IIITRI Project No. D6059

Semi-Annual Technical Report

EFFECT OF SPECIMEN SIZE ON CONFINED COMPRESSION TESTING OF ROCK CORES

for

Bureau of Mines
Twin Cities, Minnesota

July 1971

IITRI

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IIT RESEARCH INSTITUTE
Technology Center
Chicago, Illinois 60616

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EFFECT OF SPECIMEN SIZE ON CONFINED COMPRESSION TESTING OF ROCK CORES

by

Peter Jay Huck
Madan M. Singh

Monitored by

Bureau of Mines
U. S. Department of the Interior
Twin Cities, Minnesota

Sponsored by

Advanced Research Projects Agency
Washington, D.C.

July 1971

The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied of the Advanced Research Projects Agency, Bureau of Mines, or the U. S. Government.

FOREWORD

This is the semi-annual report on IIT Research Institute (IITRI) Project No. D6059, entitled, "Effect of Specimen Size on Confined Compression Testing of Rock Cores" covering the work period 29 December 1970 to 15 July 1971. This program is being performed under Contract No. H0210009 with the Bureau of Mines of the U. S. Department of the Interior, with Mr. Egons R. Podnieks of the Twin Cities Mining Research Center acting as technical monitor. The program is being sponsored by the Advanced Research Projects Agency of the U. S. Department of Defense under ARPA order no. 1579, Amendment 2.

The project is being conducted under the direct supervision of Dr. Madan M. Singh, who is serving as porgram manager. Mr. Peter J. Huck is project engineer. Other IITRI staff members contributing to the overall research effort include Drs. R. H. Cornish and A. Semmelink, and Messrs. L. A. Finlayson, P. A. Hettich, E. J. Smith, J. Vosatka and A. Wawrzysz n.

Respectfully submitted
IIT RESEARCH INSTITUTE

Madan M. Singh

Madan M. Singh, Manager
Soil and Rock Mechanics

APPROVED:

R. H. Cornish

R. H. Cornish
Director of Research
Mechanics of Materials Division

MMS/bk

IITRI PROJECT NO. D6059

Semi-Annual Technical Report

(Covering the Period 29 December 1970 to 31 July 1970)

Sponsored by

Advanced Research Projects Agency

ARPA Order No.:	ARPA 1579, Amendment 2
Program Code Number:	1F10
Contract No.:	H0210009
Title of Work:	Effect of Specimen Size on Confined Compression Testing of Rock Cores
Name of Contractor:	IIT Research Institute 10 West 35th Street Chicago, Illinois 60616
Effective Date of Contract:	29 December 1970
Contract Expiration Date:	29 January 1972
Amount of Contract:	$75,791
Principal Investigator and Phone No.:	Madan M. Singh AC312/225-9630 Ext 4784, 4785
Project Engineer and Phone No.:	Peter J. Huck AC312/225-9630 Ext 4735

Experimental Apparatus

Four sizes of rock cores are to be investigated in this program. Each core size was tested in a different pressure cell. The specimen dimensions and pertinent pressure chamber specifications are listed below:

Specimen Dia.(in.)	Specimen Length(in.)	Chamber I.D.(in.)	Chamber Pressure Rating(ksi)	Maximum Rated Axial Load(lb.)
2.06	4	4.0	30	375,000
3.65	7	6.5	30	995,000
12	24	14.7	20	3,400,000
32 or 36	60	48.3	20 axial 10 confining	36,500,000

To date only two (2) 2-in. diameter specimens have been subjected to triaxial pressure. The other cores have already been prepared and gaged. The apparatus for the tests has also been set up. The test data should become available in the near future.

Prior to testing the rock cores triaxially, the cylindrical specimens were tested acoustically to map out any major variations in acoustic velocity through them.

Triaxial Cells

Each triaxial cell consists of a thick-walled pressure chamber with a honed interior in which a floating piston moves. A typical arrangement is depicted in Figure 1. The triaxial cell for the 2-in. dia. specimens carries a spherical seat between the piston and the specimen. Because of size restrictions, spherical seats are not used in the larger specimens. Instead, all pistons are provided with special high compliance seal rings that allow the pistons to rotate to conform to the rock specimens. A capping platen covers the top of the core, with a chamber closure above it to hold the assembly in place. The strain gage leads from the rock core and are led through this closure to the data acquisition system. The confining pressure is introduced around the jacketed core, while the axial load is applied by pumping oil below the sliding piston. This scheme for applying axial pressure eliminates the need for a large separate loading machine, and can withstand fairly high loads, depending on pressure cell design.

