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A SEMIAUTOMATED COMPUTER-INTERACTIVE DYNAMIC IMPACT TESTING SYSTEM*

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ABSTRACT

A computer-assisted semiautomated system has been developed for testing a variety of specimen types under dynamic impact conditions. The primary use of this system is for the testing of Charpy specimens. Full-, half-, and third-size specimens have been tested, both in the lab and remotely in a hot cell for irradiated specimens. Specimens are loaded into a transfer device which moves the specimen into a chamber, where a hot air gun is used to heat the specimen, or cold nitrogen gas is used for cooling, as required. The specimen is then quickly transferred from the furnace to the anvils and then broken. This system incorporates an instrumented tup to determine the change in voltage during the fracture process. These data are analyzed by the computer system after the test is complete. The voltage-time trace is recorded with a digital oscilloscope, transferred to the computer, and analyzed. The analysis program incorporates several unique features. It interacts with the operator and identifies the maximum voltage during the test, the amount of rapid fracture during the test

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+Instrumentation and Controls Division.

DISCLAIMER

(if any), and the end of the fracture process. The program then calculates the area to maximum voltage and the total area under the voltage-time curve. The data acquisition and analysis part of the system can also be used to conduct other dynamic testing. Dynamic tear and precracked specimens can be tested with an instrumented tup and analyzed in a similar manner.

KEY WORDS

Charpy, dynamic, semiautomated, toughness, fracture, testing, irradiated material, computer program.

INTRODUCTION

A computer-interactive testing and analysis system for dynamic testing has been developed at Oak Ridge National Laboratory (ORNL). The primary reason for the development of the test system was to facilitate the testing of standard and subsize irradiated specimens which must be tested remotely in a hot cell. Additionally, the semiautomated nature of the process is very helpful in the testing of large quantities of specimens in the laboratory. Data collection and analysis are rapidly and reliably performed by the computer which also controls portions of the test operation. A secondary motivation for an instrumented system was for use in conducting precracked Charpy tests and larger dynamic bend tests for obtaining estimates of dynamic fracture toughness.

The primary function of this system is testing Charpy specimens. Three slightly different versions of the system exist at ORNL. This discussion will center on the most recent of these systems, and the slight differences in the other devices will be mentioned. In all cases the test results are sent to a computer after each specimen is broken, where they are analyzed and stored. These results can then be recalled and analyzed as a set. Curves can be fit to the data, and plots of the data and curve fit can be generated and stored. A range of specimen sizes and types can be tested and analyzed in a similar fashion.

The test system consists of four main components, shown in Fig. 1. A rotary transfer device, consisting of a motor, arm, specimen holder, and positioning cam, allows the specimen to be loaded and then transferred to the appropriate position. A temperature conditioning system heats or cools the specimen to the desired temperature. A Tinius-Olsen 407-J (300-ft-lb) Charpy testing machine equipped with an instrumented tup is used to break the specimen and generate a voltage-time trace for the test. A Hewlett-Packard series 200/300 computer, a Nicolet digital oscilloscope, and other controls are used to position the transfer arm, collect the data, and perform posttest analysis.

SYSTEM COMPONENTS

ROTARY TRANSFER MECHANISM

The rotary transfer mechanism is based on a similar device designed by Battelle Columbus Laboratories.[1] The original design has been modified to suit the ORNL test machine and requirements. Figures 2 and 3 show the transfer mechanism. Motion is provided by a stepper motor which allows the arm to be repeatably positioned at any location, once an initial reference is established. The new arm location is determined by sending a number of pulses to the motor, which moves a fixed increment for each pulse. Limit switches are used to define the ends of the possible motion of the arm and thereby establish the range of motion.

The transfer arm carries a specimen holder which is held by two rods. Motion of these rods is controlled by a positioning cam which contains a slotted track in which a follower rides. This follower is attached to the other end of the dual rods. As the motor turns the arm, the follower moves in the positioning cam track, causing the specimen holder to extend or retract, depending on the profile of the cam. This allows the specimen to be carried from the temperature conditioning chamber, and moves the specimen linearly through the anvil area, to aid in specimen placement.

The bottom of the specimen holder, shown in Fig. 4, is fabricated of aluminum, which helps to rapidly establish the desired temperature, due to its high thermal conductivity and low heat capacity. The middle of the holder is fabricated from a ceramic insulator to thermally isolate the bottom of the holder and the specimen in order to minimize thermal gradients within the test specimen. The holder contains a slot appropriate to the size of specimen, and the holder is readily changed depending on the size of specimen being tested. The slot contains a knife edge which positions the specimen laterally by fitting in the specimen notch, and two small magnets assist in holding the specimen in place once it has been loaded. The knife edge and magnets are held in place by small set screws. Several adjustments are possible to allow the holder to be properly located on the transfer arm. The holder is set up at room temperature so that expansion and contraction during heating or cooling will not result in misplacement of the specimen on the test anvils. A thermocouple is inserted through a hole in the holder (Fig. 4) and positioned near the specimen to allow the temperature to be monitored. Verification of the accuracy of using a thermocouple mounted in the holder to establish the specimen temperature and its uniformity was assured through extensive comparisons with dummy specimens instrumented with internal and external thermocouples. Based on these results, test procedures which specify required temperature overshoots and minimum equilibration times guarantee a specimen temperature accuracy of ±1°C.

A small air-operated finger is located at the test anvils to aid in specimen location. As the transfer arm rotates and carries the specimen to the test anvils, it contacts a switch which activates the finger. This finger holds the specimen against the anvils momentarily as the specimen is left on the anvils, and maintains the specimen position as the holder departs.

