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EXPERIMENTAL AND THEORETICAL STUDY OF PARAMETERS AFFECTING OPERATION OF BASIC GAS SYSTEM FOR SMALL ARMS AUTOMATIC WEAPONS

Timothy L. Brosseau

February 1975

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

An experimental fixture was developed in which all of the key parameters affecting the operation of a basic piston and cylinder gas system could be varied. Each parameter was varied over a wide range, and the effects on the pressure versus time in the gas cylinder of the fixture and the displacement versus time of the piston of the fixture were determined. These same parameters were also varied over the same range in a theoretical digital computer model to evaluate the validity of the computer model for use in gas systems. Comparisons

20. Abstract (Continued)

showed that the agreement between the experimental and the theoretical results was excellent. The results from the tests were also plotted so that they could be used as sensitivity curves for the design of gas systems for small arms weapons.

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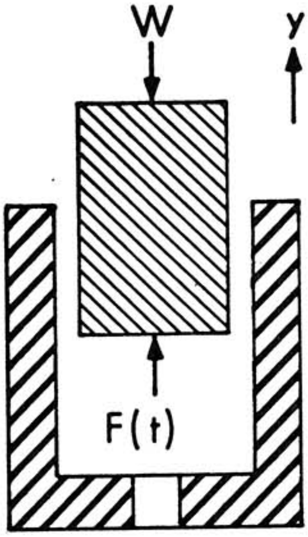
I. INTRODUCTION

The majority of present day small arms automatic weapons are gas operated. That is, in some manner propellant gas is bled from the barrel and used to perform the automatic functioning of the weapon. While gas-operated weapons have been used for a long time, the design of these weapons has been accomplished primarily through trial and error. Parameters were varied in an actual prototype of the weapon until the weapon was made to function satisfactorily. However, this method of trial and error was time consuming and in most cases an optimum weapon was not obtained because the designer did not have an understanding of the parameters that affect the operation of the gas system. Therefore, to gain more understanding of the important parameters in the functioning of gas-operated weapons, the Small Arms Systems Agency requested that the Interior Ballistics Laboratory conduct theoretical and experimental investigations of gas systems in small arms weapons. As part of this task an experimental fixture was developed in which all of the key parameters affecting the operation of a basic piston and cylinder gas system could be varied. Each parameter was varied over a wide range and the effect on the operation of the gas system was determined. These same parameters were also varied over the same ranges in a theoretical digital computer model developed by Dr. J. H. Spurk[1] and reprogrammed by Mr. J. F. Polk, Jr.[2], to evaluate the validity of the computer model for use in gas systems.

II. PARAMETERS VARIED

The key parameters that were varied in the experimental fixture and the computer model were determined using an analysis of a basic piston and cylinder gas system. The piston and cylinder were arranted in the vertical position so that the force restricting the motion of the piston would be a constant and the friction force between the piston and the cylinder would be negligible. The analysis is shown below.



$$\sum F_y = m a_y$$

$$F(t)-W = m \frac{dv_y}{dt}$$

$$A P (t)-W = m \frac{dv_y}{dt}$$

$$A P (t) - W dt = md v_y$$

$$\frac{A}{m}\int_{t_0}^{t_1} P (t) dt - \frac{W}{m}\int_{t_0}^{t_1} dt = v_y$$

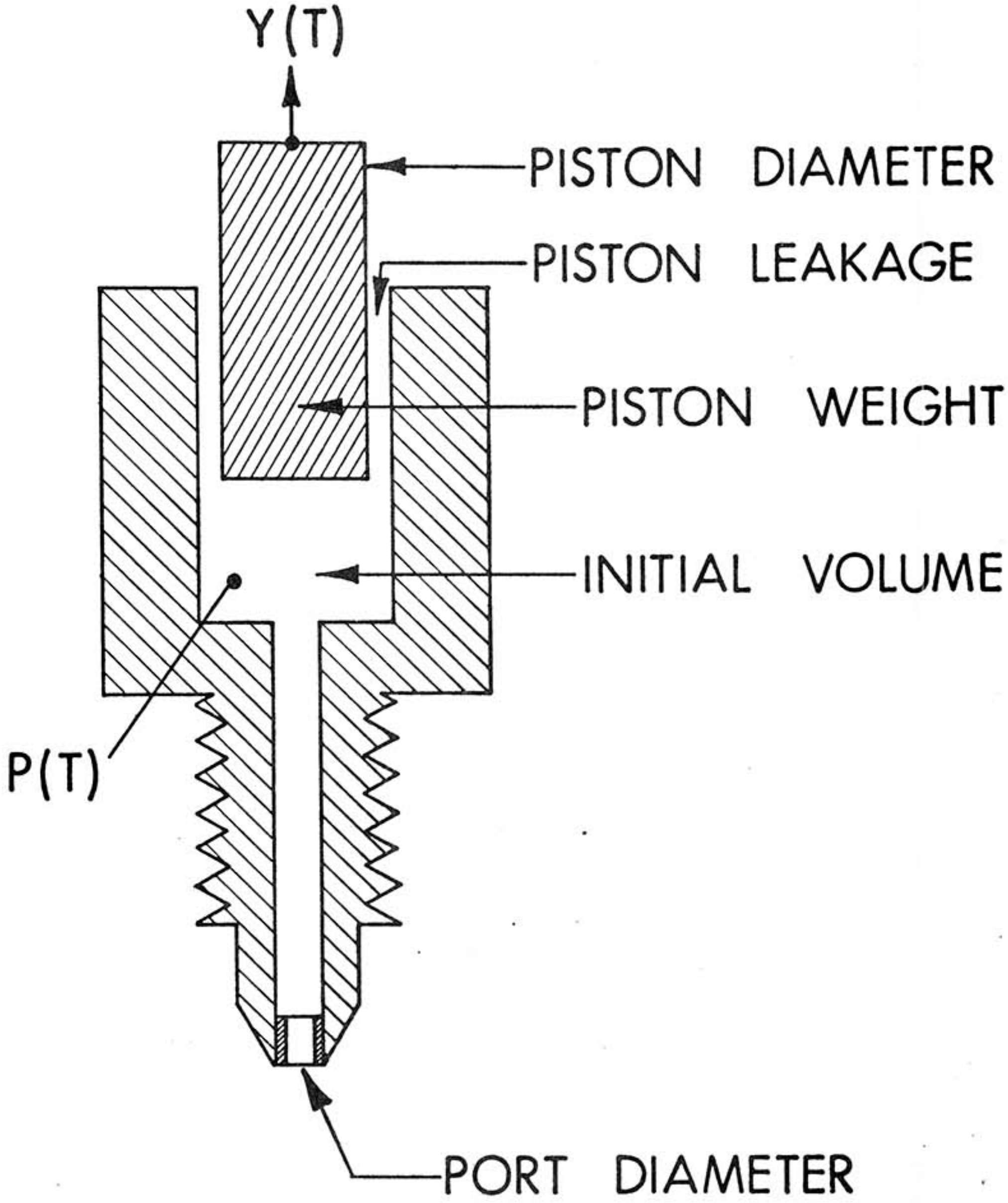


Figure 1. Parameters Varied and Measurements Made in Experimental Fixture

The key parameters affecting the output of the gas system, as shown by the analysis are the area of the piston, the mass of the piston, and the pressure versus time in the gas cylinder. The key parameters affecting the pressure versus time in the gas cylinder, at any particular location along the gun barrel, are the gas port area in the gun barrel, the initial volume of the gas cylinder, and the gas leakage area between the piston and cylinder. The parameters that were varied in the experimental fixture and the measurements made in the fixture are shown in Figure 1. The ranges over which the parameters were varied are the extreme design limits for most existing small arms gas-operated weapons. The experimental fixture was designed to fit into an existing Minihat Pressure Gage[3] hole so that existing pressure barrels could be used for the tests. The experimental fixture and its components are shown in Figure 2.

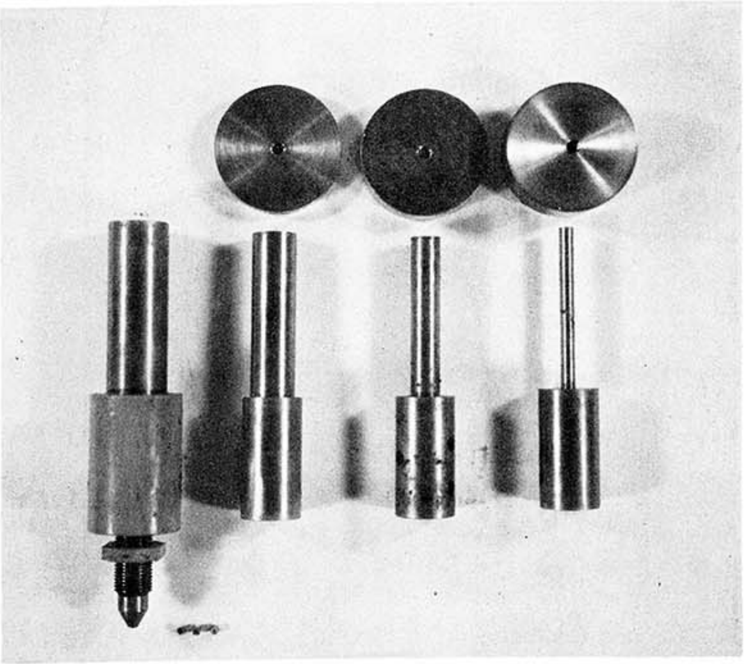


Figure 2. Experimental Fixture and Components

III. EXPERIMENTAL FIXTURE MOUNTED IN A 5.56MM PRESSURE BARREL

The experimental fixture was mounted in a 5.56mm pressure barrel at a location equal to the gas port location in the M16A1 rifle. This location is 334.5mm from the base of the cartridge case. The experimental fixture mounted in the 5.56mm pressure barrel is shown in Figure 3.

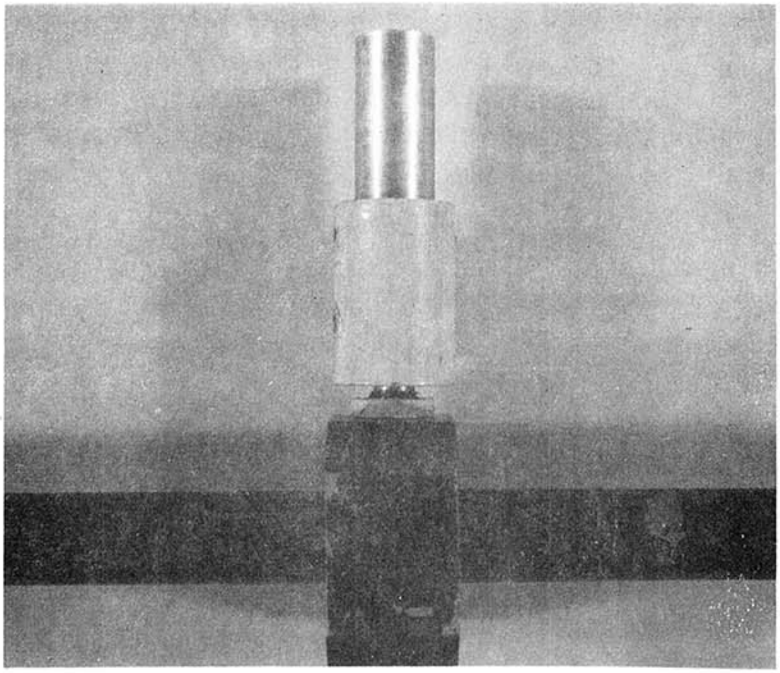


Figure 3. Experimental Fixture Mounted in 5.56mm Pressure Barrel.

A. Measurements

1. Pressure at the Mouth of the Cartridge Case. Pressure versus time at the mouth of the cartridge case was measured using a Minihat Pressure Gage. The center of the gage hole was located 45.5mm from the base of the cartridge case. The gage installation is shown in Figure 4.

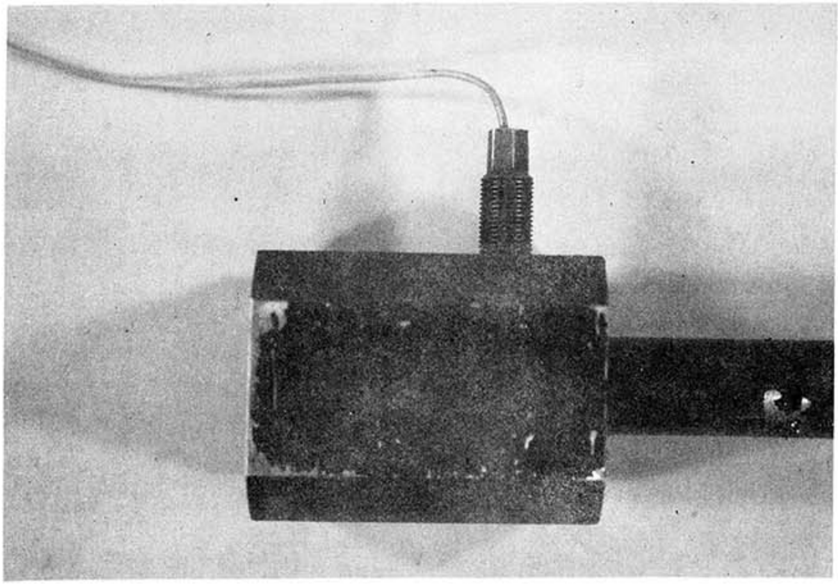


Figure 4. Installation of Pressure Gage at Mouth of Cartridge Case

2. Pressure at the Gas Port Location. Pressure versus time at the gas port location was measured using a Minihat Pressure Gage. The center of the gage hole was located at the same position as the center of the gas port in the M16A1 rifle which is 334.5mm from the base of the cartridge case. The gage installation is shown in Figure 5.

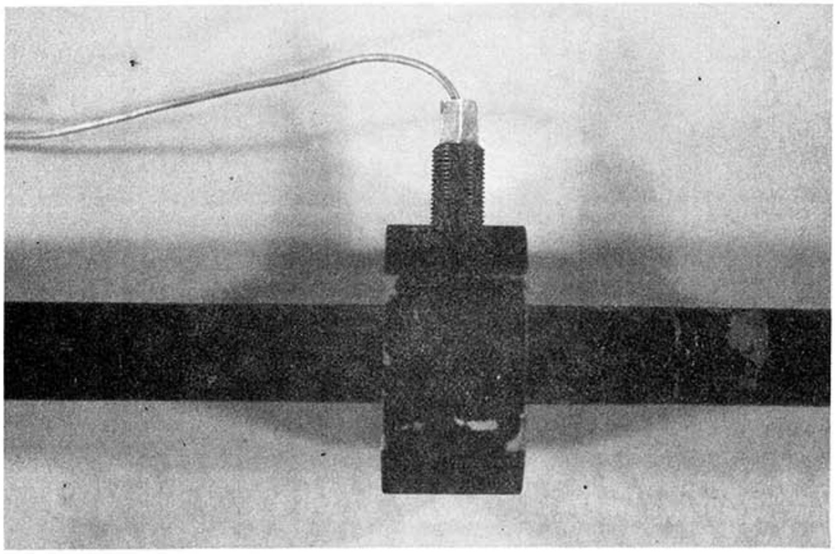


Figure 5. Installation of Pressure Gage at Gas Port Location

3. Pressure in the Cylinder of the Experimental Fixture. Pressure versus time in the cylinder of the experimental fixture was measured using a Kistler 601H Pressure Gage, because of the low pressure in the cylinder. The gage installation is shown in Figure 6.

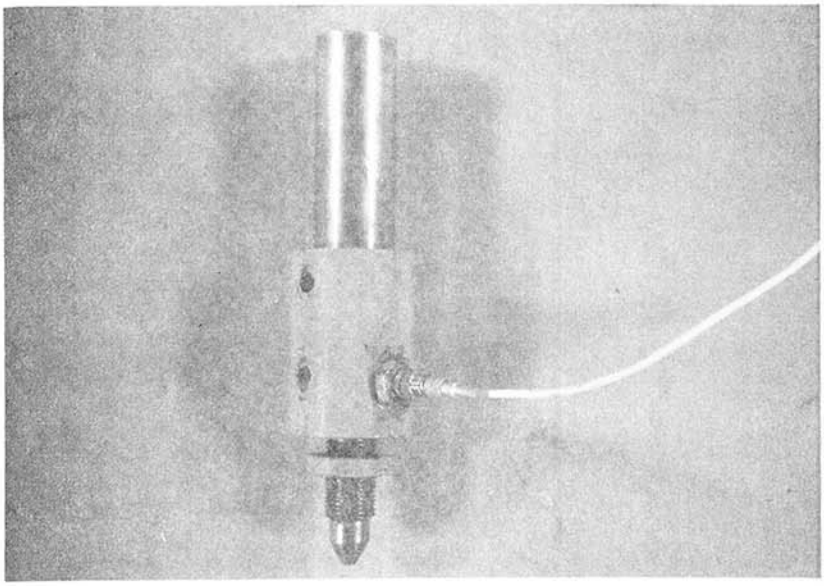


Figure 6. Installation of Pressure Gage in Cylinder of Experimental Fixture

4. Displacement of Piston of Experimental Fixture. The displacement versus time of the piston of the experimental fixture was measured using an Optron Model 501 Optical Displacement Recorder. The Optron Recorder is shown in Figure 7.