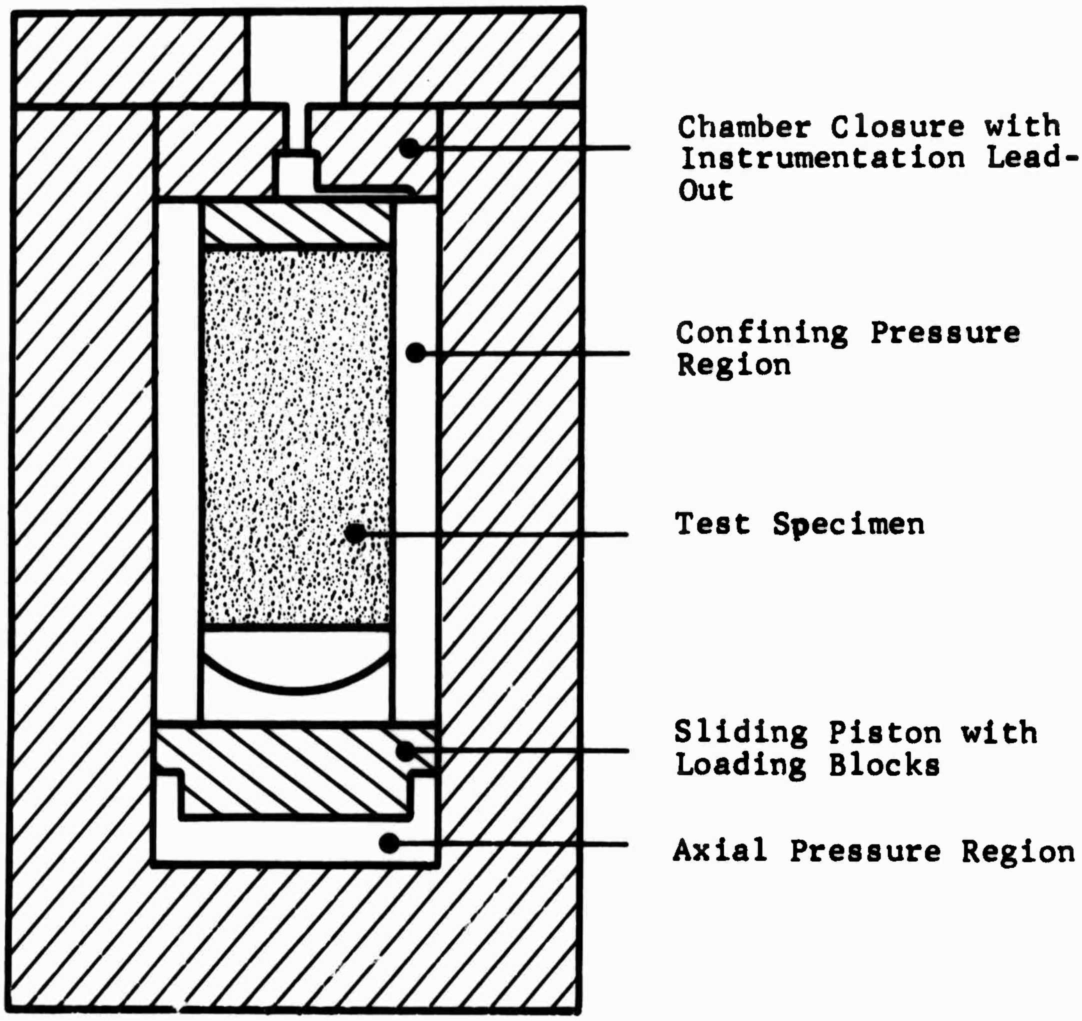


FIG. 1 TYPICAL TRIAXIAL CELL SCHEMATIC

The axial stress in the rock depends upon the ratio of the rock and piston areas and the difference in the confining pressure and the axial chamber pressure. The specimen stresses are given by the following equations:

$$\sigma_2 = \sigma_3 = P_3$$
$$\Delta\sigma_1 = (P_1 - P_3)\,\frac{Ap}{Ar}$$
$$\sigma_1 = \sigma_3 + \Delta\sigma_1$$

where.