HEATING/COOLING SYSTEM

Temperature control of the specimens is provided by a heating/cooling chamber fabricated from aluminum plate and insulated with a thick layer of machinable ceramic (trade name Lavite). Components of the system are shown in Figs. 1 and 3. Heating is provided by a commercially available hot air gun system which uses the laboratory compressed air supply. The operator controls the heating by adjusting the volume of air blown into the chamber, and the electric current sent to the heater elements. The power supply to the heater elements is interlocked with the air, so that the elements cannot be heated unless air is being blown over them. Cooling is provided by the vaporization of liquid nitrogen, which is stored in a vacuum dewar pressurized with dry nitrogen gas, and is delivered to the heating/cooling chamber through an insulated flexible hose. The operator controls the delivery of nitrogen to the chamber with an electrically activated valve. The thermocouple mounted in the specimen holder provides the operator with the specimen temperature. Operator controls for the heating and cooling are located in the control rack (Fig. 1). The chamber door is interlocked with the transfer arm so that the arm will not move unless the door is open. This system allows the specimen temperature to be readily varied from approximately -190 to 350°C.

Test specimens are heated above or cooled below the desired test temperature and then allowed to drift back to the proper temperature, in accordance with approved test procedures, at which point testing is initiated by the operator. Full-size Charpy specimens are heated or cooled to the desired test temperature, as specified in ASTM E 23, "Standard Method for Notched Bar Impact Testing of Metallic Materials." However, smaller specimens change their temperature much more rapidly than do full-size ones. Therefore, smaller specimens are either overheated or undercooled to allow for their temperature change during the predetermined time required for transfer to the anvils and subsequent testing (<5 s). The required temperature overshoots for the subsize specimens were determined by instrumenting dummy specimens with thermocouples, and monitoring their temperature change during transfer and positioning on the anvils.

The temperature conditioning method utilized in this system does not strictly meet the limited methods stipulated in the ASTM E 23 test method. That method requires the immersion of the specimen in either an agitated liquid bath or a gaseous atmosphere, maintained to within ±1°C of the desired test temperature for specified minimum times as the only acceptable means of assuring specimen temperature conditioning. It was felt that strict adherence to E 23 would be overly and unnecessarily restrictive and would result in an unacceptably slower rate of testing, particularly for the irradiated specimens. Also, previous experience indicated that gaseous atmospheres could achieve satisfactory temperature control in much less than 30 min.[2] Furthermore, the conditioning system described above does meet the alternative requirements for specimen conditioning which are allowed for Charpy impact testing under ASTM E 184, "Standard Practice for Effects of High-Energy Neutron Radiation on the Mechanical Properties of Metallic Materials."

CHARPY IMPACT MACHINE

The actual testing of the specimen is carried out on a Tinius-Olsen 407-J (300-ft-lb) capacity pendulum impact tester. The tup of this machine has been instrumented with strain gages. The tup and anvils are changed depending on the size of specimen being tested. A smaller, narrower tup and narrower anvils are used for the subsize Charpy specimens.[3] Additionally, the hammer is dropped from a lower height for subsize specimen testing. This prevents the broken specimen from being thrown large distances from the test site. In all testing, hammer release is controlled by the operator.

The test machine, like any standard Charpy tester, is equipped with a dial which indicates the energy absorbed during each test, and must be manually reset for each test. Additionally, this machine is equipped with a Tinius-Olsen supplied rotary encoder which sends a dual train of electronic pulses to the digital energy display. These pulses permit the extent and direction of motion of the hammer to be determined, from which the computer program derives the energy absorbed during the test. This calculation is based on an initial setting performed with the hammer hung motionless at bottom dead center. The energy display must also be reset manually after each test.

The tester also includes an electric brake for slowing the hammer after a test, and provisions for the installation of a clutch and motor for raising the hammer after a test. These have not been installed on the laboratory machine and the hammer must be raised and released manually. Apart from the deviations from the required specimen temperature conditioning discussed above, all aspects of the automated Charpy impact test system meet the full requirements of the ASTM E 23 standard test method.

CONTROLS AND ANALYSIS EQUIPMENT

The controls associated with the tester consist of several components. A strain gage conditioner amplifies the voltage changes in the tup strain gage bridge during testing. Filters are available for smoothing the data from the bridge, and can be bypassed if the operator chooses. Gain and zero settings are also provided. A temperature indicator displays the thermocouple reading. The energy display, supplied by Dynatup, Inc., receives motion pulses from the encoder and determines the energy absorbed during the fracture event. In addition, the encoder pulses are used to sense the hammer position (5° from bottom dead center) and send a trigger signal to the oscilloscope to capture the fracture event.

The indexing controller, supplied by Compumotor, Inc., sends pulses to the stepper motor which moves the transfer arm. Limit switches at either end of the range of the arm set motion limits, and the indexer moves the arm between these limits, based on motion commands generated by the computer. The indexer allows the operator to vary the speed of the arm motion, and it may be operated manually to change the arm position.

A Nicolet digital storage oscilloscope, model 2090 or 4094, is used to display the tup strain gage voltage vs time trace. The 4094 model has 16 kB of memory per channel, compared to 4 kB for the 2090 model. The computer program displays only 4 kB to allow either model to be used. The 4094 oscilloscope can be set from 100 ns to 10 s per point and has a full-scale voltage of ±40 V to 100 MV. The 2090 time scale varies from 500 ns to 200 s per point. The external trigger signal from the energy display can be used, or the tup voltage can trigger the scope. The external trigger signal is more dependable when testing subsize specimens which may fracture with very low energy and, thus, a small voltage signal.

