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DESIGN AND OPERATING CHARACTERISTICS OF A SPLIT HOPKINSON PRESSURE BAR APPARATUS

KENNETH D. ROBERTSON, SHUN-CHIN CHOU, and JAMES H. RAINEY
MECHANICS OF MATERIALS DIVISION

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Technical Report by

KENNETH D. ROBERTSON, SHUN-CHIN CHOU, and JAMES H. RAINEY

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A split Hopkinson bar apparatus capable of conducting compressive strain rate tests at rates ranging from 50 to 10^4 in./in./sec has been designed and assembled. In principle, the apparatus is similar to that first used by Kolsky in 1949. The design of the apparatus is presented in two parts: the stress-generating system, and the stress-determination system. Detailed drawings of major components of the stress-generating system are included. The technique used to analyze results is presented. A listing of a computer code which incororates this technique is also included. The code provides a rapid method for computing the one-dimensional response of the sample of interest. Results for 6061-T6 and 1100-C aluminum, which are in good agreement with those obtained by other investigators, are given as a check case for the system designed.

CONTENTS

I. INTRODUCTION

This report presents design details and operational procedure of a split Hopkinson bar apparatus and the technique to analyze data in the determination of dynamic stress-strain relationships of both metallic and nonmetallic materials. In principle the apparatus is similar to that used by Kolsky;[1] Campbell and Duby;[2] Krafft, Sullivan, and Tipper;[3] Maiden and Campbell;[4] Hauser, Simmons, and Dorn;[5] Davies and Hunter;[6] Chiddister and Malvern;[7] and Maiden and Green.[8] In this technique, stress-strain relationships at rates ranging from 50 in./in./sec to about 10^4 in./in./sec can be obtained by considering the transmission of a stress wave through a test specimen sandwiched between two elastic bars. The aforementioned investigators differ only in the manner in which they generate and record the stress wave. Since its first usage by Kolsky over 20 years ago to determine dynamic stress-strain curves using the split Hopkinson bar apparatus, the assumption of stress uniformity in the specimen and effect of friction at the specimen-bar interfaces and specimen geometry have been examined by many investigators. Davies and Hunter[6] have found that in order to neglect radial friction effects at the specimen-bar interfaces, the ratio of specimen length to radius should be at least unity. Effects of axial inertia and radial inertia were also investigated by Davies and Hunter; they point out that the radial and axial effects are compensating and will compensate exactly if specimens of length $l = \sqrt{3}\ \gamma_s r$ are used (where r is the specimen radius, and γ_s is an effective Poisson ratio for the specimen under the conditions of the experiment). It is also found that the axial inertia effect is a cause of the nonuniformity of conditions along the specimen and is greatest at early times when the strain acceleration is greatest. Maiden and Green[8] have found that for most of the testing time in the majority of tests, the difference between the two stress-time curves at the specimen-bar interfaces is less than 1 or 2 percent. Rajnak and Hauser[9] have also studied the variation in conditions along a specimen tested in the present manner. They concluded that although rather high stress and strain gradients exist initially in impacted thin specimens, the data obtained from such experiments do represent the average dynamic plastic behavior of materials. Most recently Jahsman[10] carried out a one-dimensional wave propagation analysis to assess the validity of the assumption of the stress uniformity along the specimen by comparing the original assumed stress-strain curve with that calculated by using the data reduction formula suggested by Kolsky. He concluded that the split Hopkinson bar apparatus when properly employed can reconstitute the stress-strain curve quite well.

II. PRINCIPLE OF TECHNIQUE

A split Hopkinson bar apparatus (shown schematically in Figure 1) has been designed and used to conduct compression tests at strain rates ranging from 50 to 10^4 in./in./sec. The actual magnitude of the strain rate is governed by the length and strength of the elastic bars and the length and strength of the test specimen.

The principle of the method is that an elastic striker is accelerated down a barrel by compressed gas to impact an elastic weigh bar. The resulting stress wave passes down the weigh bar, with part of the wave being reflected at the specimen and part being transmitted into the anvil bar. Strain gages mounted on

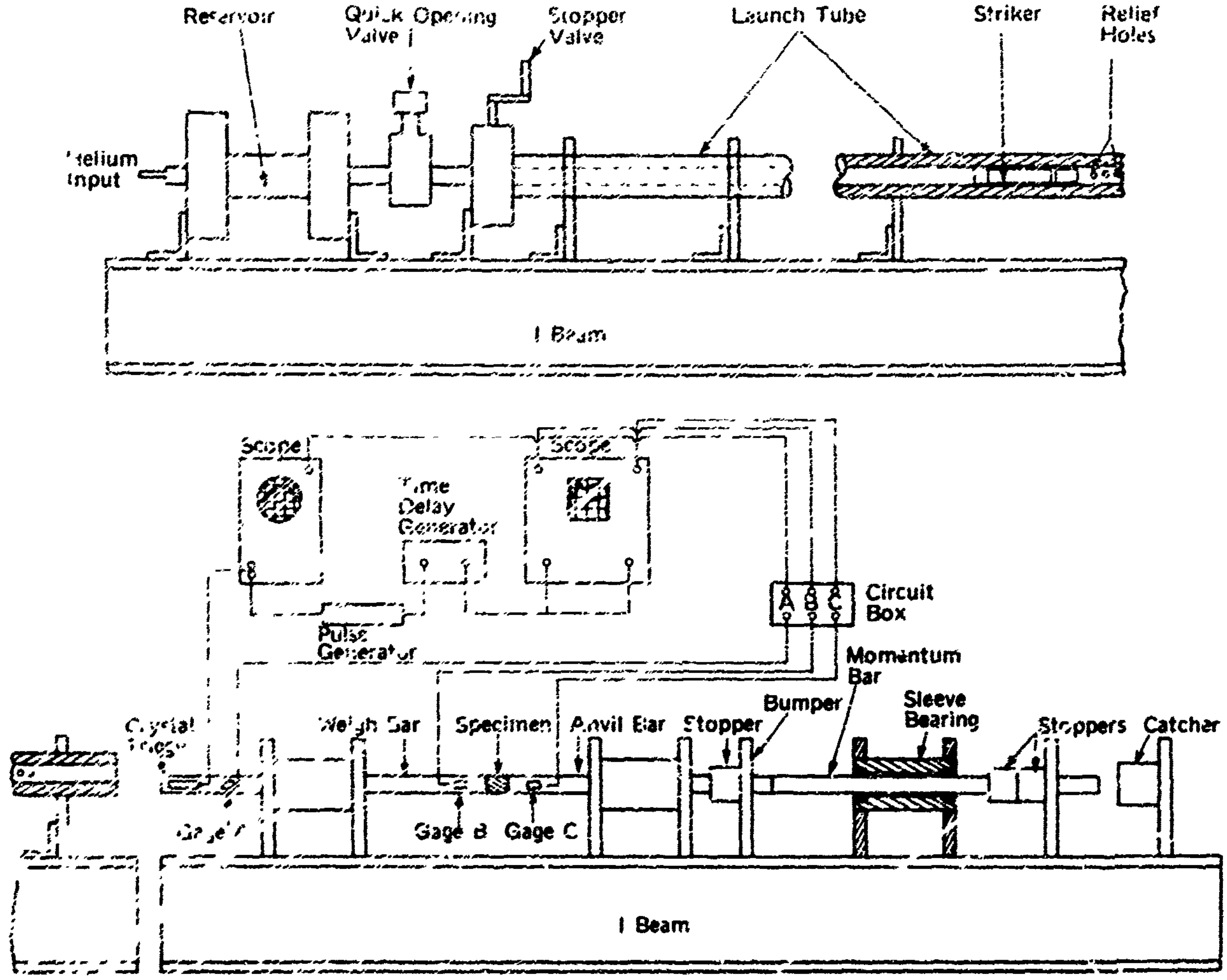


Figure 1. SCHEMATIC OF A SPLIT HOPKINSON BAR APPARATUS

the weigh bar and anvil bar record the wave shapes which are analyzed to obtain a dynamic stress-strain curve for the test material by assuming that the theory of one-dimensional wave propagation holds.

III. DESIGN DETAILS

The split Hopkinson bar apparatus primarily consist of two major sub-systems; a stress generating system and a stress determination system. Components of each of these sub-systems will be identified and discussed in detail in the following sections.

1. Stress Generating System

Figure 1 shows that the stress generating system consists of a reservoir, quick opening valve, launch tube, striker, weigh bar, anvil bar, and momentum bar, which are considered as primary equipment. In addition to the primary equipment, there is some auxiliary equipment which is also of interest. These two groups of equipment will be discussed in detail in the following two sections. Detail drawings of major components are included in Appendix A.

a. Primary Equipment

The reservoir acts as an accumulator for a measured amount of gas under high pressure. Before each testing, the reservoir is charged to the desired pressure from compressed gas cylinders; later during firing, this gas (under pressure) is suddenly released through a quick-opening valve into the launch tube and behind the striker. Expansion of this gas behind the striker accelerates it down the launch tube. The reservoir, launch tube, and striker thus constitute a unified system for converting potential gas energy into useful striker kinetic energy. It is assumed as a first approximation for design purpose that the gas obeys the perfect gas laws and that expansion occurs adiabatically. Furthermore, it is assumed that the amount of energy loss in the system is negligible. Thus a relationship among the pressure, volumes, velocity, and mass may be obtained by equating the potential energy of gas and the kinetic energy of the striker.

Potential Energy of Gas = Kinetic Energy of Striker

$$\frac{p_1V_1 - p_0V_0}{k - 1} = \frac{m_s V_s^2}{2} \tag{1}$$

where p_0 = Initial gas pressure

p_1 = Final gas pressure

V_0 = Initial gas volume

V_1 = Final volume expanded gases

m_s = Mass of striker

v_s = Final velocity of striker

k = Specific heat ratio

It should be noted here that for actual application, a calibration of gas pressure versus velocity of the striker was conducted. Using the above approximations as a starting point however, the reservoir-launch tube-striker system was designed.

The reservoir was designed with sufficient capacity (volume and pressure) to accelerate the striker to a maximum velocity of 115 fps. This reservoir was made of double extra strong (XX strong) steel pipe rated at 3,000 psi (static, nonshock), 4-inch nominal pipe size, 3.15 inch ID by 14 inches long and threaded at both ends. Threaded 900-lb flanges were fitted on each end of the pipe and the chamber was closed with 900-lb reducing flanges which reduced the inlet and outlet connections to 1-inch diameter. The reservoir volume, including the end flanges was approximately 145 cu in. The maximum anticipated operating pressure was 200 psi. This would theoretically produce a striker velocity of 115 fps. A safety pressure-control valve in the supply line was set to actuate at 205 psi.

The reservoir is connected to the launch tube through a short length of 1-inch pipe and a quick-opening valve. This valve, also 1-inch ID, is a two-way (one inlet and one outlet) through-flow solenoid activated valve. It is designed to operate between 0 and 300 psi and is normally in the closed position. When activated, it opens fully in 32 msec to allow full and unrestricted flow from reservoir to launch tube.

The launch tube is used during the firing cycle to produce controlled expansion - one-dimensional expansion - of the propellant gas accompanied by acceleration and displacement of the striker. The striker and the tube form a close fit with a 0.001-inch clearance on the diameter, minimizing propellant leakage and providing guidance for the striker. In the tube, the striker is accelerated to its final velocity (depending on the gas pressure) in the first 65.5 inches of travel. At a point 65.5 inches from the rear "breech" end, the launch tube is vented to atmosphere. Ten diametrically opposed relief holes, five on a side, 0.25 inch in diameter and 2 inches on centers, are used to relieve the propellant pressure. This allows the striker to travel the remaining distance at an essentially constant velocity before it impacts on the weigh bar.

Impact between striker and weigh bar should occur on a plane normal to the desired direction of stress propagation. To accomplish this purpose, the striker, near the end of its travel must be properly aligned with the weigh bar. The launch tube with its rugged walls and close fit on the striker provides the necessary alignment and assures proper impact conditions. It has been calculated that impact occurs with a maximum angular error of 0.04 degree.