A_p = piston area

A_r = specimen area

P_1 = axial chamber pressure

P_3 = confining chamber pressure

$\Delta\sigma_1$ = deviator stress

σ_1, σ_2 and σ_3 = principal stresses.

Reference to Fig. 1 and the above equations confirms that if $P_1 = P_3$, $\Delta\sigma_1 = 0$ and the specimen is under hydrostatic stress ($\sigma_1 = \sigma_2 = \sigma_3$). For $P_3 = 0$, the specimen is unconfined, with $\sigma_2 = \sigma_3 = 0$ and $\sigma_1 = \Delta\sigma_1 = P_1\, A_p/A_r$.

The 4 in., 6 in., and 14 in. dia. pressure chambers are incorporated into a central control panel and instrumentation system and are operated by a common pumping system. A schematic of this layout is given in Fig. 2.

In each of the tests to be performed in this program the rock core is loaded hydrostatically up to the predetermined confining pressure, and then the axial pressure is increased gradually to the desired value. It is planned to run at least one load-unload-reload cycle on each specimen. During the reload the axial stress is increased until the core fails or the capacity of the cell is attained, whichever is lower.

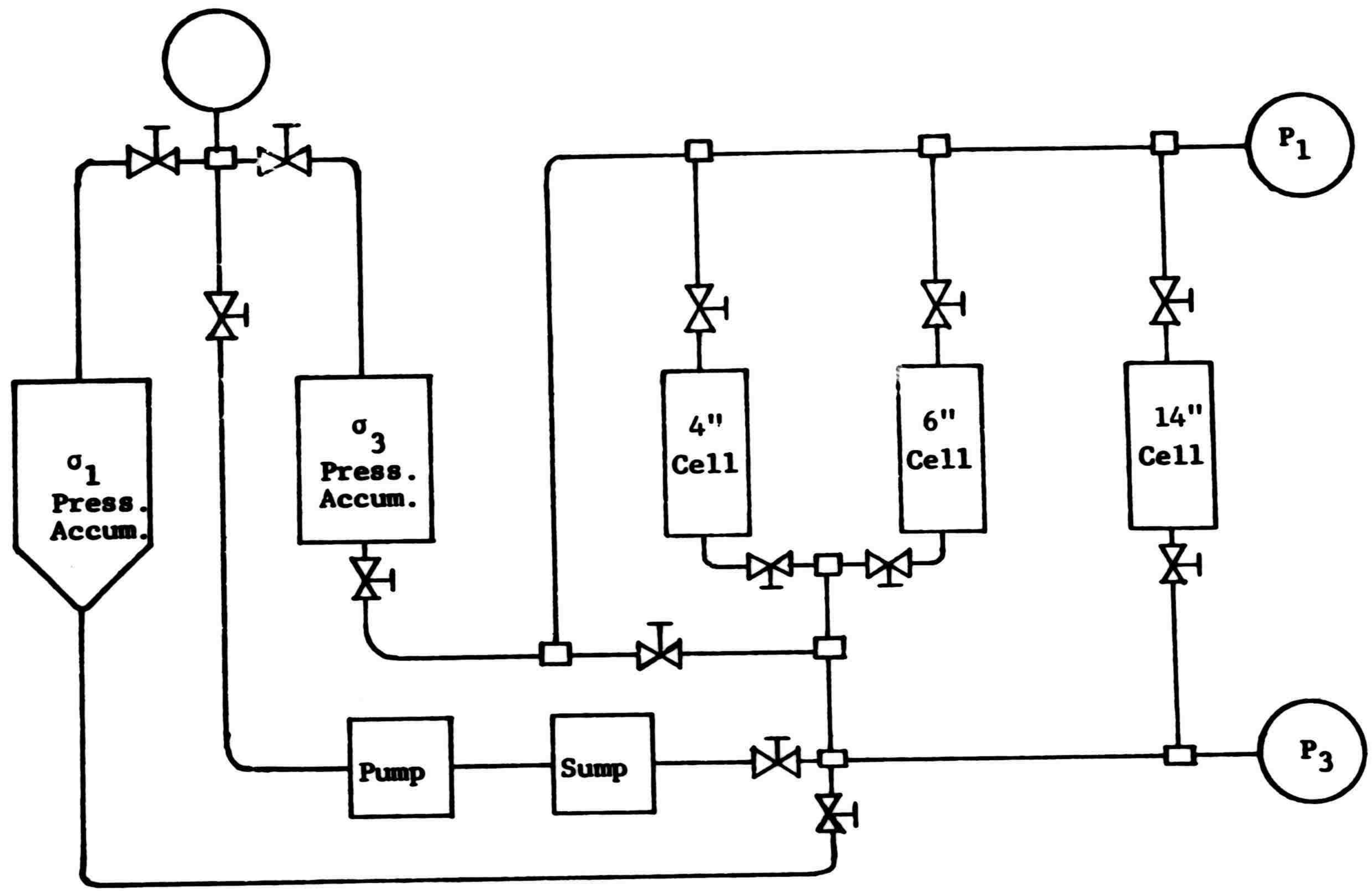


Fig. 2 SCHEMATIC OF SYSTEM FOR 4 IN., 6 IN., AND 14 IN. PRESSURE CHAMBERS

Cross-connections have been provided between the confining and axial pressure sections of the cells, to obtain true hydrostatic loading during the hydrostatic phase of each experiment.

Large Pressure Chamber