The computer which operates the system and performs the data analysis is a Hewlett-Packard series 200/300, with 4 MB RAM. Mass storage is provided by a 10-MB hard disk and a 0.67-MB, 3.5-in. floppy disk. The computer is connected to a printer and plotter for recording the test progress and outputting the data analysis.

TEST PROCEDURE

Once the BASIC operating system has been booted and the test program loaded, testing can begin. The computer prompts the operator to establish the limits of motion of the arm travel before any testing is done. The arm is driven against one of the limit switches to allow the indexer to determine a reference position. The energy display is set by first allowing the hammer to hang at bottom dead center and storing that position, and then checking the windage losses for a free swing. The computer then prompts the operator to raise and latch the hammer, reset the energy display, and test when ready. All settings of the oscilloscope are controlled by the computer, but can be changed through operator commands to the computer program. However, the switches on the front panel of the oscilloscope are overridden by the computer settings. The operator opens the heating/cooling chamber door by activating an air cylinder, and uses special function or "soft" keys on the computer keyboard to move the arm into position for loading the specimen. After the specimen is loaded, the operator uses another soft key to move the arm and holder into the temperature chamber, and then closes the door. Heating or cooling are activated manually, until the desired temperature is slightly exceeded. The temperature is then allowed to drift back to the desired temperature, thereby minimizing any temperature gradients in the specimen. The door is then opened by the operator with the air cylinder, and another soft key moves the arm around so the specimen is positioned on the anvils. The finger holds the specimen against the anvils momentarily after the specimen is released from the positioning arm, then retracts, and the operator releases the hammer after checking that the transfer arm is clear and that the specimen is seated satisfactorily against the anvils. The elapsed time from removal of the specimen from the conditioning chamber to impact is typically about 3 s.

When the operator indicates to the computer that the hammer has been released, the computer checks the oscilloscope for a trace and if present, transfers the trace into computer memory. The test data can then be analyzed or stored for later analysis. The operator raises and latches the hammer, and continues the testing according to the computer prompts.

TEST DATA ANALYSIS

Two types of analysis can be performed. The first analyzes a single test trace, while the second analyzes a set of test data. The test data analysis is usually performed while testing is being conducted. Figure 5 shows a typical trace from the computer display. The computer identifies the beginning of the test by the deviation from the base line. The time to maximum voltage is also identified by fitting the upper portion of the curve with a parabola. The high voltage region of the trace is marked by the operator using soft keys to move a cursor on a display of the voltage-time trace. If the operator does not accept the computer-determined voltage maximum, the cursor can be moved with soft keys for operator determination of the maximum. The computer then asks if any rapid fracture, seen as a sudden voltage drop (indicative of cleavage fracture[2]), occurred during the test, and displays an expanded view of the load-decreasing portion of the test for the operator to examine. If a rapid load drop occurred, the operator identifies the beginning and end of the fast fracture by using the arrow keys to move the cursor. The end of the test is taken as the time when the trace returns to the baseline. The computer then calculates and displays the maximum load (i.e. voltage), the area under the curve up to maximum load, the total area under the curve, and the load drop in rapid fracture, if any, as a percentage of the maximum voltage. Finally, a record of the test is displayed with all the calculated data, test parameters, and the voltage vs time trace.

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DATA SET ANALYSIS

Sets of test data can also be analyzed by the program. Test data, such as energy absorbed, lateral expansion, or fracture appearance (percent ductile fracture), can be loaded from disk files or through the keyboard. The data are then fitted with a hyperbolic tangent function which has four degrees of freedom. The lower shelf, mid-transition temperature, transition zone width, and upper shelf can be determined. The first three of these variables can either be determined during the fit or specified by the operator. The upper-shelf energy is always determined by the computer. The program uses an incremental nonlinear Marquardt algorithm to find the best fit of the data to an equation of the form (for the case of the energy):

$$\text{Energy} = A + B*\tanh[(\text{Temperature} - T_0)/C] \ ,$$

where

A = energy at mid-transition, J,

B = energy from mid-transition to upper (or lower) shelf, J,

C = transition zone temperature width, °C, and

T_0 = mid-transition temperature, °C.

The operator is asked for initial values for those parameters which are not fixed. The data are displayed to aid in this selection. A judicious choice of the initial values speeds the fitting and helps avoid divergence. If the algorithm does diverge, the program will request new initial values.

Once the curve fitting is complete, the temperature at specified energy (or lateral expansion or percent ductile fracture) values can be determined, if the operator wishes. Typically the operator will ask for the temperature at 40.7 and 67.8 J (30 and 50 ft-lb). Then the computer stores the fit parameters and plots out a graph of the data and/or the fit, as specified by the operator. An example of the analysis for a set of data is shown in Fig. 6. In this case, the lower shelf energy was specified by the operator at 6.78 J (5 ft-lb), but the other parameters were determined by the program. The program can combine data sets for analysis and offers the capability of correcting, deleting, or transforming data. In addition, presentation quality graphs can be produced on the plotter. A typical plot for a group of data sets is shown in Fig. 7.

OTHER TEST SYSTEMS

There are two additional test systems at ORNL. The oldest version of this system has a linear specimen transfer device, rather than rotary, and is described in more detail elsewhere.[2] The specimen is aligned in the anvils with the aid of air cylinders which drive rods against both ends of the specimen. The test machine is a 325-J (240-ft-lb) Baldwin impact tester, without a rotary encoder on the dial. The energy absorbed must be noted from the machine dial. Specimen cooling uses a nitrogen gas system similar to that described above, but heating is applied by passing an electric current through the specimen. The specimen is forced against electrodes inside the temperature conditioning box, and the current can be varied manually by the operator to bring the specimen to temperature. This system is used only for testing full-sized specimens.