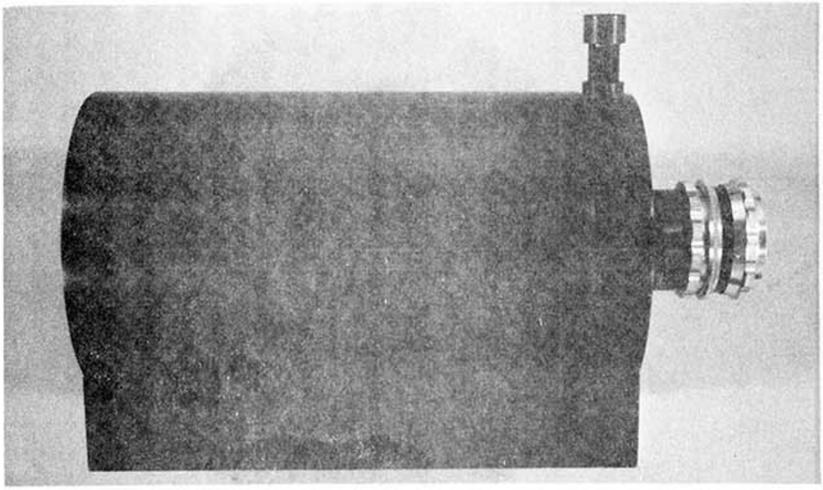


Figure 7. Optron Model 501 Optical Displacement Recorder

5. Velocity of Piston of Experimental Fixture. The velocity of the piston after 12.7mm of travel was determined from the displacement versus time measurements.

6. Muzzle Velocity. Muzzle velocity was measured by placing three Lumiline screens downrange 3.7m apart.

B. Test Setup and Procedure. The pressure barrel was constrained in a rigid mount as shown in Figure 8.

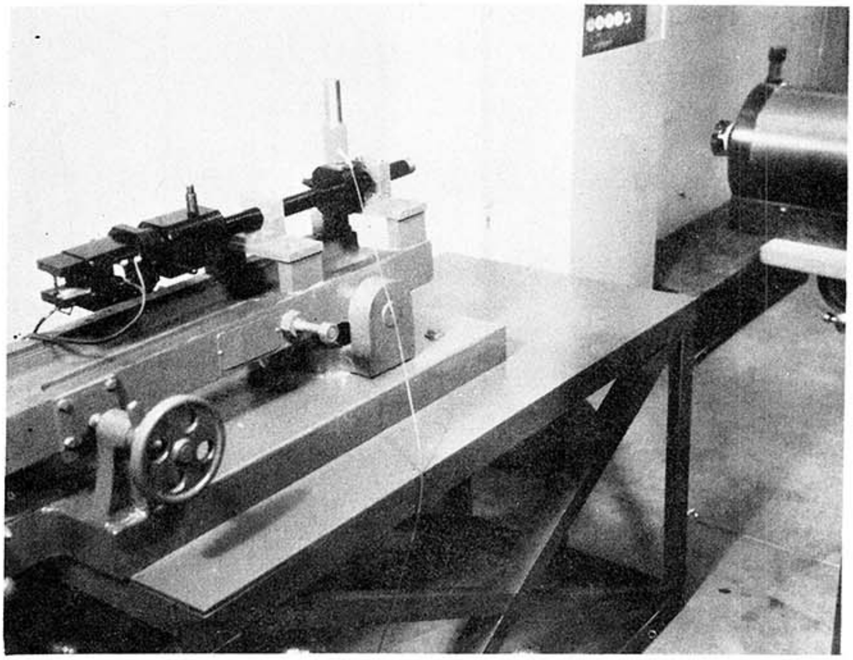


Figure 8. Rigid Mount Setup for 5.56mm Pressure Barrel

It was fired with a solenoid which was controlled by means of an electronic sequence timer. The pressures and displacement were recorded simultaneously on a Honeywell Magnetic Tape Recording System. Standard M193, 5.56mm ammunition from Lot No. TW 18209 was used throughout the test.

IV. THEORETICAL DIGITAL COMPUTER MODEL APPLIED TO A 5.56MM PRESSURE BARREL

The digital computer model mentioned in references 1 and 2 was programmed to match the physical characteristics of the experimental fixture, and was then run with the same parameters being varied over the same ranges as in the experimental fixture. The input data for the computer model consist of the measured pressure versus time at the gas port, the initial gas temperature at the gas port, the dimensions of the experimental fixture, the physical properties of the propellant gas, and the loss coefficients for the flow of the gas in the fixture.

A. Outputs Obtained from Digital Computer Model

1. Pressure in the Cylinder of the Experimental Fixture. Pressure versus time in the cylinder of the experimental fixture was computed by the digital computer model.

2. Displacement of Piston of Experimental Fixture. The displacement versus time of the piston of the experimental fixture was computed by the digital computer model.

3. Velocity of Piston of Experimental Fixture. The velocity versus time of the piston of the experimental fixture was computed by the digital computer model.

B. Procedure for Running Model. The required inputs were fed into the BRLESC computer and after approximately nine minutes of running time the measurements just described were obtained both in digital readouts and in plotted curves from a Calcomp plotter. The pressure versus time inputs were obtained from the measurements in the experimental setup. The values used in the digital computer model for the initial gas temperature at the gas port, the dimensions of the experimental fixture, the physical properties of the propellant gas, and the loss and flow coefficients for the flow of the gas in the fixture are given in Tables I through III. The symbols used in the tables are the same as those used in reference 1.

TABLE I. PROPERTIES OF PROPELLANT GAS

$\bar{C}_p$ = specific heat at constant pressure = $1.74\text{x}10^3$ $(\text{m/s})^2/\text{K}$

$\bar{C}_v$ = specific heat at constant volume = $1.38\text{x}10^3$ $(\text{m/s})^2/\text{K}$

$\bar{k}$ = thermal conductivity of gas = $0.831\text{x}10^{-1}$ $(\text{kg m})/(\text{s}^3\ \text{K})$

$\bar{R}_{gas}$ = effective gas constant for gas - $0.400\text{x}10^3$ $(\text{m/s})^2/\text{K}$

γ = effective ratio of specific heats = 1.26

$\tilde{\gamma}$ = exponent in $\bar{P}_g$, $\bar{\Theta}_g$ relation = 1.24

$\bar{\mu}$ = viscosity coefficient of gas = $4.80\text{x}10^{-5}$ kg/(m/s)

$\bar{\Theta}_{g(0)}$ = initial temperature at gas port = 1300 K

TABLE II. DIMENSIONS OF EXPERIMENTAL FIXTURE

$\bar{A}_c$ = area of piston = 31.67, 126.7, 285.0, 506.7 (mm^2)

$\bar{A}_{min}$ = port area - 1.942, 3.658, 3.658, 5.271, 7.296 (mm^2)

$\bar{A}_v$ = vent area = 0

$\bar{D}$ = diameter of duct = 3.175 (mm)

$\bar{l}$ = length of duct = 45.72 (mm)

$\bar{M}_B$ = mass of piston = .2540, .3991, .4989, .5896 (kg)

$\bar{A}_{leak}$ = leakage area = 0, 1.52, 2.54, 4.09 (mm^2)

$\bar{V}_{ci}$ = initial volume of cylinder = 1210., 2010., 8040., 14100. (mm^3)

$\bar{x}_{be}$ = maximum displacement of piston = 50.8 (mm)

$\bar{x}_{lv}$ = location of center of vent = 50.8 (mm)

$(\bar{\varepsilon}/\bar{D})$ = relative roughness of duct = .0144

TABLE III. LOSS AND FLOW COEFFICIENTS

K_f = resistance coefficient due to friction = .64

K_b = resistance coefficient due to bends and sudden enlargements = 1.14

f = friction factor = .03

ρ_e = contraction coefficient (backward flow from cylinder into duct) = .62

ρ_p = contraction coefficient (backward flow from duct into port) = .64

ρ_g = contraction coefficient (forward flow from gun barrel into port) = .62

V. EXPERIMENTAL AND THEORETICAL RESULTS

The results of the measurements made in the experimental fixture and the results of the outputs from the theoretical digital computer model are shown in Tables IV and V and Figures 9 through 35. These results are compared in Table VI.

TABLE IV. RESULTS OF MEASUREMENTS IN EXPERIMENTAL FIXTURE

Piston Area $(\mathrm{mm})^2$	Piston Weight (kg)	Initial Volume $(\mathrm{mm})^3$	Port Area $(\mathrm{mm})^2$	Leakage Area $(\mathrm{mm})^3$	Peak Pressure at Case Mouth $(\mathrm{MN/m^2})$		Peak Pressure at Gas Port $(\mathrm{MN/m^2})$		Peak Pressure in Gas Cylinder $(\mathrm{MN/m^2})$		Velocity of Piston after 12.7mm Travel (m/s)		Muzzle Velocity (m/s)	
					Av	σ	Av	σ	Av	σ	Av	σ	Av	σ
31.7	0.399	2010.9	3.658	0.000	333.	7.6	72.8	1.10	19.37	.15	3.1	.4	978.4	9.1
126.7	0.399	2010.9	3.658	0.000	331.	8.3	73.1	2.07	18.23	.18	9.2	.3	979.9	7.6
285.0	0.399	2010.9	3.658	0.000	329.	11.0	72.5	1.24	14.15	.22	14.2	.3	980.2	8.2
506.7	0.399	2010.9	3.658	0.000	334.	9.6	72.8	1.52	11.03	.21	16.0	.2	979.0	8.8
126.7	0.254	2010.9	3.658	0.000	328.	9.0	73.0	2.00	17.98	.17	12.5	.4	978.7	8.5
126.7	0.499	2010.9	3.658	0.000	332.	10.3	72.6	1.45	18.95	.16	7.8	.4	978.4	7.3
126.7	0.590	2010.9	3.658	0.000	331.	8.3	72.4	1.86	19.30	.24	6.7	.3	979.6	9.1
126.7	0.399	1206.6	3.658	0.000	330.	11.0	72.9	.96	24.19	.27	9.7	.3	978.7	8.5
126.7	0.399	8044.1	3.658	0.000	337.	9.6	73.1	.83	6.99	.17	5.9	.7	979.9	8.8
126.7	0.399	14077.3	3.658	0.000	330.	7.6	72.6	1.79	3.51	.14	4.5	.4	979.0	7.9
126.7	0.399	2010.9	1.942	0.000	334.	9.0	79.9	1.58	12.00	.21	7.4	.4	979.3	8.5
126.7	0.399	2010.9	5.271	0.000	328.	10.3	70.3	1.65	24.19	.23	10.2	.2	980.2	9.1
126.7	0.399	2010.9	7.297	0.000	332.	8.3	70.0	1.93	30.00	.23	10.9	.3	980.5	8.2
126.7	0.399	2010.9	3.658	1.525	331.	11.0	72.8	1.03	15.23	.23	7.9	.3	978.4	7.9
126.7	0.399	2010.9	3.658	2.536	330.	9.0	73.0	1.38	13.50	.19	7.3	.4	939.0	9.1
126.7	0.399	2010.9	3.658	4.046	331.	10.3	72.8	1.17	11.50	.14	6.3	.2	979.6	8.8

TABLE V. RESULTS OF OUTPUTS OBTAINED FROM DIGITAL COMPUTER MODEL

Piston Area $(mm)^2$	Piston Weight (kg)	Initial Volume $(mm)^3$	Port Area $(mm)^2$	Leakage Area $(mm)^2$	Peak Pressure in Gas Cylinder $(M\ N/m^2)$	Velocity of Piston after 12.7mm Travel (m/s)
31.7	0.399	2010.9	3.658	0.000	20.29	3.0
126.7	0.399	2010.9	3.658	0.000	19.00	9.0
285.0	0.399	2010.9	3.658	0.000	14.98	14.0
506.7	0.399	2010.9	3.658	0.000	11.70	15.7
126.7	0.254	2010.9	3.658	0.000	18.24	12.2
126.7	0.499	2010.9	3.658	0.000	19.27	7.6
126.7	0.590	2010.9	3.658	0.000	19.44	6.7
126.7	0.399	1206.6	3.658	0.000	25.98	9.8
126.7	0.399	8044.1	3.658	0.000	6.54	6.2
126.7	0.399	14077.3	3.658	0.000	3.04	4.6
126.7	0.399	2010.9	1.942	0.000	11.64	7.5
126.7	0.399	2010.9	5.271	0.000	24.56	9.9
126.7	0.399	2010.9	7.297	0.000	28.67	10.6
126.7	0.399	2010.9	3.658	1.525	16.05	7.9
126.7	0.399	2010.9	3.658	2.536	14.27	7.4
126.7	0.399	2010.9	3.658	4.046	12.13	6.6

