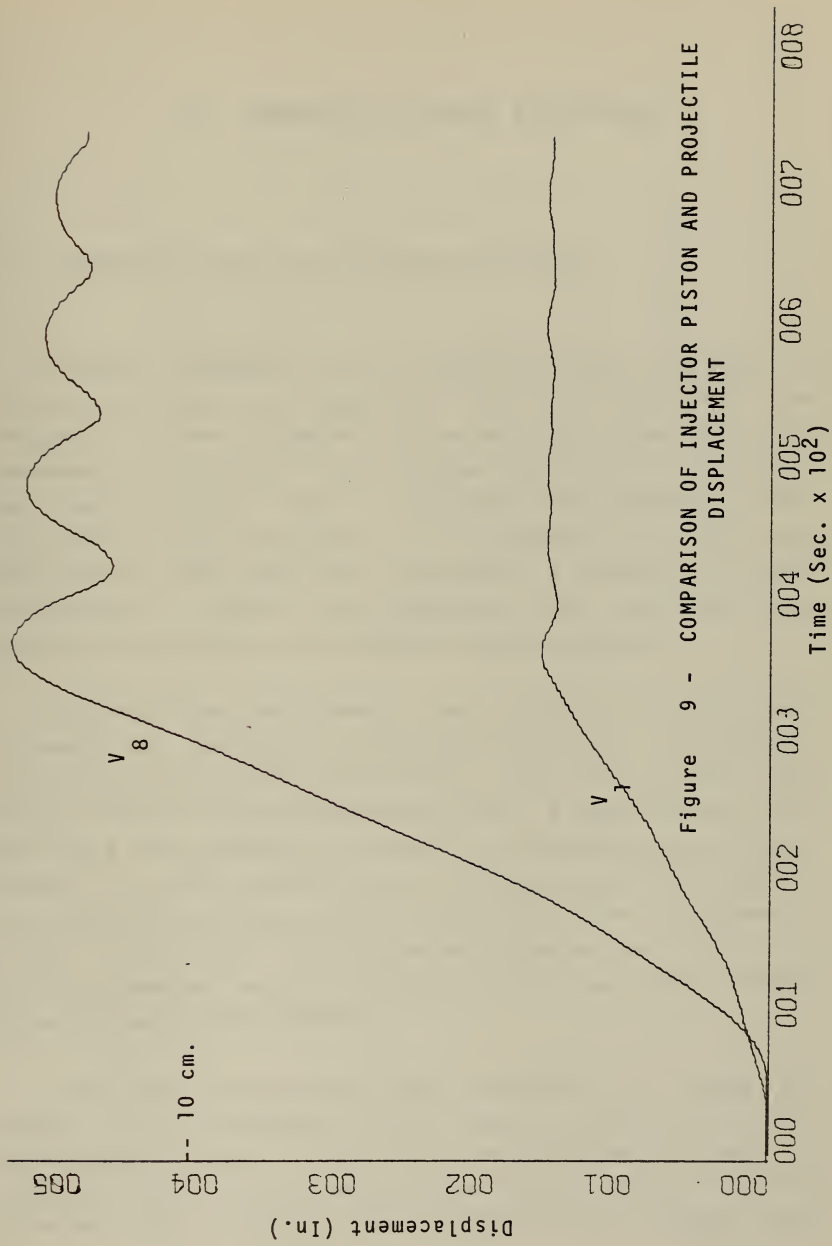


Figure 9 - COMPARISON OF INJECTOR PISTON AND PROJECTILE DISPLACEMENT

VI. ANALYSIS OF SYSTEM PERFORMANCE

A. PARAMETERS AFFECTING PROJECTILE RAM TIME

Several parameters can be varied to "tune" the model to correct ram time. In equations (1) and (9) (the force balances on the injector piston and projectile) empirical constants are included which account for any static friction and back pressure (PDI = injector back pressure, PDS = projectile back pressure). In equations (4) and (6), resistance coefficients are introduced to account for system resistances. Finally in equations (2), (5), and (8), propellant effective bulk modulus values appear.

The value for the injector and projectile total back pressure is difficult to determine precisely. Reference 1 cited an experimentally determined value of 24 psi. The analog computer model presented in Ref. 2 used a value of 46 psi for a ram pressure of 140 psi. The present model uses a value of 24 psi for PDI and 0.5 psi for PDS, or a total of 24.5 psi back pressure, which agrees with the experimental value. The value of system back pressure will vary with driving pressure and the configuration of each LPG system's injector and breech chambers.

Some basic research has been conducted to relate the value of the resistance coefficients to fluid properties. Unfortunately these studies which are described in Refs. 4 and 5, dealt with steady state fluid flow in constant diameter lines without flow restrictions, making their

results inapplicable to the present LPG feed system problem. The value of RV_2 can be related to the damping ratio of the "water hammer" pressure oscillations. The value of RV_1 was determined by an iterative process to obtain the best fit to experimental data. Figure (10) shows the dependence of ram-time on RV_1 and RV_2 , keeping all other variables constant. As expected intuitively, increasing the fluid resistance creates a larger system pressure drop, resulting in a lower pressure exerted on the face of the projectile and hence slower ram times. The slope of the two curves are almost identical so that no significant advantage would be achieved by system designs which try to minimize either RV_1 or RV_2 to the detriment of the other. It should be noted, however, that higher values for RV_2 do tend to slow down the ram time more than high values for RV_1 . Since the magnitude of RV_2 would probably depend mostly on the pressure drop at the gun valve, which seals the breech chamber, its design should be closely watched to ensure rapid ram times. Likewise the system designer will have to pay close attention to the design of the piping and valves in a large scale LPG feed system to achieve optimum performance.

The value of the effective bulk modulus was determined from the undamped natural frequency of the "water hammer" pressure oscillations as will be discussed in the next section. The bulk modulus is a fluid parameter which characterizes the spring effect of a liquid. The bulk modulus can be substantially lowered by the elasticity of the chamber and connecting line walls and the amount of entrapped gas present in the propellant fluid. As can be

seen from Figure (11), the value of the bulk modulus has only a small effect on ram time. Between bulk modulus values of 10,000 and 100,000 psi (the expected operating region of an operational system) the ram time is almost constant, varying less than a quarter of a millisecond. This is an encouraging result since minimizing entrapped gas is a difficult and costly design constraint.

