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JUN 74  C J CARTER, J J CONNELLY, R A CELLITTI  DAAG46-72-C-0162
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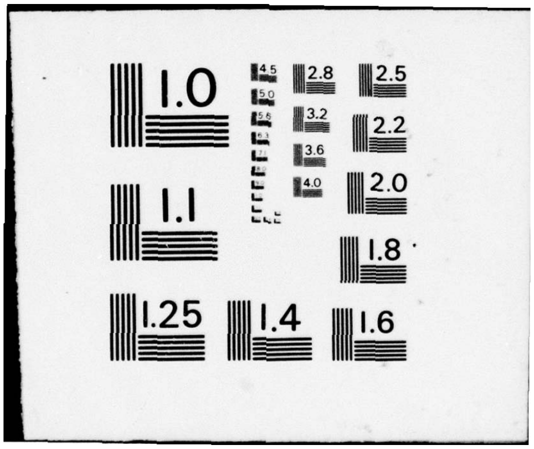
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AMMRC CTR 74-43

# INSTRUMENTATION FOR FRACTURE TOUGHNESS EVALUATION WITH CHARPY IMPACT SPECIMEN ✓

June 1974

C. J. CARTER, J. J. CONNELLY and R. A. CELLITTI
International Harvester Company
Manufacturing Services
Hinsdale, Illinois 60521

Final Report - Contract DAAG46-72-C-0162

This project has been accomplished as part of the U.S. Army Materials Testing Technology Program, which has for its objective the timely establishment of testing techniques, procedures or prototype equipment (in mechanical, chemical, or nondestructive testing) to insure efficient inspection methods for materiel/material procured or maintained by AMC.

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An instrumented impact test system comprised of analog circuits was designed, assembled and tested. The system is capable of furnishing a digital display of static ~~($K_{IC}$)~~ and dynamic ~~($K_{Id}$)~~ fracture toughness, impact energy and time to fracture along with a hard copy print-out and oscilloscope presentation of the force-time trace. The computation circuits are described along with operation procedures and principal logic inputs.

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# FOREWORD

This final technical report covers work performed under Contract DAAG46-72-C-0162 entitled "Instrumentation for Fracture Toughness Evaluation with Charpy Impact Specimen" during the period May 10, 1972, to March 12, 1974.

This project has been accomplished as part of the U. S. Army Materials Testing Technology Program, which has for its objective the timely establishment of testing techniques, procedures or prototype equipment (in mechanical, chemical, or nondestructive testing) to insure efficient inspection methods for materiel/material procured or maintained by AMC.

This contract with International Harvester Company, Manufacturing Services, Hinsdale, Illinois, was initiated by Army Materials and Mechanics Research Center and accomplished under the technical direction of Mr. A. F. Landry, C.O.R.

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# I. INTRODUCTION

The primary objective of this program was to design and assemble an instrumented impact test system for measuring fracture toughness using a Charpy specimen. The instrumentation was designed to incorporate analog circuitry, digitized read-out and oscilloscope presentation.

## Discussion

The reliable prediction of material behavior under dynamic loading necessitates the use of sophisticated engineering test methods as well as the establishment of standardized test procedures. The instrumented impact tester when adequately designed to assess a range of strength levels possesses unique capabilities to extend usefulness for both aspects. The properly designed instrumented impact test system can automatically analyze and rapidly furnish information regarding:

Maximum load
Time to maximum load
Total impact energy
Crack initiation energy
Crack propagation energy
Unstable fracture occurrence
Initial elastic energy (inertial)
$K_{Id}$ (Max. load)
$K_{Id}$ (W/A)
$K_{Id}$ (COD)
$K_{Ic}$ (empirical relationship)

It has been demonstrated that the above parameters can be ascertained with a high degree of precision using hybrid type computers for data assimilation and processing. However, these systems are somewhat costly which prohibits their widespread use.

Numerous other types of instrumented impact test systems have been introduced and are currently being utilized. However, these systems mainly suffer the limitation of providing only a visual force-time display which is photographically recorded. The subject system provides automatic electronic analyses and read-out capabilities along with oscilloscope presentation.

## II. INSTRUMENTATION

### A. Tup

The load sensing element (strain gaged tup) is similar to those employed in other systems. Figure 1 shows the arrangement of the gages on the undercut flank section of the tup. Four strain gages are bonded on each side of the tup. Two of the gages are mounted for compression loading and two are mounted for tension loading. A wiring diagram of gage circuitry is shown in Figure 2. All strain gages are MicroMeasurement type EA-06-062-AQ-350.

### B. Analog Sensing Circuits and Hardware

The principal electronic components of all circuits are operational amplifiers which are utilized as integrators, differentiators, root extraction, multipliers, peak detection etc. A circuit diagram of the system is shown in Figure 3.

Referring to Figure 3, the output signal from the strain gage bridge is transmitted to four buffer amplifiers (1, 11, 24 and 33). Since each buffer amplifier is the initial stage of a principal circuit associated with a particular terminal calculation, it is appropriate to cover the various circuits in detail separately.

1. Calculation of impact energy

Total energy absorbed by the specimen during impact loading is calculated from the area ($\sum Fdt$) under force-time curve multiplied by the average pendulum velocity ($V_a$).

Total impact energy absorbed = $V_a \sum F \cdot dt$ (1)

The output from buffer amplifier (1) is transmitted to an integrator (2) which performs the summation of $F \cdot dt$. The average velocity ($V_a$) is calculated from initial impact velocity ($V_o$) and final pendulum velocity ($V_f$) after fracture by the following equation.

$$V^a = \frac{V_o + V_f}{2} = \frac{E_o}{\sum F \cdot dt} \quad \text{, where } E_o = \text{absorbed impact energy} \tag{2}$$

The final pendulum velocity can be expressed in terms of absorbed energy and initial pendulum velocity at impact by:

$$V_f = \left(V_o^2 - \frac{2gE_o}{W_o}\right)^{\frac{1}{2}} \tag{3}$$

Substituting the equivalent of $V_f$ in equation (2),

$$2V_a = V_o + (V_o^2 - \frac{2g\,E}{W_o}) \tag{4}$$

or

$$2V_a = V_o + (V_o^2 - \frac{2g}{W_o} \cdot V_a \sum f \cdot dt) \tag{4a}$$

Simplifying and rearranging TERMS,

$$V_a = V_o - \frac{\sum F \cdot dt}{2m} \tag{4b}$$

mass of pendulum (m) = $W_o/g$

At operational amplifier (3), which is a divider, the area under the force-time curve is divided by 2m. This signal is introduced to a differentiator amplifier (4) which performs the operation $V_o - \frac{\sum F \cdot dt}{2m}$ resulting in $V_a$.