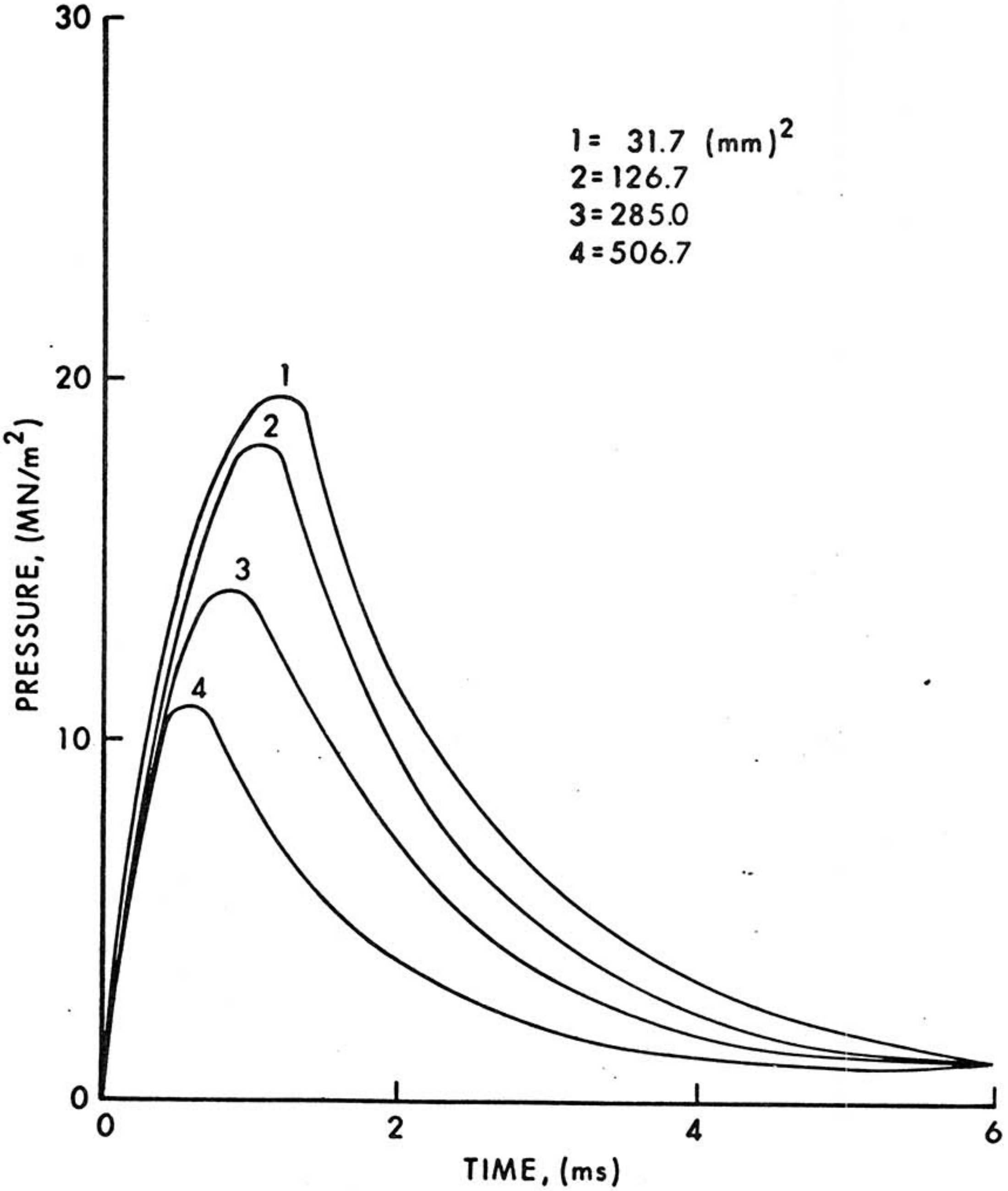


Figure 9. Experimental Effect of Piston Area on Pressure Versus Time in Cylinder

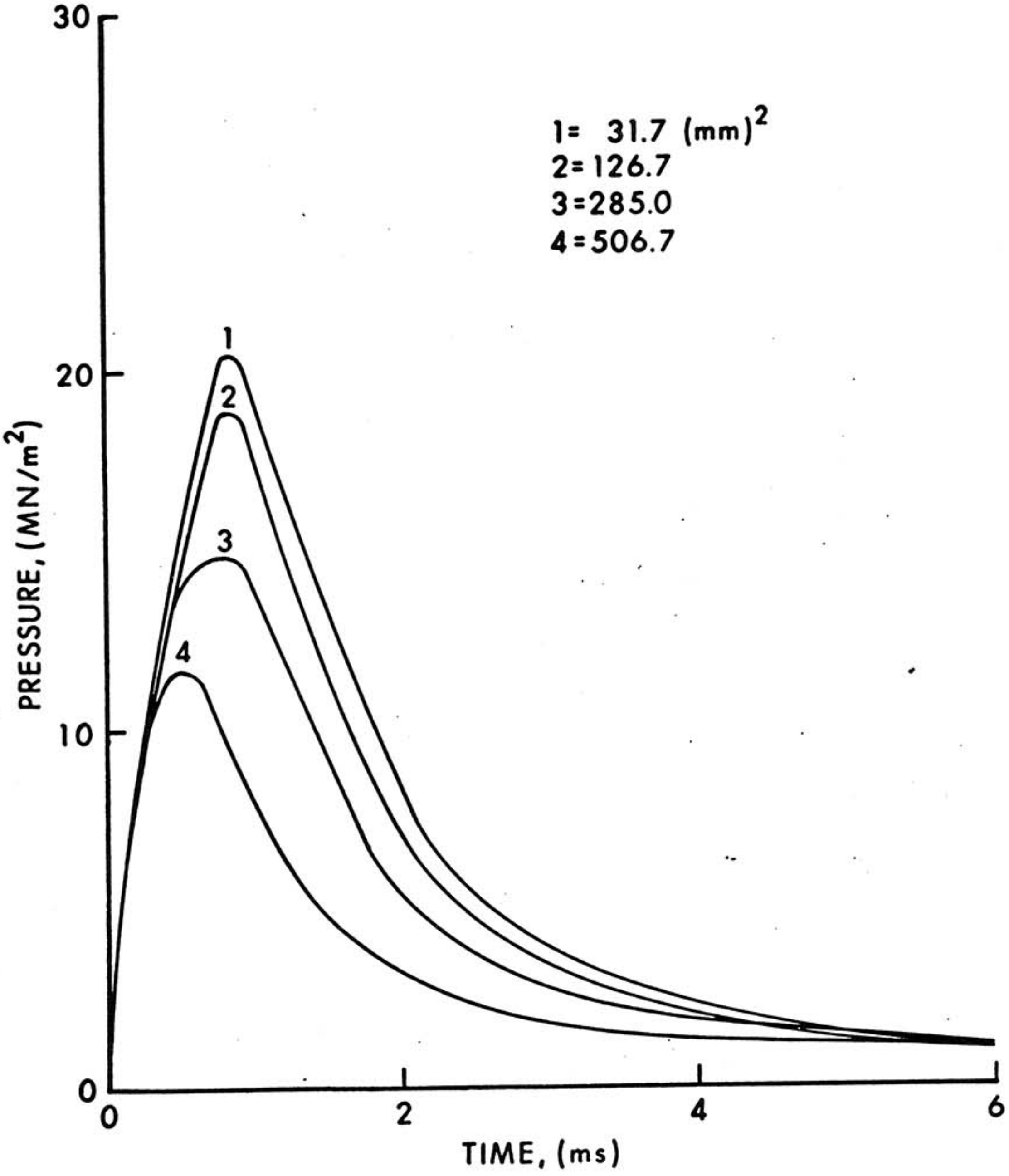


Figure 10. Theoretical Effect of Piston Area on Pressure Versus Time in Cylinder

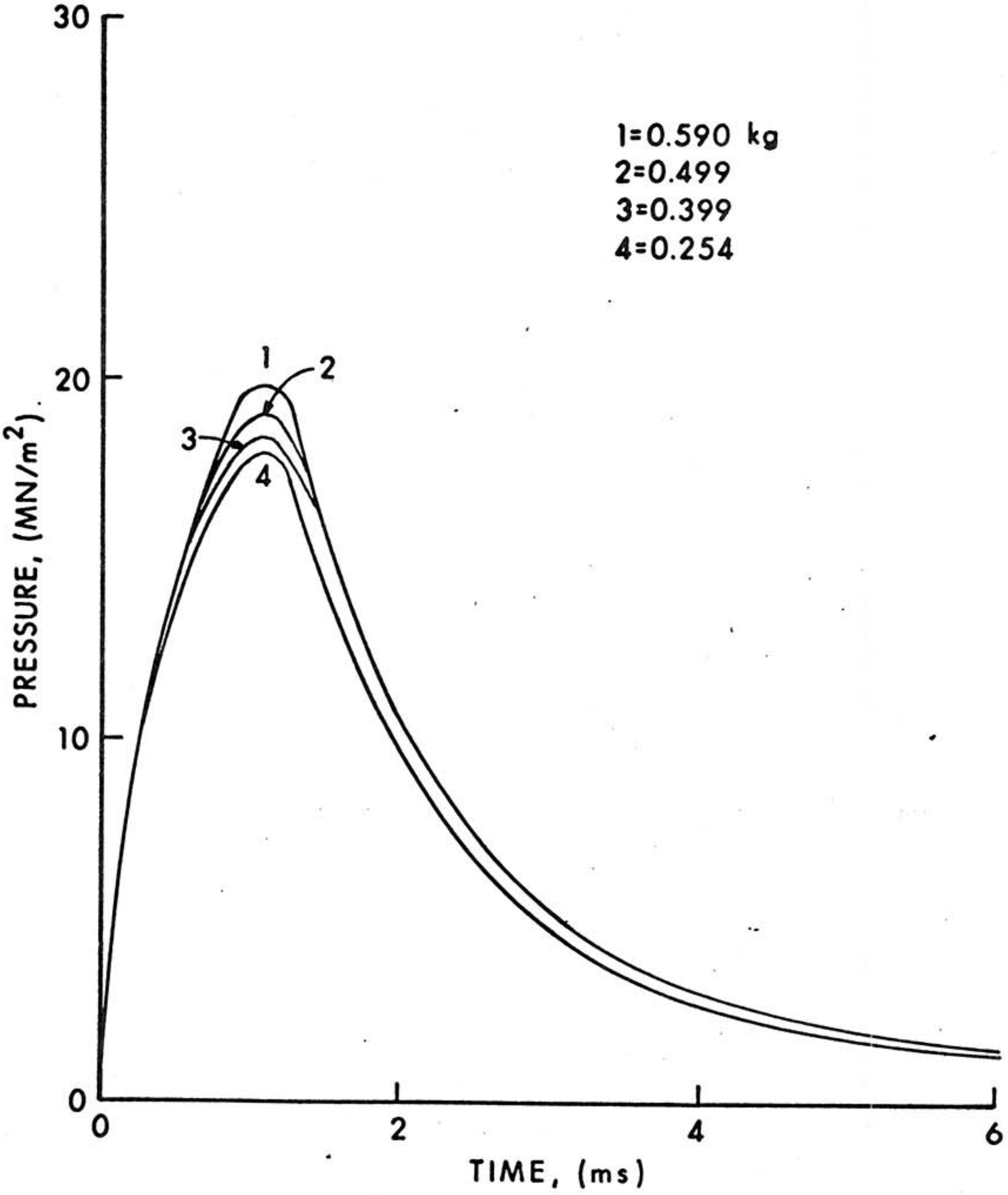


Figure 11. Experimental Effect of Piston Mass on Pressure Versus Time in Cylinder

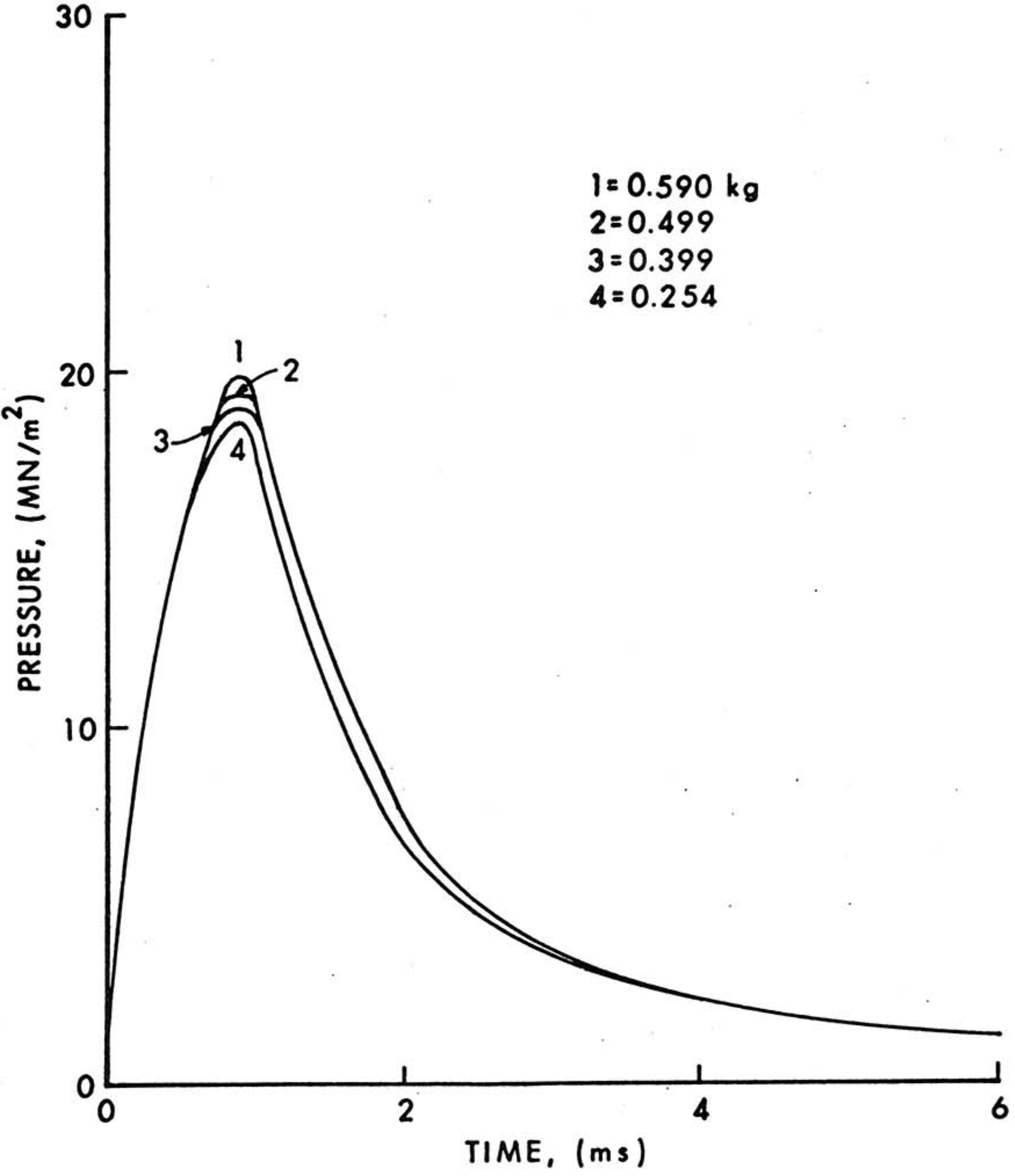


Figure 12. Theoretical Effect of Piston Mass on Pressure Versus Time in Cylinder

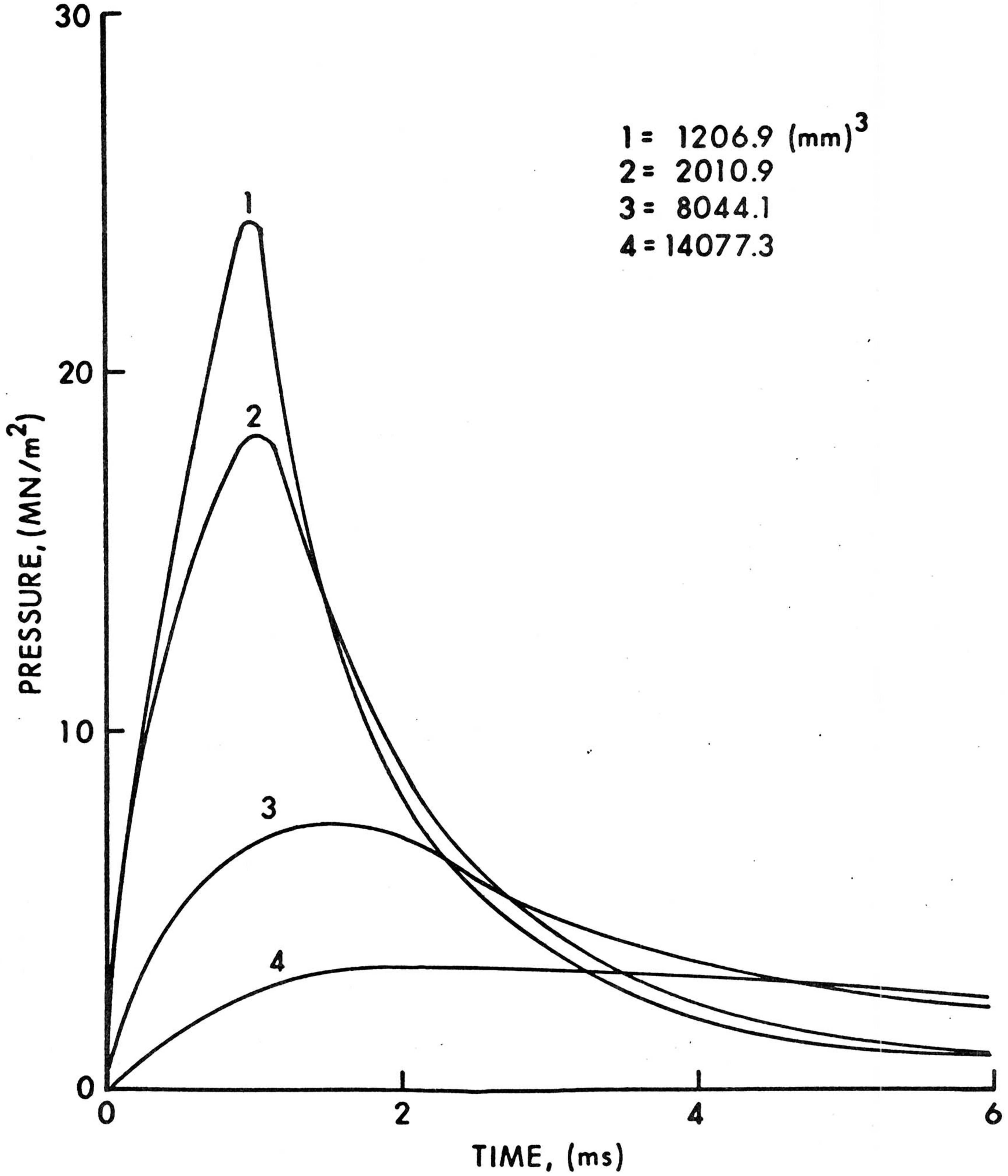


Figure 13. Experimental Effect of Initial Volume on Pressure Versus Time in Cylinder