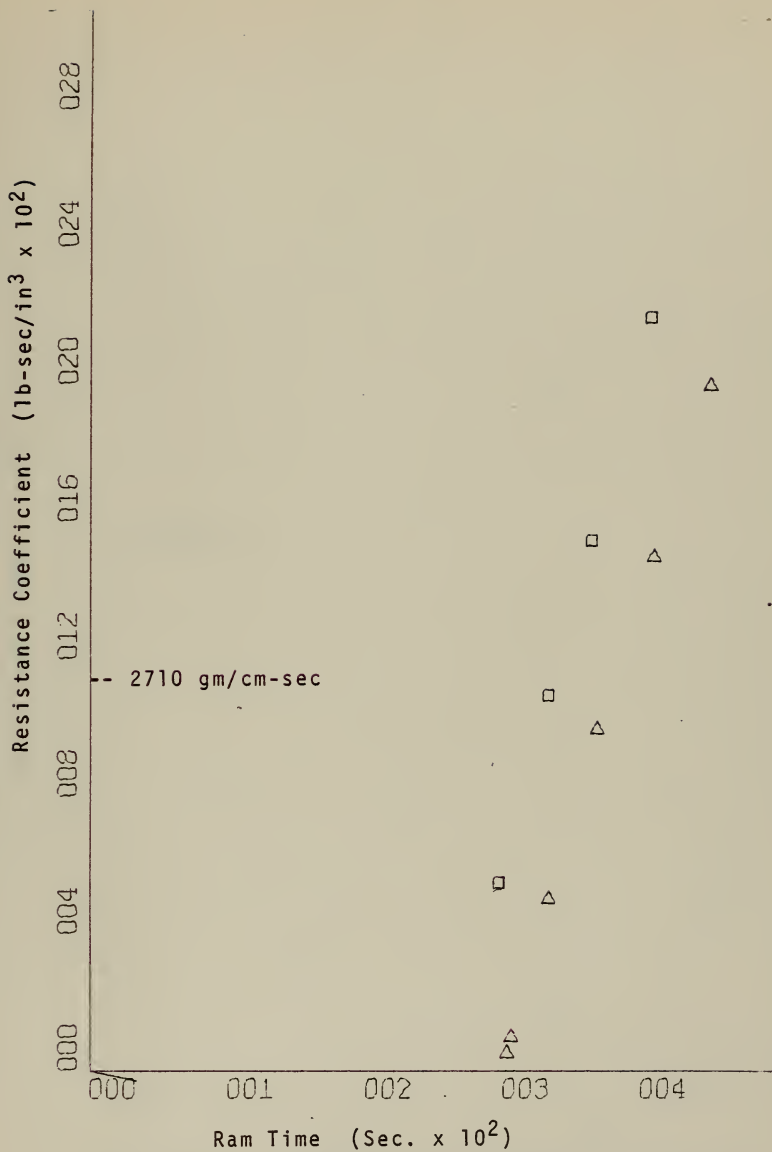


Figure 10 - RESISTANCE COEFFICIENTS VS RAM TIME

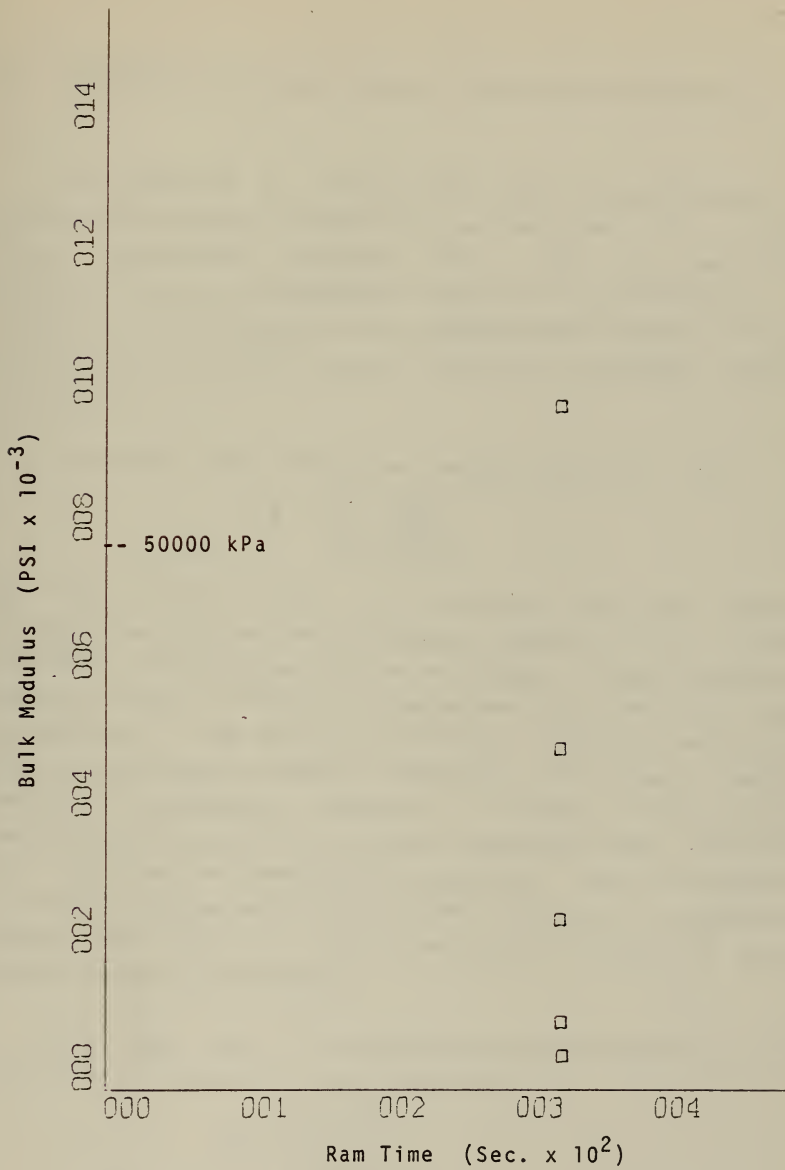


Figure 11 - BULK MODULUS VS RAM TIME

E. PARAMETERS AFFECTING CHAMBER PRESSURE OSCILLATIONS

As explained in Section III, after the projectile has stopped the chamber pressure can be described by a second order differential equation (Eqn. 10). If the system described by this differential equation is underdamped, the solution to the equation is an exponentially damped sinusoid with a characteristic damping ratio and undamped natural frequency.

From Eqn. (10), the system damping ratio, γ is:

$$\gamma = \frac{A_3}{A_2} \frac{Rv_2}{2\sqrt{\rho K}}$$

If this damping ratio is increased, the peak chamber pressure as well as the dissipation period of the system pressure oscillations will be decreased. From a designer's point of view, it would be advantageous for both of these quantities to be as low as possible. Hence, it would seem that an increase in system resistance to enhance damping would be desirable. However, as shown in the previous section, an increase in the system resistance also increases the ram time - an undesirable occurrence. Thus, alterations in system configuration which affect resistance coefficient values will have to be accomplished carefully to insure optimal system performance.

From Eqn. (10), the undamped natural frequency of the pressure oscillations in the LEG system is:

$$\omega_N = \sqrt{\frac{K}{\rho L_3 L_3}}$$

The primary effect of ullage would be to decrease the value

of effective bulk modulus and consequently to decrease the natural frequency of pressure oscillations. Hence, should it be found in future tests that the actual liquid propellant is highly sensitive to pressure oscillations, changes in ullage may be effected to decrease system ringing. Fortunately, as shown in the previous section, the effect of ullage variations on ram time is minimal.

VII. CONCLUSIONS

Several important conclusions can be drawn from the output of the LPG ram feed computer model. Thus, it is realized that serious design consideration must be given to the values of fluid resistances in the feed system in order to minimize ram time and peak pressures, and to optimize the damping of system pressure transients. Fortunately, concomitant model results also show that the effect of entrapped gas is minimal for the overall operation of a LPG feed system. The model was unable to account for any cavitation effects so this is an area that must be a subject of further studies.