The launch tube was made of annealed 4340 steel of 3 inches OD and 1 inch ID. This 1-inch wall thickness was prescribed more from straightness requirements than from strength requirements - a thick-walled tube is mechanically more stable than a thin-walled tube. The ID was honed to a surface finish of 16 microinches to reduce friction and wear. The tube and striker were initially coated with liberal amounts of oil to further reduce friction. It was subsequently found (in calibration tests) that too much oil caused excessive variations in striker velocities. Consequently, only a slight amount of oil is now applied to the striker and none to the tube.

The striker is the device used to convert the potential energy of the gases into useful kinetic energy (striker velocity) and subsequently, via impact, converted into strain energy in the weigh bar. The expansion of gases in the launch tube behind the striker accelerates it to a high velocity. During this period of acceleration, the bearings of the striker act as obturators to seal off the tube and retain the gases. The acceleration period ends when the striker passes the tube vents. Thereafter, the striker travels at essentially constant velocity. It is during this period of constant velocity and before impact that subsequent velocity measurements are made.

At the end of its travel, the striker impacts the weigh bar. This impact produces a stress wave, originating at the striker-weigh bar interface and propagating into the bars in opposite directions with a speed c, a material constant.

By assuming that one-dimensional wave theory holds, the position of the wave front at anytime is expressed by the following equation:

$$x = ct \qquad (2)$$

where x = distance, measured from interface

c = wave speed

t = time.

The stress wave which originated at the interface was compressional: this wave travels down the striker, reflects off the rear surface as a tension wave and returns to the interface. Since tension cannot be transmitted across the interface, impact ceases. The period of the stress wave generated is given by:

$$\tau = \frac{2l}{c} \qquad (3)$$

where τ = period of pulse

L = length of striker.

The stress produced in the weigh bar after impact by the striker is related to the striker velocity and the areas of both striker and weigh bar. These relations, although admittedly inexact,[1] give a reasonable approximation to the actual stress.

$$\sigma_{wb} = \frac{2A_s}{A_s+A_{wb}} \times \sigma_s \qquad (4)$$

$$\sigma_s = \frac{\rho c V}{2g} \qquad (5)$$

where σ_{wb} = stress in weigh bar

σ_s = stress in striker.

The striker is essentially a cylindrical rod, approximately 1 inch in diameter and 15 inches long fitted with bearings fore and aft. The forward bearing of the striker is recessed approximately 2 inches from the striking surface to allow the striker to protrude beyond the tube at impact.

A striker, together with a weigh bar, anvil bar, and momentum trap, to be described later, constitute a set. These sets are made of the same material and are used to test materials of lower yield strength. The present set was made of 4340 steel, heat-treated to a hardness of Rc 41. At this hardness, it has a yield strength of 175,000 psi. A striker with velocity of 100 fps will produce a pulse with maximum stress (in the weigh bar) of 155,000 psi for a duration of 150 microsecond.

The specimen is located between the weigh bar and anvil bar. The weigh bar together with the anvil bar constitute a link between the stress producing system and the stress determination system. Both bars are instrumented with strain gages, to measure strain and both bars are subjected sequentially to the stresses produced at impact. The momentum trap on the other hand is not instrumented. It is used to eliminate stress reflections and stress build-ups via reflections. It is also used to conduct energy out of the system.

The layout of the striker, weigh bar, specimen, anvil bar, and momentum trap is shown in Figure 1. These bars must be in correct alignment for proper operations. Consequently, these three bars: weigh, anvil, and momentum trap, ride in close fitting sleeve bearings supported by adjustible ring clamps. The complete assembly, launch tube, weigh bar, anvil bar, and momentum trap are accurately aligned at installation and periodically checked thereafter to assure alignment.

All bars are 20 inches long and have the same diameters, between 0.3750 inch and 0.3745 inch and all are straight within 0.0005 inch/ft. This straightness requirement is associated with the alignment problem and helps to eliminate bending stresses in the rods and specimen. The ends of all rods (except the impact end of the weigh bar) are machined normal to the rod axis. One end, the impact end, of the weigh bar is rounded with a spherical radius of 10 inches to accommodate any misalignment between strider and weigh bar. The planarity caused by this rounded end is less than 5 nanosecond.

b. Auxiliary Equipment

Certain parts of the Hopkinson bar apparatus serve subordinate roles, i.e., roles which do not affect the primary operating characteristics of the device. These parts include stoppers, bumpers, vacuum pumps, catchers, etc., and are considered auxiliary equipment which will be grouped together and described in this section.

The stoppers are rubber cylinders used to decelerate the rods when the test is finished. After a limited amount of travel, approximately 1/4-inch, these stoppers, which are attached to the rods, engage bumpers which prevent their further travel. At this time, the primary stress wave has already passed the stoppers. Subsequent operation of the stoppers depends on the development of sufficiently large frictional forces between stoppers and rods to decelerate the rods. (Since the frictional process is dissipative, this method also absorbs energy and reduces rebound of the rods.) The frictional forces previously mentioned are derived from the large radial forces existing between the rods and stoppers produced by clamps on the stoppers. (It should be noted here that the stoppers are located beyond the specimen and gages so that even if the wave form is affected by the clamping action it does not affect the test results.) With the constraints mentioned above, the rods move approximately 1 inch through the stoppers at the maximum allowable stress of 150,000 psi, before finally coming to a stop. The stoppers are slit rubber cylinders, 1-1/2-inch OD × 3/8-inch ID, and approximately 2 inches long with a 1/16-inch longitudinal slit on the side to allow for clamping compression. These stoppers are secured to the rods with adjustable clamps which can be tightened to compress the stopper on the rod. The bumpers are flat rectangular plates which are held in the vertical positions by heavy angle clamps attached to the foundation. A 3/4-inch-diameter hole near the top center of the bumpers allows the rods to protrude through, yet restricts the stoppers to limited travel.

An additional safety feature, a catcher, is located at the extreme limit of travel of the momentum trap. This catcher is used to decelerate the moving systems: striker, weigh bar, anvil bar, and momentum trap, in the event of stopper failure. It consists of a hollowed out steel cylinder, open at one end and partially closed at the opposite end. The catcher is filled with lead sheet which compacts when struck by the momentum trap. The catcher is threaded at one end and supported in a plate similar to the bumpers.

At the end of each test, the striker remains at the muzzle end of the tube. Before each test, it must be returned to the breech end of the tube. To accomplish this retrieval, a vacuum pump is attached to the breech end to evacuate the tube. To maintain the vacuum, a sleeve is moved over the vent holes and the striker is returned to its starting position by the pressure differential - atmospheric versus vacuum.

A stopper valve, located at the breech end of the tube is used to limit the return travel of the striker. This valve is always open during firing and *closed* during striker recovery. (The valve is so designed that it never closes completely, a small vent always remains open.)

Ring clamps are used to support and align the tube and bearings. These clamps allow up to 1-1/2 inches of adjustment in the horizontal or vertical direction. After alignment, the screws of the ring clamps are locked in place by double nuts.

2. Stress Determination System

The main component of the stress determination system is the strain gage. Semiconductor strain gages (BLH-SNB3-06-12S6) are chosen to eliminate the magnetostrictive effect which is often observed in tests when foil or wire gages are used. The gage has a length of 0.06 inch. The symbol "N" in the catalog number stands for negative strain sensitivity. Gages with this property are more sensitive than those with positive strain sensitivity when the strain exceeds 4,000 microinch/in.

Strain gages are cemented with Eastman 910 cement on both weigh bar and anvil bar. Since gages are repeatedly subjected to impact, certain precautions must be taken to prevent gage failure. The gage output wire is a three conductor STC-30V-3RWB wire with a resistance of 0.04 ohm/ft. Leads of the gages are looped and wrapped lightly with two layers of wax-coated harness lacing. The output wires are wrapped tightly with six layers of lacing. All the lacing is covered with a l[illegible]al coating of Duco cement.

Three sets of strain gages are used in the set up; two of them are placed at 1/2 inch from the specimen faces, and the other one is 1-3/4 inch from the impact end of the weigh bar. Each gage set consists of two gages mounted on opposite sides of the bar so resistance change due to bending will be cancelled.

A potentiometer circuit (Figure 2) which gives an essentially constant current of 0.01 ampere is used in this measuring system. The circuit consists of a power supply and a noninductive ballast resistor of 20,000 ohms. A set of gages is connected to the resistor in series. When the gages are under strain, the change of resistance (in the gages) will affect the voltage across the gages. The change of the voltage is then recorded on the oscilloscopes. The voltage output versus time may be converted to stress versus time by using the following calibrations:

a. Stress Bar (Gage) Calibration

Each set of gages on either weigh bar or anvil bar is calibrated statically on a Tinius-Olsen Machine to obtain load versus the change in resistance of gages by using a General Radio impedance bridge. The stress (load/area of bars) versus resistance is fitted with a third-degree polynomial. Since the weigh bar and anvil bar always remain in the elastic region, the static calibration is applicable in the dynamic condition.

b. Oscilloscope Gain

A decade resistance box is placed in series with the strain gages. When the decade box is set at different resistance levels, the oscilloscope beam is deflected accordingly and recorded on Polaroid film. Thus, a calibration curve of centimeters deflection against change in strain-gage resistance is obtained for each gage-oscilloscope system.

The oscilloscopes are triggered by a trigger and delay system (Figure 1). The system consists of a crystal pinducer (VP-1093-3/4), a Monsanto model 300 A Pulse Generator and a time delay generator. As the striker impacts the weigh bar, a stress wave is generated and travels through the weigh bar. When the crystal, which is cemented near the impact end of the weigh bar, is pressurized, a voltage is produced. This voltage triggers the first scope and sends a triggering output to the pulse generator, which in turn sends a triggering pulse of -2v to the time delay generator. The time delay generator has three power inputs and three output channels. The outputs are pulses from capacitor discharges. Rise time of the pulse is about 500 nanoseconds and the peak amplitude is greater than 50 volts. Each channel has a separate, adjustable delay ranging from 3 microseconds to 2 milliseconds to trigger a scope trace at a specific time during a test.

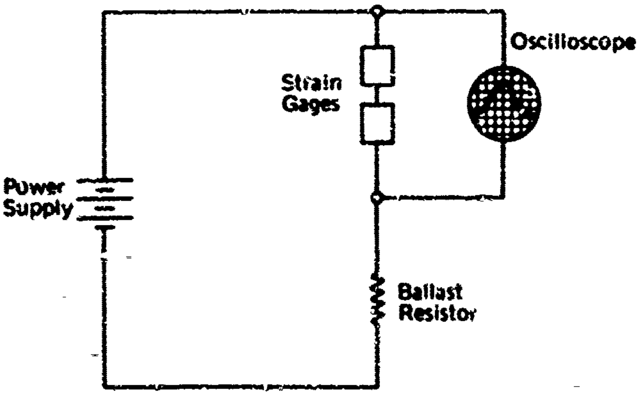


Figure 2. POTENTIOMETER CIRCUIT

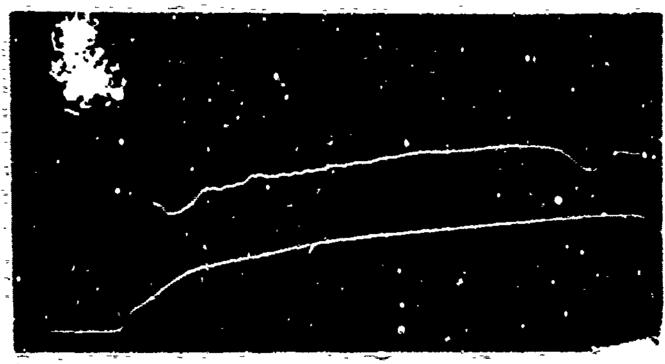
IV. ANALYSIS OF TEST RESULTS

For every test conducted, three wave forms are measured, namely: incident wave, resultant of incident and reflected waves, and transmitted wave. Figure 3 shows a set of typical Polaroid pictures obtained from a test. The top picture is the incident wave recorded from the set of strain gages near the impact end of the weigh bar. The top trace of the bottom picture is the resultant of incident and reflected waves from the weigh bar strain gages near the specimen, and the bottom trace is the transmitted wave from the anvil bar gages. Such Polaroid records are converted to digital representation using a Telereader coupled with an IBM key punch. This digital representation is then changed to stress versus time by using the proper scale factors, which consist of the measured oscilloscope gain and a curve of stress versus change in gage resistance, obtained by statically loading each bar on a Tinius-Olsen testing machine. Once these stress-time curves are obtained, the analysis to determine the dynamic stress-strain relation of a sample will proceed on the assumption that the strain in both weigh bar and anvil bar always remains elastic and that the theory of one-dimensional propagation holds.