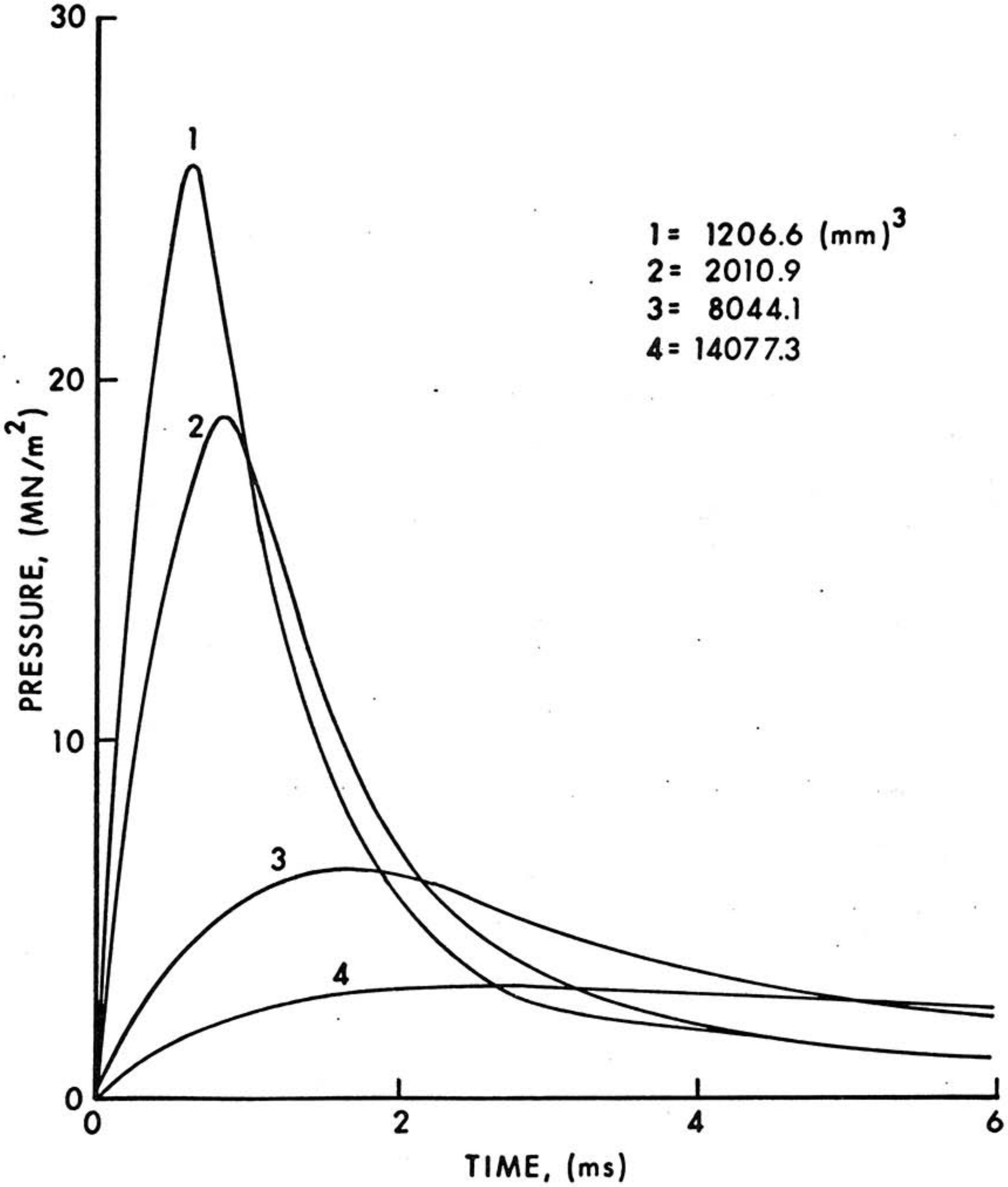


Figure 14. Theoretical Effect of Initial Volume on Pressure Versus Time in Cylinder

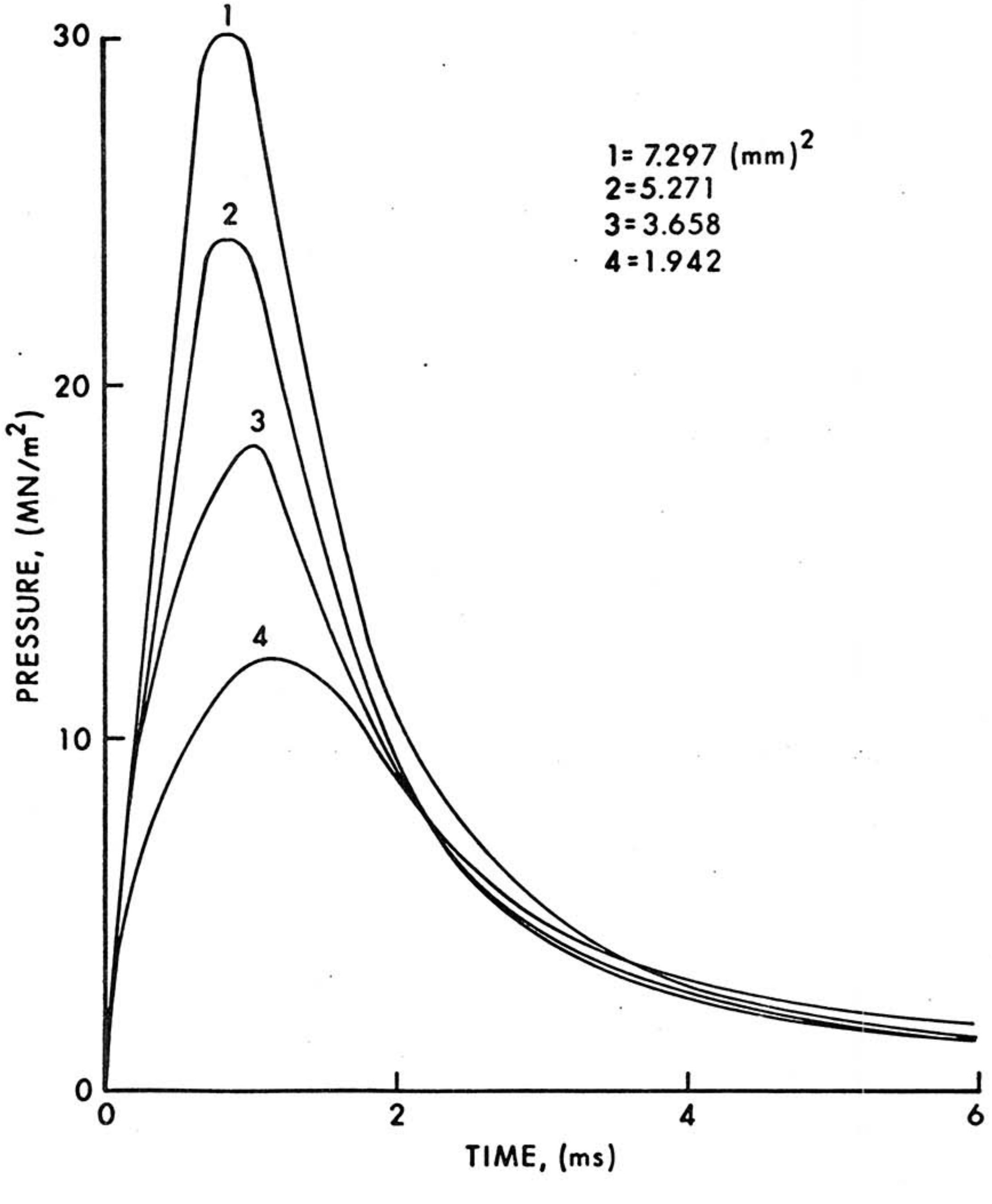


Figure 15. Experimental Effect of Gas Port Area on Pressure Versus Time in Cylinder

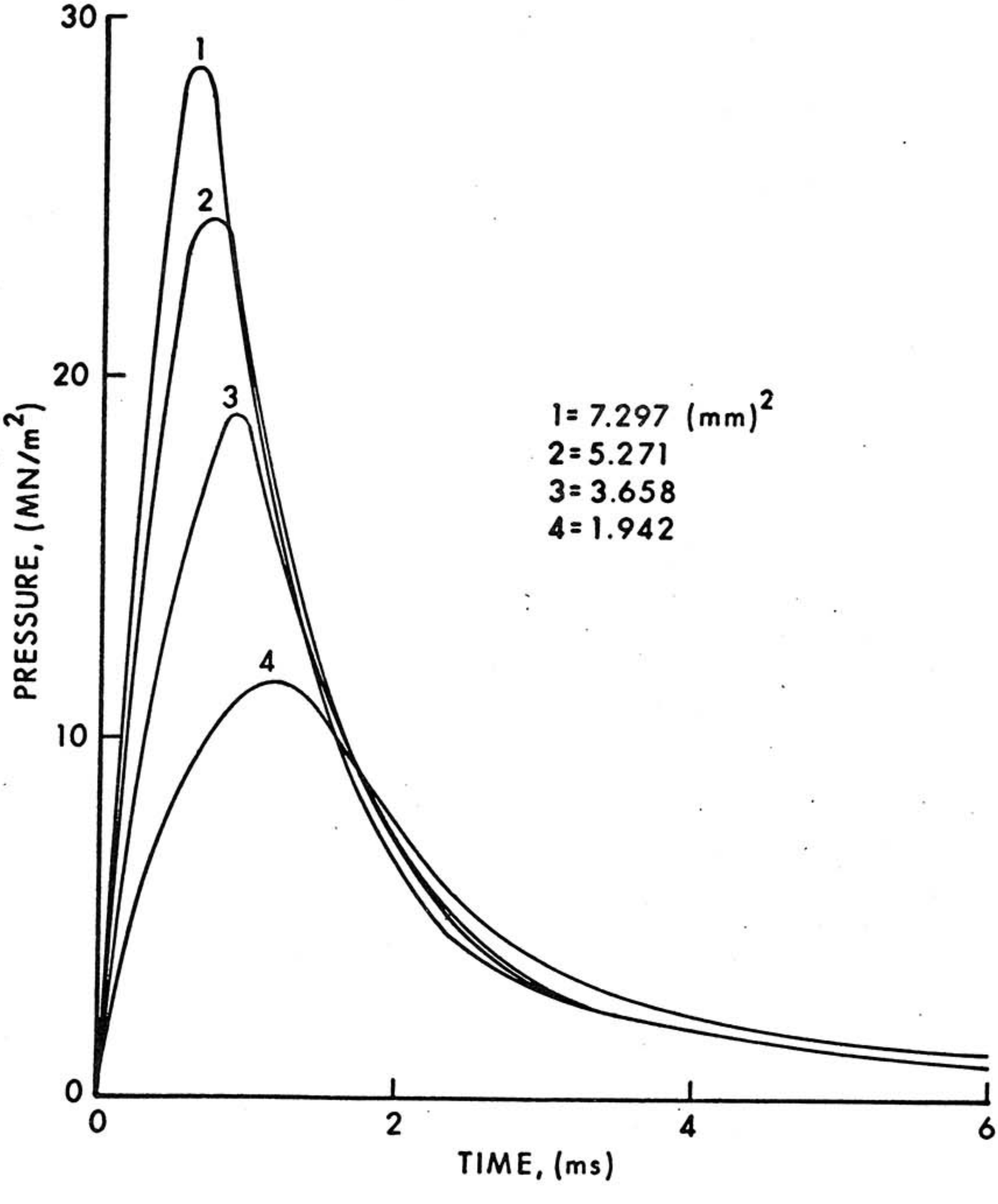


Figure 16. Theoretical Effect of Gas Port Area on Pressure Versus Time in Cylinder

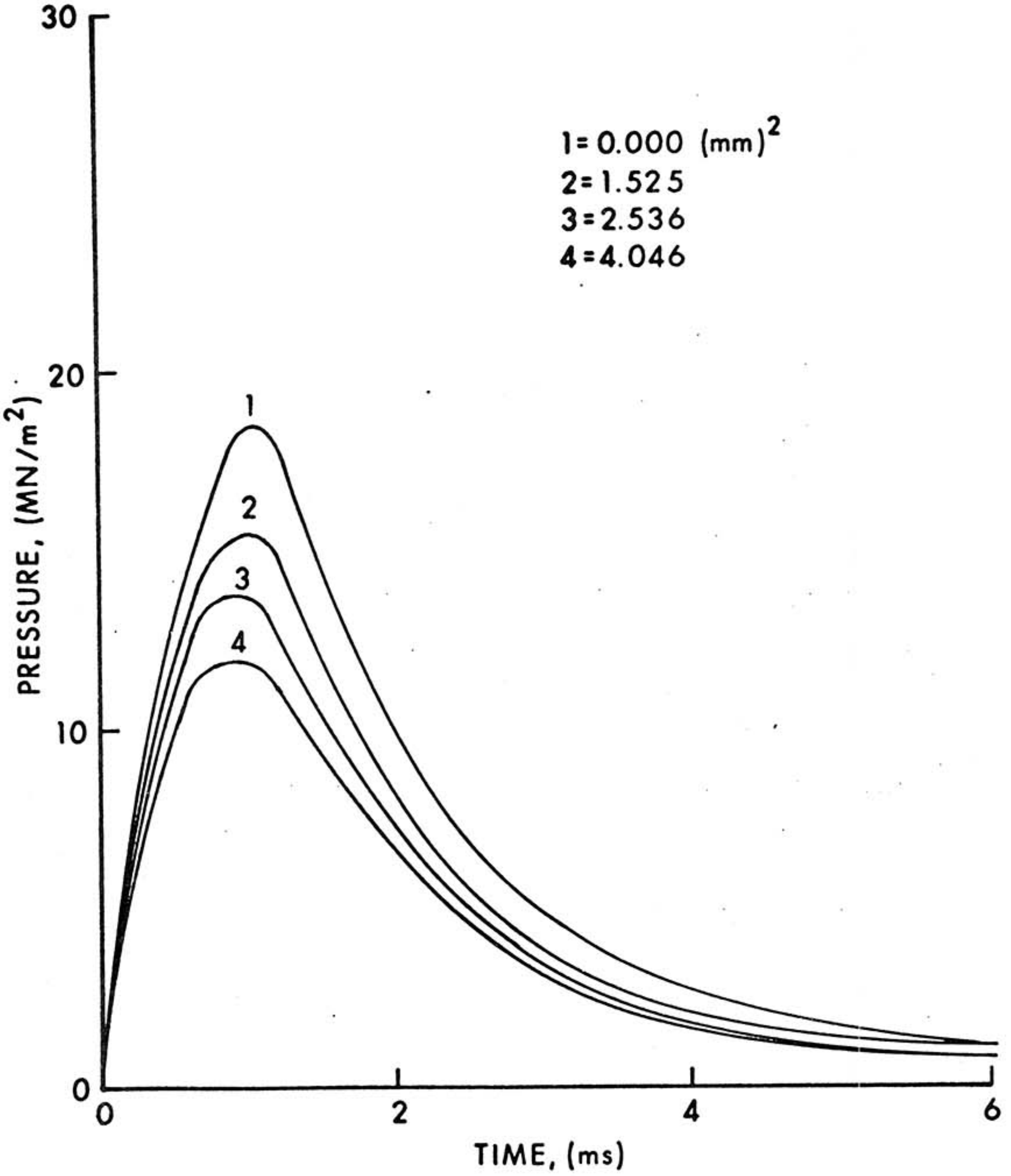


Figure 17. Experimental Effect of Leakage Area on Pressure Versus Time in Cylinder

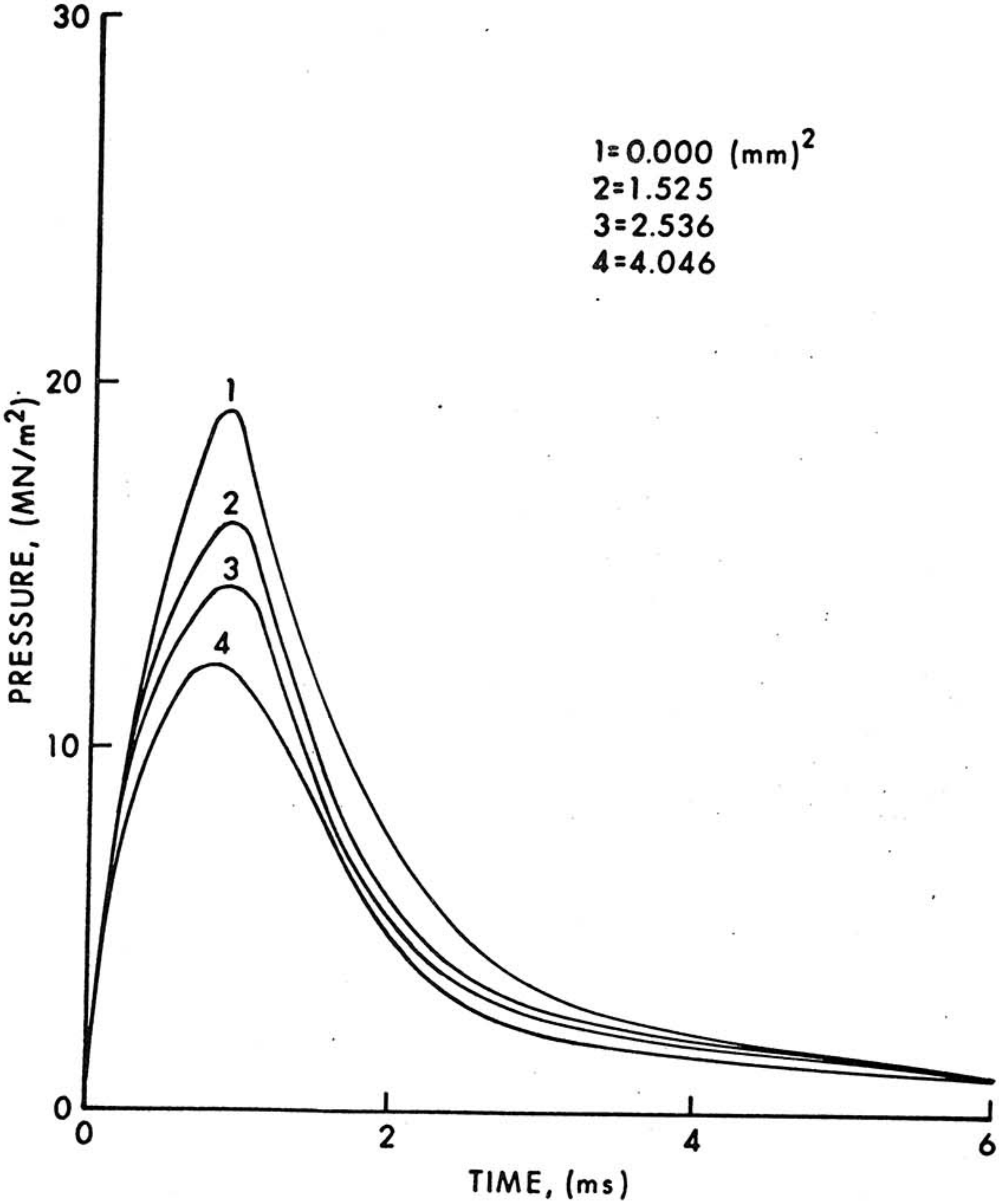


Figure 18. Theoretical Effect of Leakage Area on Pressure Versus Time in Cylinder