The fact that large pressure transients occur during the projectile ramming cycle indicates the difficulties that might arise with proposed designs for liquid propellant guns with variable propellant volumes and projectile displacements. The pressure transients experienced in these systems will undoubtedly be very complex in nature.

If further improvements are desired in the modeling of LPG feed systems, the next step should be the inclusion of thermodynamic effects. For any real fluid, resultant feed system pressure and velocity changes will cause temperature changes which may substantially affect the propellant fluid density. Consequently, propellant ignition characteristics at high rates of fire will undoubtedly be affected.

The lumped parameter LPG feed system computer model has been shown to be in favorable agreement with experimental data. It is felt that this model has been sufficiently

validated to allow its use in more complicated LPG feed system designs. It is expected that this model will be used by the Naval Ordnance Station, Indian Head, Maryland to assist in studying the fluid dynamic characteristics of a 30 mm scale model LPG feed system becoming operational in June 1976. It will be necessary to make the obvious changes to describe the different geometry of the 30 mm scale model. The additional line lengths, and the larger pressure drops due to complex valve arrangements in the 30 mm system will require different values for model back pressure and resistance coefficients. The presence of an accumulator near the breech chamber will affect the value of the system damping ratio. It is possible that the different geometry and mass characteristics of the 30 mm model could result in the injector piston being slower than the projectile. However by incorporating all of these alterations, the manner in which each of the system parameters affect total system performance will be able to be predicted by the versatile lumped parameter computer model developed in this study.

As such, computer simulation is a useful design tool. However, to remain useful, it must be viewed in its proper perspective. Full scale prototype testing is the only conclusive method of demonstrating ordnance system performance. Unfortunately, testing is both costly and time consuming. Thus, computer simulation, no matter how simple or complex, can be used to designate critical testing instances and to identify those areas where design efforts will be most productive. In this way, the time involved in optimizing system performance as well as subsequent production costs can be reduced. In explosives research and ordnance design, which is still an empirical and necessarily hazardous science, computer simulation can be particularly useful in specifying the correct approach for design testing practices. In this respect, such models as the lumped

parameter model developed in this study can be considered as critical signposts at some of the many crossroads in systems development. However, it must be realized that as such they only point the way. The vehicle for arriving at an operational system can only be diligent research and engineering based on a measured progression of system demonstrations overseen by dedicated project managers aware of the many pitfalls along the way.

APPENDIX A

COMPUTER PROGRAM LISTING

The basis of the state variable method of systems analysis is the interpretation that the energy state of the components of a system completely describes the condition of a system. As defined in Ref. 6, the state of a system is the set of variables, the "state variables", which contain sufficient information about the present condition of the system to permit the determination of all future time history of the system - provided that all future inputs to the system are known. Therefore the energy state of those elements which store energy completely describes the system. In the case of the lumped parameter model, these elements are the fluid inertia and capacitance and the inertia of the injector piston and projectile. The energy state of these storage elements can be described as a function of time in terms of the state variables - pressure, velocity, and the system input pressure. Only those variables required to completely specify the state of the system need to be included.

The first step in arriving at the computer program was to take equations (1) through (9) and normalize, or solve them for the highest derivative. The state variables then become the pressure or velocity associated with these first derivatives. The computer program was developed by combining equations and defining new variables as follows:

$$X(1) = v_1$$

$$\begin{aligned} X(2) &= F_1 \\ X(3) &= v_2 \\ X(4) &= F_4 \\ X(5) &= v_6 \\ X(8) &= F_\epsilon \\ X(9) &= v_\epsilon \end{aligned}$$

Equation (1) becomes:

$$XDOT(1) = \frac{-K_{FP}}{M_P} X(1) - \frac{A_1}{M_P} X(2) + \frac{A_R}{M_P} P_R - \frac{A_1}{M_P} P_{DI}$$

In the computer program, P_R is represented by $X(30)$ and K_{FP} and P_{DI} become program constants, $C(7)$ and $C(2)$, respectively. The value of $C(2)$ and $C(7)$ are input on data cards. Using the fact that $P_1 = P_2$, equation (2) becomes:

$$XDOT(2) = \frac{K}{L_1} X(1) - \frac{K}{L_1} X(3)$$

where K is input to the computer program as $C(3)$. By combining equations (3) and (4) and using the incompressible flow assumption $A_1 v_1 = A_2 v_2$, the next equation is derived:

$$XDOT(3) = \frac{1}{\rho L_1} (X(2) - Rv_1 \frac{A_1}{A_2} X(3) - X(4))$$

where Rv_1 becomes $C(4)$. Next equation (5) and the incompressible flow assumptions $A_1 v_1 = A_2 v_2$ and $A_2 v_2 = A_3 v_3$ yield:

$$XDOT(4) = \frac{A_1 K}{A_2 L_2} X(3) - \frac{A_3 K}{A_2 L_2} X(4)$$

and as before, $C(3) = K$. Equations (6) and (7) combine with the flow velocity equation $A_2 v_2 = A_3 v_3$ to yield:

$$XDOT(5) = \frac{1}{\rho L_3} (X(4) - Rv_2 \frac{A_3}{A_2} X(5) - X(8))$$

where Rv_2 becomes $C(5)$. Since $v_6 = v_7$, equation (8) becomes:

$$XDOT(8) = \frac{K}{L_3} X(5) - \frac{K}{L_3} X(9)$$

where K again becomes C(3). Finally, equation (9) becomes:

$$\dot{X}(9) = \frac{-KFS}{M_s} X(9) + \frac{A_3}{M_s} X(8) - \frac{A_3}{M_s} PDS$$

where KFS and PDS become C(8) and C(9) respectively. The auxiliary equations:

$$\dot{X}(6) = X(1)$$

$$\dot{X}(7) = X(9)$$

are used to calculate injector piston displacement, X(6), and projectile displacement, X(7).


```

LP000490
LP000500
LP000510
LP000520
LP000530
LP000540
LP000550
LP000560
LP000570
LP000580

```

```

XUCT(5) = (-C(8)/MS)*X(9) + (A3/MS)*X(8) - C(6)*A3/MS
XSM = X(9)
GC TO 100
XUCT(9) = XSM/3.8530E-03
XUCT(7) = X(5)
C(11) = 100.0
C(12) = 50.0
GC TO 1
ENC

```

```

50
100

```

C

```

LP000590
LP000600
LP000610
LP000620
LP000630
LP000640
LP000650
LP000660
LP000670
LP000680
LP000690
LP000700
LP000710
LP000720
LP000730
LP000740
LP000750
LP000760
LP000770
LP000780
LP000790
LP000800
LP000810
LP000820
LP000830
LP000840
LP000850
LP000860
LP000870
LP000880
LP000890
LP000900
LP000910
LP000920
LP000930

```

```

SERCUTINE CAMP1(/TC,/XC,/DX,/C/)
REPL#8 ITITLE(12),JITILE(8),KITILE(8),IBLANK/,
DIMENSION X(30),XC(30),C(12),IP(10),PR(10),GR(10),
1TX(5),TY(5),X1(900),Y1(900),X2(500),Y2(500),Y3(500),
2REAL LABEL, RUN(2), RUN', 8', 5, BT(5), 1', 2', 3', 4
1, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65, 66, 67, 68, 69, 70, 71, 72, 73, 74, 75, 76, 77, 78, 79, 80, 81, 82, 83, 84, 85, 86, 87, 88, 89, 90, 91, 92, 93, 94, 95, 96, 97, 98, 99, 100
3EQUIVALENCE (ITITLE(7), RUN(1))
INDIC = C(10)+0.0000001
GC TO (1, 2000, 50, 52, 88, 88), INDIC

```

READ DATA AND PRINT RECCD.