1. Determination of Conditions on Both Specimen Faces

Based on the condition of continuity, the stress and particle velocity in the elastic bars (weigh bar and anvil bar) at the interfaces should be the same as those in the specimen. Thus, if the stress-time histories in the elastic bars at the interfaces are obtained, the dynamic stress-strain relation of a specimen is automatically determined.

Elastic, Incident Wave
20 μsec/cm, 100 millivolts/cm (~ 10,000 psi/cm)



1100-0 Aluminum
0.375-In.-Diameter X 0.500-In.-Long Specimen
20 μsec/cm, 100 millivolts/cm (~ 10,000 psi)

Figure 3. SPLIT HOPKINSON BAR COMPRESSION TEST (0.375-INCH DIAMETER X 18-INCH LONG WEIGH BAR AND ANVIL BAR)

The elastic wave motion in a long rod may be shown on a Lagrange or x,t-diagram, (Figure 4) where x gives the position on the rod and t the time. By using the method of characteristics, it can be shown that the characteristic lines in x,t space, along which the stresses and particle velocities are related by total derivatives, are $dx/dt = \pm c$, where c is the bar speed of sound. The corresponding characteristic relations along these lines are $d\sigma = \pm \rho c dv$ respectively, where ρ is density, v is particle velocity and σ is stress at point. After integration, the relations may be shown as follows:

$$dx/dt = c \quad : \quad \sigma + \rho c v = 2\alpha \tag{6}$$

$$dx/dt = -c : \quad -\sigma + \rho c v = 2\beta \tag{7}$$

where α and β are constants. Hence, at a point where two such lines intersect

$$\sigma = \alpha - \beta \tag{8}$$

and

$$\rho c v = \alpha + \beta. \tag{9}$$

Now consider the Lagrangian diagram (Figure 4) relevant to the present experimental arrangement. The incident wave produced by the impact is measured by gage set A. Before the reflected wave travels back from the interface 1, the test is considered complete. In this situation, $\beta = 0$. Equations 6 and 7 show that

$$\sigma_A(t) = \rho c \; v_A(t) = \alpha \; (t) \tag{10}$$

where $\sigma_A(t)$ and $v_A(t)$ are the measured stress and particle velocity at time t. Since this is an elastic wave and it is assumed that the theory of one-dimensional

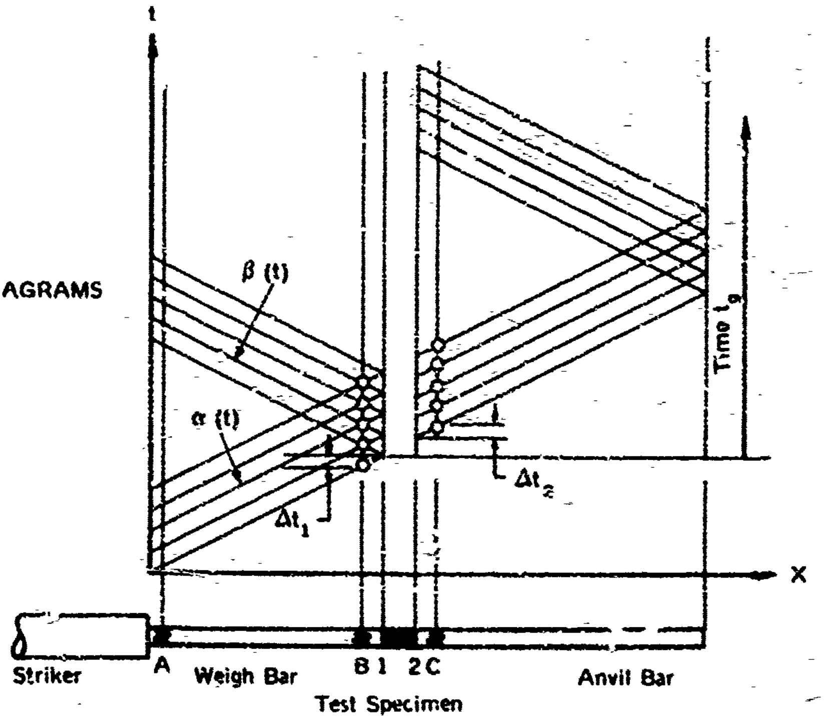


Figure 4. LAGRANGIAN DIAGRAMS

wave propagation holds, the incident wave is expected to travel from section A to section B without changing its shape. As the incident wave reaches the interface 1, part of the wave is reflected. In this case $\beta \neq 0$ and, at any time t, the value of β at section B is given by Equation 8 as

$$\beta(t) = \alpha(t) - \sigma_B(t) = \sigma_A(t) - \sigma_B(t) \tag{11}$$

where $\sigma_B(t)$ is the stress measured by the weigh bar gage set B at time t. Thus the history of stress σ and particle velocity v at the interface 1 can be determined easily since, for any point on section 1

$$\sigma_1(t_g) = \alpha_1(t_g)-\beta_1(t_g+2\Delta t_1) = \sigma_A(t_g)-\sigma_A(t_g+2\Delta t_1)+\sigma_B(t_g+2\Delta t_1) \tag{12}$$

and $$\rho c v_1(t_g) = \alpha_1(t_g)+\beta_1(t_g+2\Delta t_1) = \sigma_A(t_g)+\sigma_A(t_g+2\Delta t_1)-\sigma_B(t_g+2\Delta t_1) \tag{13}$$

where Δt_1 is the time for wave traveling from section B to section 1, and t_g is the time scale with origin at the time when the wave front just reaches gage set B.

Figure 4 also shows that, until the arrival of the reflected unloading wave from the end of the anvil bar at section C, the gage set C in the anvil bar records, with a small time delay, the stress and particle velocity on the interface 2.

$$\sigma_2(t_g) = \sigma_C(t_g+\Delta t_2) \tag{14}$$

where Δt_2 is the time for wave traveling from section 2 to section C.

2. Dynamic Stress-Strain Relation

To obtain a dynamic stress-strain curve, a mean stress-time curve is obtained by averaging the stress-time curves for the two specimen faces, i.e.,

$$\sigma(t_g) = \frac{\sigma_1(t_g)+\sigma_2(t_g)}{2} . \tag{15}$$

Also, the average strain rate in the specimen at any time is given by

$$\frac{d\epsilon(t_g)}{dt_g} = \frac{v_1(t_g) - v_2(t_g)}{\ell} \tag{16}$$

where ℓ is the specimen length, and $v_1(t_g)$ and $v_2(t_g)$ are the particle velocities on the specimen upper and lower faces. The average specimen strain history is then obtained by integration of Equation 16

$$\epsilon(t_g) = \int_0^{t_g} \frac{v_1(\tau) - v_2(\tau)}{\ell} d\tau \tag{17}$$

From the histories of mean stress, Equation 15 and mean strain, Equation 17, the dynamic stress-strain relation is found by plotting stress against strain at corresponding times. A computer program has been written to provide a rapid method for computing the average stress-, strain-time history in the specimen of interest. A listing of the code is given in Appendix B.

V. TEST RESULTS AND CONCLUSIONS

In order to verify the entire apparatus, two well characterized aluminum alloys were tested. One of them was 6061-T6 aluminum which has been determined to be strain-rate insensitive at rates up to 10^3 in./in./sec. The other material was 1100-0 aluminum which was chosen because of its widespread use in strain-rate sensitivity testing. Results of these two materials were in good agreement with those obtained by other investigators.

Figure 5 shows the results for 6061-T6 aluminum which is an intermediate strength wrought aluminum alloy. The results at each strain rate (average rates) are plotted as a succession of points, rather than lines, in order to discriminate between the various strain rates. It is noticed that results in Figure 5 show clearly that 6061-T6 aluminum is strain-rate insensitive up to strain rate of 10^3 in./in./sec. It is also shown that the yield stress in compression is about 42,000 psi.

The stress-strain strain-rate curves for 1100-0 aluminum are presented in Figure 6. The results indicate that 1100-0 aluminum is rate sensitive. The yield stress is about 4,000 psi. Many investigators have obtained dynamic stress-strain curves for 1100-0 aluminum alloy; some of the results are obtained in compression (or tension) and others are in torsion. Results obtained under these two stress states are not directly comparable, however, if the Mises criterion is applicable and the material is assumed to be incompressible, results from compression tests and torsion tests can be plotted on the same graph by multiplying the shear stress in torsion tests by $\sqrt{3}$ and dividing the shear strain by the same amount. Figure 6 shows the comparison of the present results of 1100-0 aluminum at rates of 700∿900/sec with two typical dynamic stress-strain curves obtained by Green et al.* in compression and Duff et al.[12] in torsion. It is noticed that results are in good agreement.

Agreement in the results of 1100-0 and 6061-T6 aluminum alloys with those obtained by other investigators has concluded the verification of the design of the split Hopkinson bar apparatus in compression and the computer program which is used to analyze the data. The tension and shear test modes of the split Hopkinson bar apparatus are in the process of design. They will also be verified and employed in characterization of materials in the future.

---

*Green, S. J., Schierloh, F. L., and Babcock, S. G. Unpublished results. General Motors Corporation, 1969.

