A FIXTURE FOR TESTING MATERIAL AT MEDIUM STRAIN RATES

by

HSUEH HSIAO CHEN

B. S., Naval College of Technology, Taiwan, 1953

A MASTER'S REPORT

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Mechanical Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1963

Approved by:

John C Lindholm
Major Professor

TABLE OF CONTENTS

INTRODUCTION

In explosive forming of parts and in missile applications, material properties at high rates of strain are needed. In explosive forming, is the deformability of the material improved so as to permit greater deformations without destroying the usefulness of the part? Can missile parts sustain without failure a nearly instantaneous load which greatly exceeds the load which will produce failure under conditions of quasistatic applications? These are questions that need to be answered.

Presently designs are based on material properties obtained from essentially static load tests. Incomplete data on materials subjected to pulse load of short duration indicate improved physical properties over those in quasistatic loadings. If this is true one set of properties could be used to design for continuous steady loads and another set for impulsive loads, thus permitting better control of the overall design.

The research that is presented in this report includes two main parts:

1. Investigations in the area of high strain rates.
2. A proposed new device by which medium strain effects can be studied.

PREVIOUS INVESTIGATION

General Description

The influence of rate of strain on the mechanical properties of metals and alloys has been under study by many investigators in the past.

The standard static testing of materials used to obtain most of the physical properties published in the literature is performed at a strain rate of the order of 0.001 inch per inch per second. These data are used in most engineering work.

A survey of the literature uncovered several papers that pertain to the effects of high rates of loading on material properties. A discussion of the test set-ups is given in the following. A more detailed discussion is given by each investigator in his paper.

Austin and Steidel (1) used explosive type test equipment. Their equipment was designed to give a tensile load to a standard test specimen. The load was supplied by an explosive. Austin and Steidel (1) worked in a limited but high rate of strain area. Strain rates at fracture ranged from 4,480 to 22,600 inches per inch per second. Tests were made on SAE 1018 cold-rolled steel and 6061-T6 aluminum. The steel and aluminum increased in strength as the strain rate increased. This is shown in Fig. 1 (Lindholm, 2).

Shepler (3) tested several materials at strain rates comparable to Austin and Steidel (1) tests. Materials tested were NDRC steel - 0.17c, annealed; NDRC copper - commercially pure copper, annealed; Cr-Mn steel, heat-treated; SAE 1020, annealed; G.E. cast steel and malleable iron; and some low alloy steel plates. All showed increased fracture stress with increasing strain rate. Copper had the greatest per cent increase followed by SAE 1020 and NDRC steel. The wrought steel and malleable iron were the least affected by change in the strain rate. Effect of strain rate on low carbon steel is shown in Fig. 1.

Steidel and Makerov (4) and Manjoine and Nadai (5) used a rotary impact test machine. Strain rates varied from 100 to 1000 inches per inch per second. They tested SAE 1018 cold-rolled steel and several aluminum alloys. All showed some increases in strength with strain rate as shown in Fig. 1. Aluminum alloys showed very little gain in yield strength. Properties at fracture were also obtained. Here the true fracture stress of 1018 steel was constant while the aluminum alloys showed decreased strength as the strain rate increased. The per cent elongation increased for steel and the aluminum. The per cent reduction of area increased for the aluminums, and decreased for 1018 steel with increases strain rates.

Harding, et al. (6) obtained a meager set of data for RR77 aluminum, molybdenum, and super-purity iron. Their results indicated increased strength under impact conditions over static condition. RR77 showed an increase of strength at 800 inches per inch per second strain rate followed by a drop in strength at 1750 inches per inch per second strain rate. This is shown in Fig. 1.

Whiffin (7) used a flat-ended projectile fired against armor plate at varying velocities to evaluate the compressive yield stress of mild steel. His results were limited to strain rates from 11,400 to 16,700 inches per inch per second for steel. Hardly enough data are presented to conclude other than that the

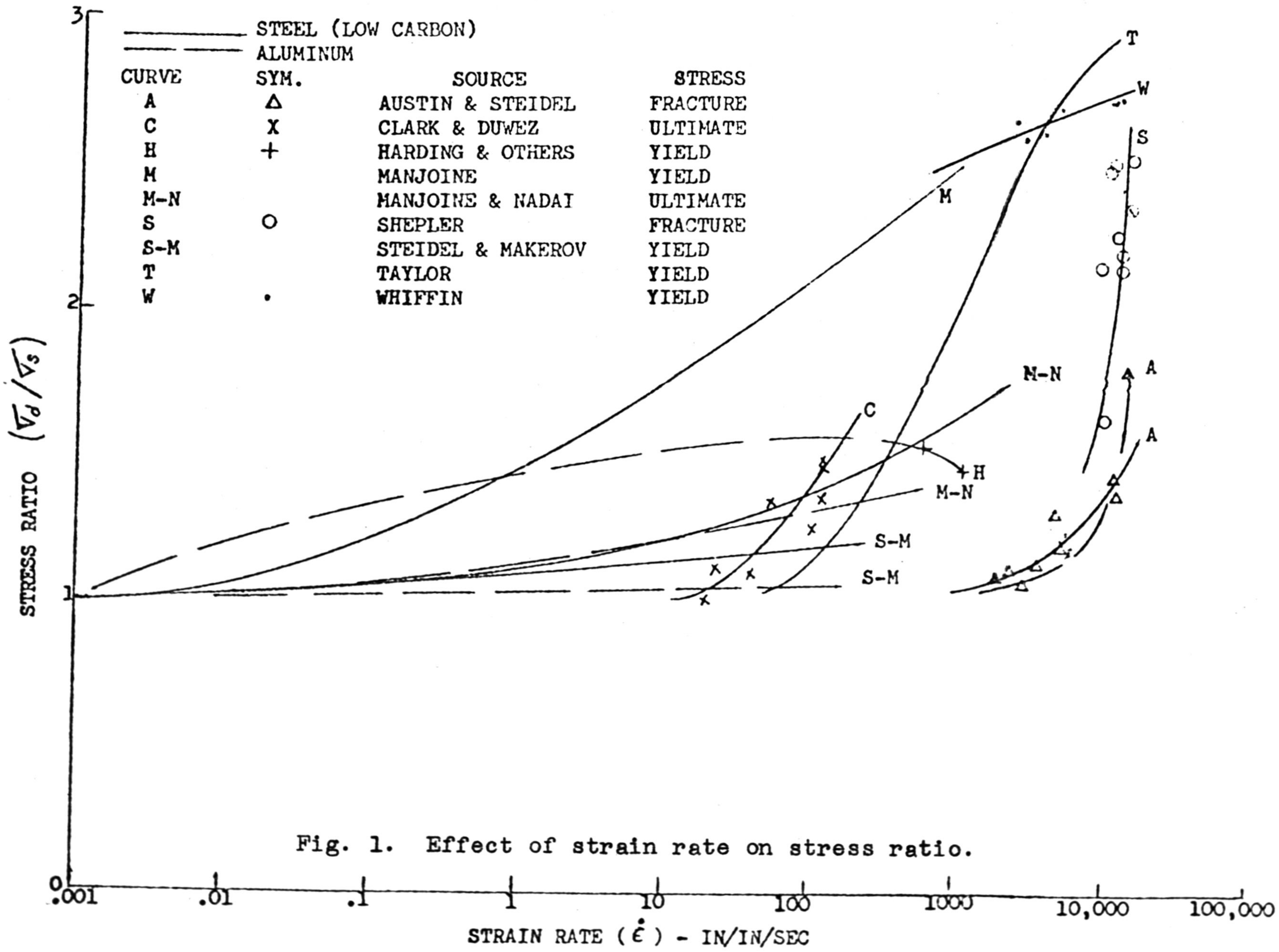


Fig. 1. Effect of strain rate on stress ratio.

yield strength is considerably higher than at static conditions. No evidence was present to indicate a steady increase or a jump in strength as strain rate increased. This is shown in Fig. 1.

Sir Geoffrey Taylor (8) developed the analytical theory used by Whiffin (7) in his work while Taylor made a study of the microstructure of the deformed projectiles. Taylor (8) compared some experimental data he obtained with an impact tester with results of Whiffin (7) and predicted a stress increase for mild steel, as shown in Fig. 1.

Clark and Duwez (9) used a unique design of equipment and test specimens to obtain their results. The test specimens were machined of SAE 1020. Each specimen was in the shape of a stepped O.D. tube. The internal diameter was honed to 0.2500 inch, ±0.0002 inch, and the external diameter of the test section was ground to 0.276 inch, ±0.0001 inch. Thus the test section was a thin-walled tube of 1-1/4-inch length supported at both ends by a 3/8-inch O.D. section. Load was applied by a dropped weight impending on a plunger. The load was transmitted from the plunger to bulge the test section by means of a confined mercury pool. The test specimen was machined so that its axis was parallel to the direction of the falling weight. The ultimate strength of the test section was obtained in the tests. Specimens of carbon-manganese and nickel-chromium steels were also tested. All three materials showed similar gains in strength with increased strain rate. (See Fig. 1 for the effect of strain rates on steel.)

Among all of these tests, two general types of equipment were used and are discussed in the following sections. The two types were the impact loading type and the explosive loading type.

Explosive Loading Type Test

The first preliminary work of an explosive nature was carried out by A. V. deForest, C. W. Macgreger, and Paul R. Shepler (3). An explosive test fixture was designed with one end of the specimen fixed and the other end moving, due to the explosion force in the explosive chamber. The load gage was attached to the fixed end. This apparatus is shown in Fig. 2.

One of the difficulties with this test fixture was the finding of a velocity and displacement gage. Because of the considerably higher speeds and violent powders used, a long single strain wire between the ends of the specimens could not be used for displacement measurements, no adequate protection against burning of the wire could be found. Later a small accelerometer, as shown in Fig. 2, was used. Strain gages were located on opposite sides of the accelerometer a definite distance from the free end. The weight forward of these wires caused a measurable force from which the acceleration could be calculated.

For the most part specimens were of 0.5 diameter. The specimen was mounted in a lathe and reference marks scribed by a diamond. Measurements of the diameter of numerous rings were made before and after the loading by a dial indicator. These measurements were used in calculating strain rate.