At this point the signal is fed into a multiplier (5) along with the signal from integrator (2) resulting in completion of the $V_a \sum F \cdot dt$ operation. This value is ultimately presented at terminal B for a print-out of total impact energy absorbed by the specimen.

2. Calculation of $K_{IC}$ (Empirical Relationship)

An empirical relationship between fcsg* Charpy impact energy and $K_{IC}$ was established in a separate study (DAAG46-69-C-0005) in which the following correlation was expressed:

$$(K_{IC}/\sigma_y)^2 = \frac{4.9(\text{fcsg energy} + 4.3)}{\sigma_y \times 10^{-3}} - 0.05 \tag{5}$$

*fcsg - fatigue crack-side groove

The $K_{IC}$ fracture toughness value is also calculated in the first circuit where the strain gage signal is transmitted to buffer amplifier (1). The sequence of events is identical to preceding impact energy circuitry through multiplier amplifier (5). At this point, however, the $K_{IC}$ circuit branches and the signal is conveyed to amplifier (6) where the inertial energy is subtracted from the total calculated energy. A selector switch with fixed resistors is provided for steel and aluminum materials. The magnitude of the initial elastic envelope due to inertial effects is a function of the material's elastic modulus. For steels, a constant magnitude of 0.60 ft-lbs has been observed. With aluminum, 0.30 ft-lbs was noted. The amplified signal continues along the path to amplifier (7) where the value of 4.3 is added. The value of 4.3 is the y-ordinate intercept obtained upon plotting conventional Charpy impact energy versus fcsg Charpy impact energy. The complete expression of the equation is:

$$\text{fcsg impact energy} = 0.77\ \text{CVN} - 4.3 \qquad (6)$$

where:

CVN = conventional Charpy impact energy

The signal is conditioned next by a multiplier (8) which multiplies the term (fcsg impact energy + 4.3) by 4.9. Next, signal conditioning continues by division of material yield strength which is effected by potentiometer (8A). A subtractor (9) receives the signal and reduces the preceding value by 0.05 which is the y-ordinate intercept of equation (5).

The signal enters the root extractor (10) and the ensuing value is multiplied by the material's yield strength at amplifier (10A). The $K_{IC}$ fracture toughness value is forthcoming at Terminal A.

3. Dynamic Fracture Toughness (Maximum Load)

With material strength levels in which fractures precedes general yielding, fracture toughness ($K_{Id}$) can be closely approximated by maximum specimen load and specimen geometry. The ASTM Plane strain fracture toughness three point bend equation which incorporates the use of maximum load and specimen geometry is given by,

$$K_Q = \frac{\alpha PL}{BW^{3/2}} \cdot f\ (a/w) \qquad (7)$$

where:

$$f(a/w)=5.8\left(\frac{a}{w}\right)^{\frac{1}{2}}-9.2\left(\frac{a}{w}\right)^{3/2}+43.6\left(\frac{a}{w}\right)^{5/2}-75.3\left(\frac{a}{w}\right)^{7/2}+77.4\left(\frac{a}{w}\right)^{9/2} \qquad (8)$$

P = maximum load in lbs

B = Specimen thickness

L = specimen one-half span support (inches)

w = Specimen depth (inches)

a = Depth of notch plus precrack length (inch) presentation or load-time curve print out has been and continues to be a controversial subject. Other investigators, notably Turner(*), suggest the use of a correction factor to obtain an effective specimen load. Figure 4 shows the Turner correction curves for various specimen stiffnesses. The inertia correction is based upon the rise time of each oscillation. Although the authors take exception to this treatment, the Turner correction concept is incorporated into the circuitry for optional use by the operator.

The output signal from the strain gage enters buffer amplifier (11) and is transmitted to peak detector amplifier (12) which senses the peak voltage or maximum load. A trigger signal is also fed into the peak detector to inhibit signal pickup during the initial 29 microseconds. The peak signal is next transmitted to a potentiometer (Turner correction factor) and then to a multiplier (13) which multiplies the corrected load (P) by the specimen half-span length (L) via a potentiometer shunted across multiplier (13). The signal corresponding to the dividend (PL) is transferred to amplifier (14) which is a divider.

The divisor quantity ($BW^{3/2}$) is conveyed to the divider (14) by a branch circuit which originates at the potentiometer (W). Two separate paths from (W) are fed into a multiplier (16) resulting in $W^2$. A third leg (W)

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*Turner, C.E., "Measurement of Fracture Toughness by Instrumented Impact Test", Impact Testing of Metals, ASTM STP 466, American Society for Testing and Materials, 1970, pp. 93-114.

which is connected to the first W path prior to entering multiplier (16) is fed along with the signal output from multiplier (16) into multiplier (17). The signal corresponding to the product ($W^3$) arrives at the root extractor (18) and continues to multiplier (19) at which site the multiplicand signal ($W^{3/2}$) is multiplied by signal (B) which is a potentiometer shunted across multiplier (19). The resulting signal ($BW^{3/2}$) is the divisor signal which is coupled with the dividend signal (PL) to effect $\frac{PL}{BW^{3/2}}$ .

The Quotient signal is transmitted to multiplier (15) and is multiplied by the specimen compliance factor f(a/w) which is indicated as a potentiometer shunted across multiplier (15). The $K_{Id}$ fracture toughness value is accessible at Terminal C. Note, the compliance factor f(a/w) must be computed manually after the specimen is broken. The value is then entered via the dial potentiometer (a/w).

4. Crack Opening Displacement ($K_{Id}$)

Although the crack opening displacement (COD) measurement can be used with high strength or brittle materials, it is primarily intended as a more reliable indicator of fracture toughness for lower strength materials in which general yielding precedes fracture. The COD equation is given by,

$$COD = x\,\theta^{c} \qquad (9)$$

where x = distance of axis of rotation below crack root

$\theta^{c}$ = bend angle in radians of the specimen at crack growth instability.

The COD can be related to fracture toughness by strain energy release rate ($G_{Id}$).

$$G_{Id} = \sigma_{yd}(COD) \qquad (10)$$

The liner elastic fracture mechanics equation permit an expression in terms of $K_{ID}$,

$$K_{ID} = (E\,G_{ID}/1-\nu^{2})^{\frac{1}{2}} \qquad (11)$$

The bend angle ($\theta^{c}$) as shown in Figure 5 can be ascertained by elapsed time (t) interval between loading of the specimen after initial inertial effects and unstable crack propagation. Referring to Figure 5,

$$\theta^{c} = 2\,d/L \qquad (12)$$

where;

d = t.v

v = pendulum velocity

L = specimen half-span support length

The value of X was experimentally determined in a previous study to be 0.0573 inch.