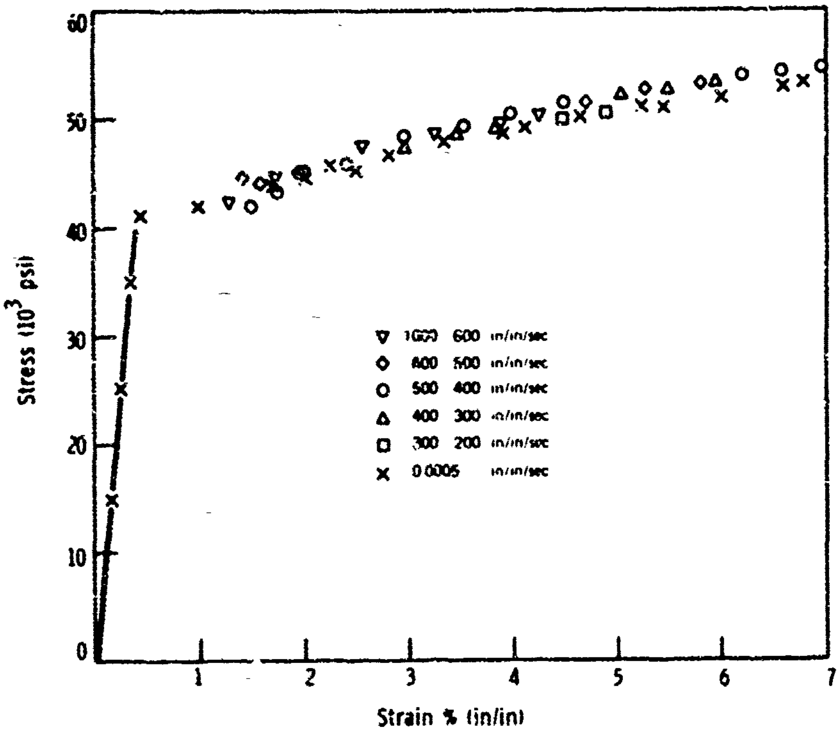


Figure 5. COMPRESSIVE STRAIN RATE TESTS ON ALUMINUM 6061 - T6

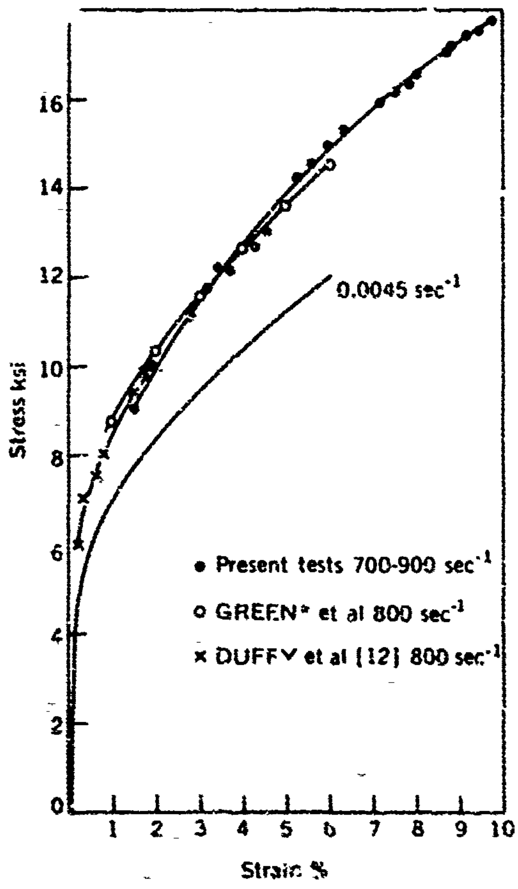


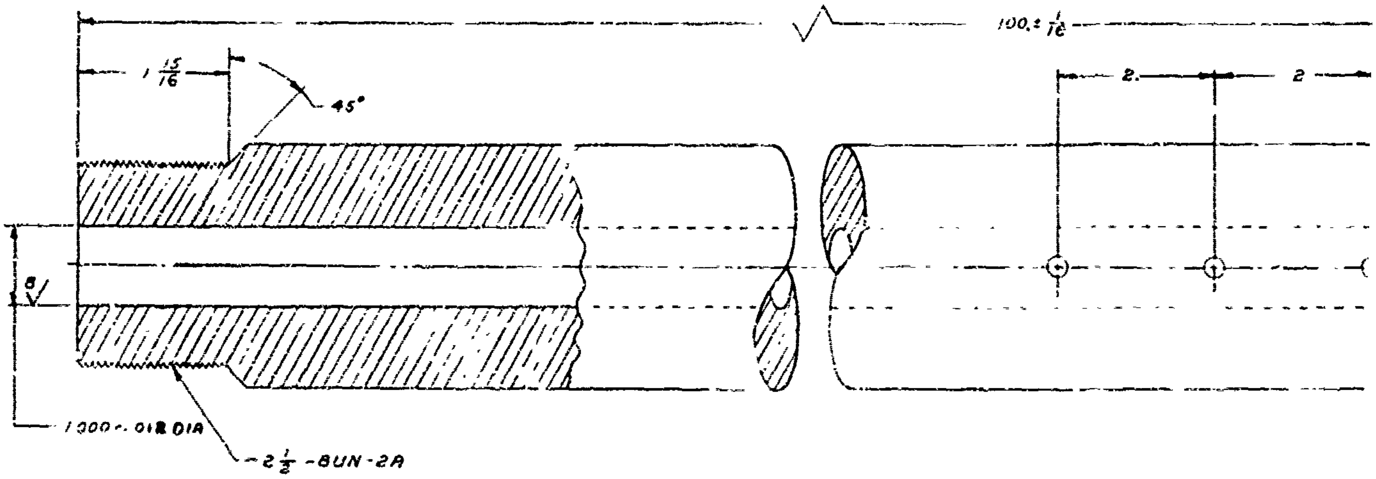
Figure 6. COMPARISON WITH RESULTS OBTAINED BY OTHER INVESTIGATORS IN COMPRESSION TESTS ON 1100-D ALUMINUM ALLOYS

*See footnote on page 12.

APPENDIX A. DETAIL DRAWINGS

1178-3

[illegible]



NOTES:

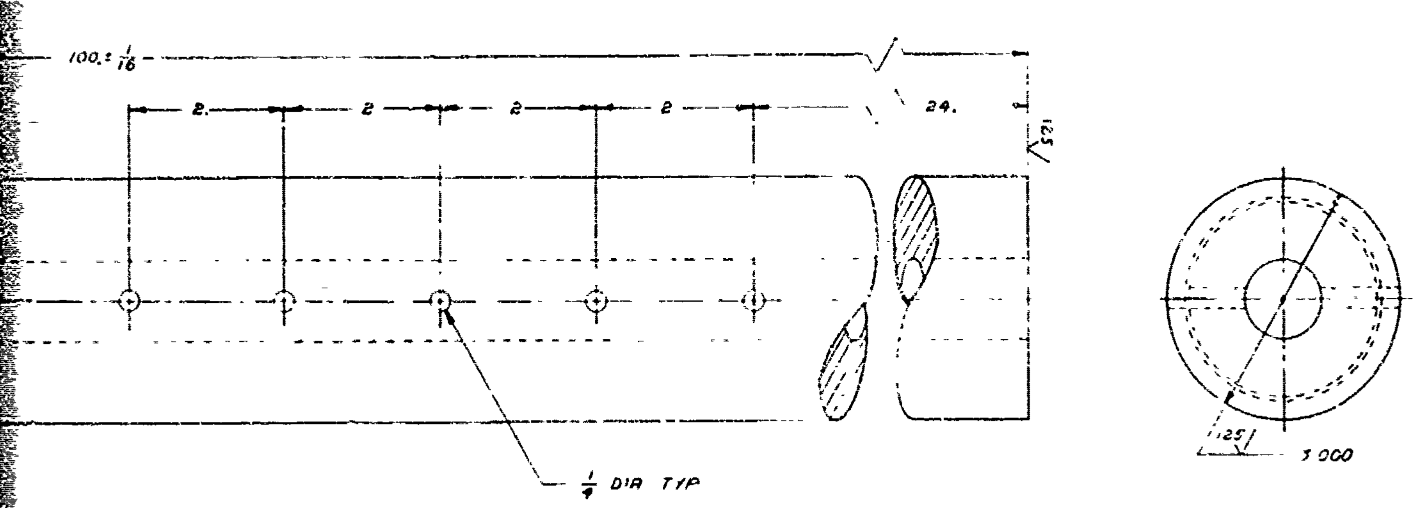
1. MATERIAL: E4140 NORMALIZED AND STRESS RELIEVED.
2. FINAL BORE DIAMETER SHALL NOT VARY MORE THAN .0005 OVER ENTIRE LENGTH.
3. BORE TO BE STRAIGHT WITHIN .001 IN./FT..
4. ENDS TO BE PERPENDICULAR TO BORE WITHIN .002 T.I.R.
5. ⊄ L. TO BE CONCENTRIC WITH BORE WITHIN .010 T.I.R..

PHYSICAL PROPERTIES

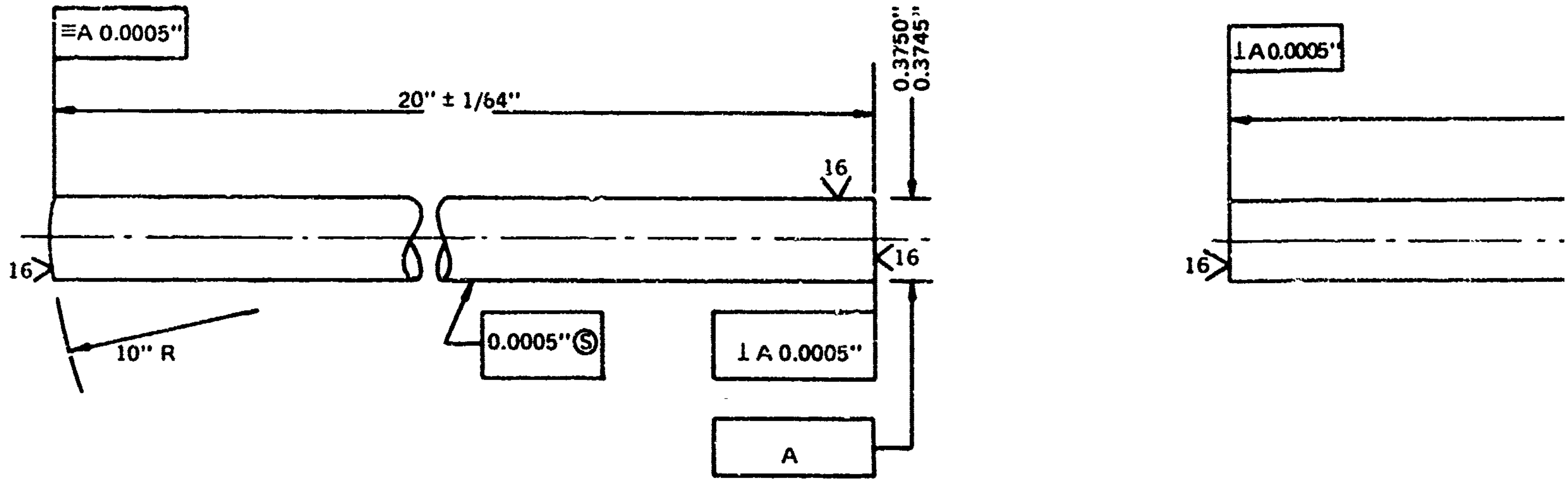
B

D

REVISIONS			
SYM	DESCRIPTION	DATE	APPROVAL

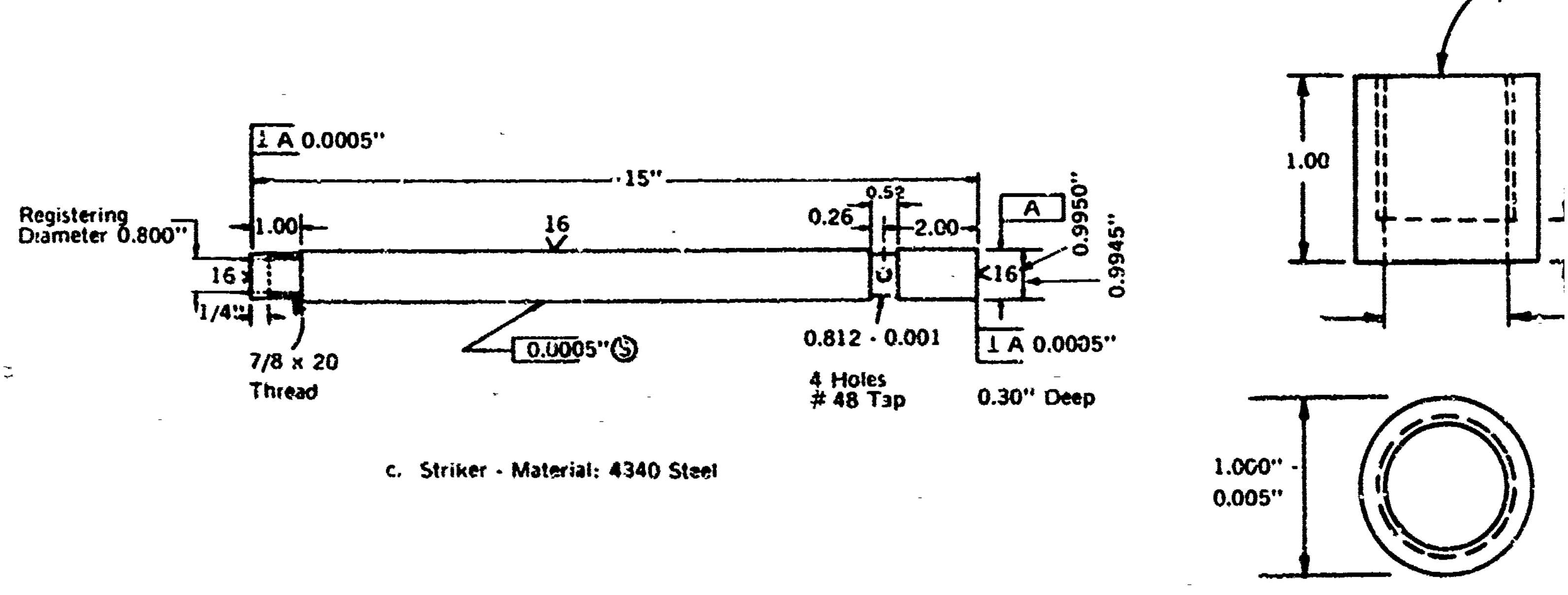


PHYSICAL PROPERTIES			TOLERANCES ON DECIMALS ± .005 ANGLES ± 1° FRACTIONS ± 1/64	ORIGINAL DATE OF DRAWING Ap. 27-71		AMMRC
	NEXT ASSY	USED ON	MATERIAL SEE NOTES	SUBMITTED	TUBE	D ES-D-148
	APPLICATION		HEAT TREATMENT SEE NOTES	APPROVED		SHEET 1 OF 1
	DO NOT	APPLY PART NO	FINAL PROTECTIVE FINISH		SCALE UNIT WT	