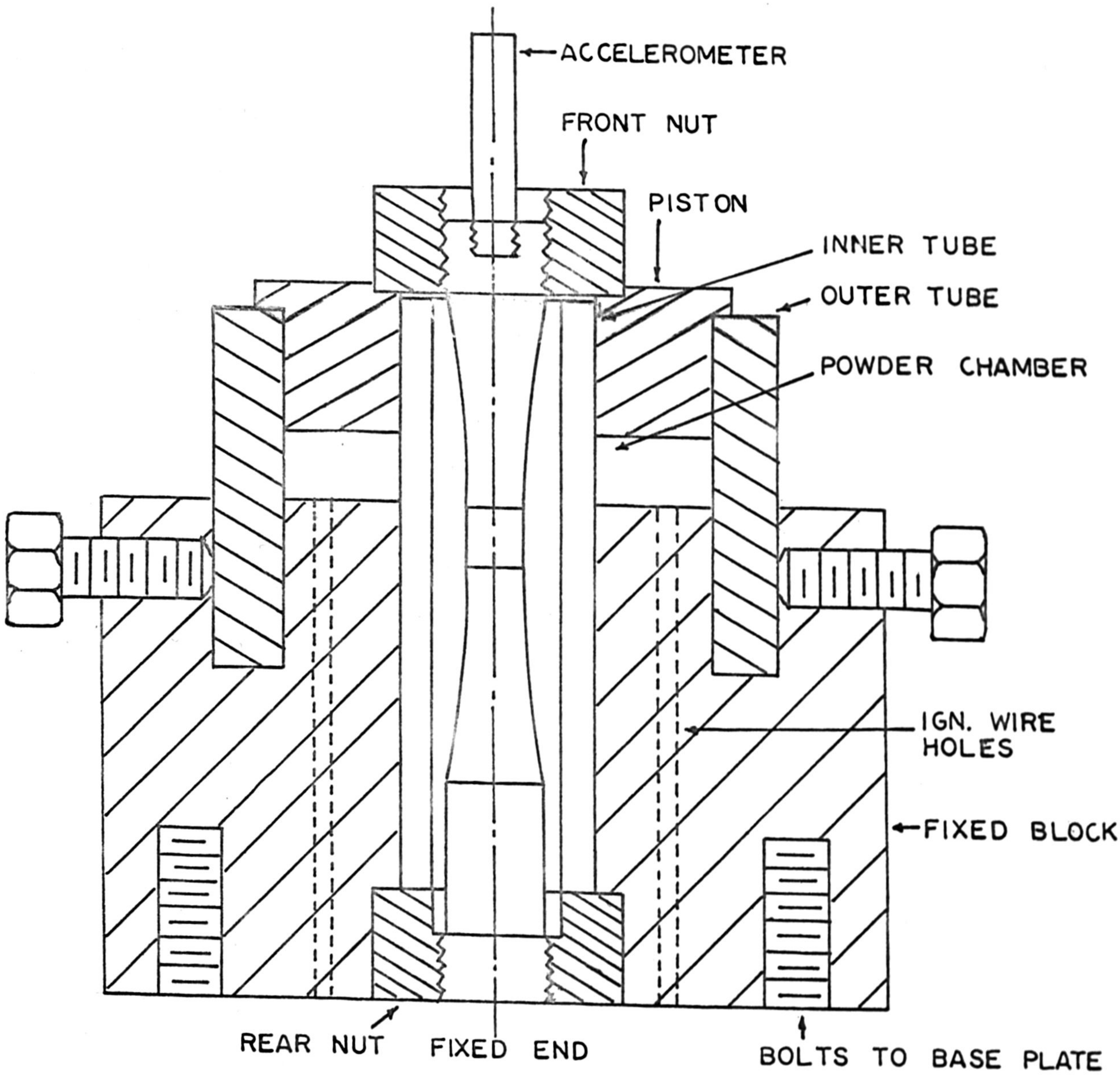


Fig. 2. Explosive loading type tester.

Black powder was placed in the annular space. The powder was fired by two sets of ignition wires and a 6-volt storage battery.

The accelerometer was attached and the whole test fixture tightened to a heavy base plate. Load gage leads, accelerometer leads, and ignition wires were then soldered to connect with the electrical apparatus, and then the fixture was ready for test.

Impact Loading Type Test

One method of securing a uniform high strain rate was to use a thin-wall hollow cylindrical specimen in which only circumferential strain was induced by an internal fluid pressure. The ability of such a system to produce a desired constant strain rate depended upon the incompressibility of the fluid employed, the ability to compress the fluid by means of a piston moving at constant velocity, and the stress-strain relation for the material being tested.

This machine is shown in Fig. 3. The frame of the machine used in these investigations consisted of two parallel rails six inches apart, providing guides for a hammer. This frame was supported on a large I-beam over a pit. In this machine an impending hammer slid between the two vertical rails and was accelerated by 40 rubber bands 3/8 inch by 1 inch. The hammer which slid between the vertical rails of the machine was lifted to the desired height by means of an elevator. A solenoid-operated trigger released the hammer.

The hammer velocity was determined by measuring the time required for the hammer to travel between fixed points of known spacing placed on the frame of the machines near the point of impact. A record of the time intervals was made by means of a cathode-ray oscillograph.

The assembly holding the specimen and actuating cylinder was threaded into the top end of a column rising from the floor of the pit through a support at the bottom of the rails, as shown in Fig. 3.

The actuating cylinder is shown in Fig. 4. A free-fitting plug closed the lower end of the specimen and rested on a dynamometer. This assembly was screwed into the column. The inner cylinder and specimen were filled with mercury. The plug transmitted the fluid pressure to the dynamometer and eliminated axial restraint in the specimen, thus providing circumferential loading.

The dynamometer consisted of a short column of heat-treated alloy steel, shown in Fig. 4, to which a resistance-sensitive element was cemented. The elastic deformation of the dynamometer column produced by the fluid force on the plug changed the resistance of the element, which caused a change of voltage in the strain-gage circuit. The voltage change was amplified and produced a vertical deflection on a cathode-ray oscillograph.

The lower end of the piston was placed in contact with the mercury column. The piston was driven into the cylinder filled with mercury by a hammer moving at the desired velocity. A copper button was placed on the piston to act as a damper to decrease the shock wave.

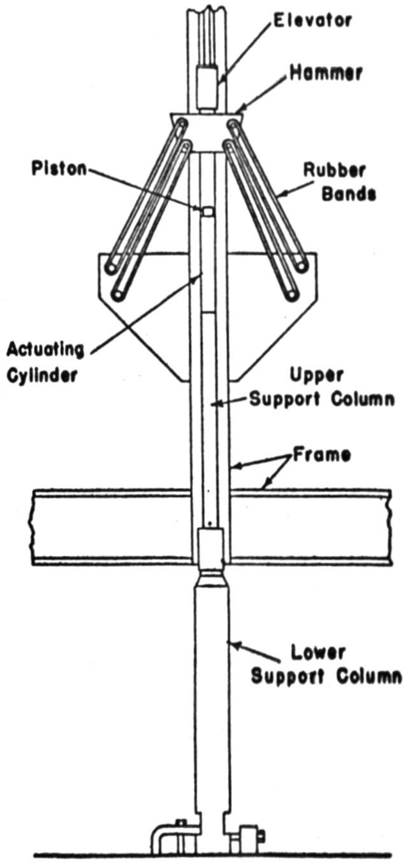


Fig. 3. Impact loading type tester.

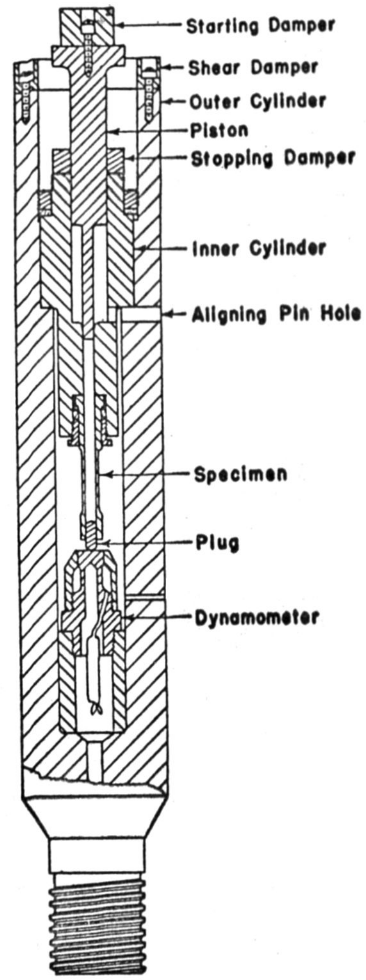


Fig. 4. Actuating cylinder assembly of strain rate machine.

Summary

For materials tested, in general strength increased with strain rates; the ductibility as measured by reduction in area increased with strain rates; and the energy of deformation increased with strain rates. However, the results of the various investigators are not in very good agreement as to the magnitude of the effect of strain rate on the strength of the materials.

NEW DESIGN

Introduction

Most of the investigations on the influence of rate of strain on the mechanical properties of metals and alloys had been made at rates of two kinds. The investigations of Winlock and Leighter (10) and Elam (11) are examples of work which had been done in the field of relatively low strain rates. Meyer (12) obtained strain rates on the order of five inches per inch per second, and found that the ultimate strength of certain materials was increased slightly at fracture.

Clark and Datwyler (13) produced strain rates of 150 inches per inch per second through the use of an Izod pendulum impact machine. Nadai and Manjoine (5) produced strain rates at 1000 inches per inch per second over temperature ranges to 1000 degrees C. on such materials as copper, aluminum, pure iron, etc., using a rotary impact machine. Clark (14) used a rotary impact machine similar to that of Nadai and Manjoine (5) capable of velocities up to 250 fps. Duwez, Clark, and Wood (15) performed a series of experiments by using a rotary impact machine and obtained velocities up to 200 fps.

Shepler (16), at the Massachusetts Institute of Technology, gave an extensive account of work done with an explosive impact tester developed by deForest and his associates. Shepler used this tester to obtain strain rates claimed to be as high as 25,000 inches per inch per second for steel, aluminum, and copper.