The other test system is located in a hot cell and is used for testing irradiated specimens. Full-, half-, and third-size specimens have been tested. The test machine, also a 407-J (300-ft-lb) Tinius-Olsen machine, is equipped with a brake, clutch, and motor which allows the hammer to be raised, latched, and released remotely. The specimens must be loaded in the holder with manipulators, and then recovered after the fracture event. To aid in the recovery, the machine has been fitted with plexiglass shields along the line of the hammer's swing, as well as cloth slings intended to catch the broken specimens. The machine dial indicator has a fan attached to it to allow a blast of air to reset the dial, although the rotary encoder is the primary energy indicator. The brake allows the hammer to be held at a lower position, a feature which is utilized in conducting precracked Charpy V-notch (PCVN) testing, for which the hammer is dropped from a fairly low position. To accommodate the lower position, the positioning cam has a slightly different shape to allow the arm and specimen holder to travel from the heating/cooling chamber to the anvils without hitting the hammer when it is held in the lower position. Special interlocks allow the hammer to be dropped only when the positioning arm is out of the travel path of the hammer, which provides additional safety for the testing equipment and protects the valuable irradiated specimens from damage due to an accidental hammer drop.

OTHER TEST TYPES

Preliminary work indicated that instrumented dynamic tear tests can be conducted on a vertical drop-weight machine using the data acquisition system described above. An instrumented tup was used, and tests at room temperature produced load vs time plots similar to those found in Charpy tests. The data analysis used for the charpy specimens was also suitable for these test results. As mentioned above, fatigue precracked bend specimens can be tested and analyzed in a manner similar to the PCVN specimen.

USER EXPERIENCE

These systems have been in regular and continuous use at ORNL for several years. They have proven to be relatively trouble free. However, there have been some problems. The specimen holders used in the rotary transfer systems have knife edges and magnets to help align and hold the specimens in place. The magnets in the holders in the hot cell have had a tendency to loosen and pull out of place. Apparently the differential thermal expansion and contraction during repeated heating and cooling loosens the set screws, allowing the magnets to move. This problem is exacerbated in the hot cell, since the irradiated specimens are frequently very brittle, and significantly higher temperatures are required to reach the upper shelf during testing. Thus, the holder is exposed to much larger thermal cycles than are typically seen for testing similar unirradiated specimens in the laboratory. Of course, repairing any such problem remotely in the hot cell is extremely difficult. For full-size specimen holders, a small tab has been soldered to the back of the magnets on the back of the specimen holder. This tab prevents the magnets from being pulled forward out of position as the specimen is removed while the specimen holder travels through the anvils.

Thermal expansion can also cause problems by causing the specimen holder to elongate, thus lowering the specimen and resulting in it being displaced as the holder approaches the anvils. Experience has shown that setting up the holder so that the specimen sits 0.25 mm (0.010 in.) above the anvil rails results in trouble-free operation, yet still assures proper specimen positioning.

SUMMARY AND CONCLUSIONS

1. Computer-interactive semiautomated dynamic impact testing systems have been developed which allow rapid, consistent, and accurate determination of toughness properties.
2. The systems have been successfully adapted for remote testing of irradiated materials.
3. Methods for testing subsize specimens have also been developed and adapted for remote operations.

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LIST OF FIGURES

Fig. 1. Overall view of the semiautomated system installed in the laboratory. The computer system and other controls are on the left, and the transfer mechanism and test machine are on the right.

Fig. 2. Close-up view of the transfer device and the test machine. The transfer arm is in position for specimen loading, and the hammer is shown in position for testing subsize specimens.

Fig. 3. A view of the transfer mechanism, showing the positioning cam used to control the extension of the transfer arm and the temperature conditioning system.

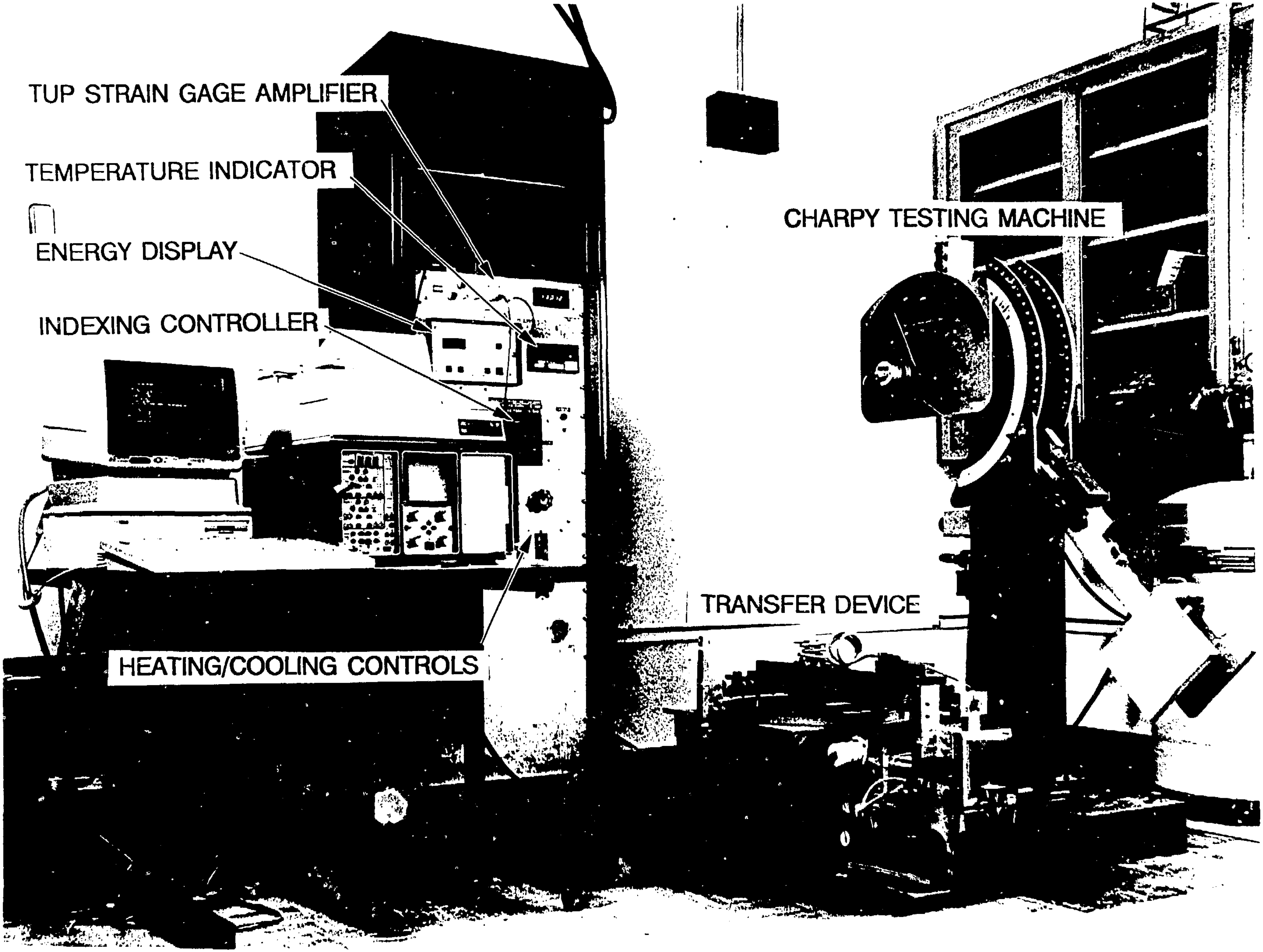
Fig 4. Detail of the specimen holder as it approaches the test anvils. The holder contains a third-size specimen.