Referring to Figure 3 , the strain gage signal output travels to buffer amplifiers (24 & 33). The signal leaving amplifier (24) branches in two directions. The signal is transmitted along one path to peak detector (25).

The second path transmits the signal directly to a comparator (26). Simultaneously, the signal leaving buffer amplifier (33) is transmitted to trigger (34) which inhibits signal transmission at the peak detector (25) for 29 microseconds to negate inertial load time. The delayed signal leaving peak detector (25) encounters a resistor which reduces the voltage 90% and enters comparator (26). This operation is solely introduced to measure a ramp voltage which is subsequently integrated (27) to provide time to unstable crack propagation. A timer is connected at the output of the integrated ramp voltage. This voltage which corresponds to time is transmitted to multiplier (28). Simultaneously, the average velocity ($V_a$) signal from the output of amplifier (4) is also delivered to multiplier (28). The product of these results in a displacement (d) signal which is transmitted to divider amplifier (29) where divisor $\frac{L}{2}$ is applied. The 2 d/L signal next encounters a fixed resistor which is a multiplier of the rotational constant value of 0.0573. At this point, the COD value has been calculated. However, no print-out or value is displayed. Instead, continuation of the circuit to express COD in terms of $K_{Id}$ is the goal. The COD signal is transmitted to multiplier (30) to which dynamic yield strength ( $\sigma_{yd}$) is multiplied. The dynamic yield strength value is initially entered by a dial potentiometer. The product signal ($2d/L.\ \sigma yd$) is fed to multiplier amplifier (31) where the multiplicand signal is multiplied by the material's elastic modulus (E). Again, this signal (E) is preset by a fixed resistor. The signal continues to a juncture where it is divided by the signal equivalent of ($1-\nu^2$). The quotient signal is acted upon by root extractor (32) after which the final signal equivalent of

$$\left[\frac{(COD)\ \sigma ydE}{1-\nu^2}\right]^{\frac{1}{2}}$$

or $K_{ID}$ based upon COD is displayed at Terminal E.

5. Strain Energy Release Rate ($G_{Id}$ or W/A)

The strain energy release rate ($G_{Id}$) approximates W/A for high strength materials or others that fracture in a predominately cleavage mode (low temperature regions). The total energy required to promote specimen fracture is equal to W/A, where W is the total work required and A is the ligament area. At low strength levels or where general yielding occurs prior to fracture, the propagation energy can be obtained by subtracting $G_{Id}$ from W/A.

Referring again to Figure 3 , the W/A circuit has two branches. The energy branch originates from buffer amplifier (1) and is identical in sequence of operations to the total energy circuit previously described which terminates at terminal B. However, the W/A circuit incurs an additional operation which negates the inertial energy envelope at amplifier (6). The output from amplifier (6) is fed to the divider (23). The second path or branch of the circuit which also arrives at divider (23) is concerned with signal conditioning to obtain the equivalent voltage corresponding to ligament area. The second branch originates at two potentiometers. Signals from potentiometer (W) and potentiometer (A) are transmitted to amplifier (20) where the (w-a) signal equivalent is achieved. This signal travels to multiplier (21) and a thickness (B) control potentiometer which is connected in parallel with multiplier (21). The resulting signal, B(W-a) is fed to multiplier (22) which effects the conversion of ft-lb to in-lb. This is the divisor signal which arrives at divider (23). The quotient (W/A) is displayed at Terminal D.

## C. Front Panel Controls and Indicators

A photograph of front panel controls and indicators is depicted in Figure 6 . The input jack on the front panel is for the insertion of an output plug from the strain gage bridge. The strain gage signal is also transmitted simultaneously to the storage oscilloscope.

1. Ready control - de-energizes integrating amplifiers by internal manual connection to a -15 volt source.
2. Reset control - de-energizes peak detector amplifiers by internal manual connection to ground.
3. Turner correction - For use at operator's option to correct for maximum load. Graph of correction factors is shown in Figure 4.

4. Crack length (a) - Depth of the notch and fatigue crack.

5. Yield strength ( $\sigma y$) - 0.2% offset yield strength

6. Dynamic yield ( $\sigma yd$) - Point of deviation from linearity at a given strain rate

a/w - Ratio of crack length to specimen depth incorporated in a power series. Used for dial setting of the compliance factor, f(a/w).

Fracture Toughness Display Controls

(From top to bottom)

$K_{IC}$ Empirical - Automatically calculates static fracture toughness using energy value and relationship with static yield strength.

$$K_{IC} = \sigma y \left[ 4.9\frac{(\text{fcsg energy} + 4.3)}{\sigma y \times 10^{-3}} - 0.05 \right]^{\frac{1}{2}}$$

$K_{Id}$ - Automatically calculates dynamic fracture toughness by detecting peak load and inserting measured specimen dimensions.

$K_{Id} = \frac{\alpha PL}{BW^{3/2}} \cdot f(a/w)$, $\alpha$ is Turner correction

f(a/w) must be calculated off-line by operator and value inserted by dial potentiometer.

Total Impact Energy - Complete area under the force-time curve multiplied by average pendulum velocity during fracture.

$$E_o = V_a \sum Fi \cdot dt$$

W/A - Energy negated for initial inertial envelope divided by the ligament area.

$K_{Id}$ (COD) - Automatically calculated dynamic fracture toughness for materials which yield before fracture by sensing time interval between end of initial inertial envelope and start of crack growth instability.

$$K_{Id} = \left[\frac{E\,\sigma_{yd}(COD)}{1-\nu^2}\right]^{\frac{1}{2}}$$

Material Selector Switch - Inhibits assimilation of force-time data corresponding to initial inertial envelope. This control can be expanded upon to include other materials such as titanium, etc.

Display & Moduprint - Digital display and print-out of fracture toughness values calculated upon selection and depression of a display control.

Time to Fracture - Digital display of time (microseconds) to crack growth instability.

D. Internal Controls

For a fixed specimen geometry and material elastic constants which do not vary for a series of tests, a continuous adjustment is not required. However, provisions have been made to alter these constants if the material is changed such as steel in lieu of aluminum or the specimen is scaled-up or scaled-down. These adjustments are provided by variable resistors (screwdriver type) that are positioned internally at various circuit sites. Internal variable resistors are:

Specimen thickness (B)

Specimen depth (W)

Specimen half-span support length (L)

Poisson's Ratio ($\nu$)

Young's Modulus (E) are fixed resistors which are accessible by a selector switch. All internal controls are identified by label attachments.