No investigations have been reported for the influence of moderate strain rates on the properties of metals. For this reason, a new device has been designed for investigation in this area.

General Description

The new device by which material properties at medium strain rates can be studied was designed and test techniques are presented. The tester, made of C-4340 wrought steel, consisted essentially of five main parts: a base, four studs, four spacers, a cylinder block, and a piston. The general assembly of the tester is shown in Fig. 5. The inside of the cylinder and specimen were filled with mercury. The lower end of the piston was placed in contact with the mercury column. The piston was driven by the stem of a Universal Testing Machine at the desired velocity.

Because of the capacity of the Universal Testing Machine in the laboratory the strain rate was limited to 25.6 inches per inch per second.

Formula of Strain Rate

The formula on strain rate is as follows:

$$\dot{\epsilon}_t = \left(\frac{r_p}{r_o}\right)^2 \frac{1}{2L} V_p$$

where $\dot{\epsilon}_t$ = strain rate

r_p = radius of piston

r_o = original inside radius of specimen

L = length of specimen

V_p = velocity of piston.

(See Appendix I for derivation.)

Comparison of Strain Rate Curves

The radius of piston r_p was assumed to be three inches and the length of specimen three times the inside diameter of the specimen. Substituting r_p = 3inches, $L = 3\ d_o$, and V_p = 1/120 inch per second in the formula of strain rate

$$\dot{\epsilon}_t = \left(\frac{r_p}{r_o}\right)^2 \frac{1}{2L} V_p$$

where 1/120 inch per second was the maximum velocity of the Universal Testing Machine. Then

EXPLANATION OF PLATE I

Bill of Materials

Item No.	Name	Number required	Material	Remarks
1	Bolt	1	Steel	For air vent
2	Piston	1	Steel $S_u \geqq 220,000$ psi	
3	Flat head screw	3	Steel	
4	Cylinder block	1	Steel $S_u \geqq 135,000$ psi	
5	O-ring	1		With two back-up rings
6	Socket head cap screw	4	Steel	3/8" - 16 NC - 2" long
7	Spaces	4	C-4340 wrought steel	
8	Base	1	Steel $S_u \geqq 135,000$ psi	
9	Plug	1		Without hole
10	O-ring	2		
11	Specimen	1		
12	Plug	1		With hole
13	O-ring	1		With two back-up rings

PLATE I

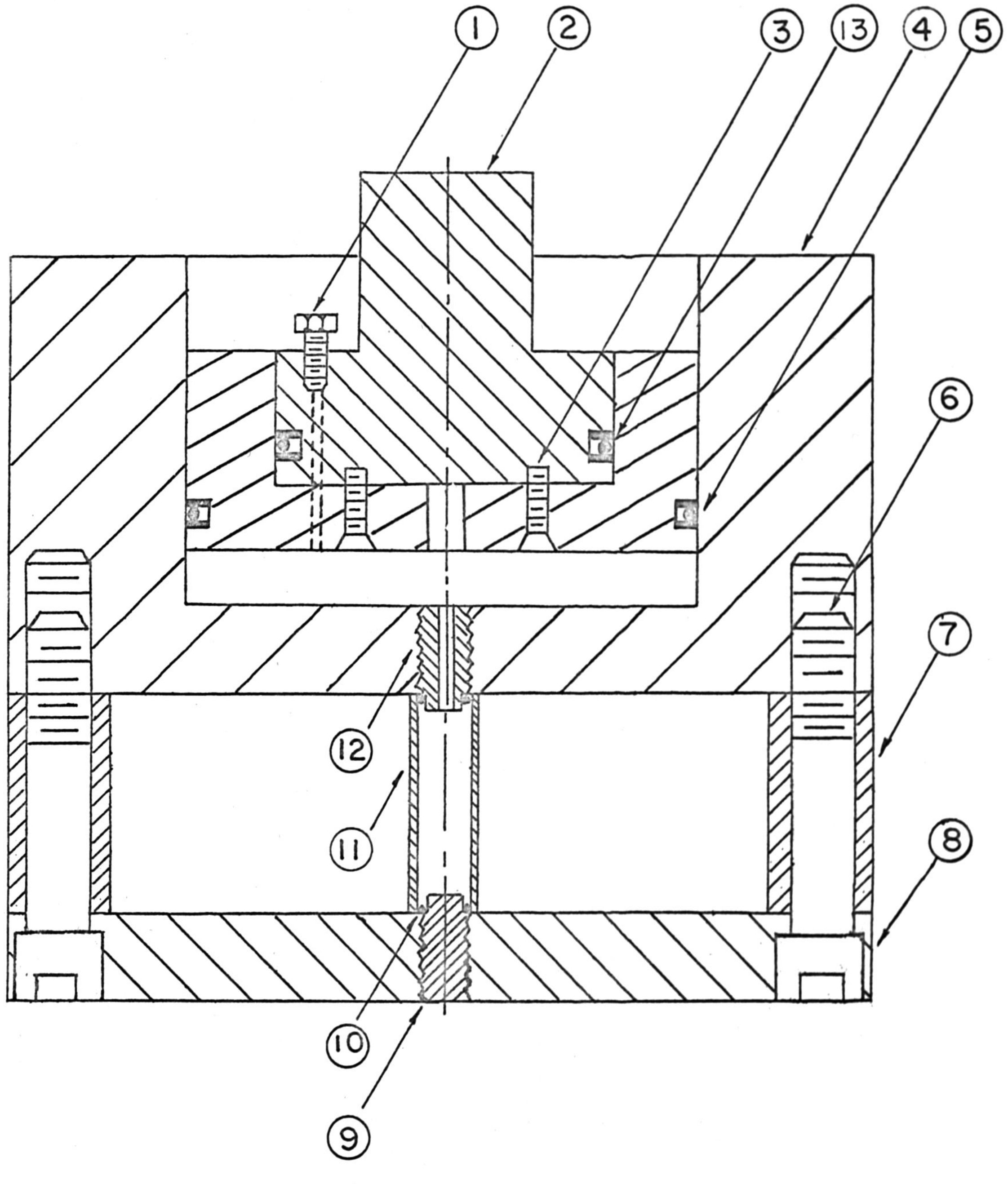


Fig. 5. General assembly of tester.

$$\dot{\epsilon}_t = \frac{3^2}{r_o^2} \cdot \frac{1}{2(3d_o)} \cdot \frac{1}{120} = \frac{1}{160} \cdot \frac{1}{r_o^3}$$

Figure 6 shows the strain rates for different sizes of specimens and actuating pistons. The tabular results are given in Table 2, Appendix I. It is very clear that by increasing the diameter of the piston or piston speed or decreasing the diameter of the specimen, an increase in the strain rate is obtained.

Maximum Force in Cylinder

Two curves, based on the capacity of the two Universal Testing Machines in the laboratory, were drawn in Fig. 7 to show the maximum pressure in the cylinder. These data were needed in establishing the sizes of the actuating piston and the test specimen. (See Appendix II for calculation in detail.)

Size of Specimen

Table 1 shows the dimensions of five test specimens. The strain rates indicated are for maximum rate of travel of the testing machine. Intermediate strain rate can be obtained by adjusting the speed of the testing machine.

Component Design

Cylinder. Using the requirement that the strain rate should be as high as possible, the six-inch diameter of the piston was

Table 1. Dimensions of five test specimens.

Inside diameter	Outside diameter	Nominal wall thickness	Length $L = 6r_i$	Max $\dot{\epsilon}_t$
0.1250 ±0.0002	0.150 ±0.0001	0.0125	0.375 ±0.005	25.6
0.1875 ±0.0002	0.225 ±0.0001	0.01875	0.5625 ±0.005	7.52
0.250 ±0.0002	0.30 ±0.0001	0.025	0.750 ±0.005	3.2
0.3750 ±0.0002	0.450 ±0.0001	0.0375	1.125 ±0.005	0.95
0.500 ±0.0002	0.60 ±0.0001	0.05	1.50 ±0.005	0.4

selected, based on Figs. 6 and 7.

Based upon the thick-walled cylinder theory (Timoshenko, 17), the thickness of the cylinder block was two inches. Detailed drawings and calculations are given in Appendix III (see Fig. 8).

Piston. The piston consists of an inner and an outer part. The outer part can be removed and put into the cylinder as a cylinder liner in order to increase the inner pressure of the cylinder, increase the wall thickness, and change the strain rate. The inner part could be used as a piston by itself.

See Appendix III for detailed drawings, Figs. 10, 11, and 12, and calculations.

Spacers. Spacers are used to maintain the distance between cylinder block and base and to protect the specimen from the compression of the Universal Testing Machine and the weight of the tester.

See Appendix III for calculations in detail, and Fig. 13 for detailed drawing.