C
C
C

```

1 REAL(5, 100) (ITITLE(I), I=1,6)
100 FCFORMAT (10A8)
101 FCFORMAT (11) INR
102 FCFORMAT (5) (102) INN
NRC = 0
IF (NRC, LE, 30) GO TO 1000
WRITE(6, 200)
FCFORMAT (///, 48H ERROR IN ORDER OF EQUATION. MUST NOT EXCEED 30. )
STOP

```

```

1000 NRC = NRC + 1
WRITE (6, 201) (ITITLE(I), I=1,6)
FCFORMAT (1H1, ///, 3EX, 6A8)
201 IF (NRC, EQ, 1, AND, NR, EQ, 1) GO TO 5
WRITE(6, 202) INR
FCFORMAT (/, 37X, 11, 20H RUNS ARE CALLED FOR )
GC TO 6
202 WRITE(6, 203)
FCFORMAT (/, 37X, 21HCNE RUN IS CALLED FOR , ///, 16H INPUT DATA RECORD)
GC TO 7
203 WRITE(6, 204) INRC

```



```

204 FCRMAT (/,34H INPUT DATA RECCRE FCR RUN NUMBER ,I1)
205 WRITE(6,205)NN
206 FCRMAT (/,22H ORDER OF EQUATIONS =,I2)
103 READ(5,103)I1,DT,TF1,DT2,TF2,DT3,TF3
103 FCRMAT (8F10.4)
TF = TF1
IF (DT2.E.0.) GO TO 9
206 WRITE(6,206)I1,TF
WRITE(6,22H INITIAL TIME =,E10.4,/)
WRITE(6,22H FINAL TIME =,E10.4,/)
207 FCRMAT (22H STEP SIZE =,E10.4)
1 WRITE(6,207)DI
FCRMAT (22H STEP SIZE =,E10.4)
5 GC TO 12
IF (DT3.NE.0.) GO TO 11
WRITE(6,206) I1,TF
WRITE(6,208)DT,I1,TF1,DT2,TF1,TF
208 FCRMAT (22H STEP SIZE =,E10.4,13H BETWEEN T =,E10.4,
1 GC TO 12
SH AND T =,E10.4)
11 TF = TF3
12 READ(5,103) (C(I),I=1,8)
REAL (5,103) (X(I),I=1,NN)
J = 0
14 CC 14 I=1,8
IF (C(I).NE.0.) J=J+1
CCNTINUE
K = 0
16 CC 16 I=1,NN
IF (X(I).NE.0.) K=K+1
CCNTINUE
17 IF (J = 17,18,19)
205 FCRMAT (/,34H ALL THE CCNSTANTS, C(I), ARE ZERG )
GC TO 423
18 WRITE (6,210)
FCRMAT (/,30F THE ONLY NON-ZERO CCNSTANT IS )
CC TO 420
19 WRITE (6,211)
FCRMAT (/,35F THE NON-ZERO CCNSTANTS, C(I), ARE )
420 IF (C(1).NE.0.) I=1,8
212 IF (C(I).NE.0.) WRITE(6,212) I,C(I)
421 FCRMAT (14X,2HC(,I2,4H) =,E10.4)
422 CCNTINUE
423 IF (K = 1) 424,425,426
424 WRITE (6,1209)
425 FCRMAT (/,36H ALL THE INITIAL CCNSTANTS ARE ZERG )
1209

```

```

LPG00540
LPG00550
LPG00560
LPG00570
LPG00580
LPG00590
LPG01000
LPG01010
LPG01020
LPG01030
LPG01040
LPG01050
LPG01060
LPG01070
LPG01080
LPG01090
LPG01100
LPG01110
LPG01120
LPG01130
LPG01140
LPG01150
LPG01160
LPG01170
LPG01180
LPG01190
LPG01200
LPG01210
LPG01220
LPG01230
LPG01240
LPG01250
LPG01260
LPG01270
LPG01280
LPG01290
LPG01300
LPG01310
LPG01320
LPG01330
LPG01340
LPG01350
LPG01360
LPG01370
LPG01380
LPG01390
LPG01400
LPG01410

```



```

C 306 IF(JJ.EQ.0) GO TO 27
WRITE(6,214) (JTITLE(I),IP(I),I=1,JJ)
FCFMAT(//,56H THE COLUMN HEADINGS AND THE CCRRESPONDING VARIABLES
214 IS ARE //,10X,A8,4X,2HX(,I2,1H))
GC TO 28
WRITE(6,215)
FCFMAT(//,25H NO PRINTOUT IS RECIRED )
215 IF(KK.EC.0) GO TO 308
IF(MULTIP.NE.0) GO TO 309
IF(KK.NE.1) GO TO 307
WRITE(6,216) (KTITLE(1),KTITLE(2),IG(1),IG(2)
216 E, //,10X,2A8,4X,2FX(I2,8H) VS. X(I2,1F))
GC TO 31
WRITE(6,217) (KTITLE(I),KTITLE(I+1),IG(I),IG(I+1),I=1,KK,2)
307 FCFMAT(//,64H THE INDIVIDUAL GRAPH TITLES AND THE CCRRESPONDING
217 IVARIABLES ARE //,(10X,2A8,4X,2FX(I2,8H) VS. X(I2,1H))
GC TO 31
WRITE(6,1217)
1217 FCFMAT(//,24H NC GRAPHS ARE RECIRED )
GC TO 31
WRITE(6,1220)
308 FCFMAT(//,52H THE GRAPH TITLE AND THE CCRRESPONDING VARIABLES ARE
1220 E, //)
WRITE(6,1221) (KTITLE(1),KTITLE(2),IG(1),IG(I+1),I=1,KK,2)
1221 FCFMAT(10X,2A8,4X,2FX(I2,8H) VS. X(I2,1F),/, (30X,2FX(I2,
C THIS ENCS THE BOOK-KEEPING. INITIALIZE BEFCFE ENTERING MAIN LCCF.
C 31 IFACE = 0
ACPTS = 0
NCPTS = 0
ITITLE(8) = IBLANK
ITITLE(11) = IBLANK
ITITLE(12) = IBLANK
IRUN(2) = ET(ARC)
C(11) = 20.
C(12) = 57.
C(13) = 07. NA
CC(13,42) = X(I1)
42 CC(11) = X(I1)
TC = T
C(10) = 2.
C RETURN