a. Weigh Bar - Material: 4340 Steel

b. Anvil Bar and M

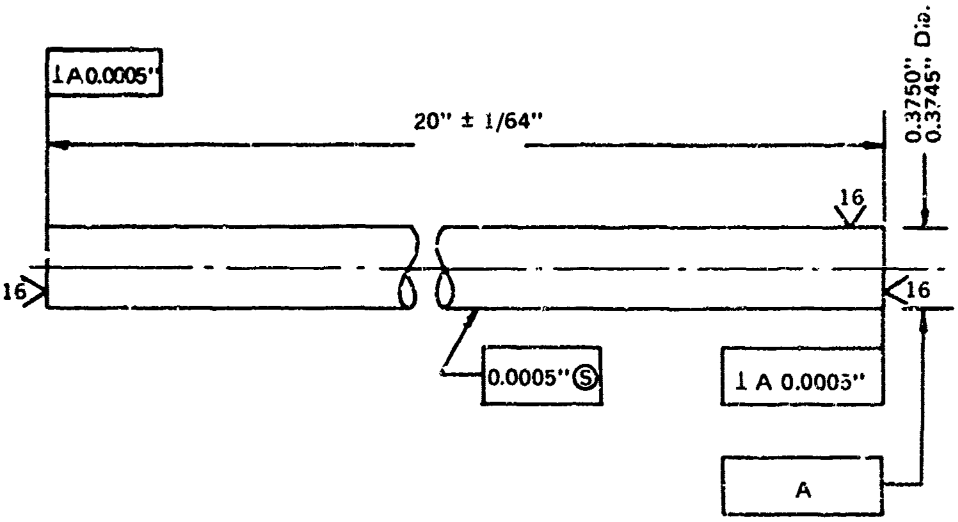


Assemble on striker before finish machining

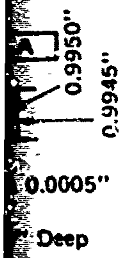
c. Striker - Material: 4340 Steel

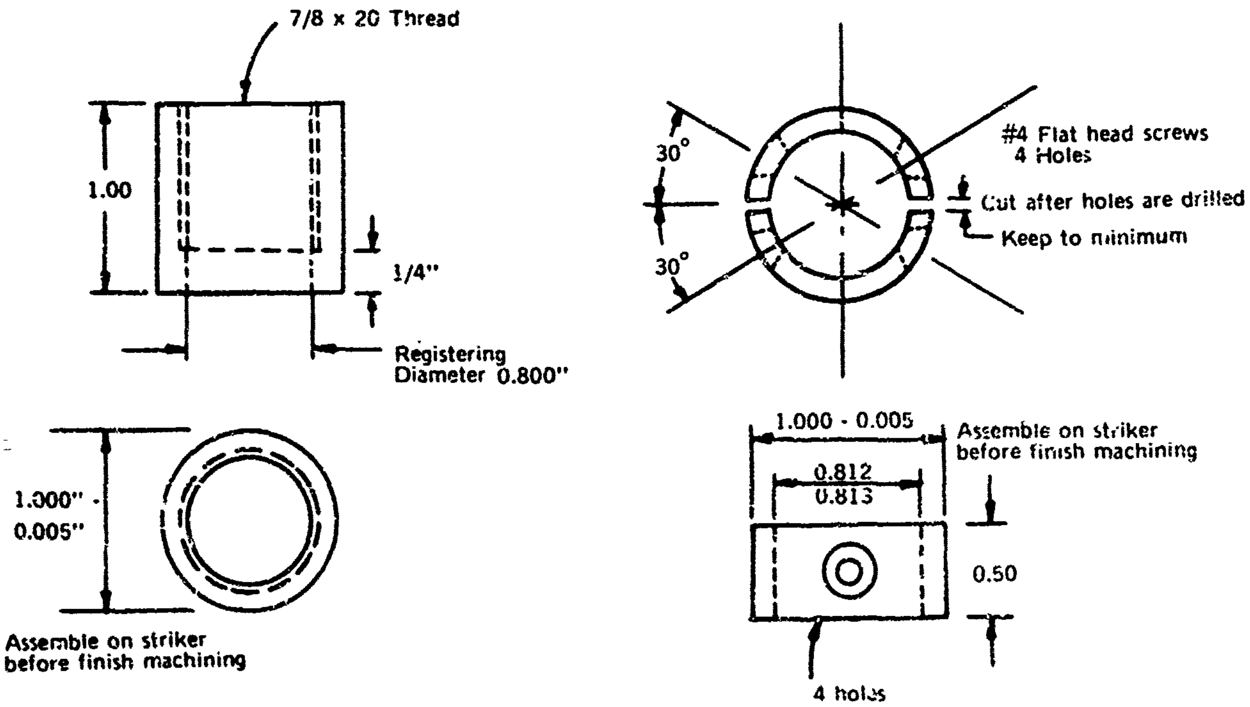
Figure A-2. WEIGH BAR, ANVIL BAR, STRIKER, AND STRIKER BEA

B



b. Anvil Bar and Momentum Trap - Material: 4340 Steel

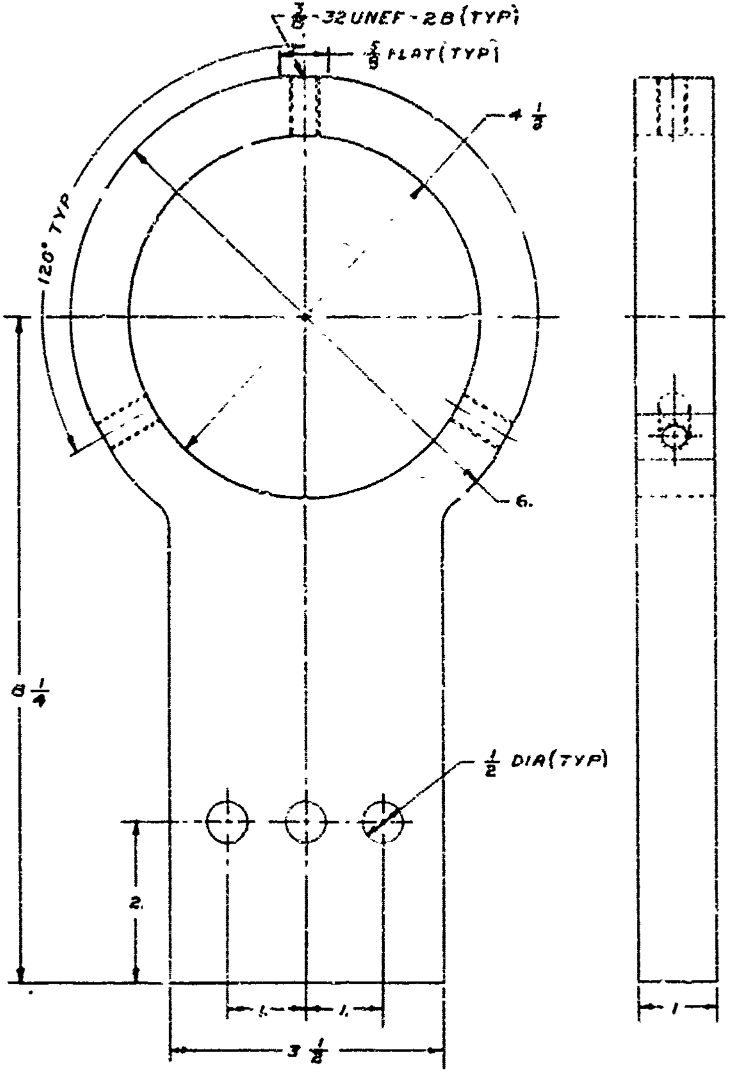




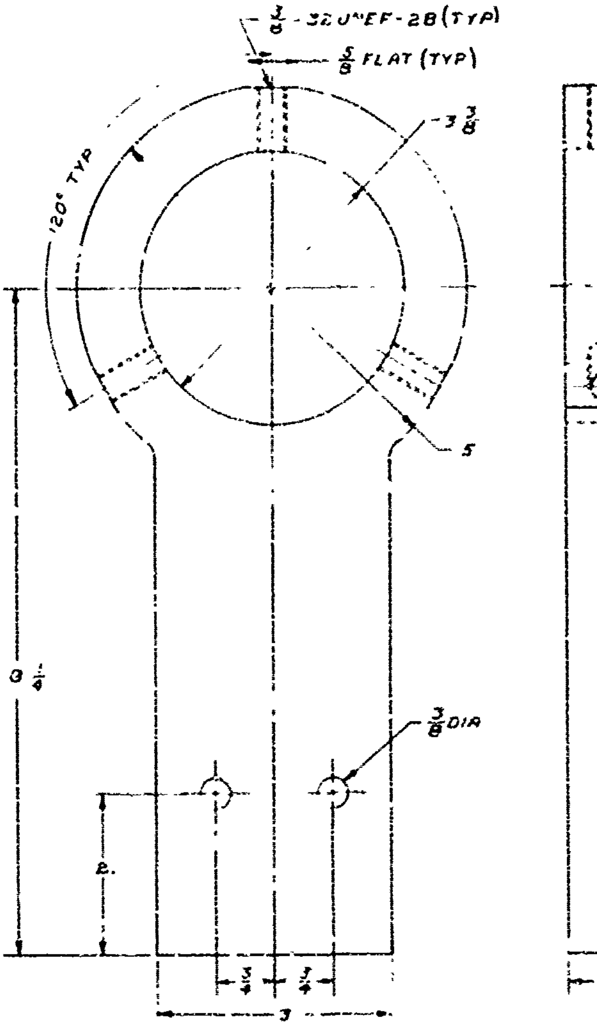
d. Striker Bearings - Material: Brass

AR, ANVIL BAR, STRIKER, AND STRIKER BEARINGS.