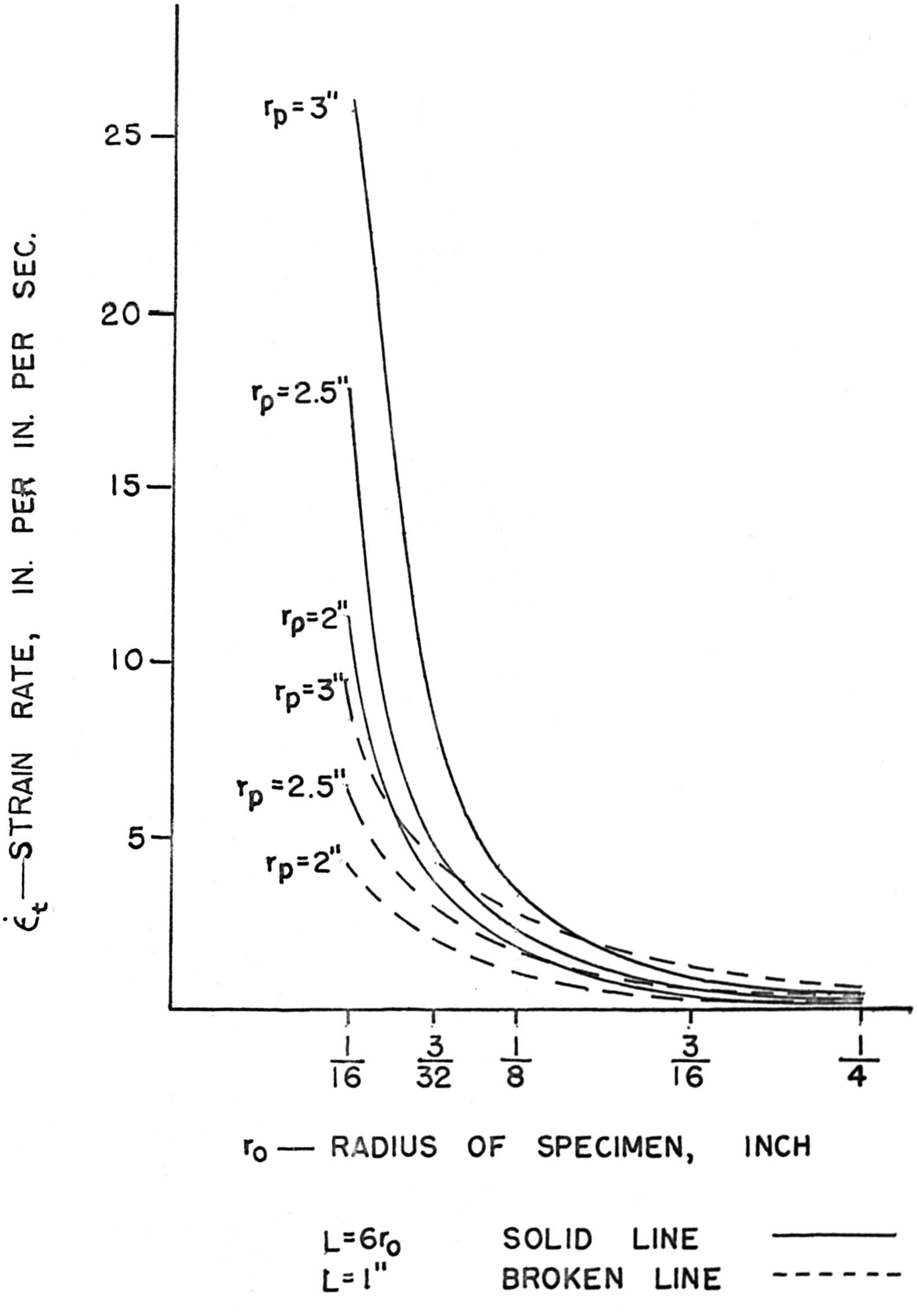


Fig. 6. Comparison of strain rate curves for different r_p, L and r_o.

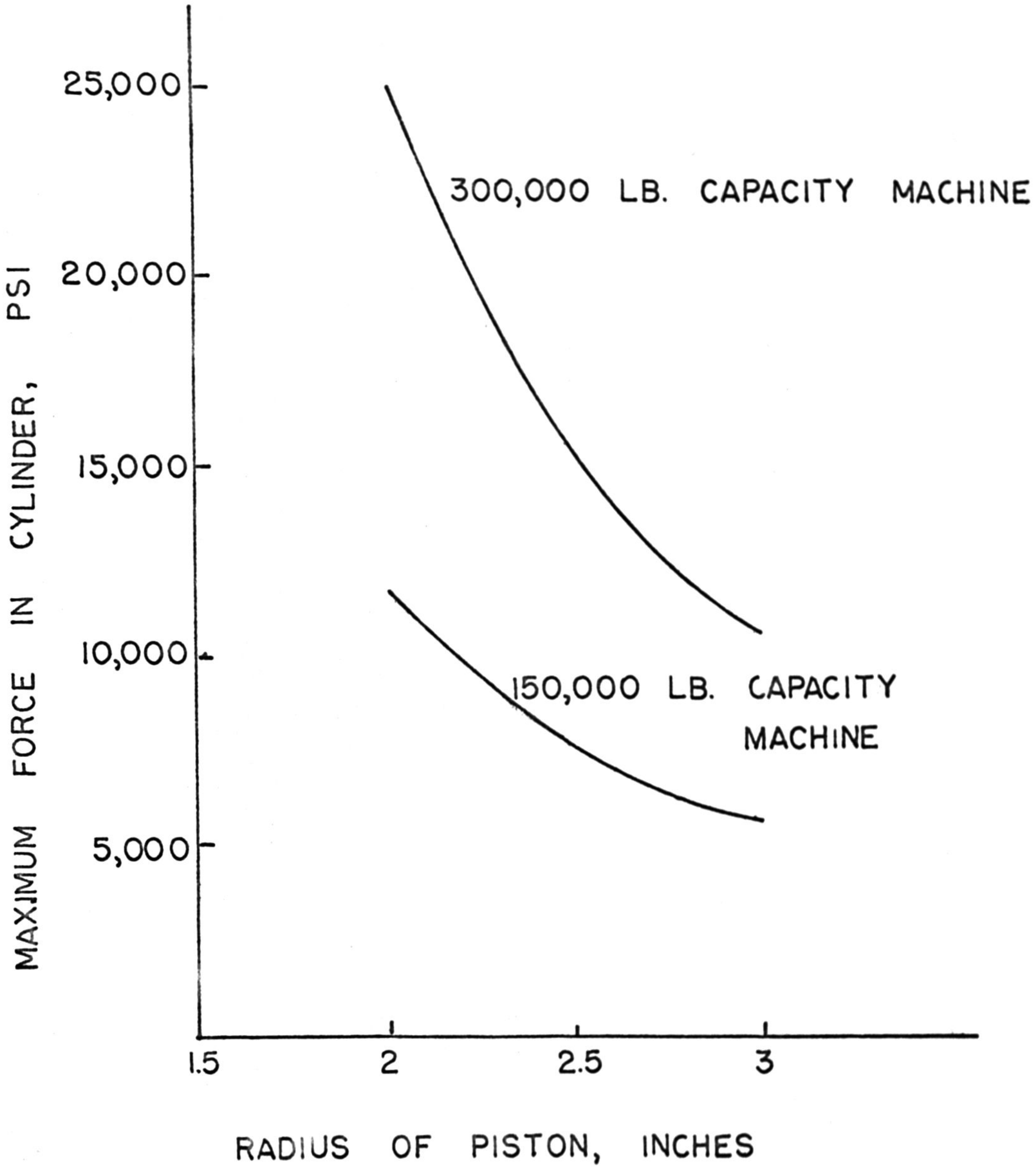


Fig. 7. Comparison between radius of piston with maximum force in cylinder.

Base. See Fig. 9 in Appendix III for detailed drawing.

Safety Device and Linkage Mechanism

A safety device is used to protect the operator from the spray of mercury when the specimen fractures. It is made of 1/4-inch thick, 2-inch diameter, transparent plastic pipe, shown in Fig. 16, Appendix IV. One slot was cut in one side, then the simple linkage could move up and down along the slot to measure the deformation of the specimen.

The linkage was designed to amplify three to four times the deformation of the specimen so the deformation could be measured more accurately. (See Plate VI, Appendix IV, for detail drawings.)

The linkage is fastened on a clamp which slides along a rod (Figs. 17 and 18, Appendix IV), at a suitable position which can be adjusted by moving the base block (Fig. 14, Appendix IV).

One end of the linkage has two pins which are kept in contact with the specimen, the other end has two lead rods used to draw traces of the deformation on the paper that is stuck on the steel plate. The angles of the pins can be adjusted to keep perpendicular to the center line of the specimen.

Test Techniques

1. Put specimen and safety device between cylinder block and base.

2. Use spacers to withstand the load and the weight of the tester.

3. Put tester on the Universal Testing Machine, fill the cylinder with mercury. The lower end of the piston is placed in contact with the mercury column. The piston is driven by the stem of the Universal Testing Machine at the desired velocity.

4. Strain rate can be obtained by two methods.

   a. By strain gage and oscilloscope. C6, C9, or C12 strain gage from Budd Company could be used.

   b. The diametrical deformation of the specimen can be determined by means of a simple linkage mechanism discussed above. Traces are made at regular time intervals. The differences of traces are used to determine the changes of diameter of the specimen. The changes of diameter divided by the time interval and the original diameter gives the strain rate. The data sheet used for recording is shown in Appendix V.

   c. Calculation of strain rate is shown in Appendix VII.

5. At the same time when the time readings are taken and the traces are drawn, the load from the dial of the Universal Testing Machine should be recorded.

ACKNOWLEDGMENT

The author wishes to express his appreciation to Dr. John C. Lindholm, Major Professor, for his advice and counsel during the preparation of this report.

BIBLIOGRAPHY

1. Austin, A. L. and R. F. Steidel.
A method for determining the tensile properties of metals at high rates of strain, Proc. of the SESA, vol. 17, no. 1, 1959.

2. Lindholm, J. C.
Unpublished report, The Martin Company, 1961.

3. Shepler, P. R.
Explosive impact tests, Proc. of the SESA, vol. 5, no. 1, 1947.

4. Steidel, R. F. and C. E. Makerov.
The tensile properties of some engineering materials at moderate rates of strain, ASTM Bulletin, July, 1960.

5. Manjoine, M. and A. Nadai.
High speed tension tests at elevated temperatures, Proc. of the ASTM, vol. 40, part II, 1940.

6. Harding, L., E. O. Wood, and L. D. Campbell.
Tensile testing of material at impact rates of strain, Journal of Mechanical Engineering Science, vol. 2, no. 2, June, 1960.

7. Whiffin, A. C.
Part II of Item 2. II Tests on various metallic materials, Royal Society of London Proceedings, vol. 194A, 1948.

8. Taylor, Sir Geoffrey.
The use of flat-ended projectiles for determining dynamic yield stress. I. Theoretical consideration. Royal Society of London Proceedings, vol. 194A, 1948.

9. Clark, D. S. and P. E. Duwez.
The influence of strain rate on some tensile properties, Proc. of the ASTM, vol. 50, 1950.

10. Winlock, J. and R. W. E. Leighter.
Some factors affecting the plastic deformation of sheet and strip steel and their relation to deep drawing properties, Transactions Amer. Soc. Metals, vol. 25, p. 163, 1937.