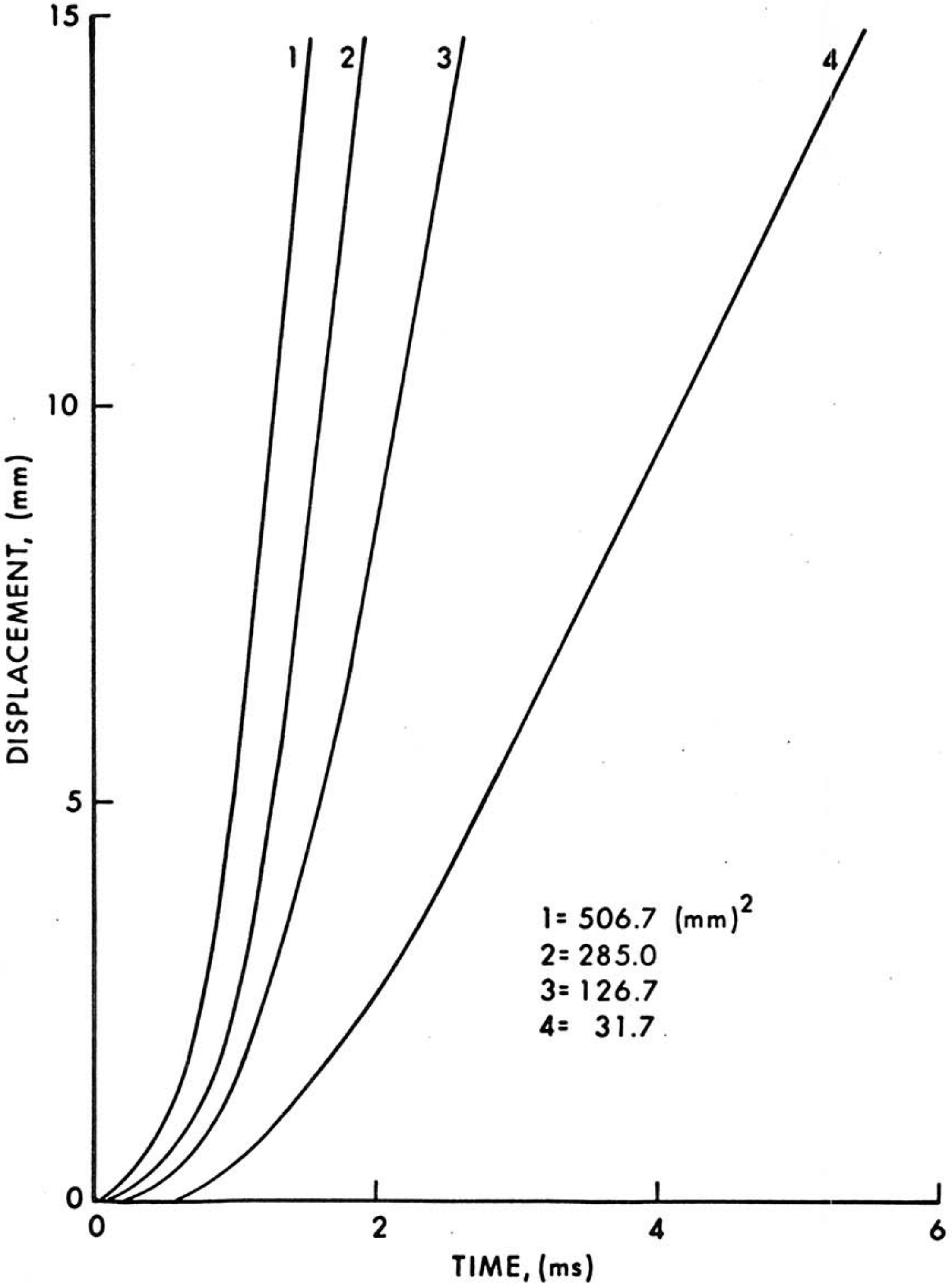


Figure 19. Experimental Effect of Piston Area on Displacement Versus Time of Piston

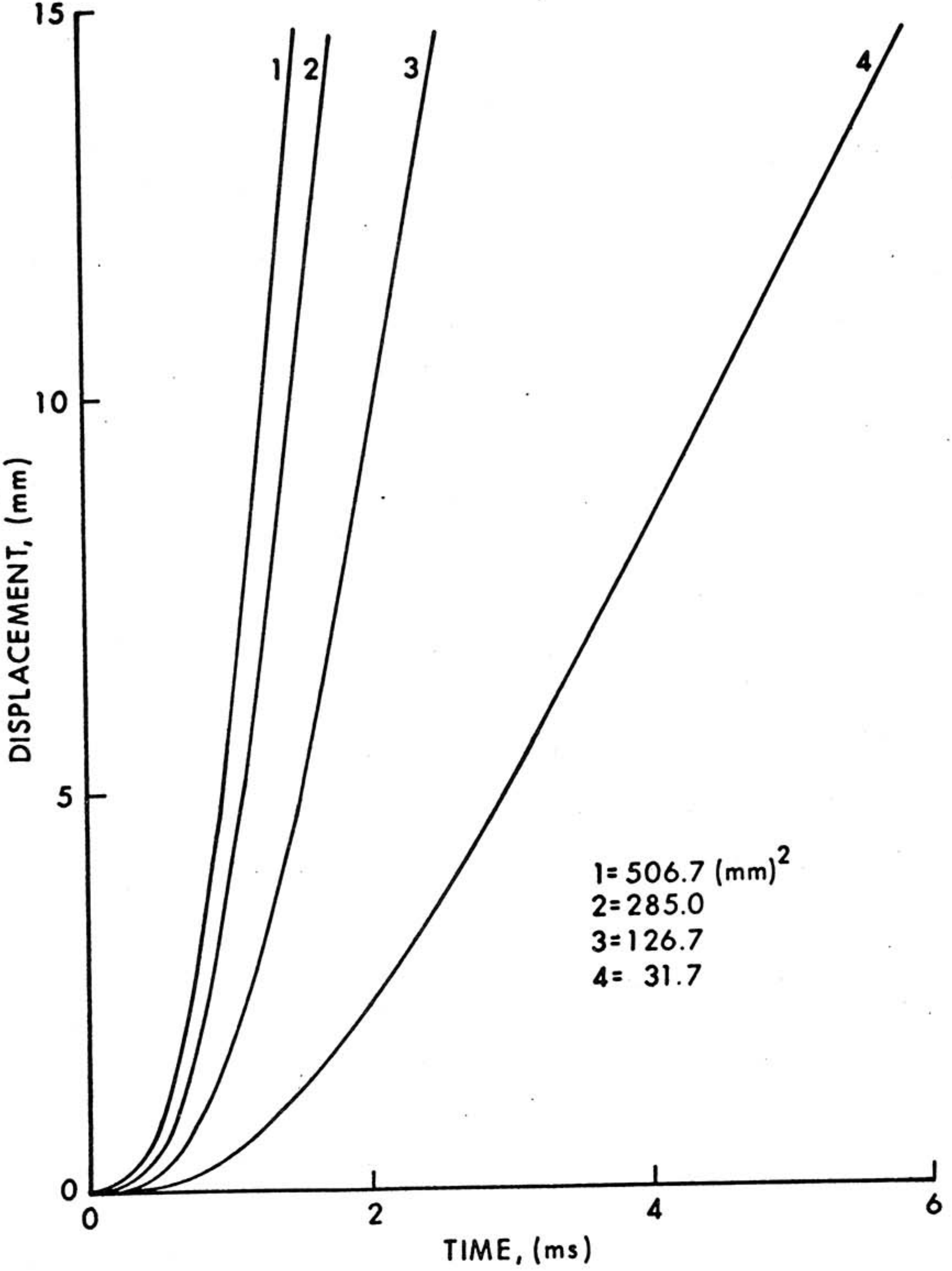


Figure 20. Theoretical Effect of Piston Area on Displacement Versus Time of Piston

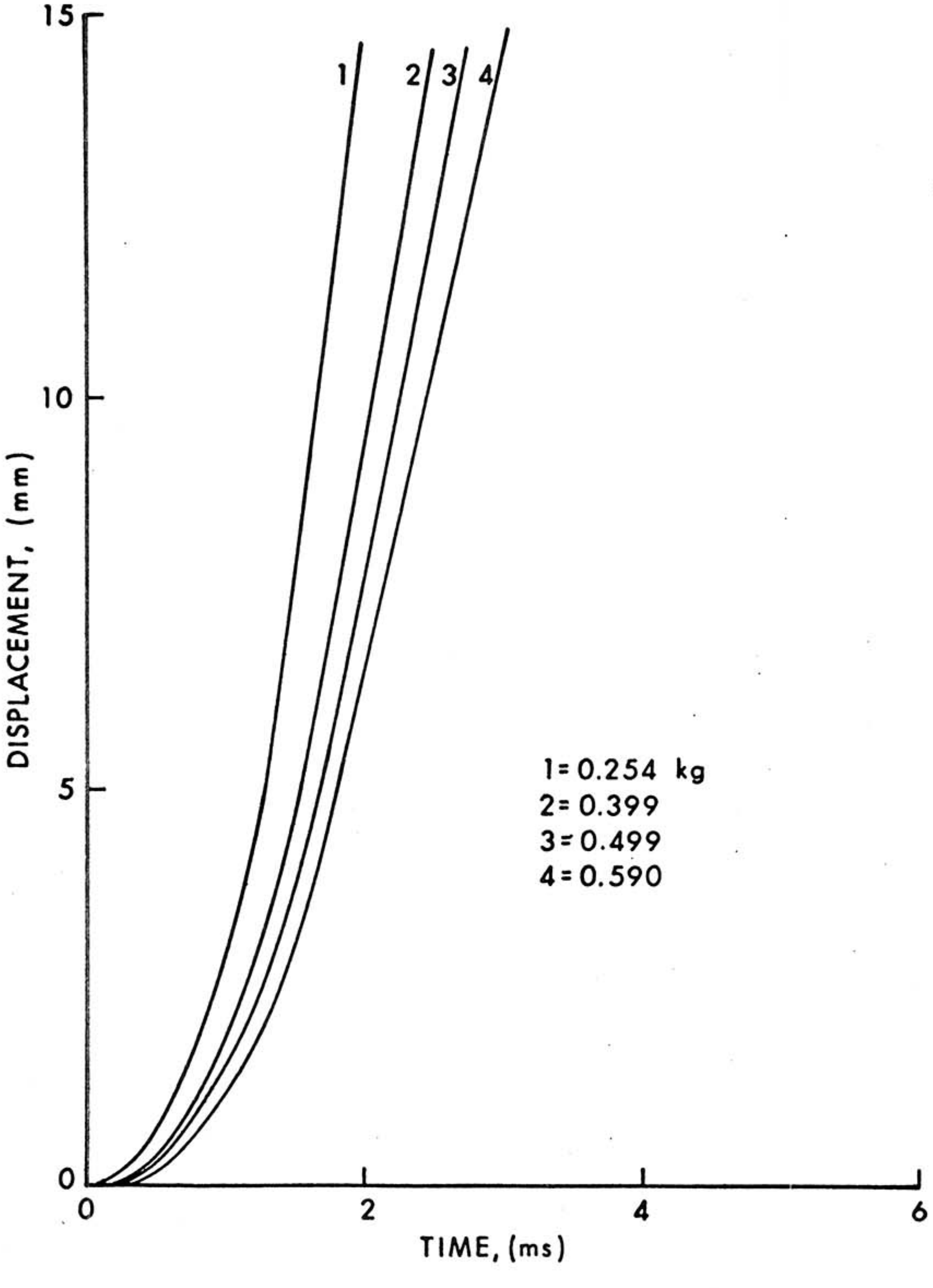


Figure 21. Experimental Effect of Piston Mass on Displacement Versus Time of Piston

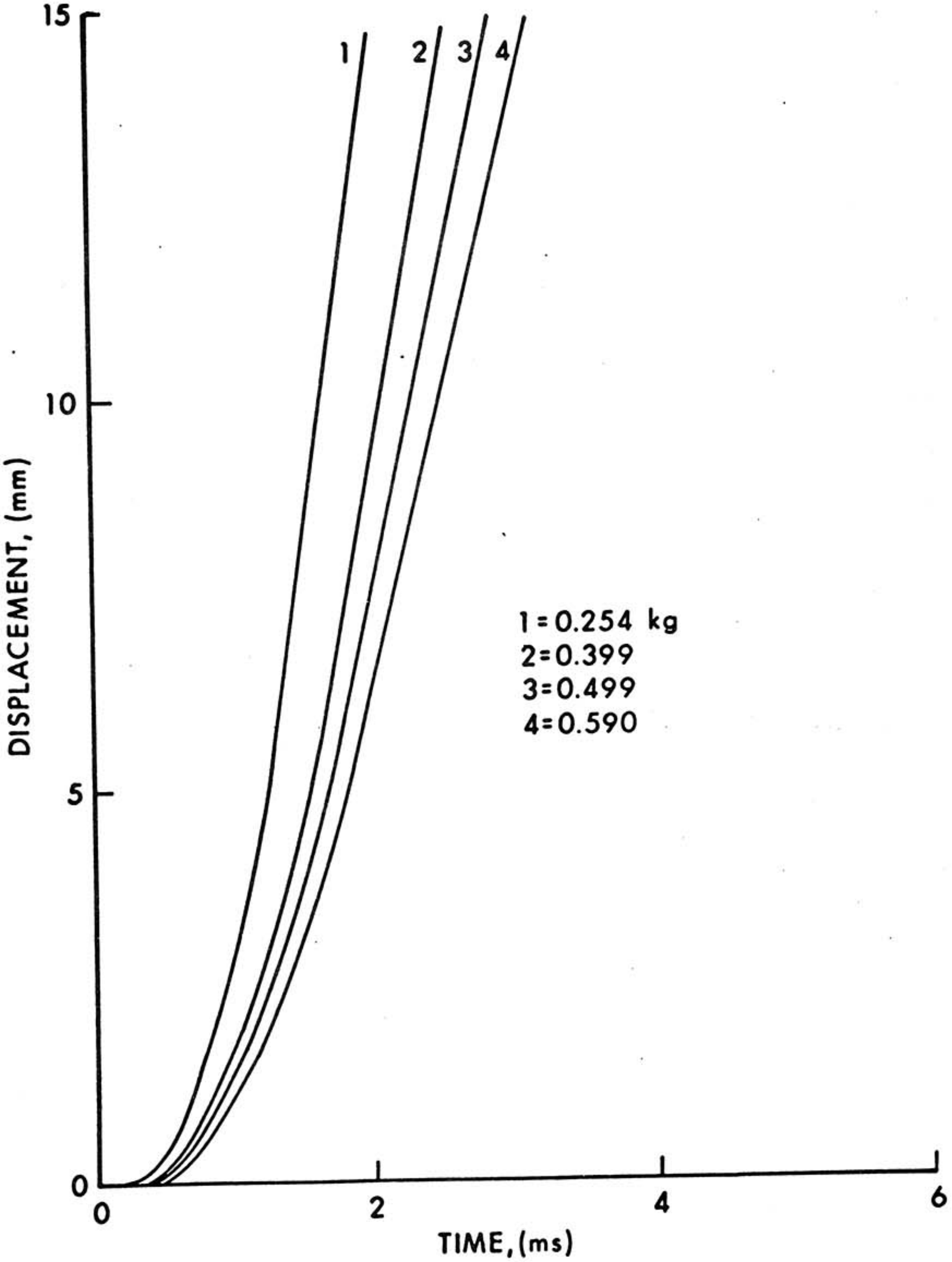


Figure 22. Theoretical Effect of Piston Mass on Displacement Versus Time of Piston