Fig. 5. A typical voltage-time trace for a full-size Charpy specimen test. The program identifies the start and end of the test, and, with operator assistance, the maximum voltage (i.e., load) and any rapid load drop. The labels on the drawing and axes have been added for clarity, and are not typically present.

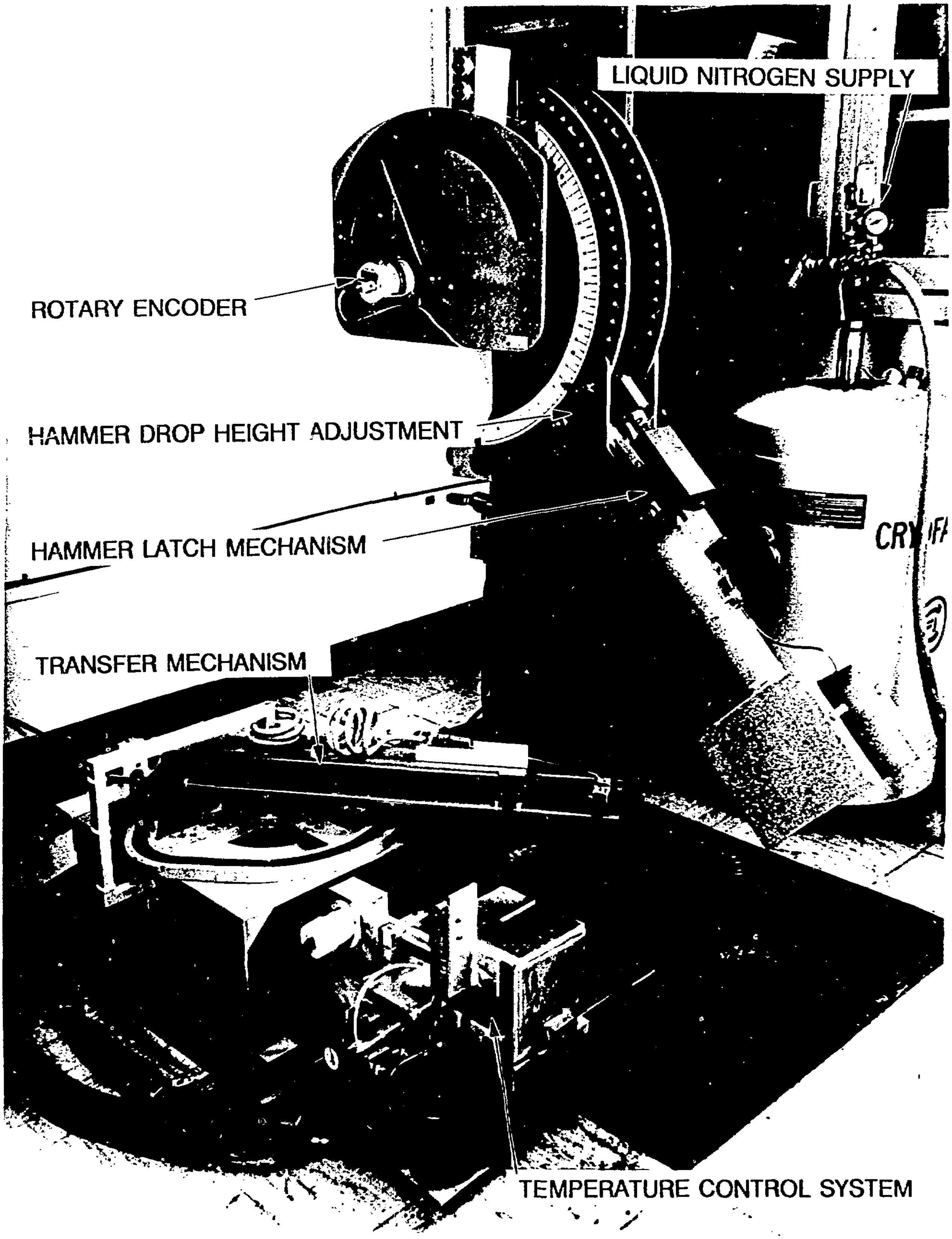
Fig. 6. A typical analysis of a set of data, in this case for full-size Charpy specimens of type 308 stainless steel weld metal aged for 20,000 h at 343°C. In this case, the lower shelf was set at 6.78 J (5 ft-lb), and the program fitted all other parameters.