11. Elam, C. R.
The influence of rate of deformation on the tensile test with special reference to the yield point in iron and steel, Proc. Royal Soc., vol. 165, p. 568, 1938.

12. Meyer, E.
Der Verlauf des Zugversuches beiraschem Zerreissen. Forschungsarbeiten des Vereines Deutscher Ingenieure, no. 295, pp. 62-73, 1927.

13. Clark, D. S. and G. Datwyler.
Stress relations under tension impact loading. Proc. of the ASTM, vol. 38, II, pp. 98-111, 1938.

14. Clark, D. S.
The influence of impact velocity on the tensile characteristics of some aircraft metals and alloys, NACA Technical Note 868, October, 1942.

15. Duwez, P. E., D. S. Clark, and D. S. Wood.
The influence of impact velocity on the tensile properties on plain carbon steel and of a cast steel armor plate, NDRC Report A-154, OSRD, No. 1274.

16. Shepler, P. R.
Impact research. Sc. D. Thesis submitted to Mechanical Engineering Department, M. I. T., September 27, 1943.

17. Timoshenko, S.
Strength of materials, 3rd ed. New York: McGraw-Hill Book Company, 1956.

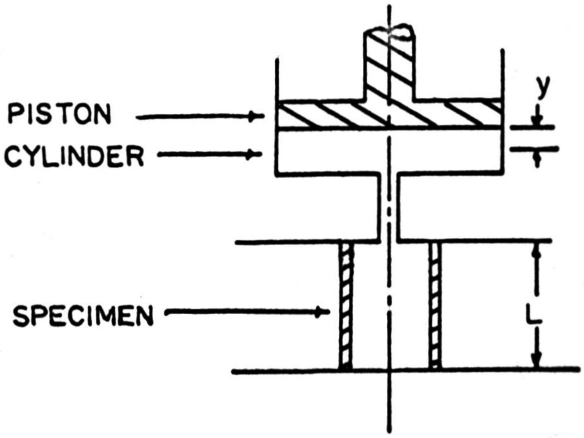
18. Faires, V. M.
Design of machine elements, 3rd ed. New York: The Macmillan Company, 1961.

19. Catalog for the Graphic-Industrial Arts and Sciences. Modern School Supplies, P. O. Box 358, Hartford 1, Conn. 1962.

APPENDICES

APPENDIX I

Calculation of Strain Rate



The inside of the cylinder and specimen was filled with mercury. The lower end of the piston was placed in contact with the mercury column. After the piston moved y distance, the change of volume in cylinder and specimen would be:

$$\Delta V_p = \pi\, r_p^2 \cdot y$$

$$\Delta V_s = \pi\, r^2 L - \pi\, r_o^2 L = \pi(r^2 - r_o^2)L$$

where ΔV = change of volume

p = piston

s = specimen

r_o = original radius

r = radius after deformation

L = length of specimen

$$\Delta V_p = \Delta V_s$$

$$\pi(r^2 - r_o^2)L = \pi\, r_p^2 \cdot y$$

$$(r - r_o)(r + r_o) = \frac{r_p^2}{L} y$$

$$(r_o + \Delta r - r_o)(r_o + \Delta r + r_o) = \frac{r_p^2}{L} y$$

$$2 r_o \Delta r = \frac{r_p^2}{L} y - \Delta r^2$$

$$\Delta r = \frac{r_p^2}{2r_o L} y - \text{infinitesimal of higher order}$$

$$\Delta r = \frac{r_p^2}{2r_o L} y$$

$$\frac{\Delta r}{\Delta t} = \frac{r_p^2}{2r_o L} \quad \frac{y}{\Delta t}$$

$$\frac{dr}{dt} = \frac{r_p^2}{2r_o L} V_p$$

where V_p = velocity of piston.

ϵ_t = strain in radial direction $= \frac{r - r_o}{r_o}$

$\dot{\epsilon}_t$ = strain rate

$$= \frac{d}{dt} \left(\frac{r - r_o}{r_o}\right) = \frac{d}{dt} \left(\frac{r}{r_o} - 1\right)$$

$$= \frac{1}{r_o} \quad \frac{dr}{dt} = \frac{1}{r_o} \quad \frac{r_p^2}{2r_o L} V_p = \left(\frac{r_p}{r_o}\right)^2 \frac{V_p}{2L}$$

Table 2. Comparison of strain rate curves for different r_p, L, and r_o.

V_p in/sec	$\frac{1}{120}$	$\frac{1}{120}$	$\frac{1}{120}$	$\frac{1}{120}$	$\frac{1}{120}$	$\frac{1}{120}$
L in	$6r_o$	$6r_o$	$6r_o$	1"	1"	1"
r_p in	3"	2.5"	2	3"	2.5"	2
ϵ_t	$\frac{1}{160}\frac{1}{r_o^3}$	$\frac{1}{230}\frac{1}{r_o^3}$	$\frac{1}{360}\frac{1}{r_o^3}$	$\frac{1}{80}\frac{1}{r_o^3}$	$\frac{1}{38.4}\frac{1}{r_o^3}$	$\frac{1}{60}\frac{1}{r_o^2}$
1/16"	25.6	17.8	11.3	9.6	6.67	4.27
3/32"	7.52	5.31	3.49	4.02	2.79	1.78
1/8"	3.2	2.22	1.42	2.4	1.66	1.06
3/16"	0.95	0.66	0.421	1.07	0.743	0.475
1/4"	0.4	0.278	0.178	0.6	0.417	0.268

APPENDIX II

Maximum Force in Cylinder

$$p = \frac{\text{load}}{\text{area}}$$

A. 300,000-lb Testing Machine

$$p = \frac{300{,}000}{\pi r^2}$$

$= 24{,}850$ psi when $r = 2''$

$= 15{,}300$ psi when $r = 2.5''$

$= 10{,}600$ psi when $r = 3''$

B. 150,000-lb Testing Machine

$$p = \frac{150{,}000}{\pi r^2}$$

$= 11{,}950$ psi when $r = 2''$

$= 7{,}650$ psi when $r = 2.5''$

$= 5{,}310$ psi when $r = 3''$

APPENDIX III

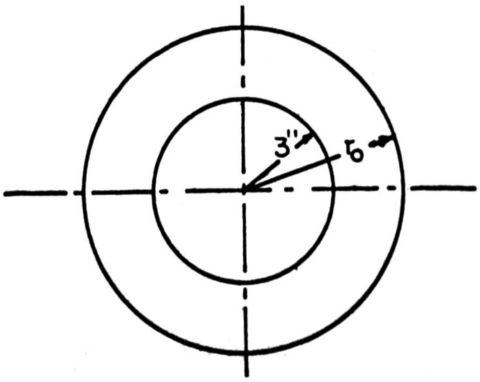
Component Design

Calculation of the thickness of cylinder wall.

Let $r_i = 3''$ Load = 300,000 lbs

$$P_i = \frac{300,000}{9\pi} = 10,600 \text{ psi}$$

$$\sigma_r = A - \frac{B}{r^2}$$



when $r = 3''$ $$-10,600 = A - \frac{B}{9} \qquad (1)$$

when $r = r_o$ $$0 = A - \frac{B}{r_o^2} \qquad (2)$$

from Eq. (2), $$A = \frac{B}{r_o^2} \qquad (3)$$

Substituting Eq. (3) in Eq. (1), gives

$$-10,600 = \frac{B}{r_o^2} - \frac{B}{9}$$

$$B = \frac{10,600 \times 9 \times r_o^2}{9 - r_o^2}$$

$$A = -\frac{10{,}600 \times 9}{9 - r_o^2}$$

$$\sigma_r = -\frac{10{,}600 \times 9}{9 - r_o^2} + \frac{10{,}600 \times 9 \times r_o^2}{9 - r_o^2} \cdot \frac{1}{r^2}$$

$$\sigma_\theta = -\frac{10{,}600 \times 9}{9 - r_o^2} - \frac{10{,}600 \times 9 \times r_o^2}{9 - r_o^2} \cdot \frac{1}{r^2}$$

When $r = r_i = 3''$ $\quad \sigma_\theta$ = maximum value.

If C-4340 Q and T 800 wrought steel was used, from reference (18), Table 2, p. 34,

$$S_u = 222{,}000 \text{ psi}$$

From Table 1, p. 10, reference (18), for repeated one-direction gradual load,

$$N = \text{safety factor} = 6$$

$$\text{Design stress} = \frac{S_u}{N} = \frac{222{,}000}{6} = 37{,}000 \text{ psi}$$

$$37{,}000 = -\frac{10{,}600 \times 9}{9 - r_o^2} - \frac{10{,}600 \times 9 \times r_o^2}{9 - r_o^2} \cdot \frac{1}{9}$$

$$37{,}000 = -\frac{10{,}600}{9 - r_o^2}(9 + r_o^2)$$

$$3.7(9 - r_o^2) = -1.06(9 + r_o^2)$$

$$(3.7 + 1.06) \times 9 = (3.7 - 1.06)r_o^2$$

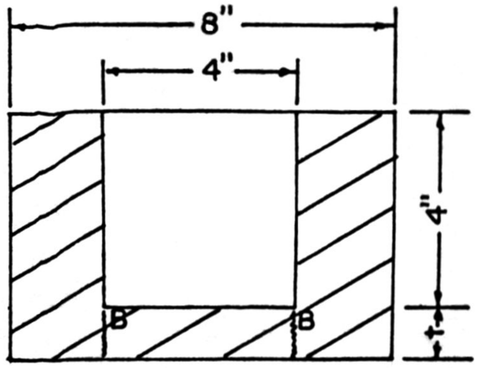
$$r_o^2 = 16.25$$

$$r_o = 4.03 \cong 4''$$

Thickness of the cylinder wall = 4 - 3 = 1 inch.

To facilitate mounting and attaching of parts, the thickness was increased to two inches. Based on this thickness, a material with an ultimate strength in tension of 135,000 psi will have a safety factor of 6.

Calculation of the shear stress on bottom of cylinder.