## III. OPERATING PROCEDURE

### A. Storage Oscilloscope

1. Connect power cord from oscilloscope to 110 VAC 50/60 Hertz single phase outlet.
2. Turn on oscilloscope (push-pull switch). Pull to active oscilloscope.
3. Set oscilloscope controls as follows:

   Note: Strain gage output is connected to CH1 (Channel 1). Figure 7 shows photographic illustration of the storage oscilloscope.

   a. Depress CH1 pushbutton on vertical mode switch.
   b. Set VOLTS/DIV switch to 2V.
   c. Set AC/DC switch to DC.
   d. Adjust TIME/DIV scale to .1MS.
   e. Set TRIGGER SOURCE switch to CH1.
   f. Depress UPPER and LOWER SCREEN STORE pushbutton.
   g. Set MODE switch to single.
   h. Set LEVEL switch +.

i. Set SLOPE selector to slightly +.

j. Depress RESET pushbutton (the READY light should glow).

k. When specimen is fractured by impact pendulum, force-time trace will be displayed on scope screen.

l. To eliminate trace, depress ERASE pushbutton on the UPPER and LOWER screen.

m. Depress the RESET pushbutton (the READY light should glow).

m. The oscilloscope is now ready for the next specimen.

B. Front Panel Controls

Front panel controls are photographically illustrated in Figure 6. Position controls as indicated below.

1. Connect power cord from the unit to 110 VAC 50/60 Hertz single phase outlet.
2. Turn on power switch.
   a. Set MATERIAL selector to appropriate position (Steel or aluminum)
   b. Adjust dial on STATIC YIELD control to appropriate setting. If 0.2% offset yield is 186,000 psi, set dial to 186.
   c. Adjust dial on DYNAMIC YIELD control to appropriate setting. If dynamic yield strength is 224,000 psi, adjust dial to read 224.
   d. Adjust MAXIMUM CONTROL CORRECTION dial to read 999.
   e. Depress RESET button.
   f. Depress READY button.
   g. Place specimen in anvel supports and release hammer to break specimen.

h. Measure precrack length in accord with ASTM Method E399.

i. Adjust dial "a" to read total notch depth and precrack length. If notch depth is 0.079 in. and precrack length is 0.030 in., set dial to read 109.

j. Calculate f(a/w), or read value which corresponds to a/w from prepared chart.

k. Adjust f(a/w) dial from calculated or chart converted value. If value is 0.276, set 276 on dial.

l. If a correction for maximum load is desired, note time to fracture on digital display. Refer to Figure 4 in which correction factor is plotted versus rise time to maximum load.

m. Adjust MAXIMUM LOAD CORRECTION for corresponding rise time value.

n. If no correction is desired, set dial to read 999.

o. Press $K_{IC}$ button.

p. Press PRINT MAN button.

q. Press $K_{Id}$ (max. load) button.

r. Press PRINT MAN button.

s. Press ENERGY button.

t. Press PRINT MAN button.

u. Press W/A button.

v. Press PRINT MAN button.

w. Press $K_{Id}$ (COD) button.

x. Press PRINT MAN button.