Fig. 7. An example of the graphical output for the analysis of a group of data sets, in this case for full-size Charpy specimens of type 308 stainless steel welds, as welded and aged for 3,000, 10,000, and 20,000 h at 343°C (labeled AR, 3, 10, and 20, respectively). The program allows the axes to be labeled and offers a variety of plot symbols.

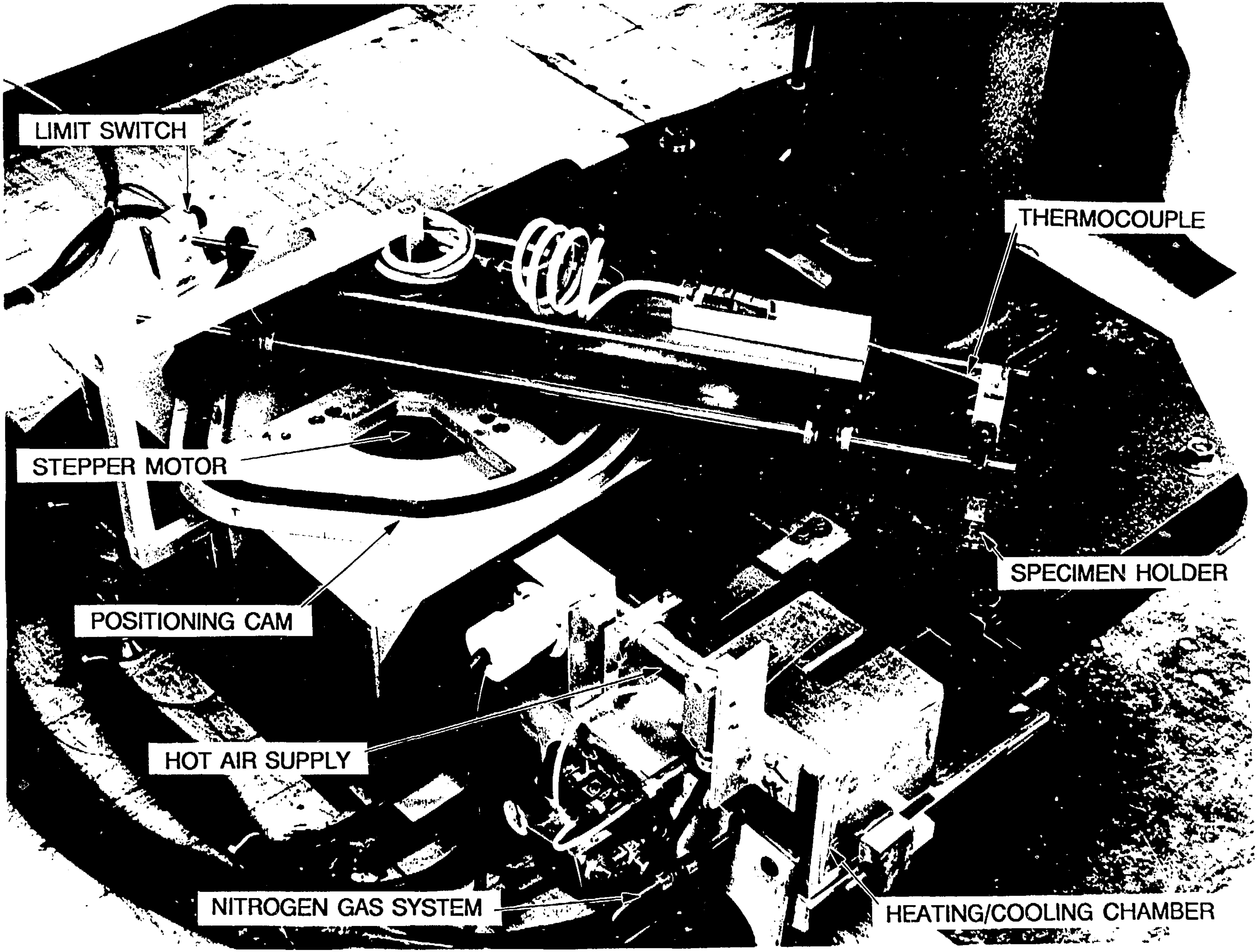
COMPUTER INTERACTIVE CHARPY TESTING SYSTEM