The cylinder may fail by shearing across the section B in the above figure.

$$F = S_s \cdot A$$

From reference (18), Table 2, p. 34, if a material with an ultimate strength in tension is about 135,000 psi, shear strength is 103,000 psi.

$$300{,}000 = \frac{103{,}000}{6} \cdot 4\pi \cdot t \quad \text{where } t = \text{thickness}$$

$$t = \frac{300{,}000 \times 6}{103{,}000 \times 4\,\pi} = 1.4''$$

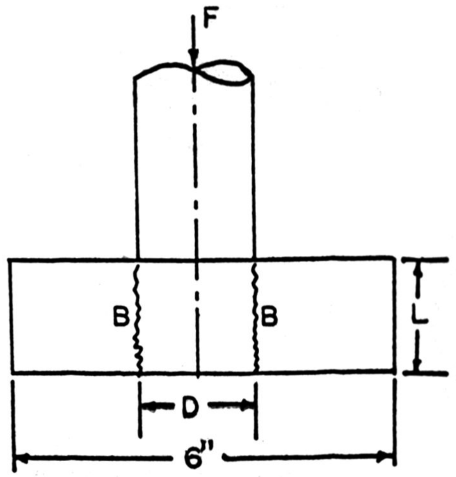
t = 1" was selected before because the safety factor is 6. The selection is quite safe and will not be changed.

Calculation of piston dimensions.

The piston may fail by shearing across the section B in the following figure. The section area is π DL.

$$F = S_s A$$

$$300{,}000 = \frac{185{,}000}{6} \cdot \pi\, DL$$



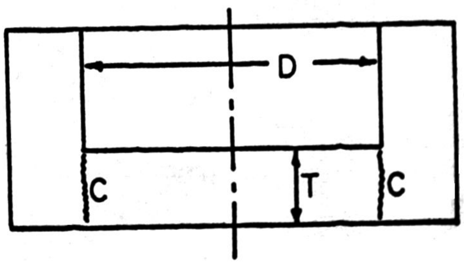
where S_s = 185,000 psi for C-4340 wrought steel

N = 6

$$DL = \frac{300,000 \times 6}{185,000 \times \pi} = 3.05$$

D = 2" L = 1.5" were selected

For the outer part of the piston, the thickness T should be calculated because the piston may fail by shearing across the



section C. The circumferential section area is π DT.

$$F = S_s A$$

$$300{,}000 = \frac{185{,}000}{6} \times \pi\ DT = \frac{185{,}000}{6} \times 4\ \pi T$$

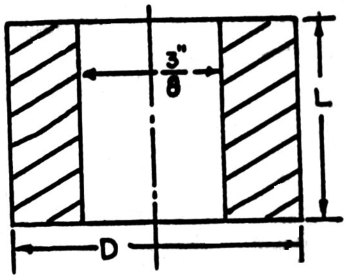
where S_s = 185,000 psi for C-4340 wrought steel

$N = 6$

$$T = \frac{300{,}000 \times 6}{185{,}000 \times 4} = 0.774''.$$

$$T = 0.78125'' = \frac{25}{32}$$ was selected

Spacer



$$F = nsA$$

where F = load = 300,000

n = number of spacers

$$s = \text{design stress} = \frac{222{,}000}{6} = 37{,}000 \text{ psi}$$

$$A = \text{contact area} = \frac{\pi(D^2 - 0.375^2)}{4}$$

$$300{,}000 = 4 \times 3700 \times \frac{(D^2 - 0.375^2)\pi}{4}$$

$$30 = 3.7\,\pi(D^2 - 0.141)$$

$$D^2 = \frac{30}{3.7\pi} + 0.141$$

$$= 2.58 + 0.141 = 2.721''$$

Therefore $$D = 1.65 \cong 1\,\frac{21''}{32}$$

$$L = \text{height of specimen} + 0.002''$$

EXPLANATION OF PLATE II

Fig. 8. Cylinder block.

(1) 4 holes equally spaced to match base; 3/8" - 16-UNC-2B - 1½" deep

(2) Screw plug with hole, ½"-13-UNC-2A

(3) Two O-rings, Linear, Incorporated.

Fig. 9. Base.

(4) Screw plug, without hole, ½"-13-UNC-2A.

Scale: ½" = 1"

Material: C-2340 wrought steel

Surface roughness of cylinder wall: 10 RMS

Clearance between piston and cylinder: 0.003" maximum.

Table of plugs and O-rings

Inside diameter of specmen	Plug (2)	Plug (4)	O-ring		
	A	A	Outside diameter	Inside diameter	Section diameter
1/8"	7/64"	7/64"	1/8"	7/64"	0.070 ±0.003
3/16"	1/8"	1/8"	3/16"	1/8"	0.070 ±0.003
1/4"	1/8"	1/8"	1/4"	1/8"	0.070 ±0.003
3/8"	1/4"	1/4"	3/8"	1/4"	0.070 ±0.003
1/2"	3/8"	3/8"	1/2"	3/8"	0.070 ±0.003

PLATE II

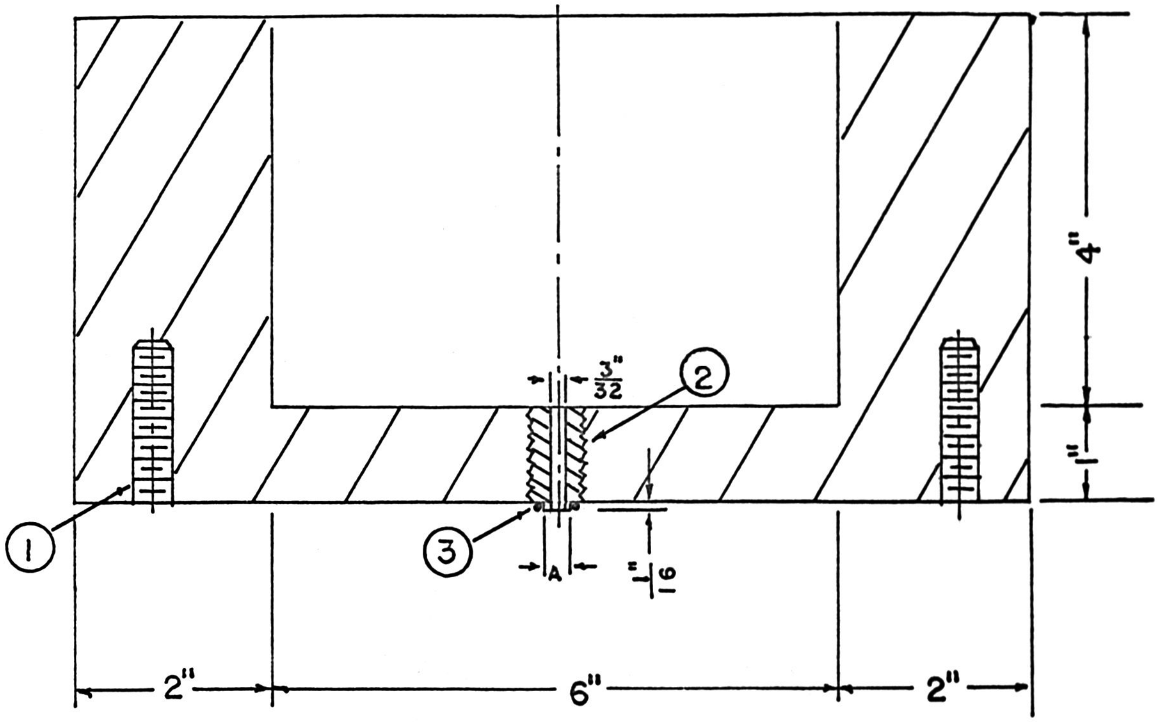


Fig. 8.

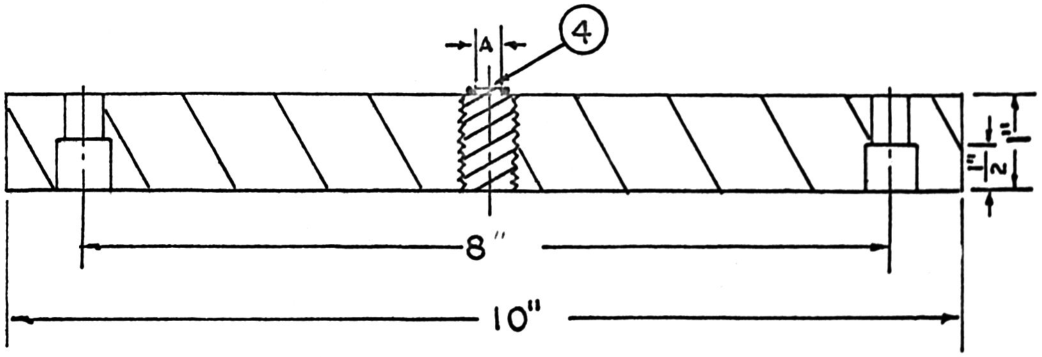


Fig. 9.

EXPLANATION OF PLATE III

Fig. 10. Piston.

(1) Bolt for air vent, 1/4" - 20 UNC-2A - 3/4" long.

(2) Flat head screw, 1/4" - 20 UNC-2A - 1-1/4" long.

Piston surface: 10 RMS - cylindrical only.

Fig. 11. Enlarged view of O-ring groove on piston.

Groove surface: 40 RMS.

Fig. 12. O-ring.

(3) Two leather back-up rings for reducing extrusion, ID = $5\frac{1}{2}$", OD = 6".
(4) O-ring, 1820, Dash No. 60, Linear, Incorporated, ID = $5\frac{1}{2}$", OD = 6".
(5) Two leather back-up rings for reducing extrusion, ID = 3-5/8", OD = 4".
(6) O-ring, 1820, Dash No. 45, Linear, Incorporated, ID = 3-5/8", OD = 4".

Scale: 1/2" = 1".
Material: C-4340 wrought steel.

Fig. 13. Spacers.