Because of the unique design of the 48-in. diameter pressure vessel, it deserves separate discussion in this report. Detailed descriptions of the design and chamber may be found elsewhere[1,2]. A schematic of the vessel layout is depicted in Figure 3, and a photograph of it is shown in Figure 4. Essentially the vessel is comprised of a 48-in. I.D., 86-in. working length hollow cylinder capable of withstanding 20,000 psi internal static pressure. The ends of this hollow chamber can be closed with steel plugs, which react against a flexible frame built up of strap steel. The cylindrical chamber walls consist of 12-in. long, 13 1/2 in. thick steel rings, placed end to end and held together by a single 3/4 in. thick steel liner along the inside diameter. The reaction structure consists of a basic frame held together by steel strap wrapped around it. The entire vessel weighs 140 tons, which is substantially less than conventionally designed chambers having the same capabilities. The cell can withstand axial loads of over 36 x 10^6 lb.

The pumping and control systems for this unit are simpler than those for the smaller chambers. A separate pump is used at each end of the chamber, as is seen in the schematic in Figure 5. Accumulators are not used because the chamber volume itself is large in comparison with other available pressure chambers.

The operation of this chamber is similar to that of the smaller chambers, except that the turn-around time between tests is on the order of a week instead of an hour. The tests in this chamber differed slightly from those in the