```

```

LP601500
LP601510
LP601520
LP601530
LP601540
LP601550
LP601560
LP601570
LP601580
LP601590
LP602000
LP602010
LP602020
LP602030
LP602040
LP602050
LP602060
LP602070
LP602080
LP602090
LP602100
LP602110
LP602120
LP602130
LP602140
LP602150
LP602160
LP602170
LP602180
LP602190
LP602200
LP602210
LP602220
LP602230
LP602240
LP602250
LP602260
LP602270
LP602280
LP602290
LP602300
LP602310
LP602320
LP602330
LP602340
LP602350
LP602360
LP602370

```



```

C 2000 IF (JJ.EC.0) GO TO 54
      INACPR = C(11)+0.0000001
      C(11) = 20.
      IF (MCD (NCPTS,50*INACPR).EQ.0) GC TC 46
      IF (MOD (NCPTS,10*INACPR).EQ.0) GC TC 47
      IF (MCD (NCPTS,10*INACPR))54,48,54
      46 IPAGE = IPAGE + 1
      IF (MCD (NCPTS,10*INACPR).EQ.0) GO TO 1047
      WRITE (6,218) (JTITLE(I),I=1,6), IPAGE, JTITLE(7), (JTITLE(I),I=1,8)
      GC TO 47
      1047 WRITE (6,218) (ITITLE(I),I=1,6), IPAGE, (JTITLE(I),I=1,8)
      GC TO 47
      47 WRITE (6,219)
      218 FCFMAT (11,1,///,20X,6A8,10X,5HPAGE,11,14H CF OUTPUT FOR, A8,////,
      121E FCFMAT (11,1,///,20X,6A8,30X,5HPAGE,11,1,////,11X,8(AE,5X))
      219 FCFMAT (11,1,///,20X,6A8,30X,5HPAGE,11,1,///,11X,8(AE,5X))
      45 TC = T
      C(10) = 3.
      RETURN
C 50 LC 53 I=1, JJ
C
      PR(I) = T
      IF (IP(I).NE.0) PR(I)=XC(IP(I))
      CONTINUE
      53 WRITE (6,220) (PR(I),I=1, JJ)
      220 FCFMAT (7X,8E13.5)
      54 IF (KKK.EC.0) GO TO 62
      INACGR = C(12)+0.0000001
      55 IF (MCD (NCPTS, INACGR).NE.0) GO TO 62
      LC 57 I=1, NN
      C(11) = X(I)
      57 TC = T
      RETURN
C 58 LC 61 I=1, KKK
C
      GR(I) = T
      IF (IG(I).NE.0) GR(I)=XC(IG(I))
      CONTINUE
      61 IF (KKK.GE.8) GO TO 1610

```


LPG03340
 LPG03350
 LPG03360
 LPG03370
 LPG03380
 LPG03390
 LPG03400
 LPG03410
 LPG03420
 LPG03430
 LPG03440
 LPG03450
 LPG03460
 LPG03470
 LPG03480
 LPG03490
 LPG03500
 LPG03510
 LPG03520
 LPG03530
 LPG03540
 LPG03550
 LPG03560
 LPG03570
 LPG03580
 LPG03590
 LPG03600
 LPG03610
 LPG03620
 LPG03630
 LPG03640
 LPG03650
 LPG03660
 LPG03670
 LPG03680
 LPG03690
 LPG03700
 LPG03710
 LPG03720
 LPG03730
 LPG03740
 LPG03750
 LPG03760
 LPG03770
 LPG03780
 LPG03810

```

80  GC TO 87
    IF (IF.CE.T) GO TO 74
    IF (IF1.LT.T) GO TO 76
    IF (IF2.LT.T) 78,79,75
87  C(10) = 5.
C   EE CALL RKLTTA (NN,T,X,DT,C,TC,XC,DX)
C
C   50  IF (C(10).EQ.6.) RETURN
      T = T + DT
      GC TO 200
81  IF (KK.EC.0) GO TO 330
    IF (MULTIP.NE.0) GO TO 57
C   PRINT PLOT UP TO 4 INDIVIDUAL CURVES
C
5558 NUMPTS=-NUMPTS
      CCRTM=1, KK
      WCFRMAT(6,1H1)
      ITITLE(5)=KTITLE(2*II-1).
      CALL TO (311, 312, 313, 314), II
      CALL FLCTP(X1,Y1,NUMPTS,0)
311  GC TO 310
      CALL FLCTP(X2,Y2,NUMPTS,0)
312  GC TO 310
      CALL FLCTP(X3,Y3,NUMPTS,0)
313  GC TO 310
      CALL FLCTP(X4,Y4,NUMPTS,0)
314  WCFRMAT(6,5558) ITITLE
9999 FLCFMAT(1,0,8X,12A8)
      GC TO 320
C   PLCT DUMMY CURVE ALCNG AXES TO SET SCALES FCR MULTIPLE PLCT
C
57  BIGX = 0.
      BIGY = 0.
      SMLX = 0.
      SMLY = 0.
      SCLX = 1.970
      XMAX = AMAX1 (X1(1), X2(1), X3(1), X4(1), X3(1), X4(1))
      YMAX = AMAX1 (Y1(1), X2(1), X3(1), X4(1))
      XMIN = AMIN1 (X1(1), X2(1), X3(1), X4(1))
      YMIN = AMIN1 (Y1(1), Y2(1), Y3(1), Y4(1))
      IF (BIGX.LT.XMAX) BIGX=XMAX
      IF (BIGY.LT.YMAX) BIGY=YMAX
      IF (SMLX.GT.XMIN) SMLX=XMIN
  
```


8E4 FCFMAY(' GRID NOT SETUP WHEN PLCT INITIALIZED. NC PLCT UNTIL GRP
 1) PROPERLY SETUP,)
 RETURN
 END
 PLCP2370
 PLCP2380
 PLCP2390
 PLCP2400

```

C
SUBROUTINE PSCALE(XMAX,XMIN,IDIV,ISCT)
  IDIV=IDIV
  ROUNDCND=MAXIMUM TO NEXT HIGHEST 2 SIG FIGS
  IF(ISCT.LT.3) XMAX=SMAXI(0.,XMAX)
  IF(ALL ROUNDCND.(XMAX,IMX,FMX))
    IF(ABS(XMX).LE.1.E-7) XMX=0.0
    IF(X=IMX-1
      IF(X=FMX*10.**IMX
        IF(XMX.GE.XMAX) GO TO 2
        IF(X=FMX
          IF(X=FMX
            IF(X=IMX
              GO TO 3
            ROUNDCND=MINIMUM TO NEXT LOWEST 2 SIG FIGS
            IF(ISCT.LT.3) XMIN=AMINI(0.,XMIN)
            CALL ROUNDCND (XMIN,IMX,FMX)
            IF(X=IMN-1
              IF(X=FMN*10.**IMN
                IF(XMX.LE.1.E-7) XMX=0.0
                IF(X=FMN
                  IF(X=FMN
                    IF(X=IMN
                      GO TO 4
                    ROUNDCND=MAX & MIN TO 1. OR .1 IF RANGE LARGE
                    IF(XMX.LE.1.E-7) XMX=0.0
                    IF(X=FMN-XMN
                      IF(X=IM+1
                        ROUNDCND=CIV.LE.SM) GC TO 12
                        IF(ABS(XMN).LT.SM.AND.ABS(XMN).GT.0.) XMN=SIGN(SM,XMN)
                        IF(ABS(XMX).LT.SM.AND.ABS(XMX).GT.0.) XMX=SIGN(SM,XMX)
                        IF(CIM.GT.0) GO TO 19
                        IF(X=IM+1
                          ROUNDCND=MAX-MIN) TO 2 SIG FIGS
                          IF(X=FMN-XMN (XSC,IS10,FACTX)
                            CALL ROUNDCND WHICH IS MULTIPLE OF IDIV
  15
  C
  14
  11
  5
  12
  C
  15
  C
  