Table of length of spacers

Inside diameter of specimen	Length of specimen	Length of spacer L
1/8 = 0.125"	0.375"	0.375 + 0.002
3/16 = 0.1875"	0.5625"	0.5625 + 0.002
1/4 = 0.25"	0.75"	0.75 + 0.002
3/8 = 0.375"	1.125"	1.125 + 0.002
1/2 = 0.5"	1.5"	1.5 + 0.002

PLATE III

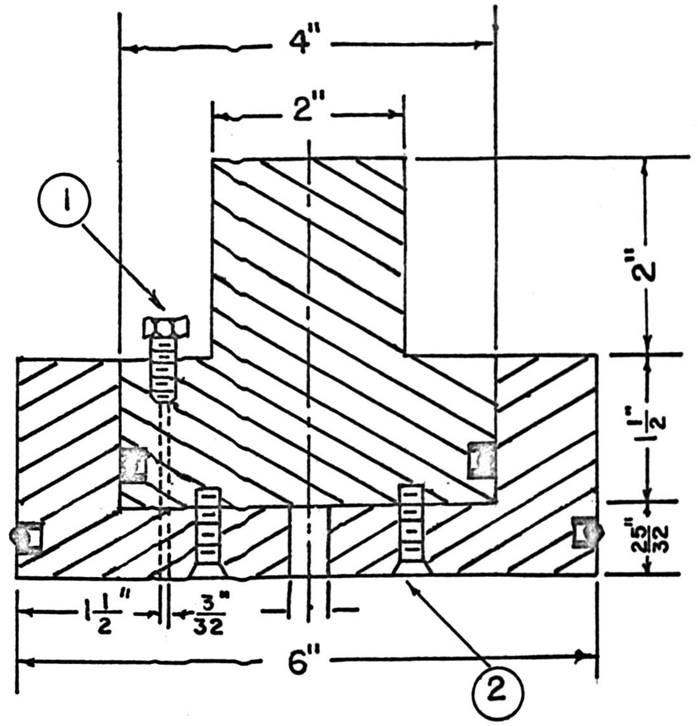
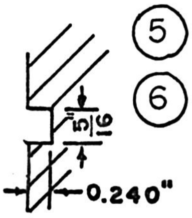


Fig. 10.



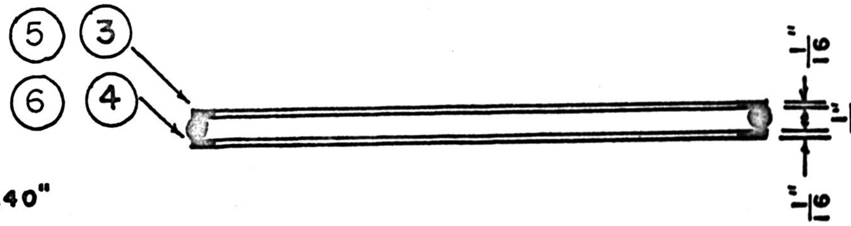


Fig. 11.

Fig. 12.

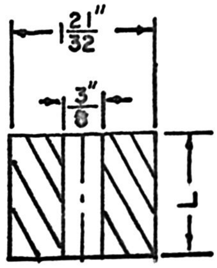


Fig. 13.

APPENDIX IV

Safety Device and Linkage Mechanism Used to Measure Diametrical Deformation of the Specimen

EXPLANATION OF PLATE IV

Fig. 14. Arrangement of linkage mechanism and safety device.

(1) Cylinder block.

(2) Base.

(3) Shield.

(4) Specimen.

(5) Stand.

(6) Slider.

(7) Linkage mechanism.

(8) Steel trace plate.

PLATE IV

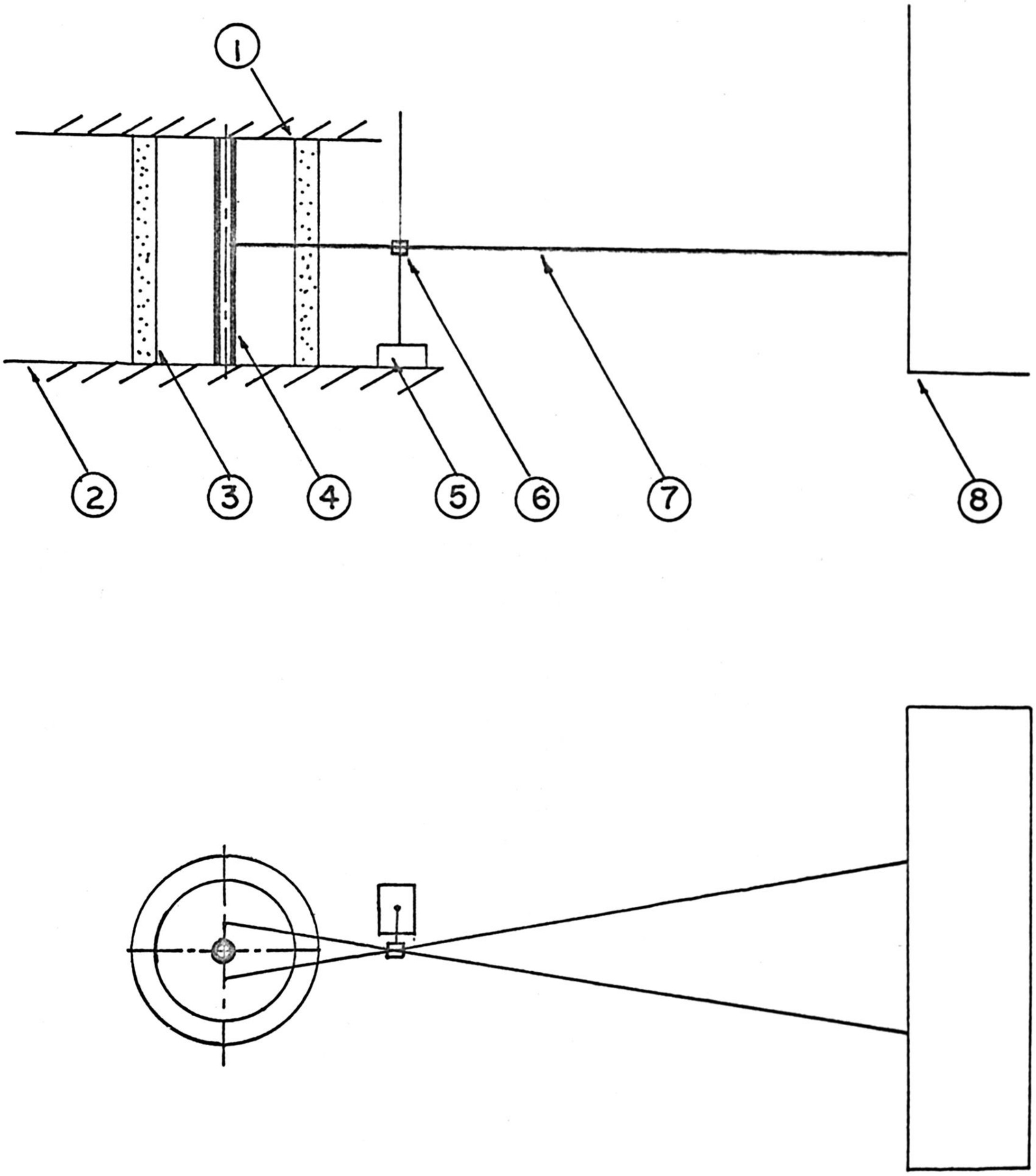


Fig. 14. Arrangement of linkage mechanism and safety device.

EXPLANATION OF PLATE V

Fig. 15. Trace plate.

Fig. 16. Safety device.

Table of length of safety device

Inside diameter of specimen	Length of specimen	Length of safety device L
0.125	0.375	0.375 - 0.002
0.1875	0.5625	0.5625 - 0.002
0.25	0.75	0.75 - 0.002
0.375	1.125	1.125 - 0.002
0.5	1.15	1.5 - 0.002

PLATE V

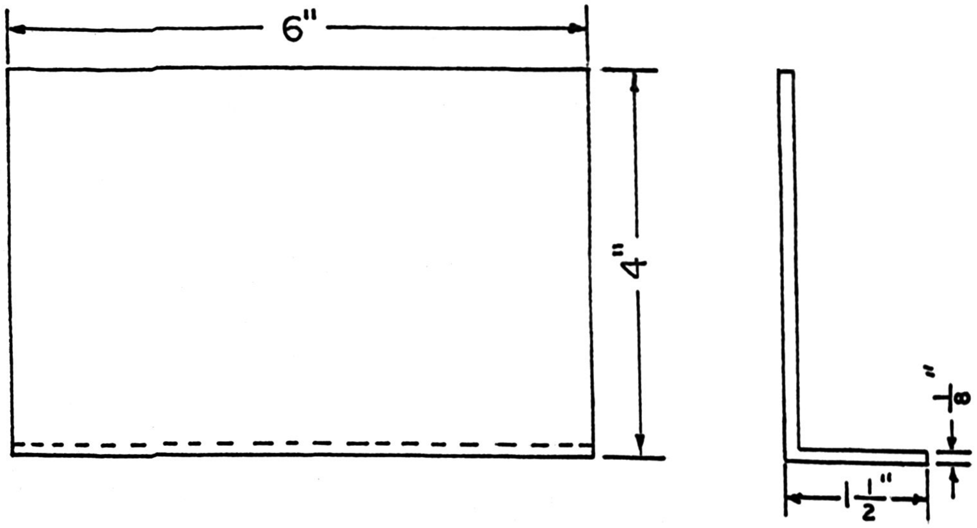


Fig. 15. Trace plate.

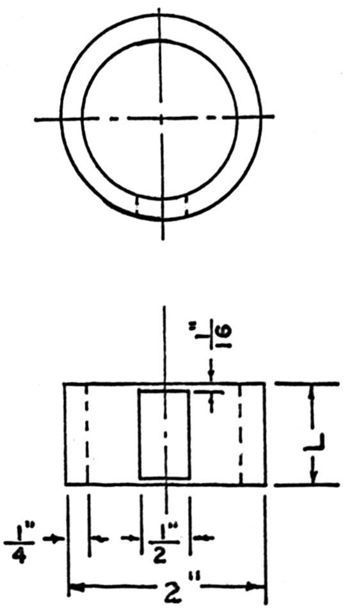


Fig. 16. Safety device.