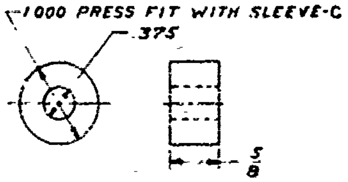
[illegible]



RING, SUPPORT-A
MAT'L : STEEL



RING, SUPPORT-B
MAT'L : STEEL



BEARING - D
MAT'L : BRASS

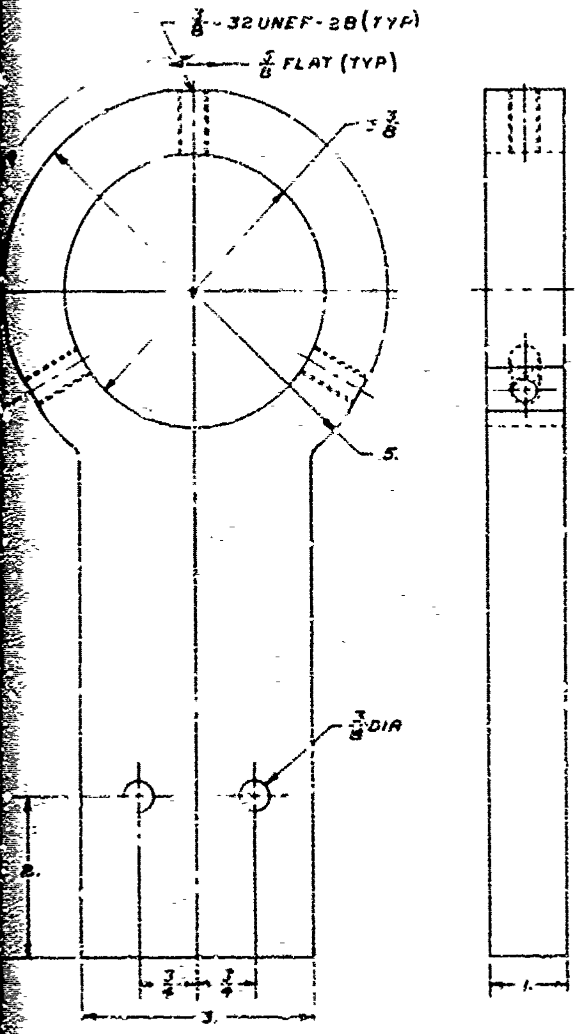
PHYSICAL PROPERTIES

B

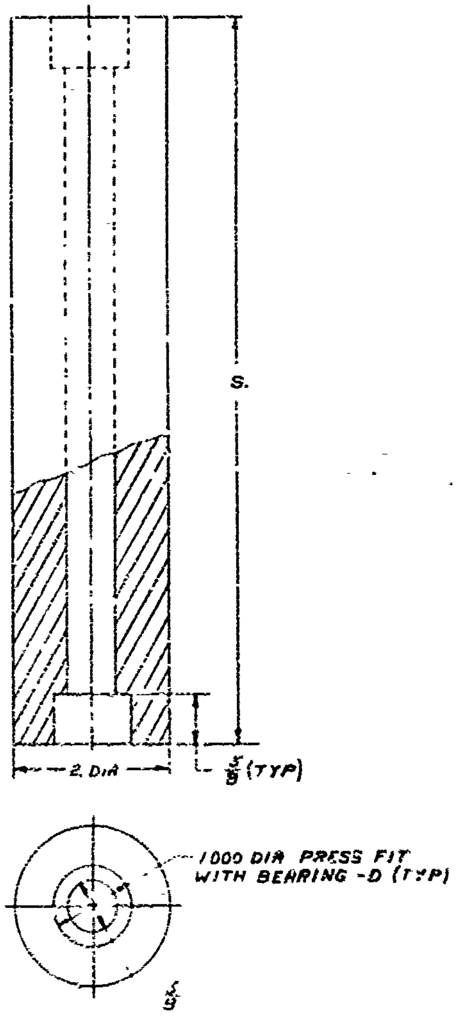
D

REVISIONS

SYM	DESCRIPTION	DATE	APPROVAL



RING, SUPPORT-B
MAT'L : STEEL



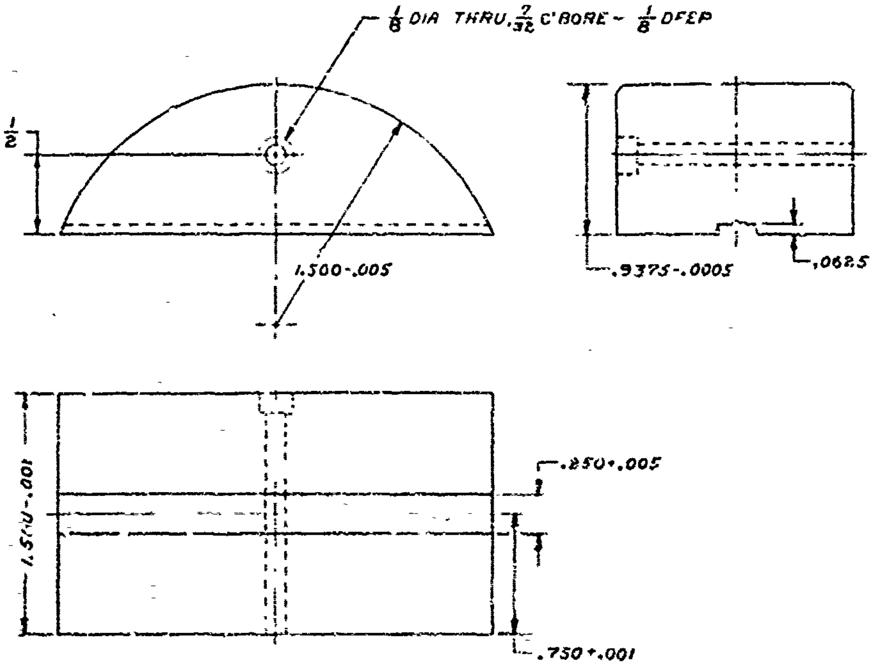
SLEEVE-C
MAT'L : STEEL

PHYSICAL PROPERTIES

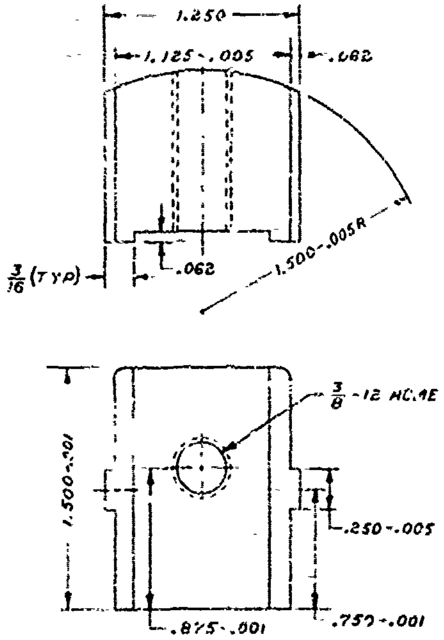
APPLICATION
DO NOT APPLY PART NO
TOLERANCES ON DECIMALS ± .SXX ANGLES ± ½° FRACTIONS ± 1/64
MATERIAL AS NOTED
HEAT TREATMENT
FINAL PROTECTIVE FINISH
ORIGINAL DATE OF DRAWING Ap. 26-71
SUBMITTED
APPROVED
RINGS-SUPPORT, SLELVE AND BEARING
SCALE
UNIT WT
AMMRC
SIZE D
ES-D-149
SHEET 1 OF 1

1178-8

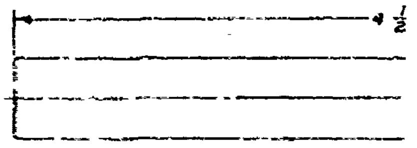
[illegible]