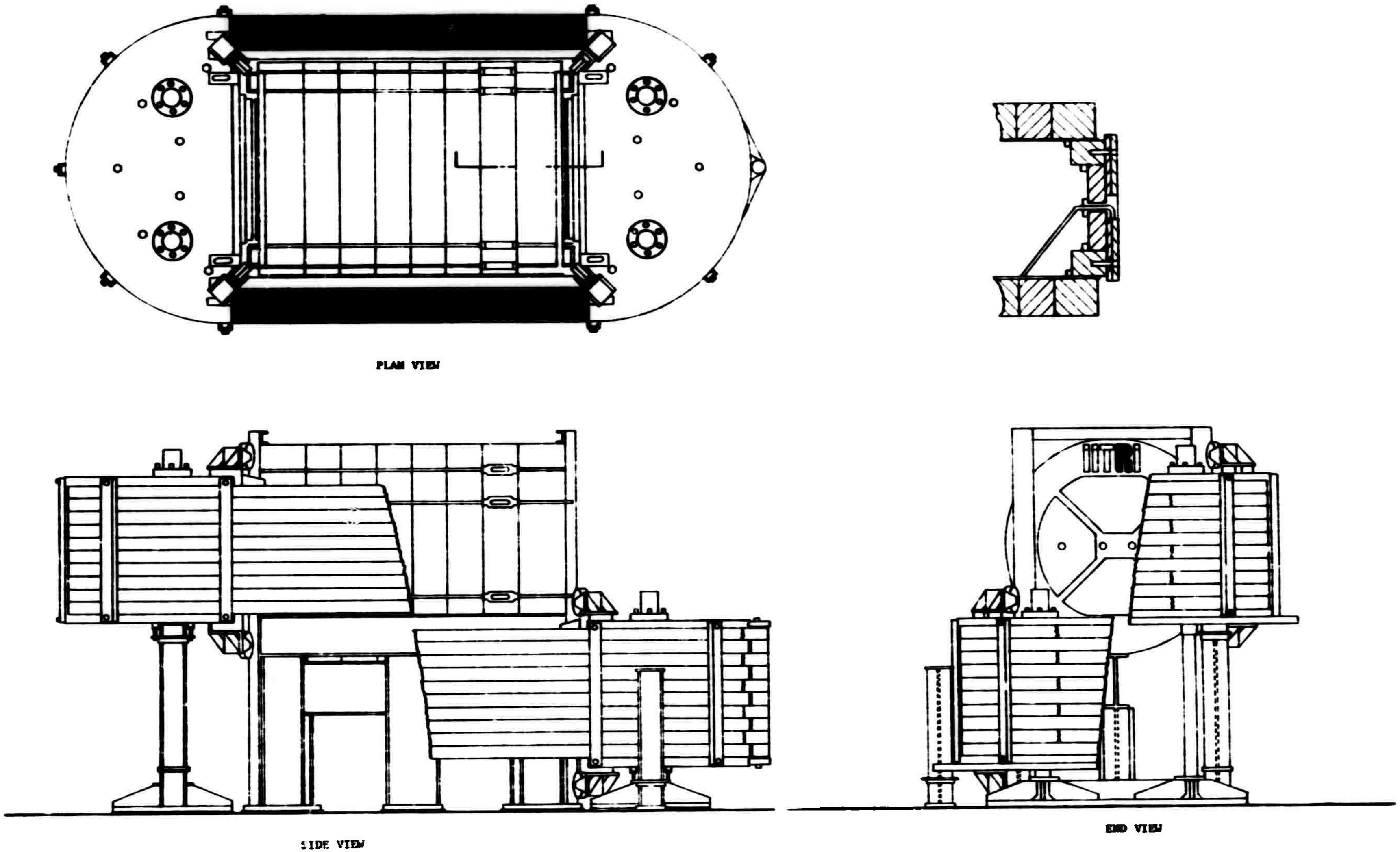


Fig. 3 48-INCH PRESSURE CHAMBER LAYOUT

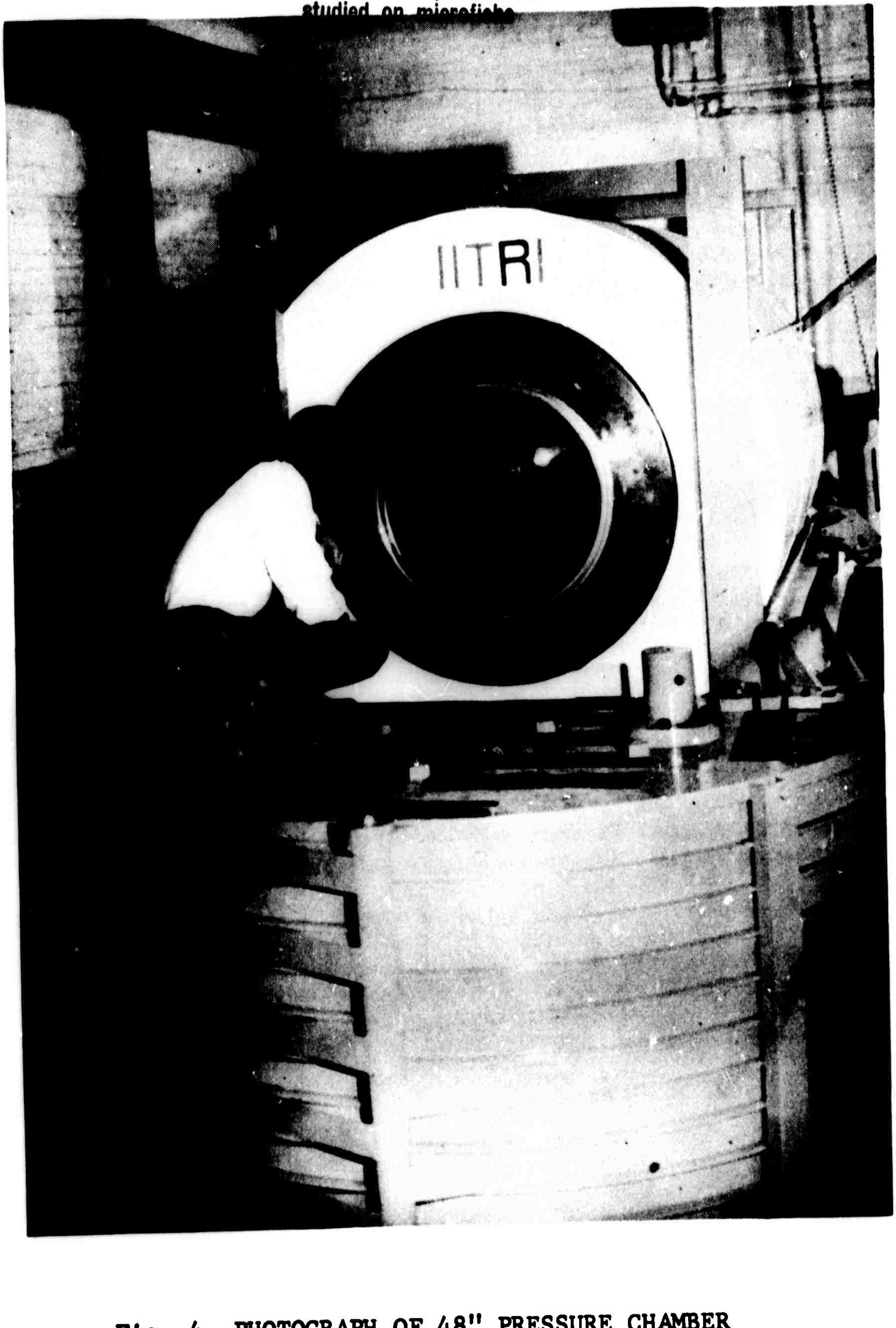


Fig. 4 PHOTOGRAPH OF 48" PRESSURE CHAMBER

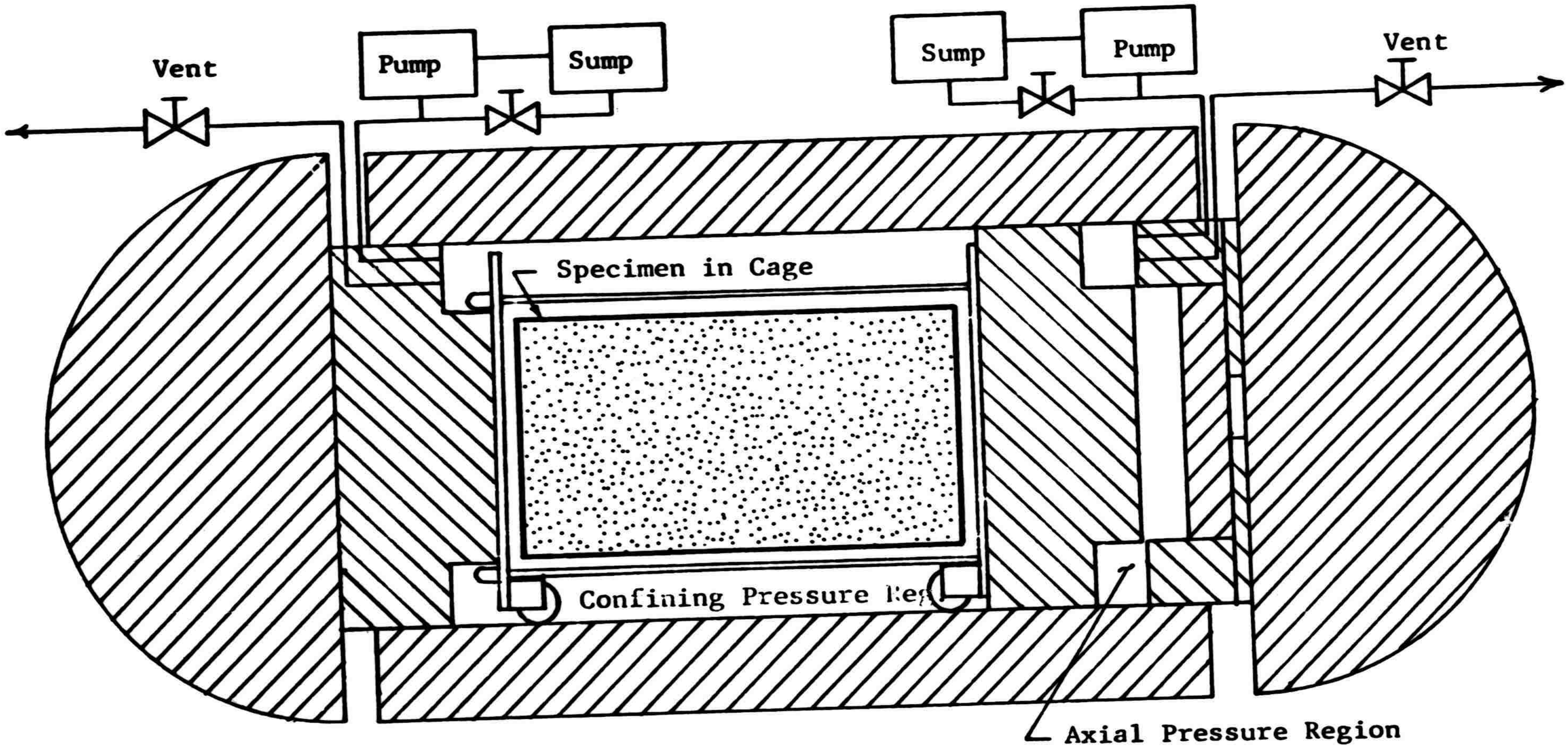


Fig. 5 SCHEMATIC OF 48 IN. DIA. TRIAXIAL CELL

smaller test cells. In order to maintain seal integrity, a positive pressure differential of about 200 psi will be maintained across the sliding piston during the "hydrostatic" portions of the triaxial tests, and the axial pressure will not be allowed to drop below 400 psi at the bottom of the load-unload-reload cycle. If these precautions are not taken, there would have been danger of upsetting the piston seal, thus aborting the remainder of the test.

Specimen Reparation