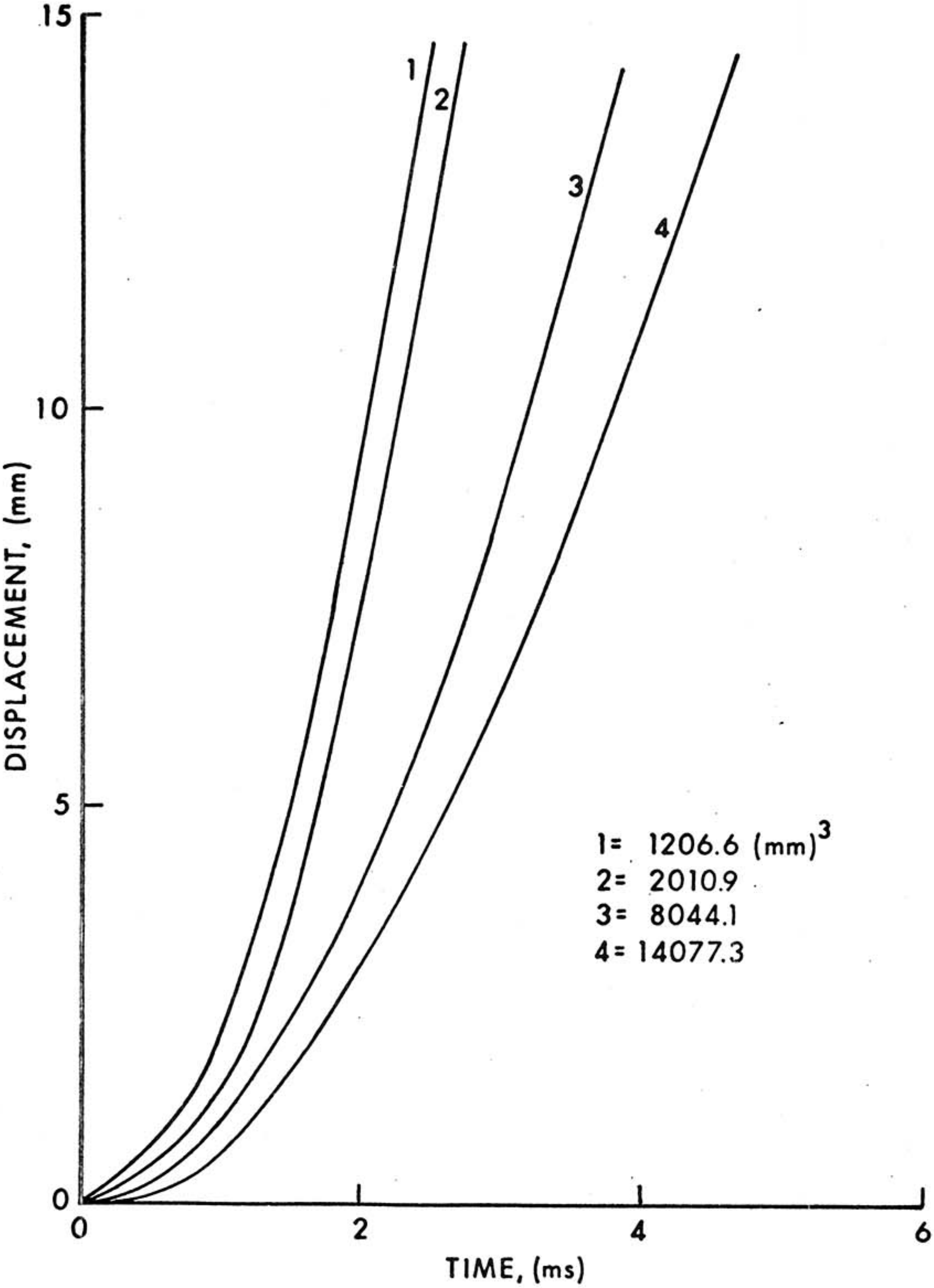


Figure 23. Experimental Effect of Initial Volume on Displacement Versus Time of Piston

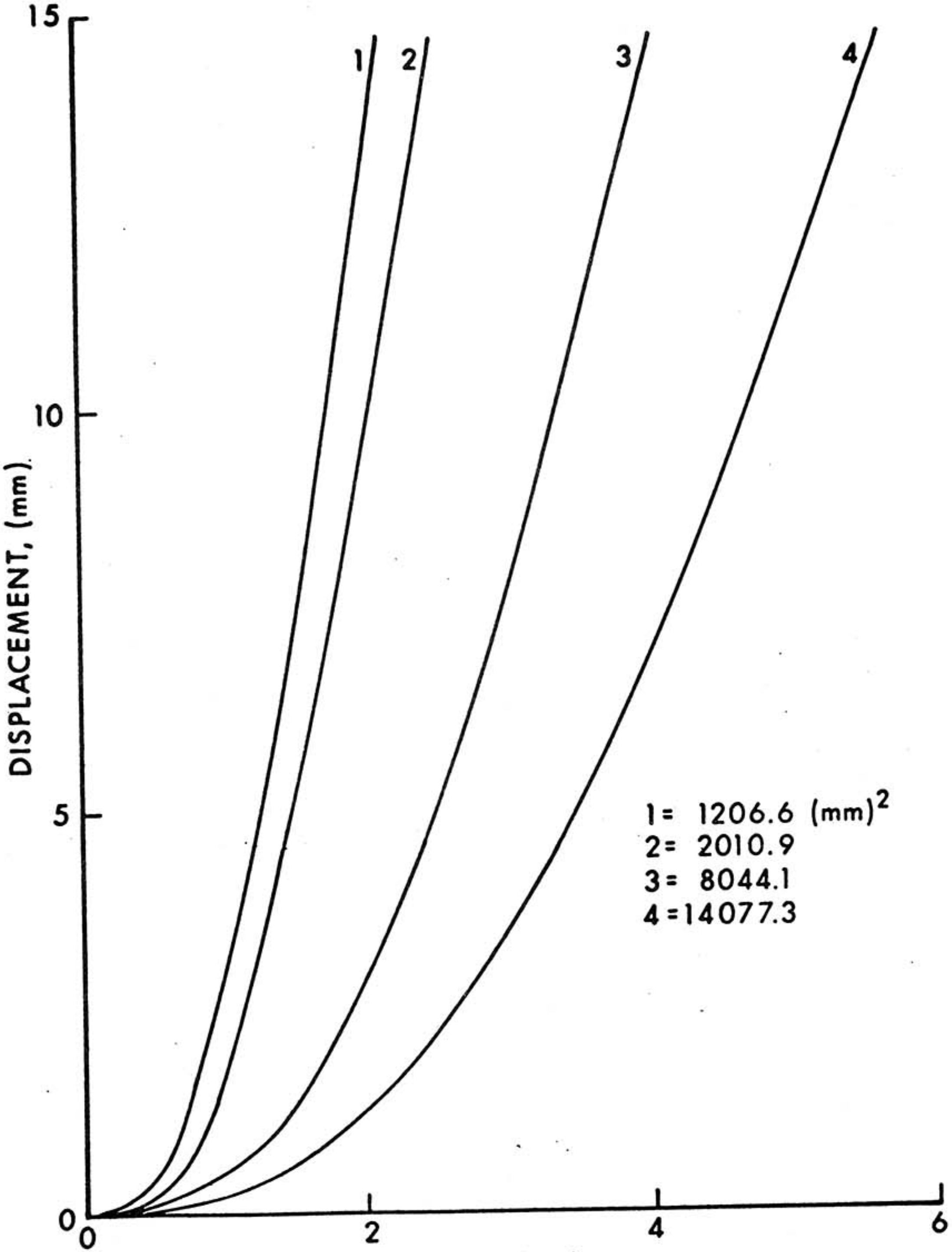


Figure 24. Theoretical Effect of Initial Volume on Displacement Versus Time of Piston

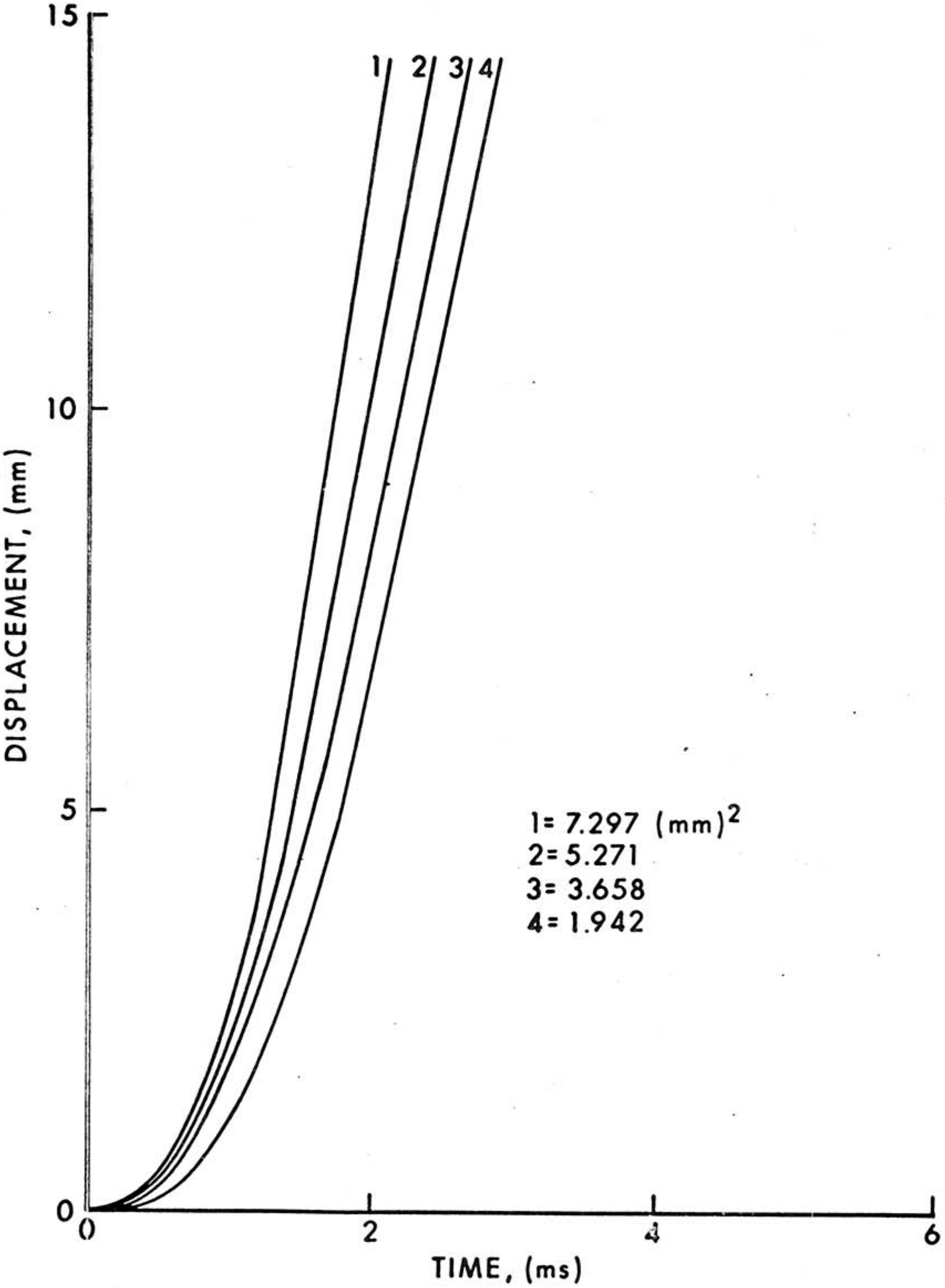


Figure 25. Experimental Effect of Gas Port Area on Displacement Versus Time of Piston

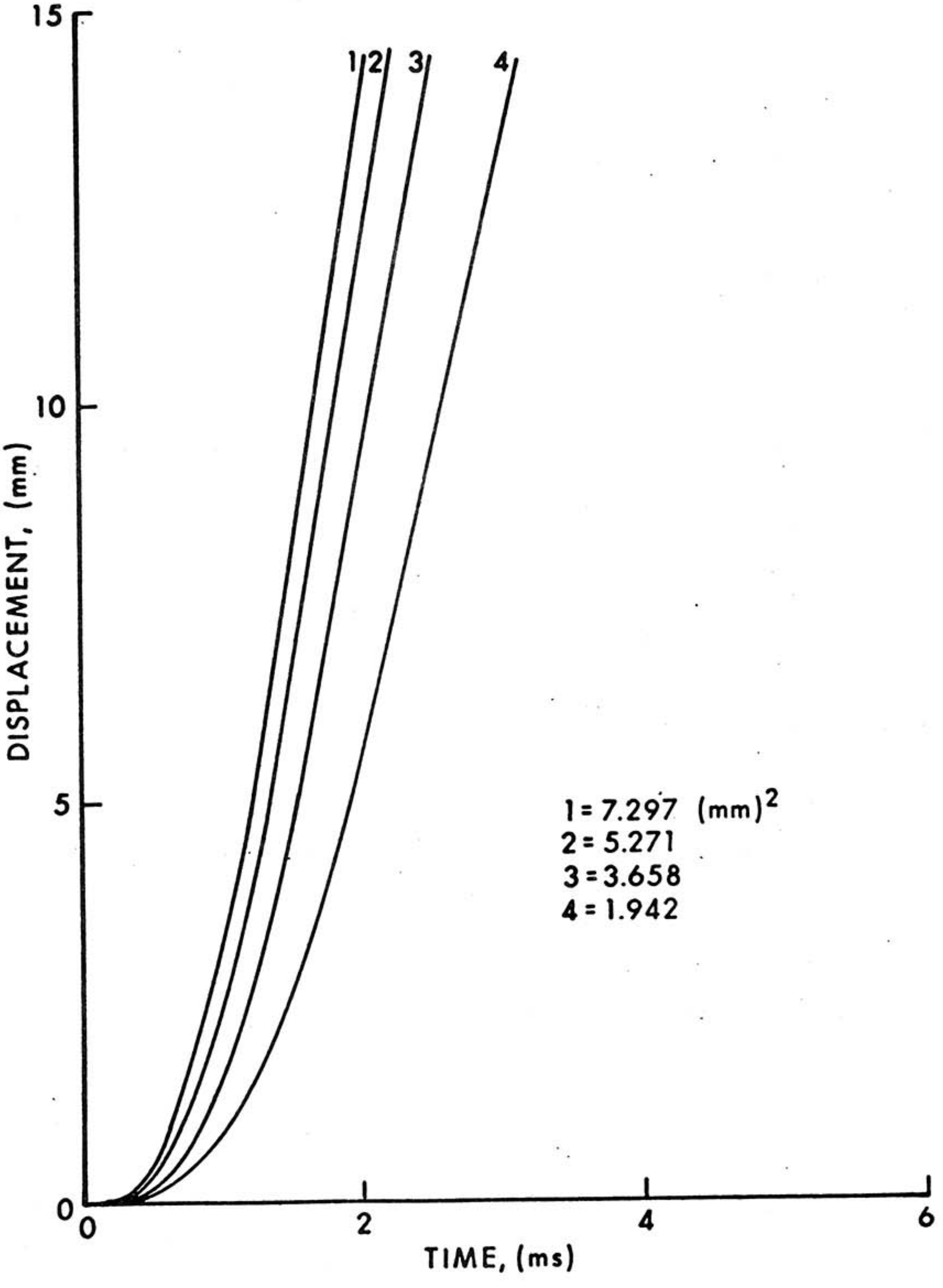


Figure 26. Theoretical Effect of Gas Port Area on Displacement Versus Time of Piston

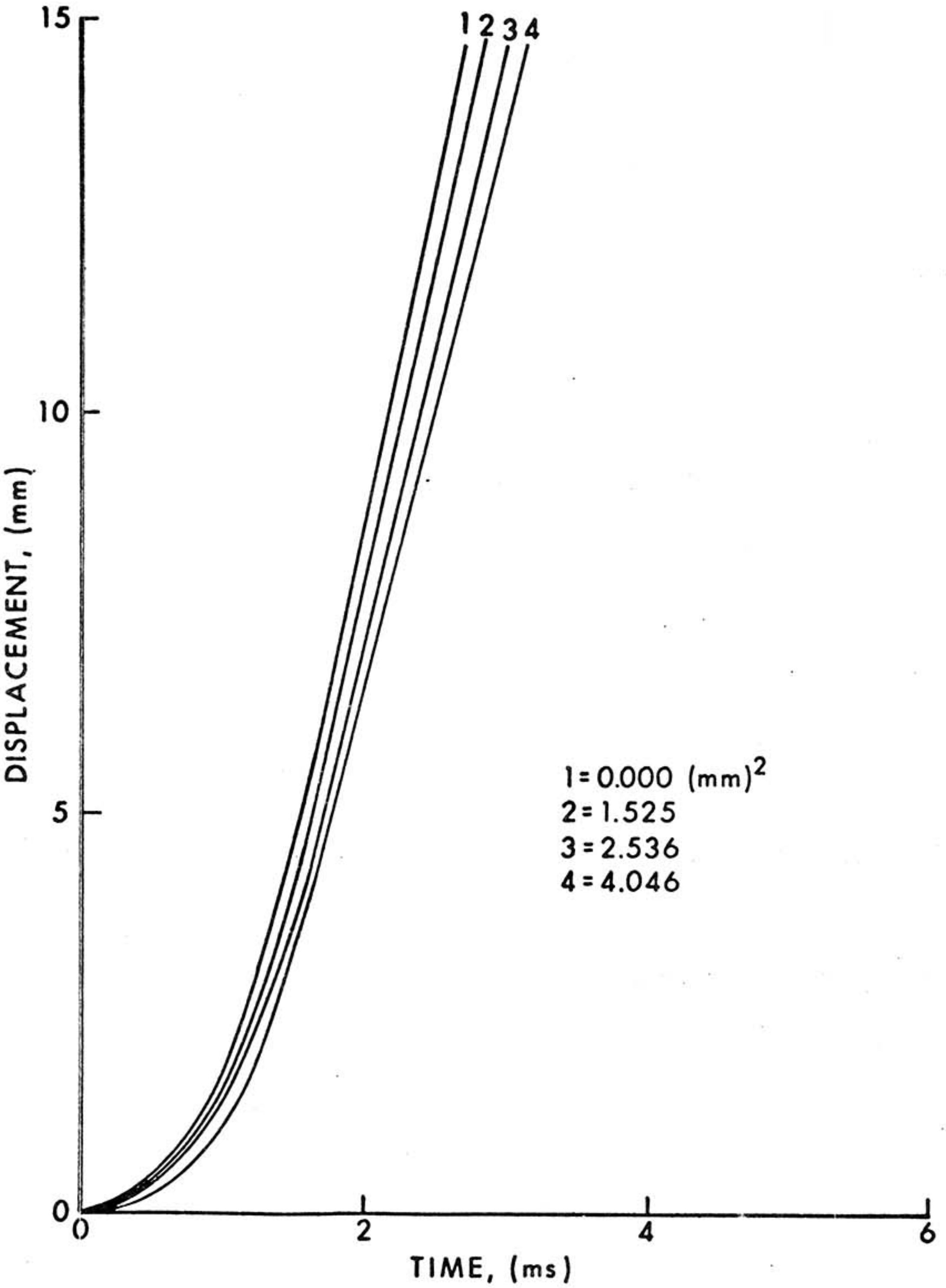


Figure 27. Experimental Effect of Leakage Area on Displacement Versus Time of Piston