```


PLCP3270
 PLCP3280
 PLCP3290
 PLCP3300
 PLCP3310
 PLCP3320
 PLCP3330
 PLCP3340
 PLCP3350
 PLCP3360
 PLCP3370
 PLCP3380
 PLCP3390
 PLCP3400
 PLCP3410
 PLCP3420
 PLCP3430

```

C IS=IS+ILD
  RCUND MANTISSA TO 2 SIG FIGS
  IFACT=FACT*10+.05
  IFACT=IFACT
  IFACT=FACT/10.
  IF (FACT .LT. 10.) GO TO 20
  SET TIC 1 IF LESS THAN 10.
  FACT=1.
C IS=IS+I
  IF INPUT NEGATIVE, SET MANTISSA NEGATIVE
  20 IF (ANUM .LT. 0.) FACT=-FACT
  RETURN
C SET TO C. IF 0.
  IFACT=0.
  IS=0
  RETURN
  END
  
```

CAMFIER,CR LPG SIMULATION

```

105 C 0.0 0.0001 0.075 0.180 0.5 0.001 0.001
    140.0 24.0 3200. 0.040 0.040 0.040 0.040 0.040 0.040 0.040
TIME 00 XI 06 XS 07 PS 08 PI 02 VS 09 PL 04 V6 05
XI VS TIME 0600 V6 VS TIME 0500 XS VS TIME 0700 PS VS TIME 0800
  
```


INT110020
 INT110050
 INT110060
 INT110070
 INT110080
 INT110090
 INT110100
 INT110110
 INT110120
 INT110130
 INT110140
 INT110150
 INT110160
 INT110170
 INT110180
 INT110190
 INT110200
 INT110210
 INT110220
 INT110230
 INT110240
 INT110250
 INT110260
 INT110270
 INT110280
 INT110290
 INT110300
 INT110310
 INT110320
 INT110330
 INT110340
 INT110350
 INT110360
 INT110370
 INT110380
 INT110390
 INT110400
 INT110410
 INT110420
 INT110430
 INT110440
 INT110450
 INT110460
 INT110470
 INT110480
 INT110490
 INT110500

SUBROUTINE DAMPI

DESCRIPTION OF PARAMETERS AND DATA CARDS

EQUATION STATEMENTS

THE NUMBER OF XDOT EQUATIONS IS N, WHICH MUST NOT EXCEED 30. THESE EQUATIONS ARE SUPPLIED BY THE USER, WHO DEFINES EACH XDOT IN TERMS OF THE DEPENDENT VARIABLES, X(I), THROUGH X(N), AND THE INDEPENDENT VARIABLE 'T'. IN WRITING THESE EQUATIONS THE USER MAY INTRODUCE AT HIS CONVENIENCE:

- A) ANY UNSUBSCRIPTED VARIABLES
- B) THE SUBSCRIPTED VARIABLES X(I), (N.LT.I.LE.30).
- C) THE CONSTANTS C(I), (I .LE. 8, TO BE ENTERED AS DATA)
- D) ANY NORMAL FORTRAN TECHNIQUE OR FUNCTION
- E) ROUTINES FROM ANY SOURCE LIBRARY OR USER-SUPPLIED SUBROUTINES

NOTE 1: THE USE OF 'AUXILIARY' X(I) (WHEN I .GT. NUMBER OF EQUATIONS) TO BE INTEGRATED DOES NOT ALTER THE VALUE OF N, THE ORDER OF THE EQUATIONS.

NOTE 2: LOOPS, EITHER WITH OR WITHOUT A DO STATEMENT ARE BEST AVOIDED.

NOTE 3: 'IF' STATEMENTS, PROVIDED THAT THEY DO NOT CREATE A LOOP, CAN BE USED TO TRANSFER CONTROL WITHIN THE USER'S EQUATIONS. FOR EXAMPLE, THE STATEMENT
 IF (T .GT. 10.) C(3) = 0
 WOULD CAUSE C(3) TO TAKE THE VALUE ZERO FOR ALL T GREATER THAN 10.

CONSTANTS

THE CONSTANTS C(1) THROUGH C(8) MAY BE USED AS DESCRIBED IN THE ABOVE EXAMPLES, AND ARE REAC IN FROM A DATA CARD. C(10) MUST NEVER BE USED, EXCEPT AS INDICATED IN THE STANCARD CS/360 CHECK ABOVE. C(11) AND C(12) CONTROL THE OUTPUT. FOR EXAMPLE, IF THE STATEMENTS

CF THREE SEGMENTS OF DIFFERING STEP SIZE. THE DATA, IN COLUMNS
 I C AS ABOVE, THEN TAKES THE FORM
 T1 - D11 - TFI - D12 - TF2 - D13 - TF

FIFTH: THE VALUES OF THE CONSTANTS C(1), C(2) I...; C(8) ARE
 PUNCHED, WITH DECIMAL POINTS, IN COLUMNS 1-10, 11-20, ...; 71-80.
 IF BLANK COLUMNS MAY BE USED FOR A ZERO OR UNLSECC CONSTANT.
 IF NO CONSTANTS ARE USED, THIS ENTIRE CARD WILL BE BLANK ---
 BUT IT MUST NOT BE OMITTED.

SIXTH: THE INITIAL VALUES OF X(1), X(2), ..., X(N) ARE PUNCHED,
 WITH DECIMAL POINTS, IN COLUMNS 1-10, 11-20, ...; ADDITIONAL
 CARC (S) ARE REQUIRED IF N.GT.8. TEN BLANK COLUMNS MAY BE USED
 FOR A ZERO INITIAL VALUE.

NEXT TO LAST: THIS CARD CONTROLS THE CHOICE OF VARIABLES
 FOR PRINTOUT: EACH GROUP OF 10 COLUMNS, 1-10, 11-20, ... UP TO
 71-80 MAY BE USED TO SPECIFY A COLUMN HEADING (8 CHARACTERS)
 AND A 2 DIGIT, RIGHT JUSTIFIED SUBSCRIPT IDENTIFYING THE CARC-
 RESPONDING VARIABLE.