The 12-in. and 32-in. dia. cores of Charcoal Black granite were obtained from the Cold Spring Granite Company, Cold Spring, Minnesota, and the 12-in. and 36-in. dia. specimens of Indiana limestone were ordered from Rechal Stone Co., Glenview, Illinois. These specimens required no further preparation. Extra rock was ordered with each of the two types, so as to permit coring of the 2-in. and 4-in. dia. specimens. The smaller cores were cut parallel to the axis of the larger cores so as not to introduce complications due to anisotropy. One direction along all the cores of Indiana limestone were marked at the quarry. It was also marked on the cores drilled in the laboratory.

End preparation of the 2-in. and 4-in. dia. cores consisted of facing on a lathe until the ends were plane and parallel to 0.001 inches. The larger cores will be capped in a specimen cage to permit handling. The capping material to be used is a steel-filled epoxy. The cage tie rods were designed with end fittings that would accept tensile load only. Since the maximum tensile load that could be applied to the cage by these tie roads corresponds to 30 psi compressive stress in the rock specimen, the effect of the cage on the rock will be negligible.

An array of foil strain gages have been mounted on each specimen. The number used ranged from three rosettes on the 2-in. cores to thirty rosettes on the 32-in. cores. These were two element rosettes with 1/4 in. gage length placed with the direction of rolling parallel to the specimen axis. The gage placement procedure included the following steps:

* grind the rock surface
* apply two thin coats of gage cement
* visually inspect for voids in the cement base
* affix and wire gages
* apply two coats of gage cement for water proofing
* check gage for continuity and response (soft eraser) and replace if necessary.