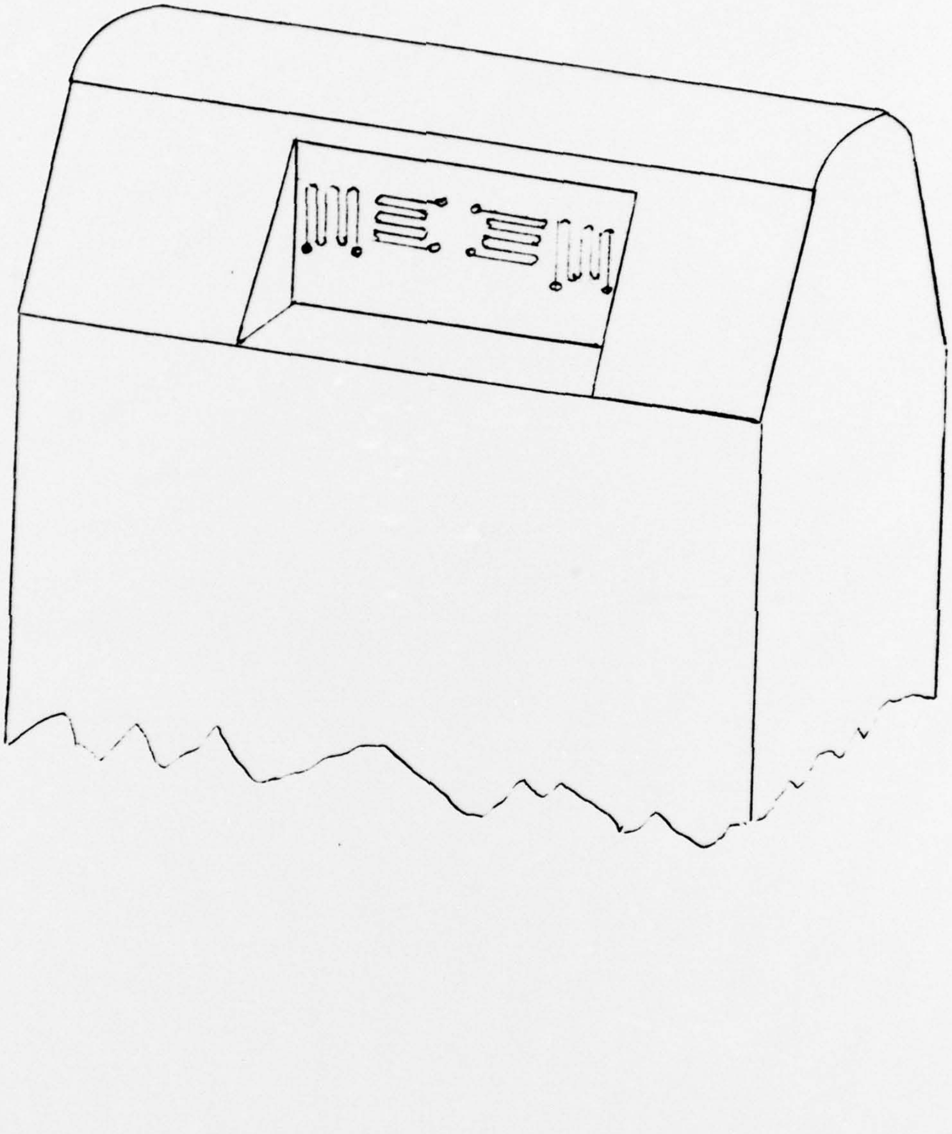


Figure 1

Tup with Recessed Surface and
Arrangement of Strain Gages