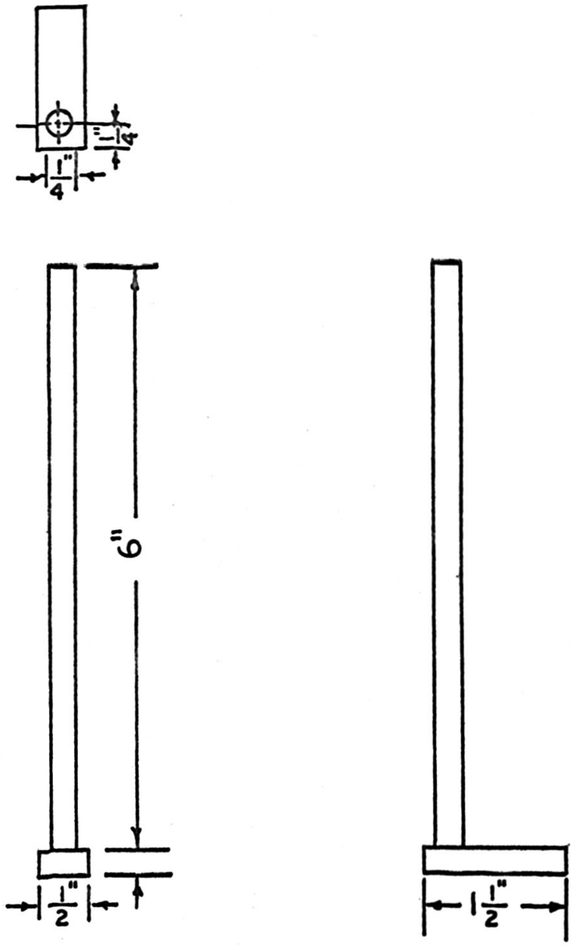


Fig. 17. Stand.

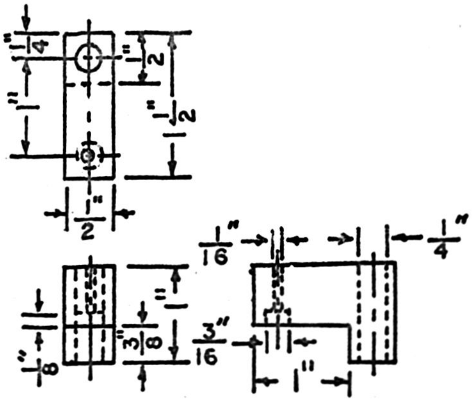


Fig. 18. Slider.

EXPLANATION OF PLATE VI

Fig. 19. Linkage mechanism.

(1) Arm - steel.

(2) Arm - steel.

(3) Closed chuck pencil leg, No. R11,on p. 20, Ref. (19).

(4) T-bolt, large, 2, No. B13, on p. 19, Ref. (19).

(5) Bolt and nut, No. EE, on p. 19, Ref. (19).

(6) Eye bolts and screw, 2, No. B5, on p. 19, Ref. (19), needle point, 2, No. A, on p. 19, Ref. (19).

Fig. 20. Arm (1).

Fig. 21. Arm (2).

PLATE VI

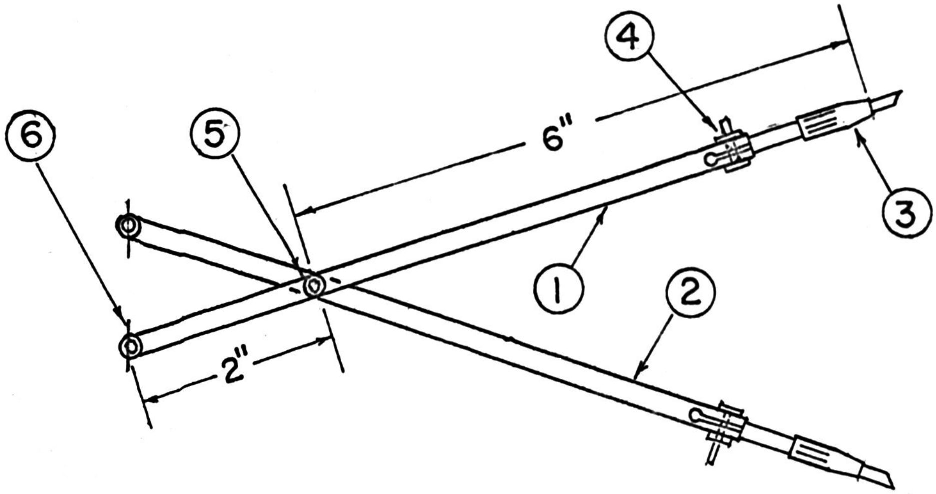


Fig. 19.

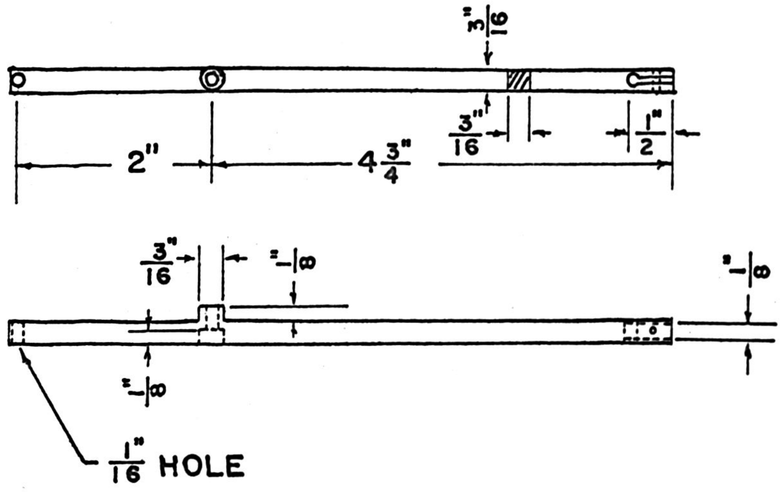


Fig. 20.

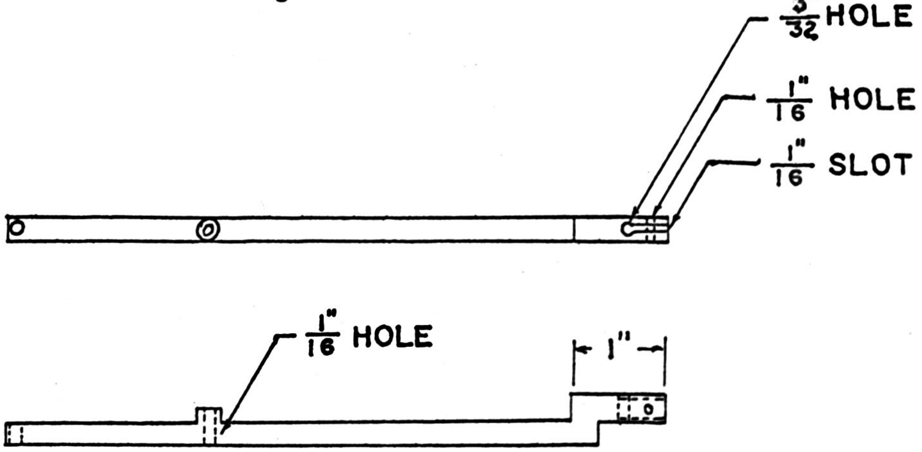


Fig. 21.

APPENDIX V

Data Sheet

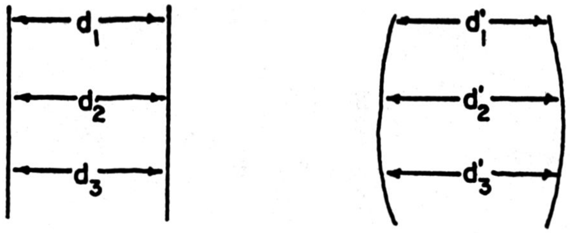
Time: Hour	Time: Min-utes	Time: Sec-onds	Load on dial	(A) Distance between traces	(B) Original traces	Difference of (A) - (B)	Time interval	Strain rate[1]

[1]See Appendix VI for calculation of strain rate.

APPENDIX VI

Example of Calculation of Diametrical Deformation

Let d_1, d_2, and d_3 be the outside diameters (see figure below) of the specimen at time 10:20. After one minute, for example, d_1', d_2', and d_3' were measured from the paper traced



Traces on the paper by linkage mechanism

At time 10:20

At time 10:21

by the linkage measured from the paper traced by the linkage mechanism at the same places of the specimen. Then the strain rate would be:

$$\frac{d_m' - d_m}{C \times d_m(21 - 20) \times 60} = \text{strain rate inch per inch per second}$$

$$m = 1, 2, 3$$

where C is the proportional ratio of the linkage.

A FIXTURE FOR TESTING MATERIAL
AT MEDIUM STRAIN RATES

by

HSUEH HSIAO CHEN

B. S., Naval College of Technology, Taiwan, 1953

AN ABSTRACT OF
A MASTER'S REPORT

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Mechanical Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1963

Many designs and manufacturing processes in use today subject materials to very high impulsive type loads with accompanying high rates of straining. Explosive forming, which has been developed in recent years, and missiles, are examples where this kind of loading exists. Designing for this type of loading requires a better knowledge of material behavior in order to achieve a good design. Most of the properties of materials have been obtained for essentially static load conditions. Some work has been done in the area of impact testing. In recent years some work on material properties at high strain rates has been reported. Little data has been reported for intermediate strain rates.

This report consists of two parts: (1) A review of previous investigations of material properties, and (2) a proposed test device for obtaining properties for intermediate rates of strain.

Two general types of equipments used in previous investigations, explosive loading type test and impact loading type test, are discussed in this report.

For materials tested the strength usually increased with strain rates. However, the results of the various investigations are not in very good agreement as to the magnitude of the effect of strain rate on the strength of the materials.

The new design is proposed to be used with the Universal Testing Machine. Strain rate up to 25.6 inches per inch per second can be obtained in this tester. The test specimen is a cylindrical section and loaded by internal pressure. The pressure is obtained by using a fluid in the piston and cylinder arrangement of the fixture.

Different strain rates are obtained by (1) controlling the speed of the testing machine, (2) changing the size of specimens, and (3) changing the size of piston and cylinder combination.