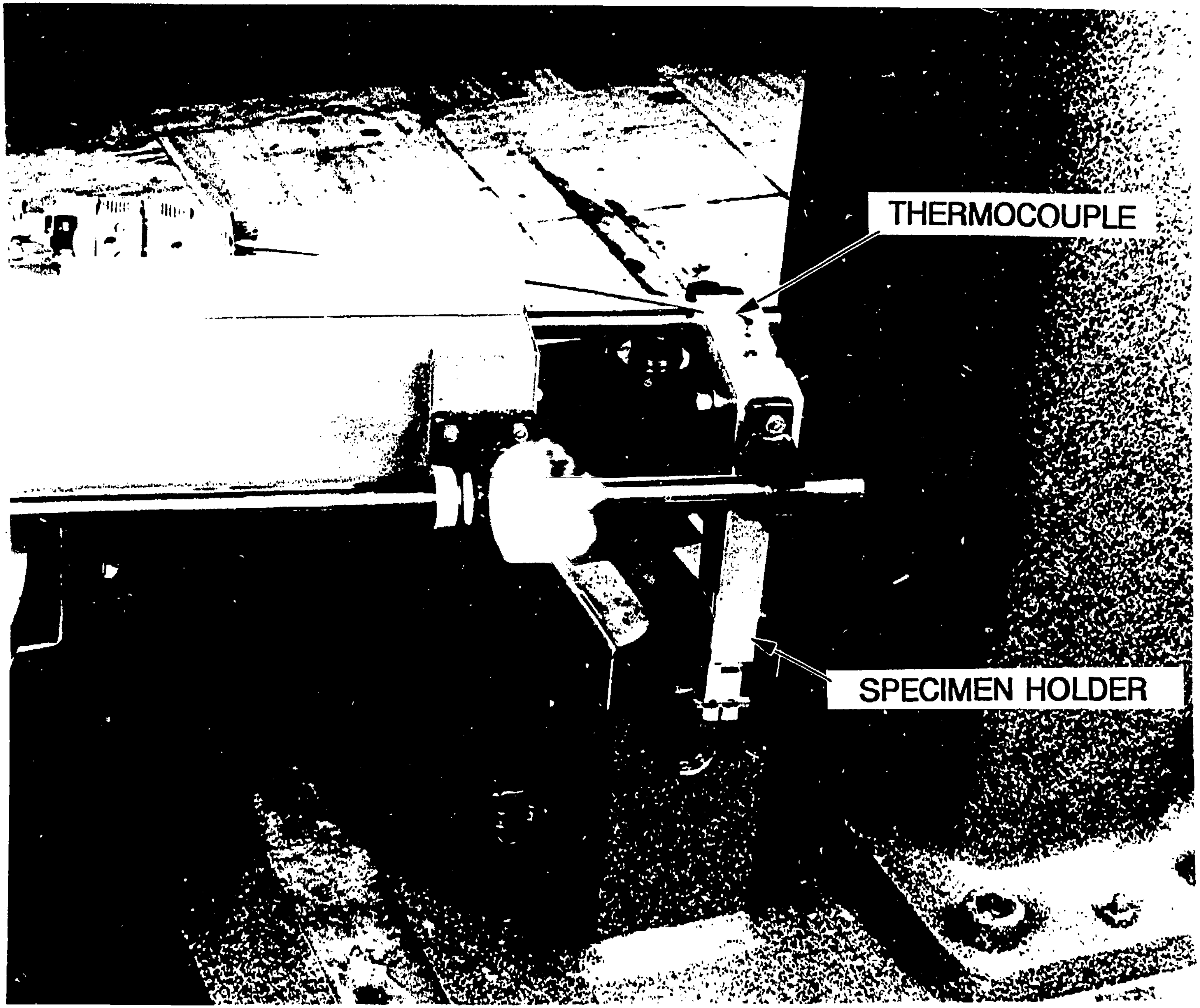
CHARPY TEST MACHINE AND TRANSFER SYSTEM



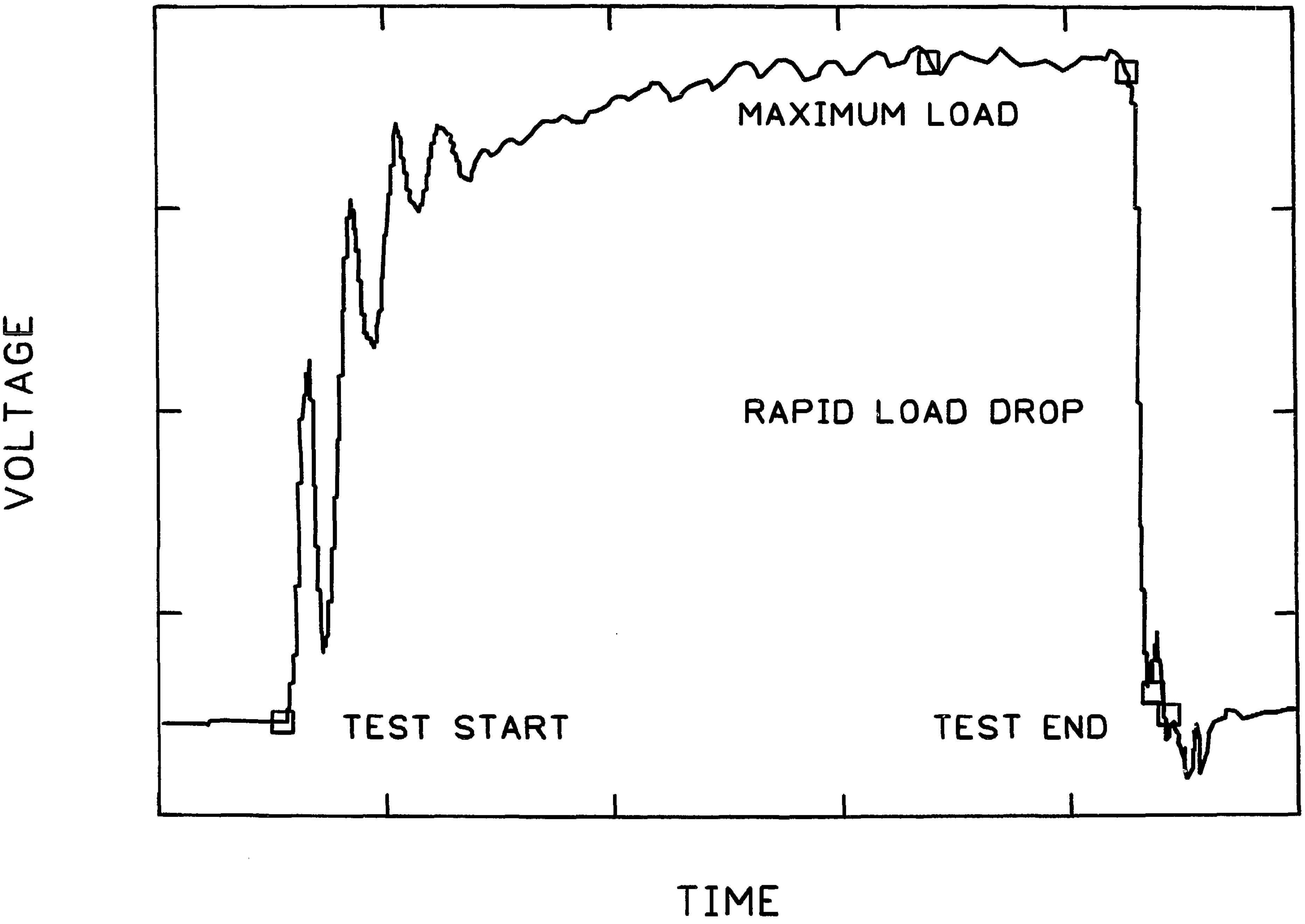
DETAIL OF TRANSFER DEVICE AND TEMPERATURE CONTROL SYSTEM