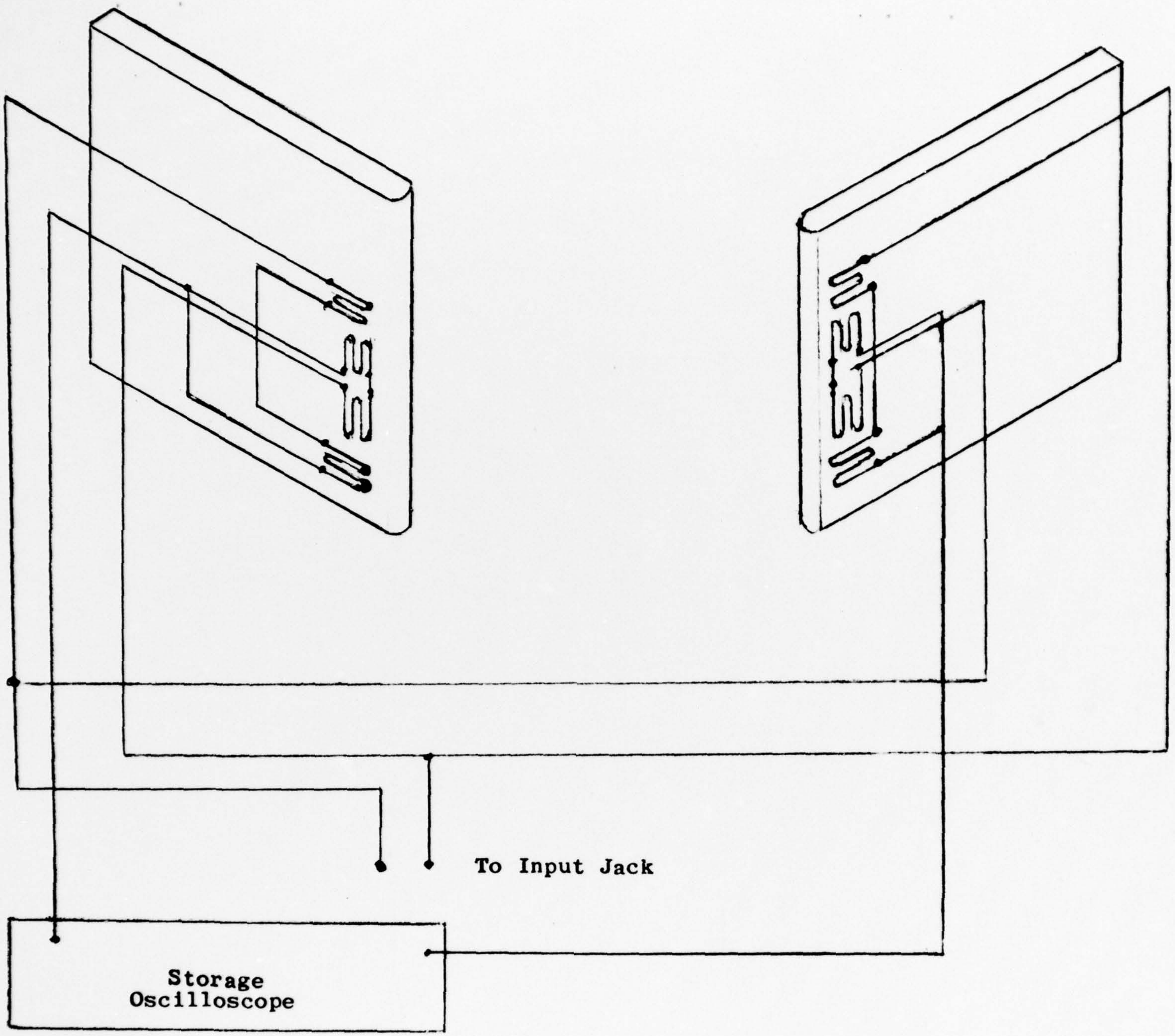
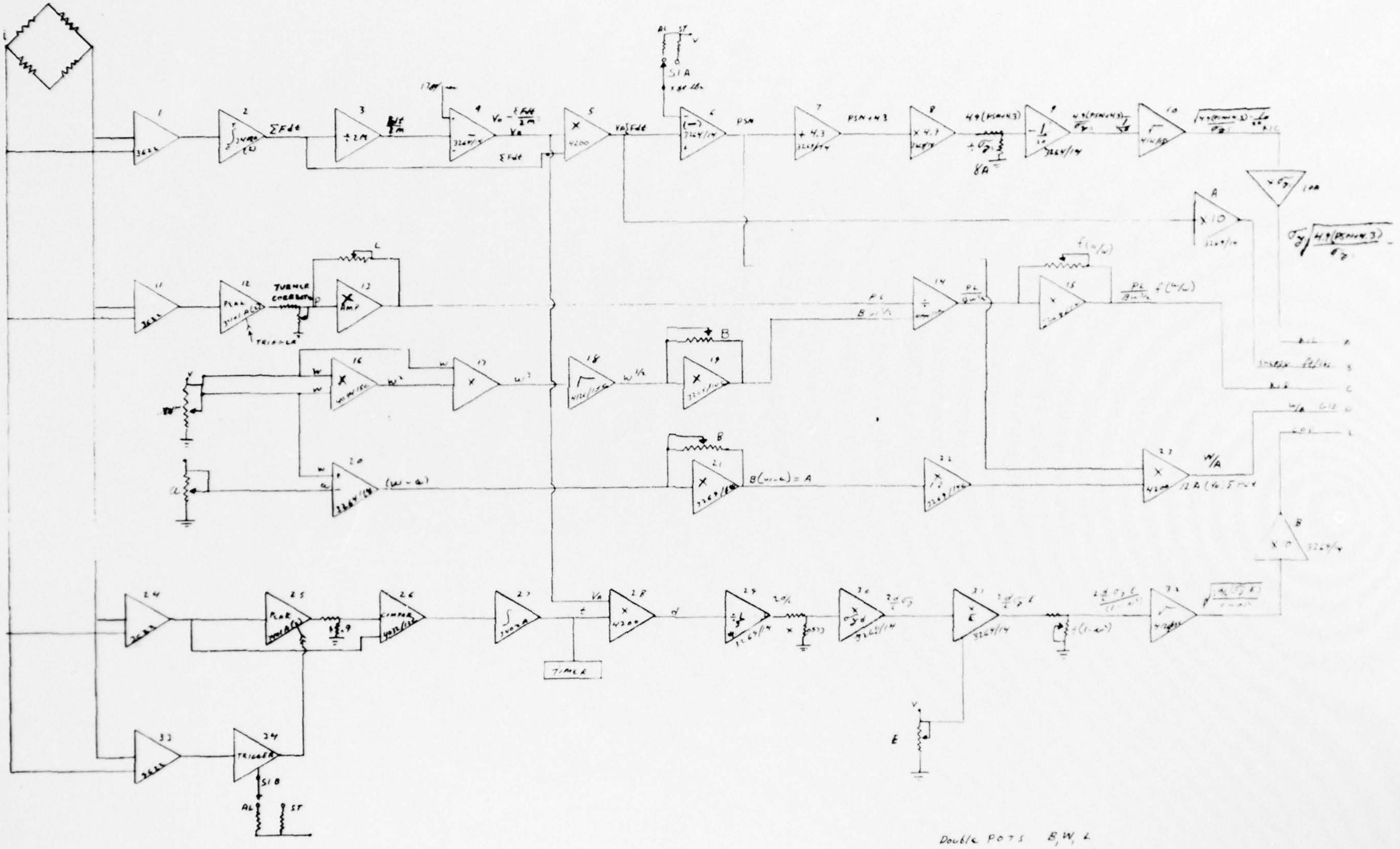