FOR EXAMPLE:

TIME 00 AND 11-20 WOULD CAUSE THE INDEPT-
 SPENT 03 IN COLUMNS 1-10 AND 11-20 WOULD CAUSE THE SUBSCRIPT
 VARIABLE 1 TO BE PRINTED ON THIS CARD BY THE CARC 03
 END VARIABLE 1 TO BE PRINTED UNDER THE COLUMN HEADING TIME, AND THE
 VARIABLE X(3) TO BE PRINTED ON THE OUTPUT DURING THE RUN. IF NO
 MORE THAN 8 VARIABLES CAN BE OUTPUT DURING THE RUN.
 PRINTOUT IS DESIRED, THIS CARD MUST BE BLANK.

LAST: THIS CARD CONTROLS THE CHOICE OF VARIABLES FOR GRAPH
 CUPPLS T. UP TO 4 CURVES CAN BE PLOTTED, EITHER ALL ON SEPARATE
 GRAPHS OR ALL ON A SINGLE GRAPH. EACH GROUP OF 20 COLUMNS 1-20,
 21-40, ... SPECIFIES A CURVE. EXAMPLE: GROUP 1-20, CURVE 1, TO BE
 PLOTTED VS. TIME 0300 AGAINST THE INDEPENDENT VARIABLE X(2).
 PLOTTED VERTICALLY AGAINST THE INDEPENDENT VARIABLE X(1).
 VARIABLE. (AGAIN THE SUBSCRIPT 00 REPRESENTS THE SPEED VS. TIME.)
 NOTE THAT THE FIRST 16 COLUMNS OF EACH GROUP ARE USED FOR THE
 LABEL, THE 17TH AND 18TH FOR THE Y-ORDINATE, AND THE LAST
 TWO FOR THE X-ORDINATE.

IF THE CURVES ARE TO BE ON SEPARATE GRAPHS, EACH GRAPH MUST
 HAVE A LABEL. IF THE CURVES ARE TO BE ALL ON ONE GRAPH, CALLY
 THE FIRST LABEL MUST BE PROVIDED (IN COLUMNS 1-16). THE OTHER

IN111770
 IN111780
 IN111790
 IN111800
 IN111810
 IN111820
 IN111830
 IN111840
 IN111850
 IN111860
 IN111870
 IN111880
 IN111890
 IN111900
 IN111910
 IN111920
 IN111930
 IN111940
 IN111950
 IN111960
 IN111970
 IN111980
 IN111990
 IN112000
 IN112010
 IN112020
 IN112030
 IN112040
 IN112050
 IN112060
 IN112070
 IN112080
 IN112090
 IN112100
 IN112110
 IN112120
 IN112130
 IN112140
 IN112150
 IN112160
 IN112170
 IN112180
 IN112190
 IN112200
 IN112210
 IN112220
 IN112230
 IN112240

CC

LABELS MUST BE BLANK. THE ENTIRE CARD MUST BE BLANK IF NC GRAPH-
 OUTPUT IS REQUIRED.

MULTIPLE RUNS

IF SEVERAL SOLUTIONS OF THE SAME EQUATIONS (WITH DIFFERENT
 CONSTANTS OR INITIAL CONDITIONS) ARE REQUIRED, THE NUMBER OF
 RUNS IS SPECIFIED ON THE SECOND DATA CARD. FOR ALL RUNS AFTER
 THE FIRST, ONLY THE FOURTH THROUGH THE LAST DATA CARDS ARE TO
 BE SUPPLIED. EXCEPT FOR THE DATA ON THE FIRST THREE CARDS, AND
 THE EQUATIONS THEMSELVES, NO INFORMATION IS RETAINED BETWEEN
 RUNS.

SLEROUTINE PLOTP/CPLTP

CALLING SEQUENCE

CALL PLOTPIX,Y,N,MCCCUR)

CALL DPLTP(X,Y,N,MCCCUR)

DESCRIPTION OF ARGUMENTS

X VECTOR OF ABSCISSAE (REAL*4 WHEN CALLING PLCTP AND REAL*8
 WHEN CALLING DPLTP)

Y VECTOR OF ASSOCIATED ORDINATES (REAL*4 WHEN CALLING PLCTP
 AND REAL*8 WHEN CALLING DPLTP)

N NUMBER OF (X,Y) PAIRS

MCCCUR CONTROLS THE NUMBER OF CURVES ON ONE GRAPH. SEE BELOW
 FOR EXPLANATION OF MULTIPLE VALUES OF MCCCUR.

- =0, 4, OR 8 THERE IS ONLY ONE CURVE ON THIS GRAPH
- =1, 5, OR 9 THIS IS THE FIRST OF TWO OR MORE CURVES ON
 THIS GRAPH.
- =2, 6, OR 10 THIS IS AN INTERMEDIATE CURVE ON THIS GRAPH.
- =3, 7, OR 11 THIS IS THE LAST CURVE ON THIS GRAPH.

SCALING

SCALING IS PERFORMED ONLY ON THE FIRST SET OF POINTS (WHEN
 MCCCUR IS 0, 1, 4, 5, 8 OR 9.) FOR A MULTIPLE CURVE GRAPH,
 THE USER SHOULD CALL THE SUBROUTINE INITIALLY WITH THE LARGEST
 CURVE TO INSURE OPTIMUM SCALING.

INT12250
 INT12260
 INT12270
 INT12280
 INT12290
 INT12300
 INT12310
 INT12320
 INT12330
 INT12340
 INT12350
 INT12370
 PLCP0020
 PLCP0030
 PLCP0040
 PLCP0120
 PLCP0130
 PLCP0140
 PLCP0150
 PLCP0160
 PLCP0170
 PLCP0180
 PLCP0190
 PLCP0200
 PLCP0210
 PLCP0220
 PLCP0230
 PLCP0240
 PLCP0250
 PLCP0260
 PLCP0270
 PLCP0280
 PLCP0290
 PLCP0300
 PLCP0310
 PLCP0320
 PLCP0330
 PLCP0340
 PLCP0350
 PLCP0360
 PLCP0370
 PLCP0380
 PLCP0390
 PLCP0400
 PLCP0410
 PLCP0420
 PLCP0430

CC

PLCPO920
 PLCPO930
 PLCPO940
 PLCPO950
 PLCPO960
 PLCPO970
 PLCPO980
 PLCPO990
 PLCPI000
 PLCPI010
 PLCPI020
 PLCPI030
 PLCPI040
 PLCPI050
 PLCPI060
 PLCPI070
 PLCPI080
 PLCPI090
 PLCPI100
 PLCPI110
 PLCPI120

IN THE X DIRECTION (COLUMN-WISE), THERE WILL BE 5 VALUES:
 THE MAXIMUM, THE MINIMUM, AND 3 INTERMEDIATE EQUALLY SPACED
 VALUES.
 IN THE Y DIRECTION (ROW-WISE), THERE WILL BE 7 VALUES: THE MAXI-
 MUM, THE MINIMUM, AND 5 INTERMEDIATE EQUALLY SPACED VALUES.
 IF THE LABELS HAVE A VALUE BETWEEN 1. AND 10**8, THEY WILL BE
 PRINTED IN AN F11.2 FORMAT, OTHERWISE THEY WILL BE PRINTED IN
 IPE1C.3 FORMAT.