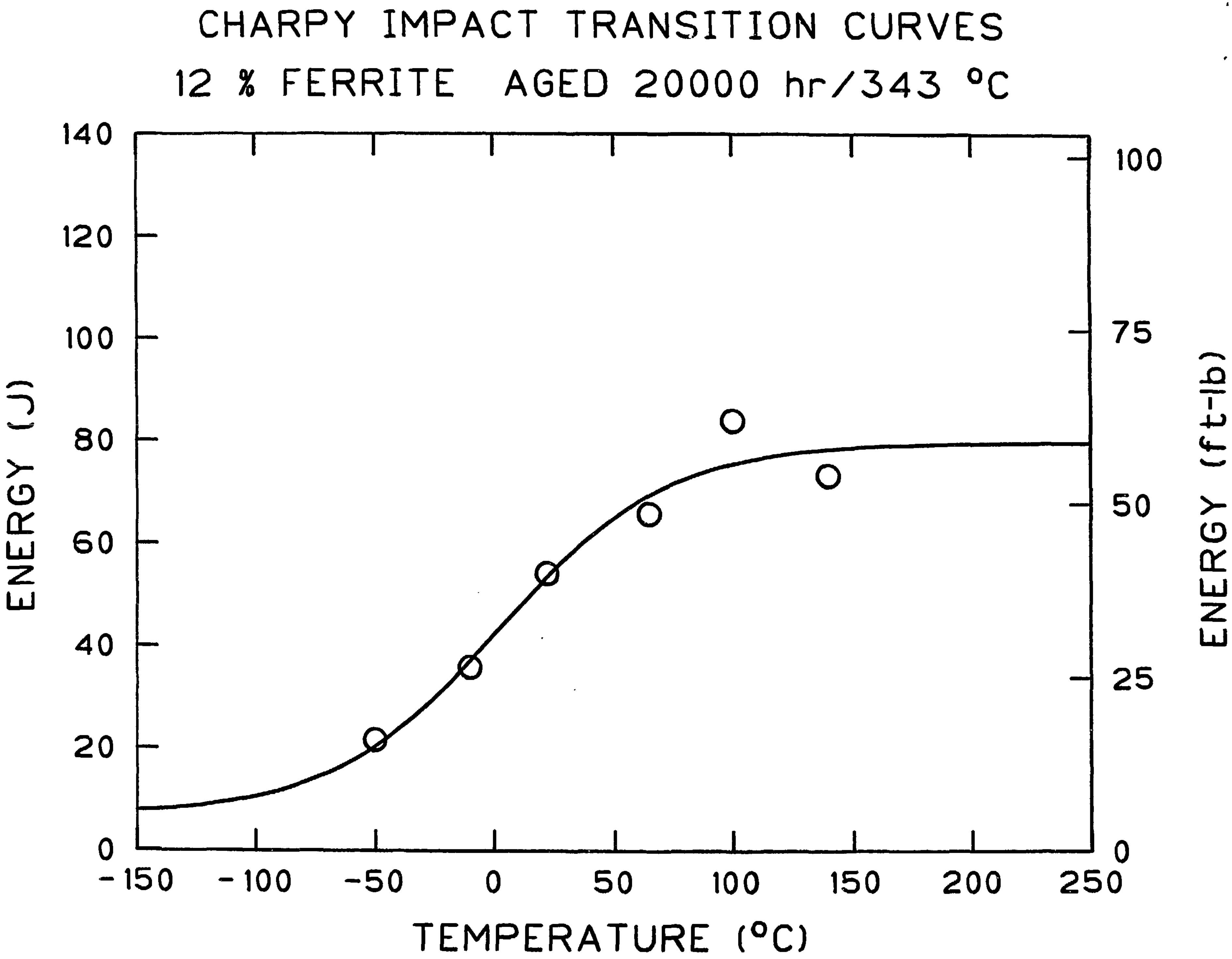


DETAIL OF SPECIMEN HOLDER



TYPICAL PROGRAM OUTPUT





CHARPY IMPACT TRANSITION CURVES

12 % FERRITE AGED 20000 hr/343 °C

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12 % FERRITE