Figure 2 Wiring Diagram of Strain Gage Circuit



Double POTS B, W, L
Single W/A, $\sigma_y$, E, a, N
Switch S1 4 Pole, 3 position

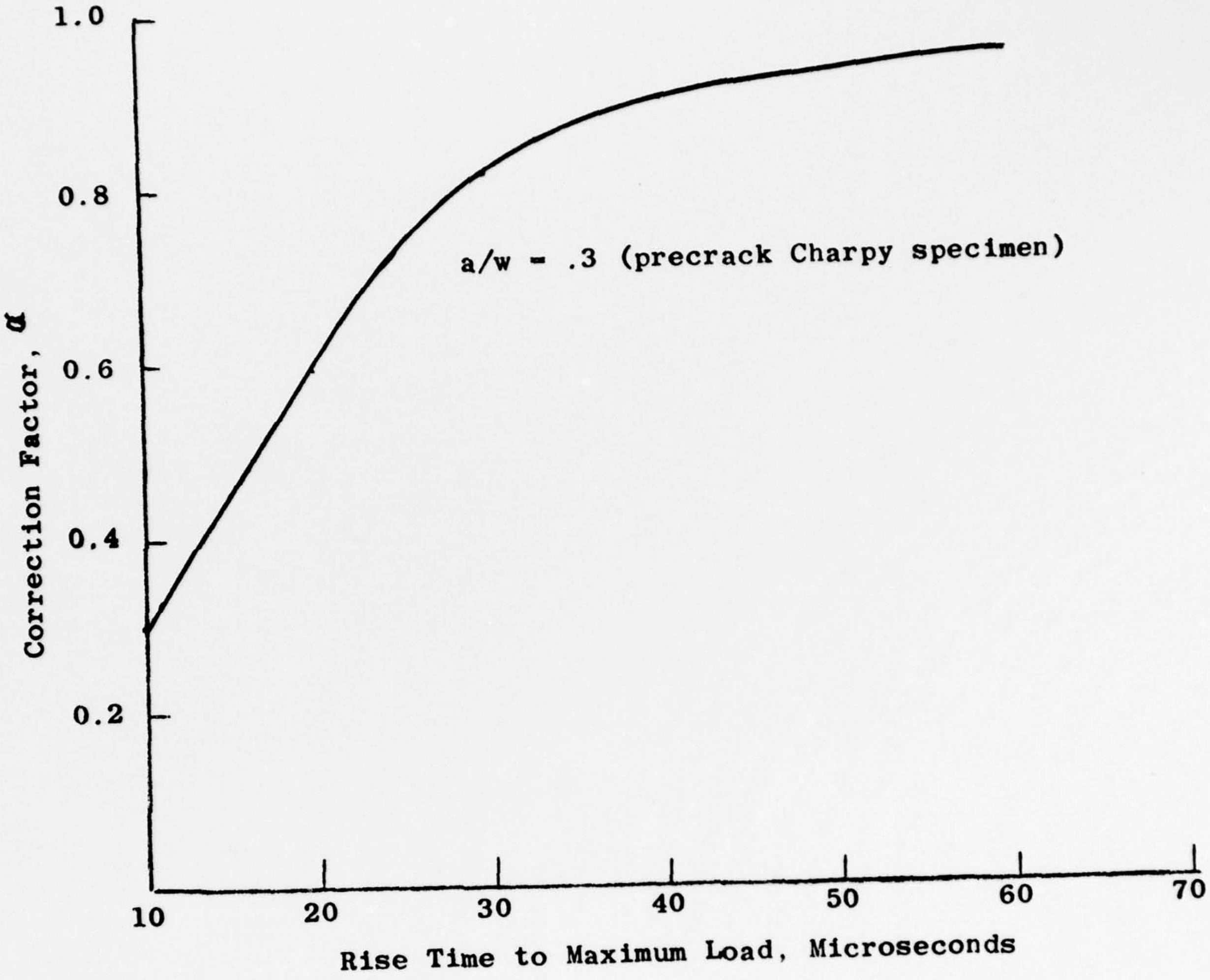
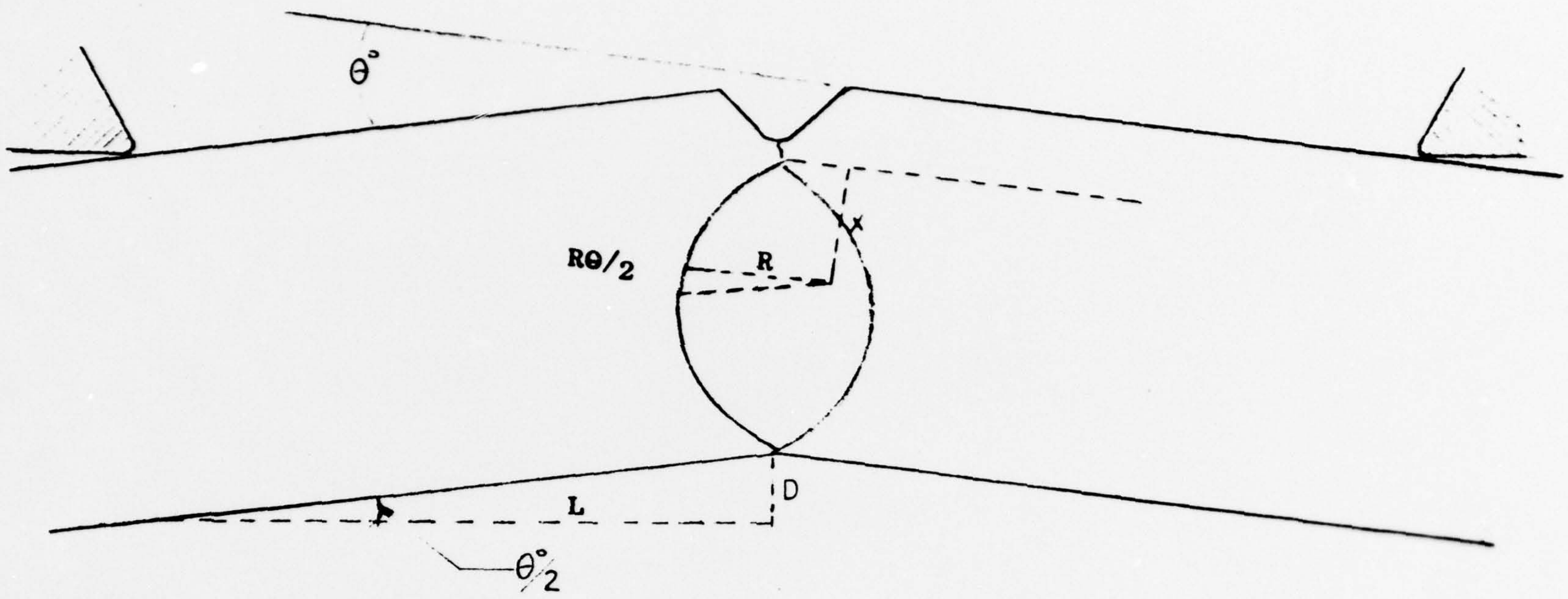