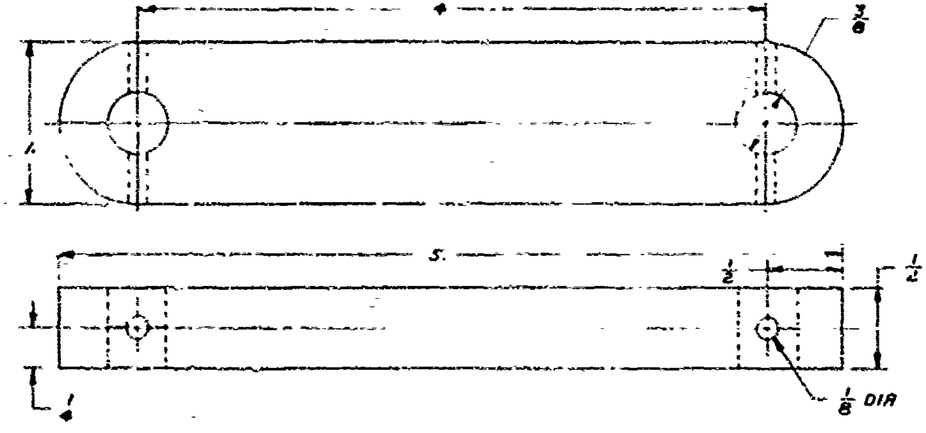
GUIDE-D
MAT'L : STEEL



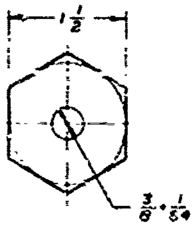
SLIDE-E
MAT'L : STEEL



H
M



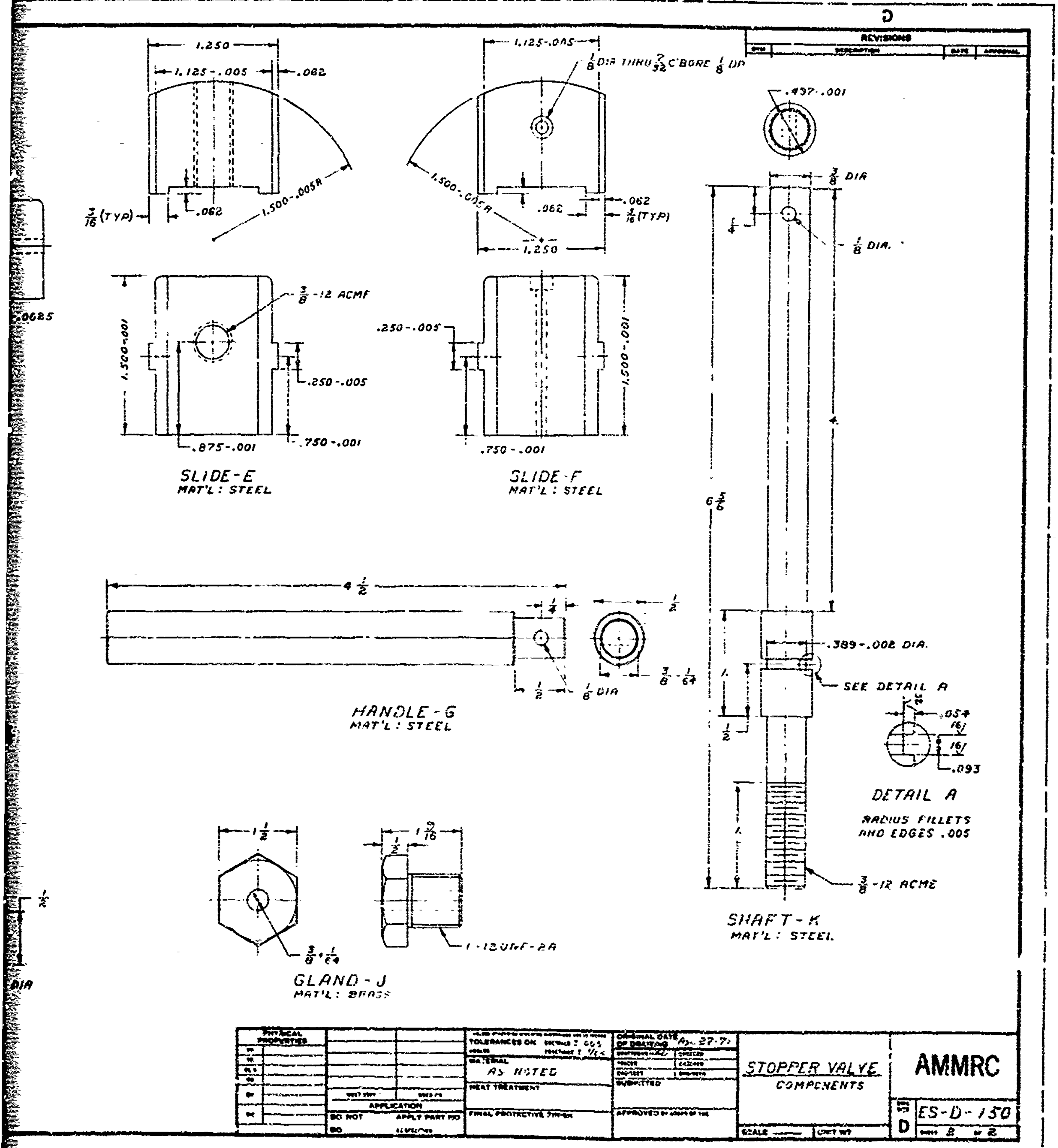
ARM-H
MAT'L : STEEL



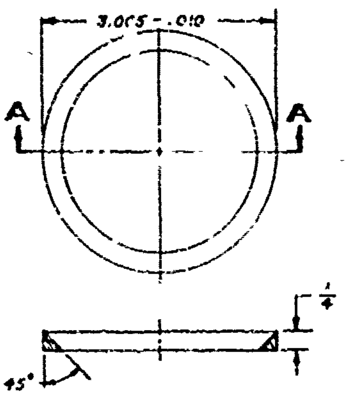
GLAND
MAT'L : BI

PHYSICAL PROPERTIES

B

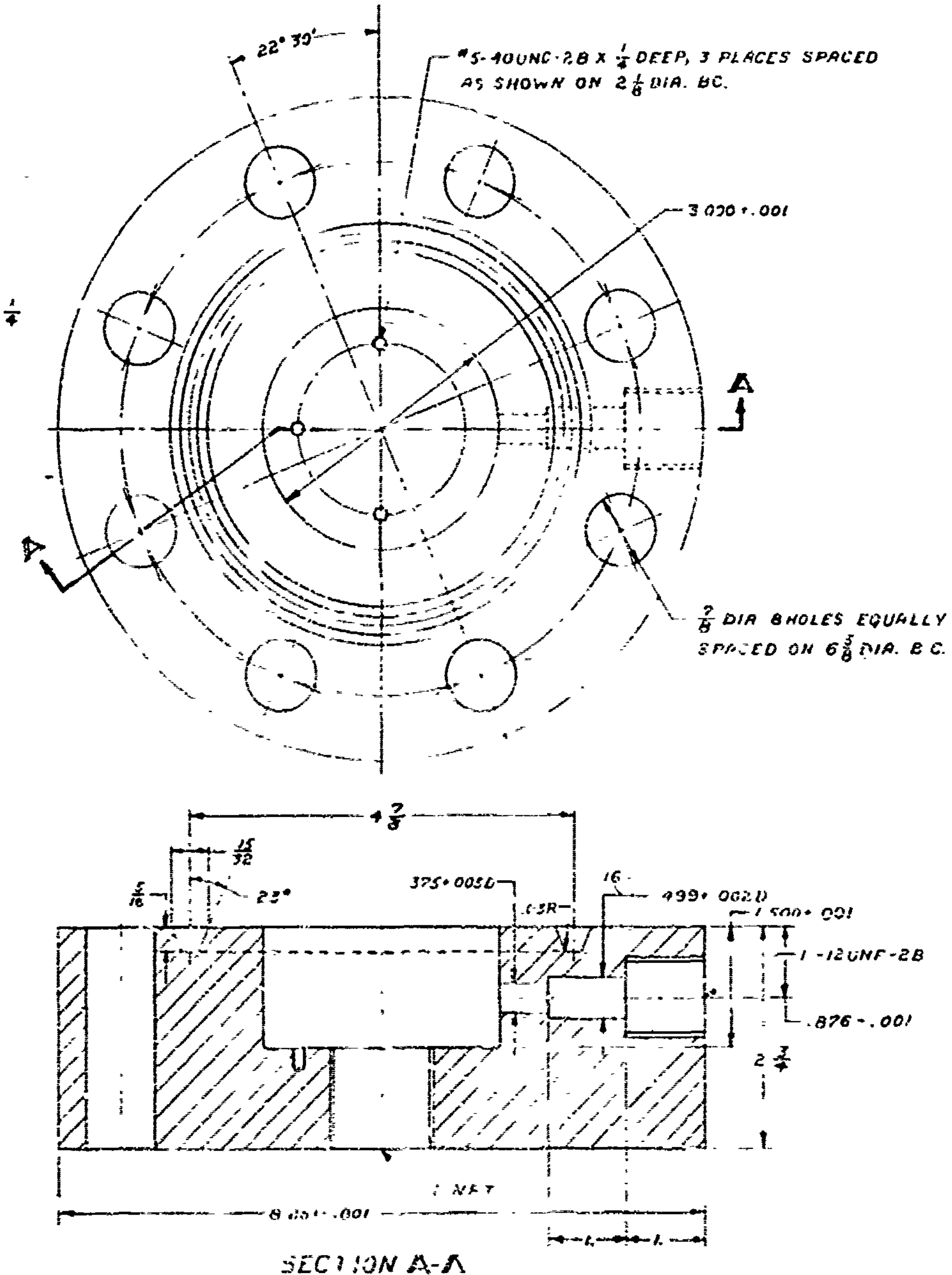

REVISIONS
1.250
1.125-.005
.062
1.500-.005R
3/16 (TYP)
.062
SLIDE-E
MAT'L: STEEL
3/8 -12 ACME
1.500-.001
.250-.005
.875-.001
.750-.001
1.125-.005
1/8 DIA THRU 7/32 C'BORE 1/8 DP
1.500-.005R
.062
3/16 (TYP)
1.250
.250-.005
1.500-.001
.750-.001
SLIDE-F
MAT'L: STEEL
4 1/2
1/4
1/2
1/2
1/8 DIA
3/8 - 1/64
HANDLE-G
MAT'L: STEEL
1 1/2
1 9/16
1/2
3/8 + 1/64
1-12UNF-2A
GLAND-J
MAT'L: BRASS
.437-.001
3/8 DIA
1/4
1/8 DIA.
4.
6 5/8
.389-.002 DIA.
SEE DETAIL A
1.
1/2
1.
3/8 -12 ACME
SHAFT-K
MAT'L: STEEL
.054
.093
DETAIL A
RADIUS FILLETS AND EDGES .005
.0625
1/2
DIA
PHYSICAL PROPERTIES
APPLICATION
DO NOT
APPLY PART NO
TOLERANCES ON DECIMALS ± .005 FRACTIONS ± 1/64
MATERIAL
AS NOTED
HEAT TREATMENT
FINAL PROTECTIVE FINISH
ORIGINAL DATE OF DRAWING Ap. 27-71
SUBMITTED
APPROVED
STOPPER VALVE
COMPONENTS
AMMRC
SCALE
UNIT WT
D
ES-D-150
SHEET 2 OF 2

11763



SECTION A-A

RING-A
MAT'L: COPPER



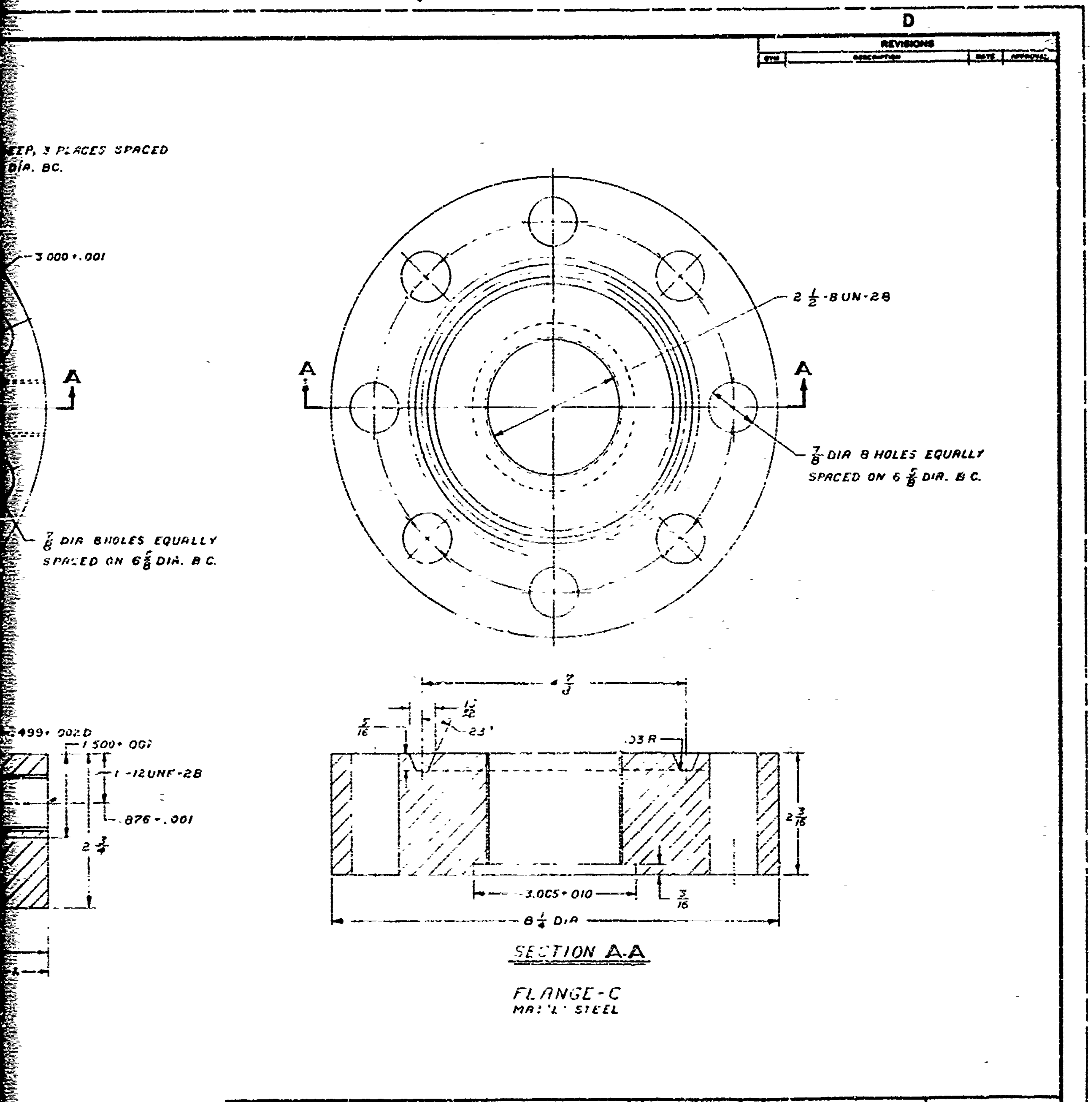
SECTION A-A

HOUSING-B
MAT'L: STEEL

PHYSICAL PROPERTIES

DO NOT

B



SECTION A-A

FLANGE-C
MAT'L STEEL

PHYSICAL PROPERTIES	APPLICATION	TOLERANCES ON DECIMALS ± .005 ANGLES ± 0° 30' FRACTIONS ± 1/64	ORIGINAL DATE OF DRAWING Apr 20 71	STOPPER VALVE (COMPONENTS)	AMMRC
	DR. NOT APPLY PART NO	MATERIAL AS NOTED	SUBMITTED		D ES-D-150
		HEAT TREATMENT	APPROVED	SCALE UNIT WT	SHEET OF 2
		FINAL PROTECTIVE FINISH			

APPENDIX B. LISTING OF COMPUTER PROGRAM

MAIN PROGRAM

NRUN - number of cases
TEMP - temperature of test
TESTN - test number
PRES - chamber pressure
NCPLOT - control for stress-time plots
STPLOT - control for stress-strain plot
SL - specimen length
RHO - density of elastic bars
E - modulus of elastic bars
SPDIA - specimen diameter
NU - Poissons ratio in plastic region
BDIA - diameter of elastic bars
XB - distance of gage set B from specimen interface
XC - distance of gage set C from specimen interface
TF - final time of test
TINC - increments of time
C - wave speed in the elastic bars
CON - constant used in determining particle velocity
TTB - time required for wave to travel from set B to interface
TTC - time required for wave to travel from set C to interface
SIGMAW - stress in weigh bar
SIGMAA - stress in anvil bar
SIGMA - average specimen stress
VW - particle velocity in weigh bar
VA - particle velocity in anvil bar
DEDT - strain rate
EPS - strain in specimen
TWM - time measured for interface
TWP - time transfer from gage set B to interface and return
TAP - time transfer from gage set B to gage set C
SETWM - stress in set A at TWM
SWTWP - stress in set B at TWP
SETWP - stress in set A at TWP
CATAP - stress in anvil bar at TAP
DDIA - area ratio between specimen and elastic bars

SUBROUTINES* CALA, CALB, CALC

T - time
N - number of points on oscilloscope traces
XSCALE - time between time-mark pips
YSCALE - volts/div on scopes
A,B,C,D - coefficients of polynomial to change from voltage to stress
XXA* - number of units between time mark pips
YYA* - number of units between divisions on trace
FA,GA* - zeros the X and Y axis
TA* - time on the traces
SA* - stress on the trace at time TA
STA - stress on the trace at time T