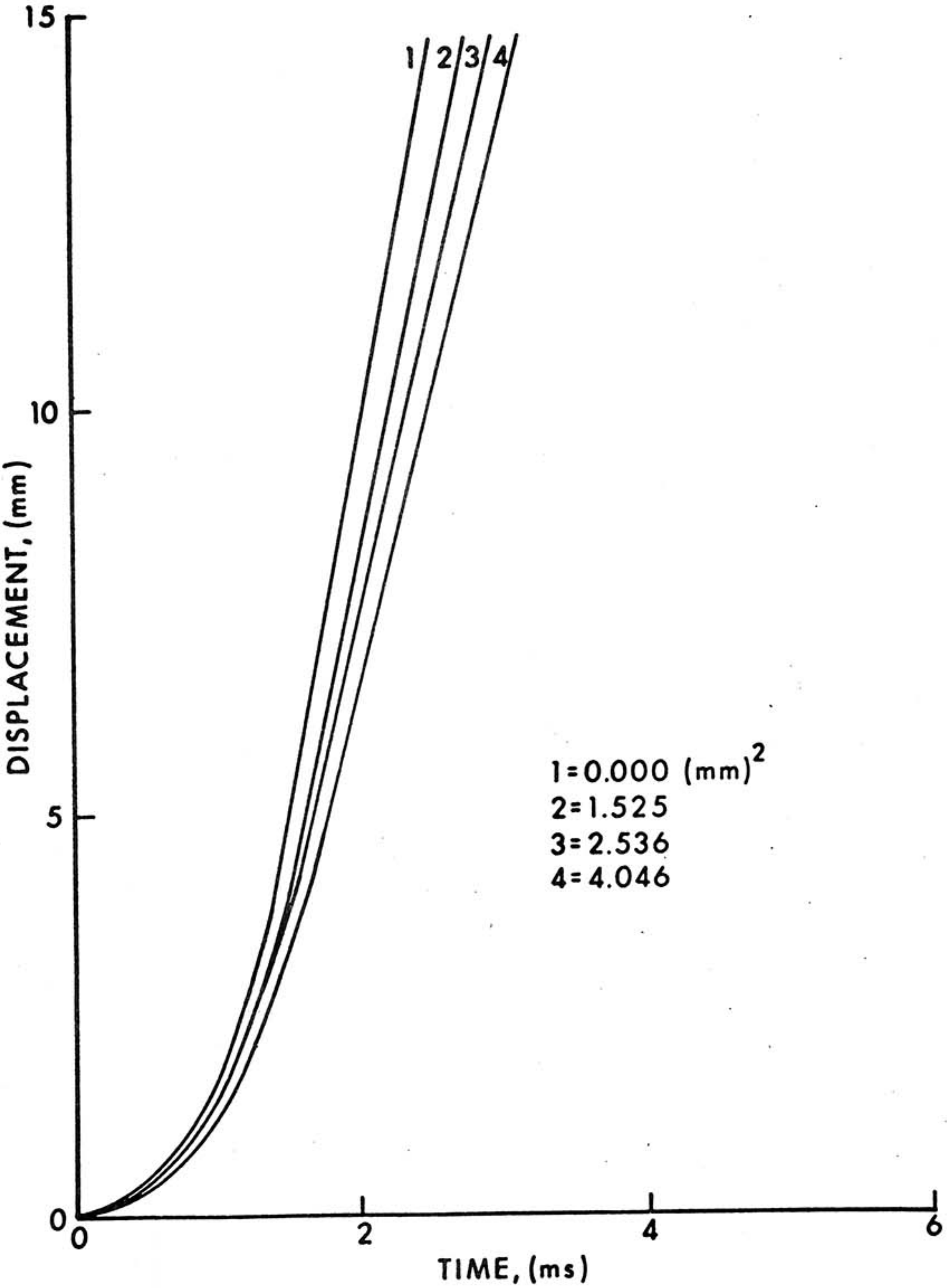


Figure 28. Theoretical Effect of Leakage Area on Displacement Versus Time of Piston

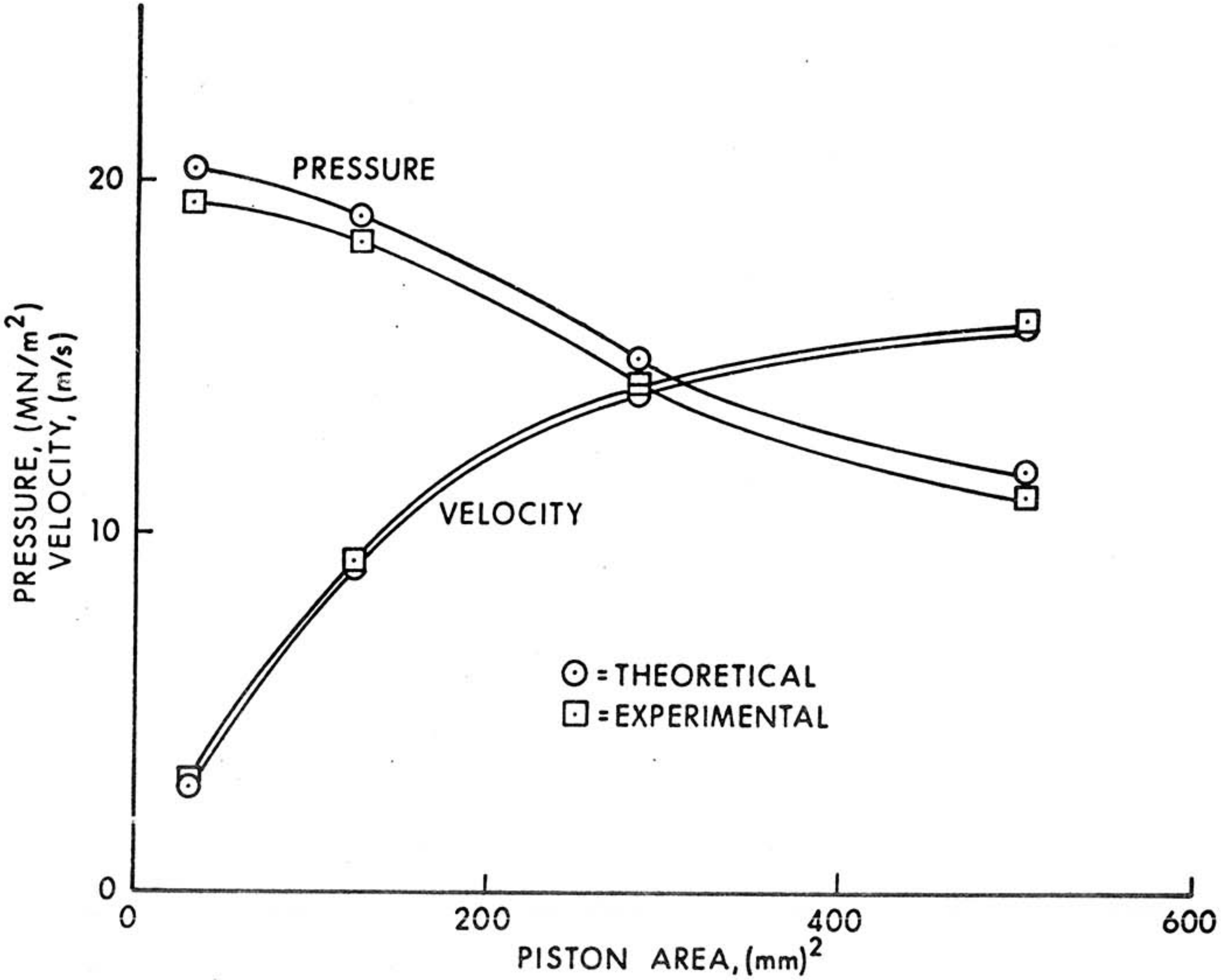


Figure 29. Experimental and Theoretical Effect of Piston Area on Peak Pressure in Cylinder and Velocity of Piston after 12.7mm Travel

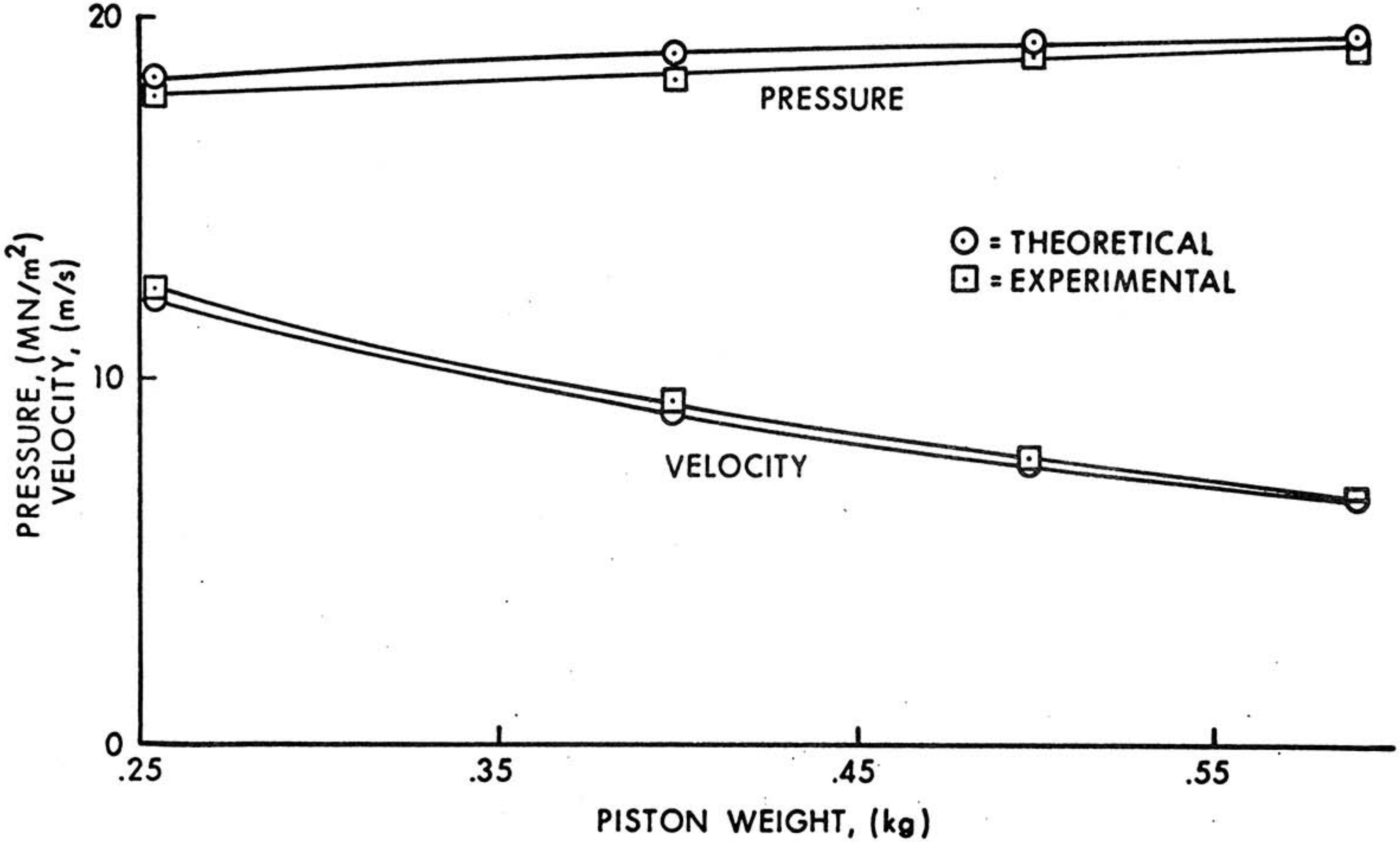


Figure 30. Experimental and Theoretical Effect of Piston Mass on Peak Pressure in Cylinder and Velocity of Piston after 12.7mm Travel

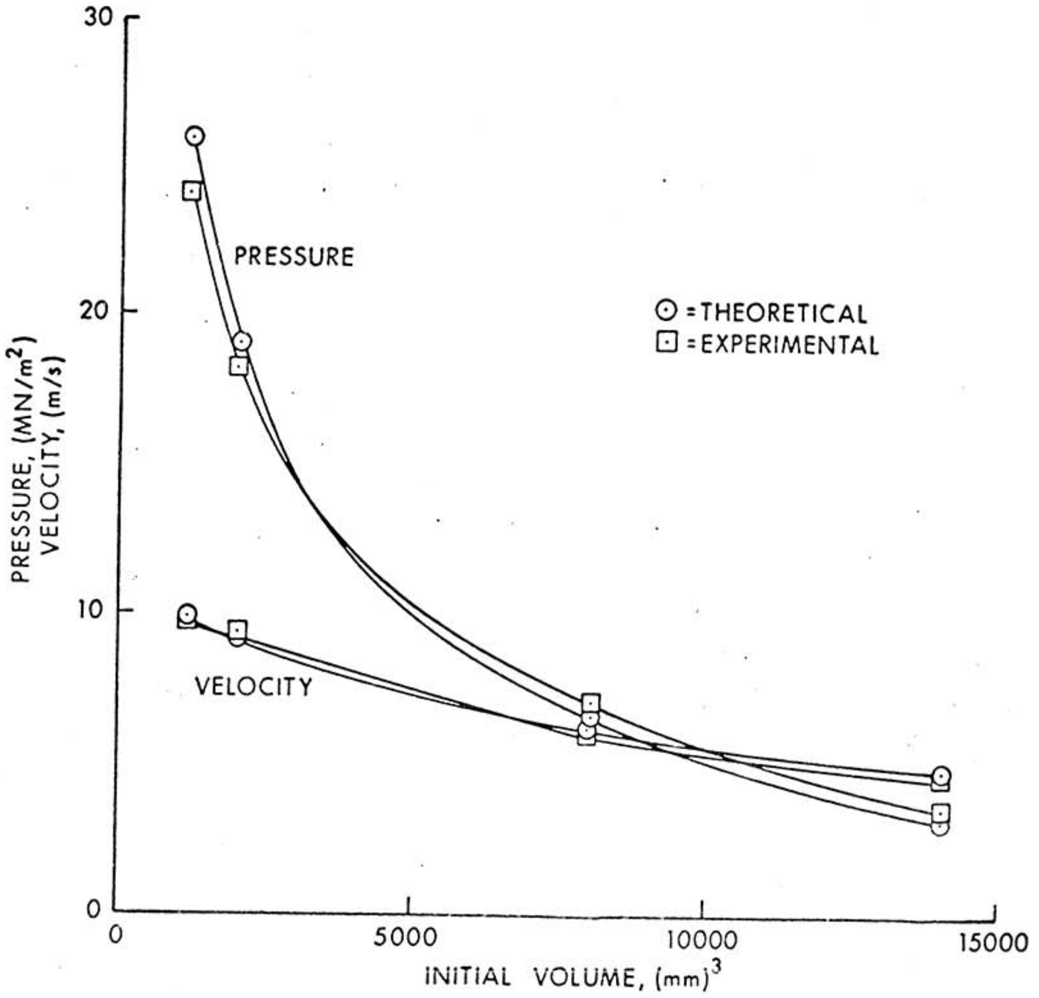


Figure 31. Experimental and Theoretical Effect of Initial Volume on Peak Pressure in Cylinder and Velocity of Piston after 12.7mm Travel