FLOTTING

FOUR CHARACTERS ARE USED FOR PLOTTING CURVES: " ", "+", "*", "X",
 AND "X". WHEN MORE THAN ONE CURVE IS PLOTTED ON A GRAPH, EACH IS
 USED IN TURN IN THE ABOVE ORDER. IF MORE THAN 4 CURVES ARE
 PLOTTED IN THE ABOVE CYCLE OF CHARACTERS IS REPEATED. IF A NEW
 CURVE IS TO BE PLACED IN THE PLOTTING GRID WHERE AN OLD CURVE
 EXISTS, THE CHARACTER REPLACES THE OLD ONE. IF
 IDENTICAL CURVES ARE PLOTTED, THEY WILL APPEAR AS ONE CURVE
 COMPOSED OF "X"'S.

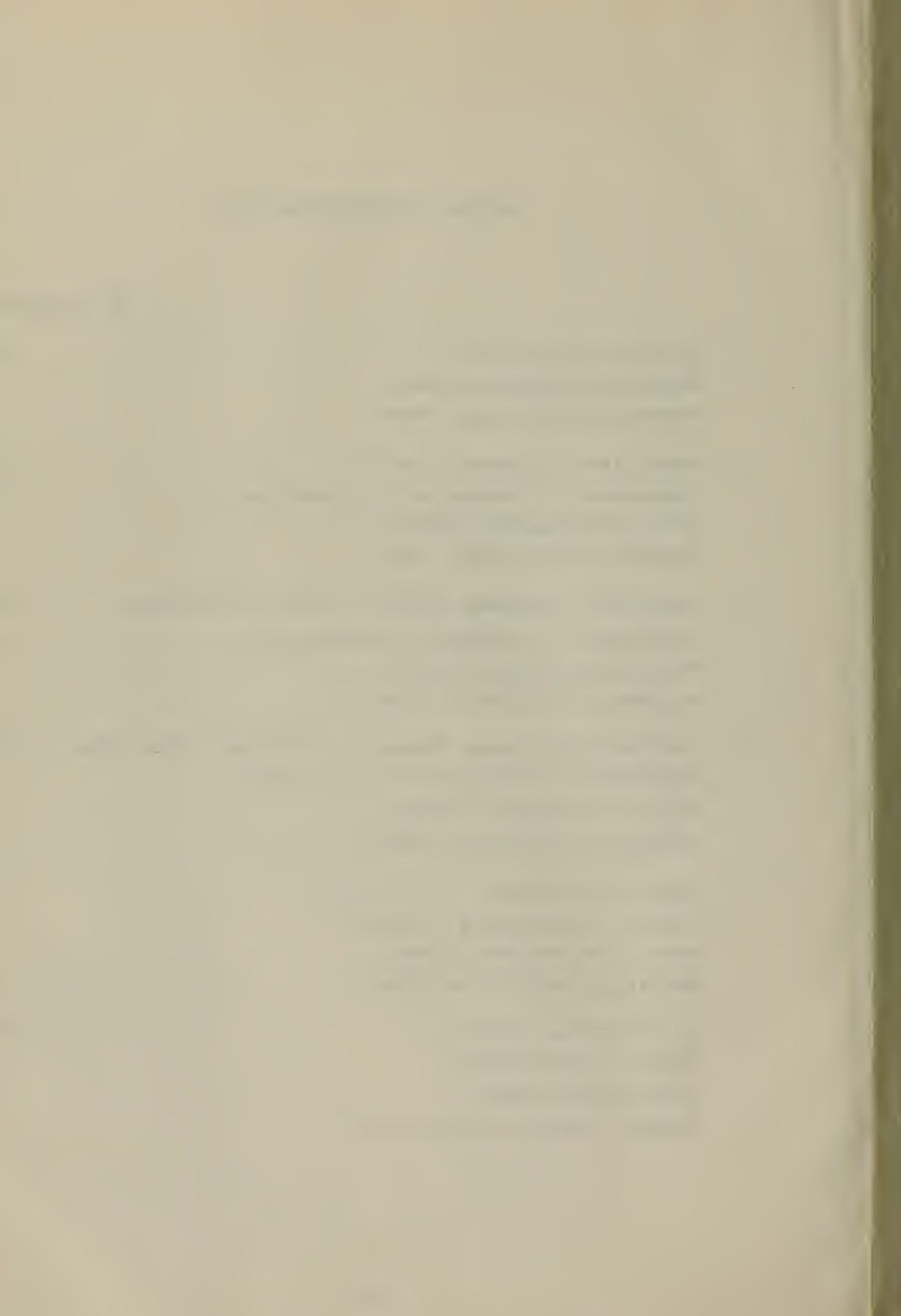
CCCCCCCCCCCCCCCC

LIST OF REFERENCES

1. Gibson, E.J., Experimental Investigation of the Fluid Dynamic Characteristics of Liquid Propellant Gun Loading Systems, M.S. Thesis, Naval postgraduate School, 1975.
2. Naval Postgraduate School Report NPS-59Nn75061A Dynamics of Liquid Propellant Gun Loading Systems, Annual Progress Report, by R.H. Nunn and E.J. Gibson, 1 June, 1975.
3. Goodson, R.E. and Leonard, R.G., "A Survey of Modeling Techniques for Fluid Line Transients", Journal of Basic Engineering, v. 94, p. 474 to 482, June, 1972.
4. Leonard, R. G., A Simplified Model for a Fluid Transmission Line, Ph.D. Thesis, Pennsylvania State University, 1970
5. Karan, J. T. and Tindall, R. R., "A Refinement of a Simplified Model for Transients in Fluid Lines", Journal of Fluids Engineering, v. 97, p. 376 to 377, Sept, 1975.
6. Martens, H. R. and Allen, D. R., Introduction to Systems Theory, p. 71, Charles E. Merrill Publishing Co., 1969.

INITIAL DISTRIBUTION LIST

	No. Copies
1. Library, Code 0212 Naval Postgraduate School Monterey, California 93940	2
2. Department Chairman, Code 59 Department of Mechanical Engineering Naval Postgraduate School Monterey, California 93940	2
3. Associate Professor Robert H. Nunn, Code 59Nn Department of Mechanical Engineering Naval Postgraduate School Monterey, California 93940	1
4. Associate Professor Thomas M. Houlihan, Code 59Hm Department of Mechanical Engineering Naval Postgraduate School Monterey, California 93940	1
5. Curricular Officer Weapons Engineering Programs Naval Postgraduate School Monterey, California 93940	1
6. Lt. Craig R. Lampier Class 53, SWOSCOLCOM Building 446, NETC Newport, Rhode Island 02840	1



Thesis

D14754

c.1

Dampier

166485

Computer simulation
of a propellant feed
system for a liquid
propellant gun.

Thesis

D14754

c.1

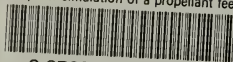
Dampier

166485

Computer simulation
of a propellant feed
system for a liquid
propellant gun.

thesD14754

Computer simulation of a propellant feed



3 2768 002 095 14 3

DUDLEY KNOX LIBRARY