*Last letter refers to the gage set.

```
      PROGRAM HOP(INPUT,OUTPUT)
      DIMENSION T(200)
      DIMENSION STA(200),STB(200),STC(200)
      DIMENSION SIGMAW(200),SIGMAA(200),SIGMA(200),VW(200),VA(200),
     1DEDT(200),EPS(200),BB(10),IPLOT(90,9)
      COMMON TF,NCPLOT,TINC
C   NUMBER OF STACKED RUNS
      READ 67,NRUN
      DO 1009 III=1,NRUN
      PRINT 9
C     TEMPERATURE AND TEST NUMBER
      READ 68,TEMP,TESTN
C     CHAMBER PRESSURE
      READ 67,PRES
C *******  NCPLOT=1 PLOT  TIME STRESS *** STPLOT=1   STRESS STRAIN PLOT
      READ 67,NCPLOT,STPLOT
C    SPECIMEN LENGTH  POISSONS RATIO   BAR MODULUS  SPEC. DIAMETER
      READ 1,SL,RHO,E,SPDIA
C     NU  PLASTIC POISSONS RATIO(USUALLY ZERO FOR ENG. STRESS    BAR  DIAMETER
      READ 61,NU,BDIA
C   DISTANCE FROM GAGE SET B  TO SPECIMEN  INTERFACE       SET C TO INTERFACE
      READ 1,XB,XC
C   FINAL TIME        TIME INCREMENT
      READ 61,TF,TINC
C     COMMENT CARD
      READ 13,(BB(I),I=1,10)
 1    FORMAT(5E15.7)
 13   FORMAT(10A8)
 61   FORMAT(5F10.5)
 67   FORMAT(4I5)
 68   FORMAT(I5,A8,I5)
      C=SQRT(E/RHO)                                                     CMPT 040
      CON=1.0/(RHO*C)                                                   CMPT 041
      TTB=XB/C*1.0E+06
      TTC=XC/C*1.0E+06
      N=100
      PRINT 102
 102  FORMAT(1X,* HOPKINSON BAR TEST RESULTS *,////)
      PRINT 103,TESTN,TEMP,PRES
 103  FORMAT(1X,* TEST NUMBER *,A8,//*  TEMPERATURE = *,I5,//,*  CHAMBER
     1 PRESSURE = *,I5,* PSI *,//)
      PRINT 104,SL,RHO,E,SPDIA
 104  FORMAT(1X,* SPECIMEN LENGTH = *, F7.4,* INCHES *,//*  ELASTIC BAR
     1 DENSITY = *,E10.4,//*  ELASTIC BAR MODULUS = *,1PE12.5,* PSI*,//,
     2*  SPECIMEN DIAMETER = *,0PF7.4,* INCHES *,/)
      PRINT 111,BDIA,NU
 111  FORMAT(1X,* ELASTIC BAR DIAMETER = *,F8.4,* NU = *,F6.3,//)
      PRINT 105,XB,TTB
 105  FORMAT(1X,* THE DISTANCE BETWEEN GAGE SET B AND THE SPECIMEN INTER
     1FACE = *, F7.4,* INCHES *,//,*  THE TIME BETWEEN GAGE SET B AND TH
     2E SPECIMEN INTERFACE = *,F7.3,* MICROSECONDS *,//)
      PRINT 106,XC,TTC
 106  FORMAT(1X,* THE DISTANCE BETWEEN THE SPECIMEN INTERFACE AND GAGE S
     1ET C = *, F7.4,* INCHES *,//,*  THE TIME BETWEEN THE SPECIMEN INTE
     2RFACE AND GAGE SET C = *,F7.3,* MICROSECONDS *,/)
      PRINT 107,C,CON
 107  FORMAT(1X,* THE WAVE SPEED IN THE ELASTIC BARS = *,2PE15.3,* INCHE
     1S PER SECOND *,//*  THE PARTICLE VELOCITY CONSTANT = *,0PE12.6,//)
      PRINT 108
 108  FORMAT(///,*  COMMENTS *,//)
      PRINT 13,(BB(I),I=1,10)
      CALL CAL(T,STA)
      CALL CAL(T,STB)
      CALL CAL(T,STC)
      TF=TF-TINC*2.
      J=1                                                               CMPT 080
      SIGMAW(1)=0.0                                                     CMPT 081
      SIGMAA(1)=0.0                                                     CMPT 082
      SIGMA(1)=0.0                                                      CMPT 083
      VW(1)=0.0                                                         CMPT 084
      VA(1)=0.0                                                         CMPT 085
      DEDT(1)=0.0                                                       CMPT 086
      EPS(1)=0.0                                                        CMPT 090
      KL=2                                                              CMPT 091
      IST=1                                                             CMPT 092
      PRINT 9
 9    FORMAT(1H1)
      PRINT 6
```

```
6     FORMAT(6X,*  TIME          STRESS        STRAIN      STRAIN RATE
     1 WEIGH STRESS      ANVIL STRESS      WEIGH VEL      ANVIL VEL     *,//)
      DO 400 I=2,N
      IF(T(I+1) .GT. TF ) GO TO 410                                     CMPT 120
      J=J+1                                                             CMPT 130
      TWM=T(I)
      TWP=T(I)+TTB*2.
      TAP=T(I)+TTC*2.
      IF(TWM .GT.0.0 ) GO TO 170                                        CMPT161
      SETWM =0.0                                                        CMPT 162
      GO TO 230                                                         CMPT 163
170   DO 220 K=KL,N                                                     CMPT 170
      IF(T(K) .LE. TWM) GO TO 210                                       CMPT 180
      CALL LNR(T(K-1),T(K),STA(K-1),STA(K),TWM,SETWM)
      GO TO 230                                                         CMPT 200
210   KL=KL+1                                                           CMPT 210
220   CONTINUE                                                          CMPT 220
230   DO 270 K=KL,N                                                     CMPT 230
      IF (T(K) .LE. TWP) GO TO 270                                      CMPT 240
      CALL LNR(T(K-1),T(K),STB(K-1),STB(K),TWP,SWTWP)
      CALL LNR(T(K-1),T(K),STA(K-1),STA(K),TWP,SETWP)
      GO TO 280                                                         CMPT 260
270   CONTINUE                                                          CMPT 270
280   DO 300 K=KL,N                                                     CMPT 280
      IF(T(K) .LE. TAP) GO TO 300                                       CMPT 290
      CALL LNR (T(K-1),T(K),STC(K-1),STC(K),TAP,SATAP)
      GO TO 310                                                         CMPT 292
300   CONTINUE                                                          CMPT 300
310   CONTINUE
      VW(J)=CON*(SETWM+SETWP-SWTWP)                                     CMPT 340
      VA(J)=CON*SATAP                                                   CMPT 350
      DEDT(J)=(VW(J)-VA(J))/SL                                          CMPT 360
      DSTRN=(0.5*(T(I+1)-T(I))*(DEDT(J)+DEDT(J-1)))*1.0E-6              CMPT 361
      EPS(J)=EPS(J-1)+DSTRN                                             CMPT 370
      DDIA=(BDIA)**2/((SPDIA**2)*(1.+NU*EPS(J))**2)
      SIGMAA(J)=SATAP
      SIGMAW(J)=(SETWM+SWTWP-SETWP)
      SIGMA(J)=0.5*(SIGMAW(J)+SIGMAA(J))*DDIA
      PRINT 7,T(J),SIGMA(J),EPS(J),DEDT(J),SIGMAW(J),SIGMAA(J),VW(J),VA(
     1J)
7     FORMAT(1X,F15.1,F10.0,F10.4,F15.0,10X,F10.0,9X,F10.0,2F15.1,/)
400   CONTINUE                                                          CMPT 400
410   CONTINUE
      IF(STPLOT.EQ.0) GO TO 1009
      PRINT 9
      YMAX=0.
      DO 19 I=1,J
      IF(SIGMA(I).GT.YMAX) YMAX=SIGMA(I)
19    CONTINUE
      DO 21 II=1,90
21    IPLOT(II,1)=0.0
      J=J-1
      DX=.001
      N=YMAX/( 25.*88.)
      DY=(N+1)*25
      DO 20 I=7,J
      M=EPS(I)/DX+.5
      IF(M.GT. 100) GO TO 20
      NN=90.-SIGMA(I)/DY+.5
      IPLOT(NN,1)=IPLOT(NN,1)+1
      K=IPLOT(NN,1)+1
      IPLOT(NN,K)=M
20    CONTINUE
      DO 22 JJ=1,40
      IF(IPLOT(JJ,1).NE. 0 ) GO TO 24
      PRINT 31
      GO TO 22
24    DO 23 KK=1,200
23    SIGMA(KK)=1H
      NIPLOT=IPLOT(JJ,1)+1
      DO 41 I=2,NIPLOT
      M=IPLOT(JJ,I)
41    SIGMA(M)=1H*
      PRINT 32,(SIGMA(I),I=1,100)
 22   CONTINUE
      DO 46 I=1,100
```

```
 46   SIGMA(I)=1H%
      PRINT 32,(SIGMA(I),I=1,100)
 32   FORMAT(2H Y,100A1)
  31  FORMAT(2H Y)
 1009 CONTINUE
      END                                                             CMPT 483
      SUBROUTINE CAL(T,STA)
      DIMENSIOG T(200),SA(200),TA(200)
      DIMENSION STA(200)
      DIMENSION XA(200),YA(200),FA(200),GA(200)
      COMMON TF,NCPLOT,TINC
C   NUMBER OF DATA POINTS  TIME SETTING ON SCOPE       VOLTAGE SETTING
      READ 1,N,XSCALE,YSCALE
C    POLYNOMIAL   CURVE  FROM  FROM  VOLTAGE TO STRESS
      READ 2,A,B,C,D,EE
C    DISTANCE TO TIME CONVEPSION          DISTANCE TO VOLTAGE  CONVERSION
      READ 5,XXA,YYA
      ASK=1H*
      YMAX=0.
      DO 4 I=1,N
      READ 3,XA(I),YA(I)
      FA(I)=ABS(XA(I)-XA(1))
      GA(I)=ABS(YA(I)-YA(1))
 3    FORMAT(3F5.0)
      TA(I)=FA(I)*XSCALE/XXA
      GA(I)=GA(I)*YSCALE/YYA
      SA(I)=(A+B*GA(I)+C*GA(I)**2+D*GA(I)**3+EE*SA(I)**4)
      IF(SA(I).GT.YMAX) YMAX=SA(I)
 4    CONTINUE
      IF(NCPLOT.EQ.0) GO TO 99
      PRINT 17
      PRINT 87
 87   FORMAT(*     TIME  STRESS  VALUES FOR GAGE SET A   *,///)
      AINC=90./YMAX
      DO 46 K=1,100
 46   XA(K)=1HS
 17   FORMAT(1H1)
      PRINT 11,(XA(I),I=1,100)
      DO 9 I=1,N
      DO 12 K=1,200
 12   XA(K)=1H
      M=AINC*SA(I)+1.5
      DO 18 J=1,M
 18   XA(J)=1H
      PRINT 10,TA(I),SA(I),(XA(JJ),JJ=1,M),ASK
 9    CONTINUE
 10   FORMAT(1X,F10.1,F15.0,5X,2H I,100A1)
 11   FORMAT(31X,2H I,100A1)
 1    FORMAT(I5,3F10.3)
 2    FORMAT(5E15.7)
 5    FORMAT(3F10.5)
 99   TT=0.
      J=1
      DO 91 I=2,100
      IF(TA(I-1).EQ.TT) GO TO 101
      IF(TA(I).GT.TT) GO TO 90
      GO TO 91
 90   CALL LNR(TA(I-1),TA(I),SA(I-1),SA(I),TT,SIGA)
      T(J)=TT
      STA(J)=SIGA
      GO TO 103
 101  T(J)=TA(I-1)
      STA(J)=SA(I-1)
  103 CONTINUE
      J=J+1
      IF(J.GT.100) GO TO 89
      TT=TT+TINC

      IF(TT.GT. TF) GO TO 89
      IF(TT.LT.TA(I)) GO TO 90
 91   CONTINUE
  89  CONTINUE
      RETURN
      END
      SUBROUTINE LNR(X1,X2,Y1,Y2,XPR,YPR)
      YPR=Y1+(Y2-Y1)*(XPR-X1)/(X2-X1)
      RETURN
      END
```

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