Figure 4 Correction Factor for Precrack Charpy During the Maximum Load Cycle (After Turner)



D (deflection) = time x velocity

L = Half-Span Support

COD = $X\theta^{o}$

$\theta^{c}$ (radians) = 2D/L

Figure 5 Mechanism of Computerized Determination of Specimen Bend Angle by Time at Onset of Unstable Crack Propagation

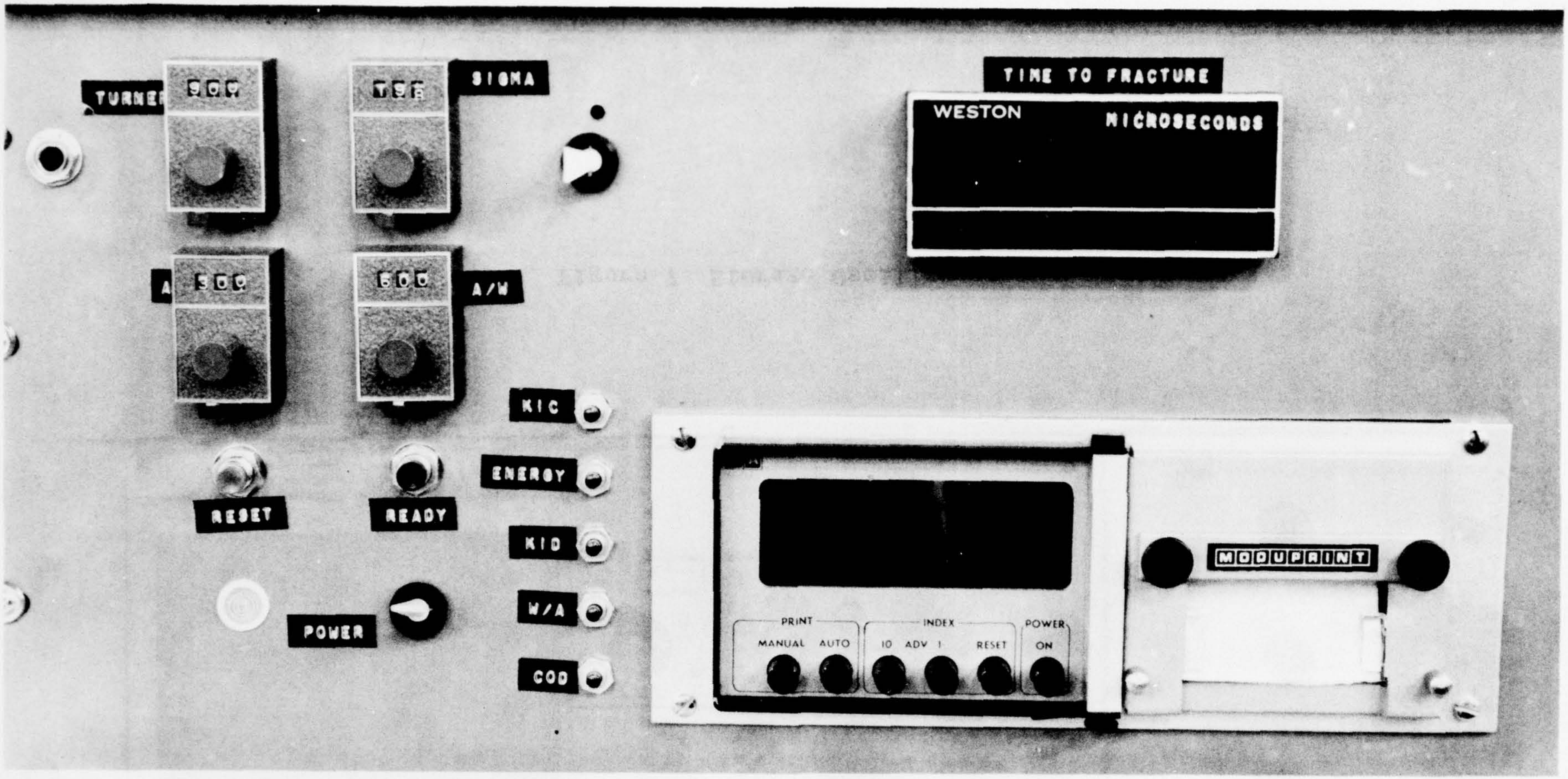


Figure 6 Analog Impact Test Unit
Showing Front Panel Controls

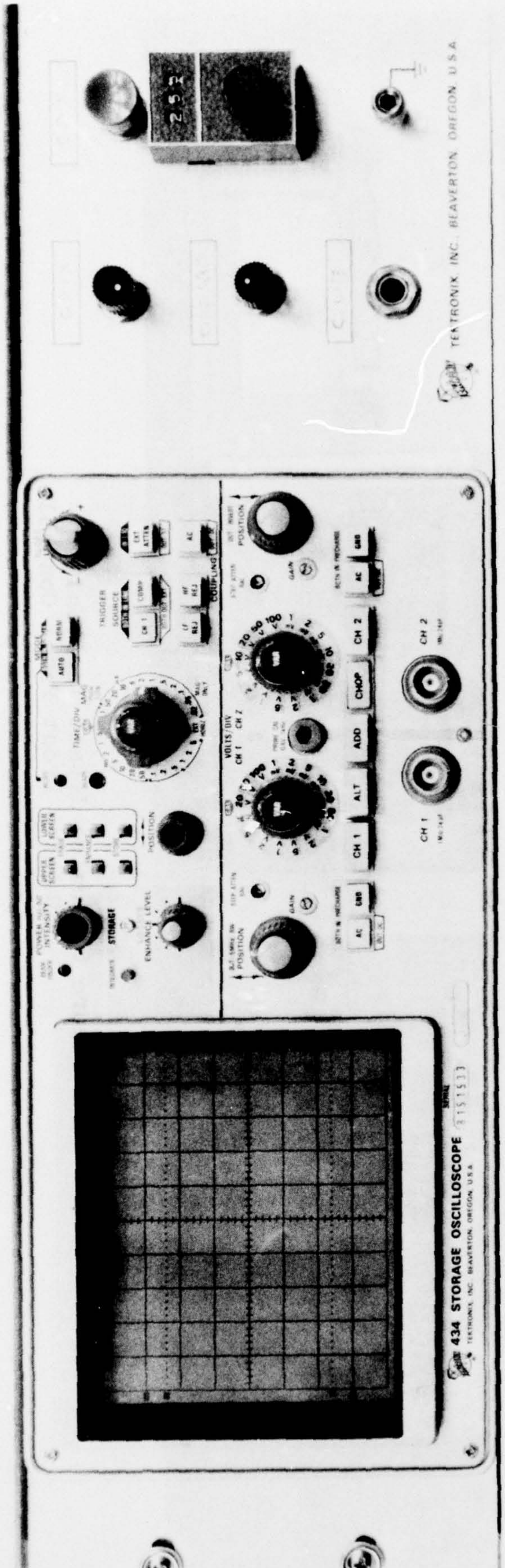


Figure 7 Storage Oscilloscope

# PARTS LIST

| Symbol or Part | Manufacturer's Part No. | Description |
|---|---|---|
| 1 | BB 3622 | Operational Amplifier |
| 2 | BB 9580/15, 3402, 9859/15 | Integrator |
| 3 | 100 KΩ, 43K | Resistors |
| 4 | BB 3264/14 | Subtractor |
| 5 | BB 4200 | Multiplier |
| 6 | BB 3264/14 | Operational Amplifier |
| 7 | BB 3269/14 | Operational Amplifier |
| 8 | BB 3269/14 | Operational Amplifier |
| 9 | BB 3264/14 | Operational Amplifier |
| 10 | BB 4126/15C | Square Rooter |
| 10A | BB 4094/15C | Multiplier |
| 11 | BB 3622 | Operational Amplifier |
| 12 | BB 3401A (2) | Peak Detector |
| 13 | BB 3009/15C | Operational Amplifier |
| 14 | BB 4094/15C | Multiplier |
| 15 | BB 3269/14 | Operational Amplifier |
| 16 | BB 4094/15C | Multiplier |
| 17 | BB 4094/15C | Multiplier |
| 18 | BB 4126/15C | Square Rooter |
| 19 | BB 3269/14C | Operational Amplifier |
| 20 | BB 3264/14 | Operational Amplifier |
| 21 | BB 3269/14 | Operational Amplifier |
| 22 | BB 3269/14 | Operational Amplifier |
| 23 | BB 4200 | Multiplier |
| 24 | BB 3622 | Operational Amplifier |
| 25 | BB 3401A (2) | Peak Detector |
| 26 | BB 4032/12C | Comparator |
| 27 | BB 9580/15, 3402, 9859/15 | Integrator |
| 28 | BB 4200 | Multiplier |
| 29 | BB 3269/14 | Operational Amplifier |
| 30 | BB 3264/14 | Operational Amplifier |
| 31 | BB 3269/14 | Operational Amplifier |
| 32 | BB 4126/15C | Square Rooter |
| Timer | Weston 0-9.99 vde Meter | Voltmeter |
| Oscilloscope | Tektronics #434 | Storage Oscilloscope |
| DVM | Practical Automation #PDM600 | Printer |
| $\sigma\bar{y}$ | 1K | Potentiometer |
| a | 50K | Potentiometer |
| Turner | 50K | Potentiometer |
| E | 50K | Potentiometer |
| f (a/w) | 20K | Potentiometer |
| L | 10K | Potentiometer |
| W | 20K | Potentiometer |
| Power Supply | Lambda Model 4000 ±15vdc | Power Supply |

Figure 8

# LIST OF SYMBOLS

| | |
|---|---|
| a | Depth of notch plus fatigue crack |
| A | Charpy specimen ligament area, B(w-a) |
| $\alpha$ | Turner correction factor |
| B | Specimen thickness |
| COD | Crack opening displacement |
| CVN | Impact energy (conventional Charpy specimen) |
| d | Specimen deflection at crack instability |
| dt | Incremental time interval |
| E | Young's modulus |
| $E_o$ or $W_1$ | Total impact energy as measured by area under force-time curve |
| F | Force or load on specimen |
| fcsg | Fatigue crack-side grooved |
| g | Acceleration due to gravity |
| $G_{IC}$ | Strain energy release rate |
| $K_{IC}$ | Plane-strain static fracture toughness |
| $K_{Id}$ | Plane-strain dynamic fracture toughness |
| L | One-half specimen span support |
| m | Mass of pendulum |
| $\nu$ | Poisson's ratio |
| P | Maximum load applied to specimen |
| $\theta^c$ | Specimen bend angle at crack instability (in radians) |
| t | Time to crack instability or fracture |
| $V_a$ | Average pendulum velocity |
| $V_f$ | Final pendulum velocity |
| $V_o$ | Initial pendulum velocity |
| W | Specimen depth |
| $W_o$ | Weight of pendulum |
| $W_1$ or $E_o$ | Total impact energy as measured by area under force-time curve |
| $\sigma_y$ | 0.2% offset yield strength |
| $\sigma_{yd}$ | Dynamic yield strength |
| x | Rotational constant for plastic hinges |

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EVALUATION WITH CHARPY IMPACT SPECIMEN
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