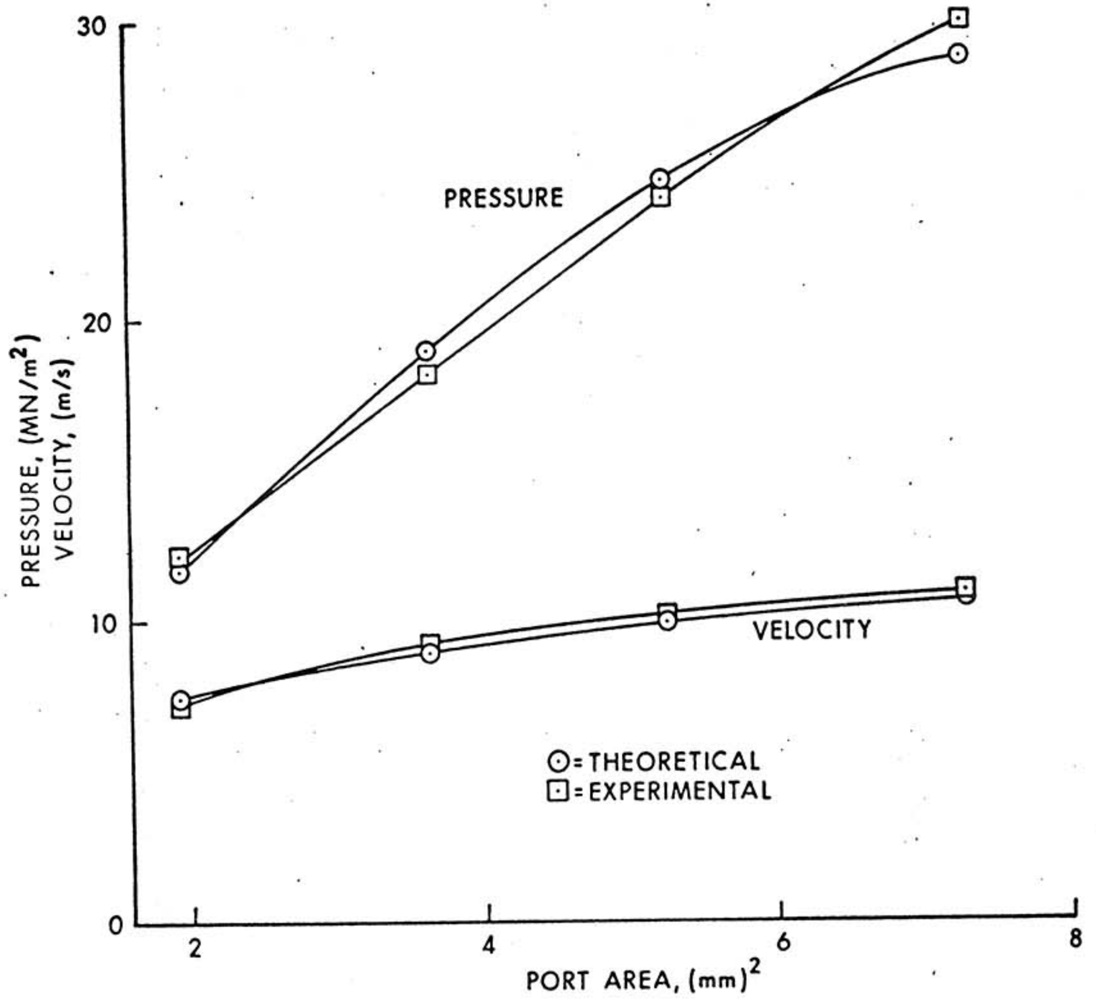


Figure 32. Experimental and Theoretical Effect of Gas Port Area on Peak Pressure in Cylinder and Velocity of Piston after 12.7mm Travel

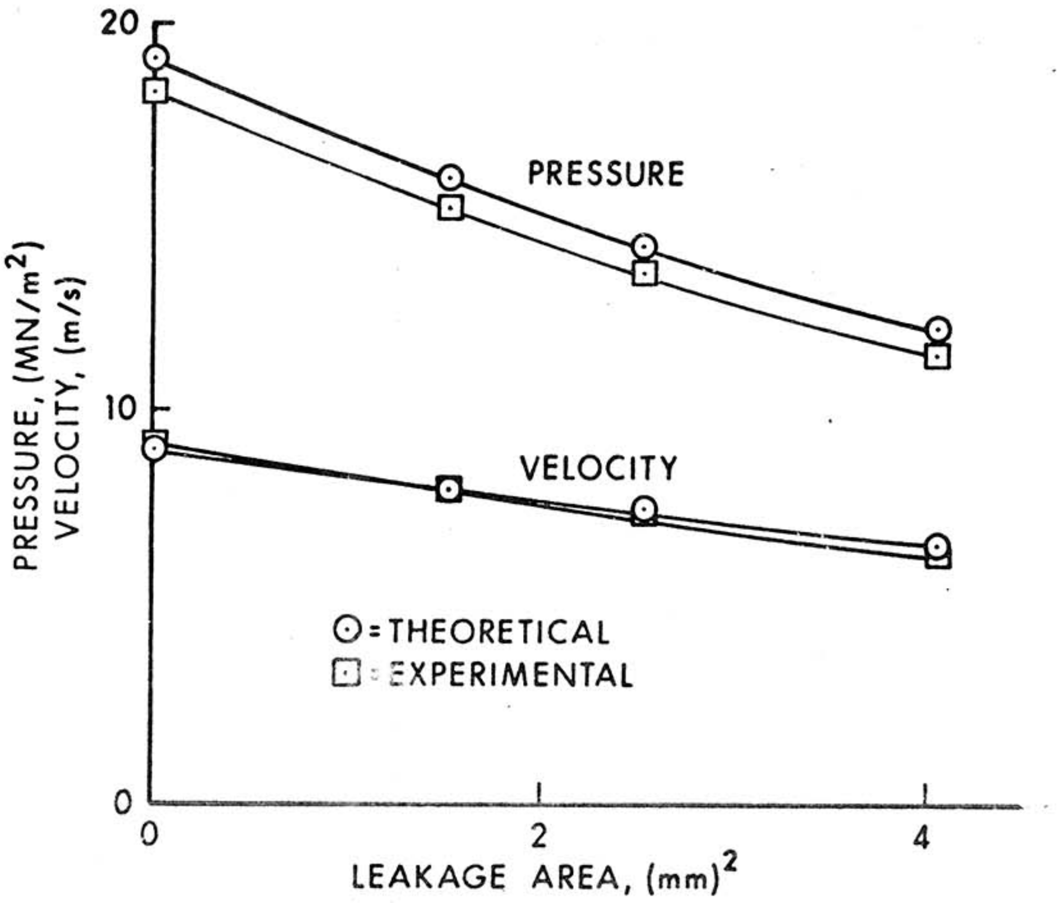


Figure 33. Experimental and Theoretical Effect of Leakage Area on Peak Pressure in Cylinder and Velocity of Piston after 12.7mm Travel

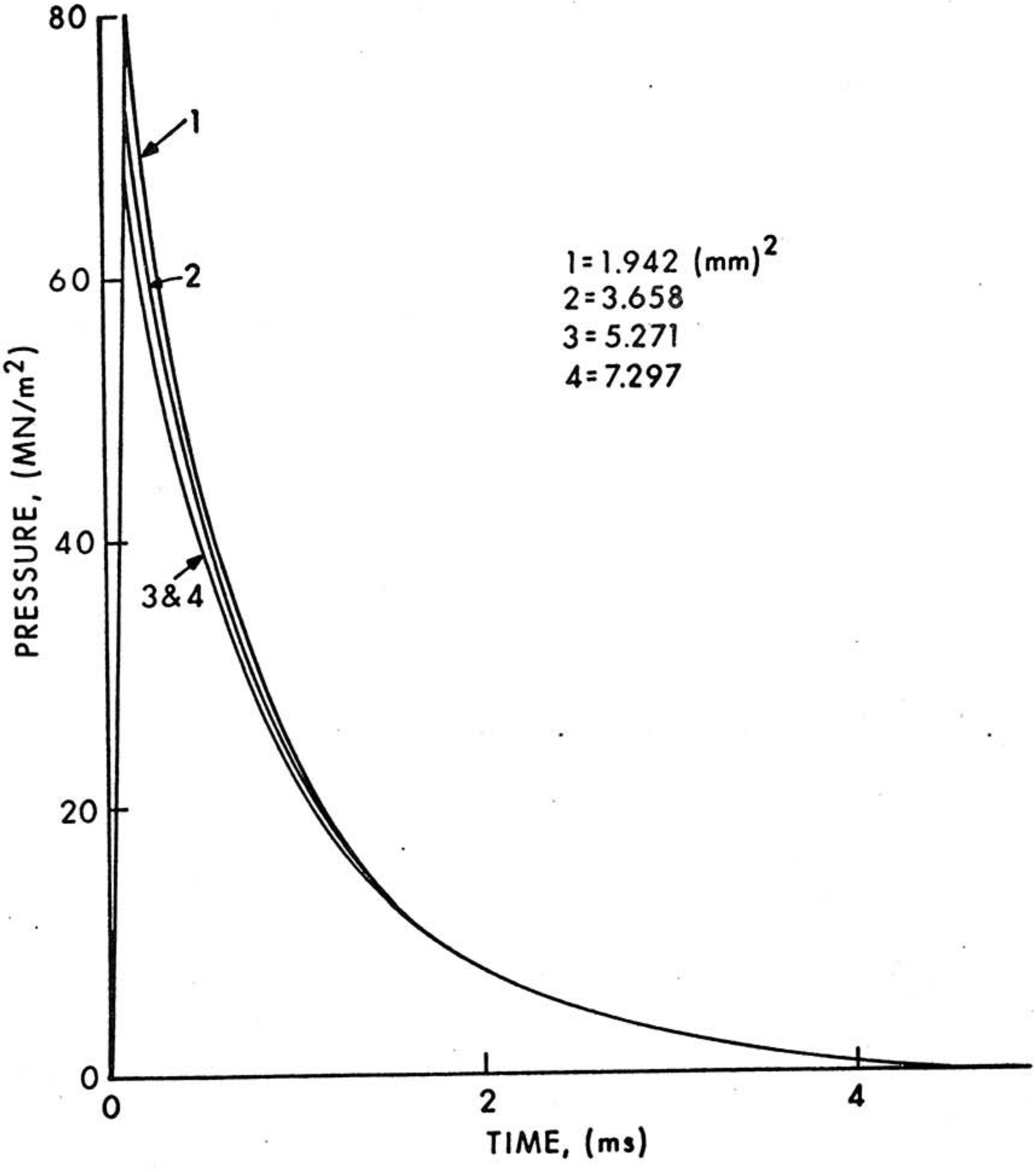


Figure 34. Effect of Gas Port Area on Pressure Versus Time at Gas Port

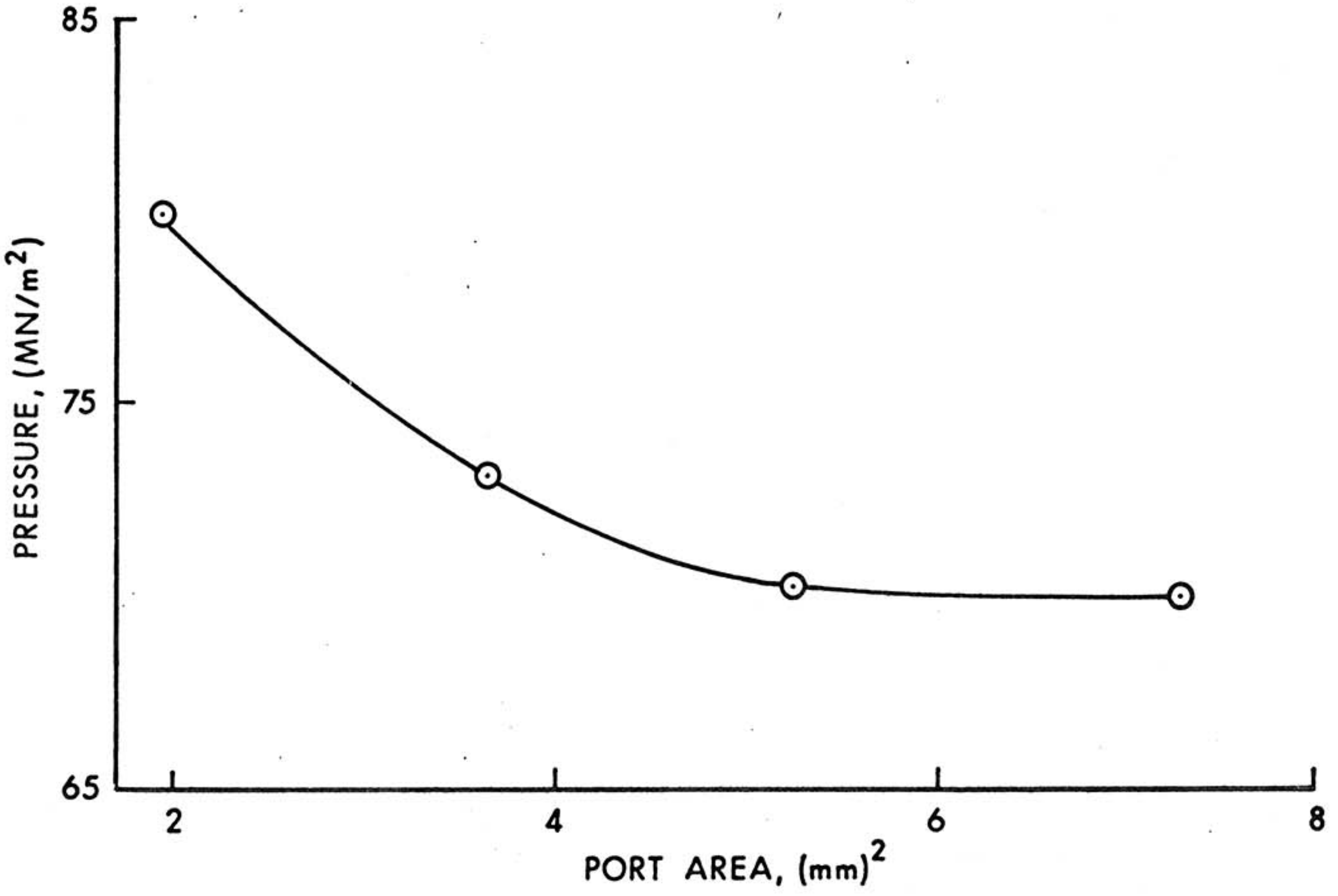


Figure 35. Effect of Gas Port Area on Peak Pressure at Gas Port

TABLE VI. COMPARISON BETWEEN EXPERIMENTAL AND THEORETICAL RESULTS

Piston Area $(mm)^2$	Piston Weight (kg)	Initial Volume $(mm)^3$	Port Area $(mm)^2$	Leakage Area $(mm)^2$	Difference in Peak Pressure in Cylinder (MN/m^2)	Difference in Velocity of Piston after 12.7mm Travel (m/s)	Difference in Peak Pressure in Cylinder (%)	Difference in Velocity of Piston after 12.7mm Travel (%)
31.7	0.399	2010.9	3.658	0.000	.92	.1	4.5	3.2
126.7	0.399	2010.9	3.658	0.000	.77	.2	4.0	2.2
285.0	0.399	2010.9	3.658	0.000	.83	.2	5.5	1.4
506.7	0.399	2010.9	3.658	0.000	.67	.3	5.7	1.9
126.7	0.254	2010.9	3.658	0.000	.26	.3	1.4	2.4
126.7	0.499	2010.9	3.658	0.000	.32	.2	1.7	2.6
126.7	0.590	2010.9	3.658	0.000	.14	0	.7	0
126.7	0.399	1206.6	3.658	0.000	1.79	.1	6.9	1.0
126.7	0.399	8044.1	3.658	0.000	.45	.3	6.4	4.8
126.7	0.399	14077.3	3.658	0.000	.47	.1	13.4	2.2
126.7	0.399	2010.9	1.942	0.000	.36	.1	3.0	1.3
126.7	0.399	2010.9	5.271	0.000	.37	.3	1.5	2.9
126.7	0.399	2010.9	17.297	0.000	1.33	.3	4.4	2.8
126.7	0.399	2010.9	3.658	1.525	.82	0	5.1	0
126.7	0.399	2010.9	3.658	2.536	.77	.1	5.4	1.4
126.7	0.399	2010.9	3.658	4.046	.63	.3	5.2	4.5

VI. CONCLUSIONS

The comparison between the experimental and theoretical results show that the agreement between the two is excellent. The agreement is excellent both at the peak values of the measurements and also in the distribution of the measurements as a function of time. This indicates that the theoretical model would be a very useful tool for use in the design of gas systems for future small arms weapons.

Since the ranges over which the parameters were varied are the extreme limits for most existing small arms gas-operated weapons, the plots shown in the results can be used as sensitivity curves for the design of gas systems for small arms weapons. The only range of parameters that is not realistic for a 5.56mm weapon is when the port area becomes larger than 4.5mm^2. As the port area becomes larger than this, pieces of the jacket are sheared off as the projectile passes the gas port.

ACKNOWLEDGMENT

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