The instrumented cores will be waterproofed with latex cement over the foil gages, and at least two coats of latex paint with a thickening agent over the entire rock surface. Waterproofing is very important in a triaxial test since both the loading conditions and the character of the rock can be changed by intrusion of oil into the rock voids. In those tests where the specimens can not be loaded to failure on the second load cycle, the specimen will be recovered intact and stripped of paint for visual inspection.

<u>Instrumentation and Data Reduction</u>

The foil strain gage on the rock specimen provide the mechanical properties information required in this project. These gages are driven by a bank of bridge balance units, wired to provide temperature and pressure compensation for the leads. Temperature gages are provided in the chamber adjacent to the rock specimens to monitor environmental temperature. The data are recorded by a Hewlett-Packard series 2012 data acquisition system that scans all data channels on demand, printing the voltages on paper tape. As the data system scans the strain gages, the axial and confining pressures are read on Heise bourdon gages, and these readings are manually inserted on the printed data system output.

Data reduction is performed using IITRI's Univac 1108 computer. The printed data system output is keypunched and input in an editing program. This program reads all the raw data and prints it out in a convenient array for checking. This program also plots the strain data so that any keypunching errors or bad strain readings can easily be found and corrected. After the data has been checked in the editing program it is input in an analysis program. This program solves the strain-gage bridge equation individually for each gage, and computes the elastic moduli. The reduced data are printed out, and the following computer plots are provided:

- deviator stress vs. shear strain
- volumetric stress vs. mean stress
- axial and radial strain vs. axial stress
- bulk, shear and elastic moduli vs. mean stress.

These plots will be included in an appendix to the final report as the most meaningful and convenient method for presenting the experimental data. Finally, the reduced stress and strain data are punched by the computer to provide ready access to the data for further analysis and model fitting.

Nondestructive Test Program

A series of nondestructive tests was planned for all specimens in order to measure any anisotropy and to locate any inhomogeneities in the larger specimens. These tests included Schmidt hammer, Shore scleroscope and dilatational wave velocity. These tests are now complete with the exception of the 12-in. dia granite specimens.

Schmidt Hammer

Schmidt hammer readings were taken at each gage location, with the following exceptions. The 32-in. dia and 36-in. dia cores were tested at every second gage location, for a total of 18 tests on each core, and the 3-in. dia and 4-in. dia cores were tested on the ends only. The readings on the small cores was strongly influenced by the boundary conditions on the side of the specimen opposite the hammer impact because of the small core diameter. After experimenting with various seating and clamping arrangements, it was decided to conduct these tests along the longest core dimension available. Each Schmidt hammer test consisted of 8 readings, the first 3 of which were discarded and the last 5 of which were averaged to give the Schmidt hammer value at that location. This procedure is necessary because of local crushing that occurs during the first few impacts at a point.

The Schmidt hammer data is summarized in Table 1. Note that the values for the 2-in. dia cores is low in both cases. This is attributed to the small specimen size, rather than any actual difference in character. The numbers in parenthesis are grand means excluding the 2-in. dia specimens, and represent the best overall values for the two rock types.

Shore Scleroscope

The Shore scleroscope indicates hardness by the measuring rebound of a small diamond tipped striker dropped on the rock. A test consists of 10 readings taken near a single point. The instrument is moved approximately 0.1 in. between readings so the striker does not fall in the small conical depression left by a previous reading. In granite, the scleroscope reading depends strongly upon the type of grain impacted. Tests were conducted near alternate gage locations on the 12-in., 32-in., and 36-in. dia specimens, and at all gage locations on the small cores. The results

Table 1 SCHMIDT HAMMER SUMMARY

Core Dia.	Indiana Limestone		Charcoal Black Granite	
	Mean	Number	Mean	Number
2 in.	24	24	35	14
4 in.	28	10	48	10
12 in.	28	90	-	-
36 in. (32 in.)	30	54	50	54
All Specimens	28 (29)*	178 (154)	47 (49)	78 (64)

*Parenthesis indicates 2 in. dia specimens exluded from mean.

are tabulated in Table 2. An indication of the scatter involved is shown in Figure 6, which is a histogram of the 54 individual readings taken on the three 36-in. dia limestone specimens.

Acoustic Velocity Mapping

The velocity of the dilatational wave was measured at all gage locations on all cores (with the exception of the 12-in. dia cores which are not yet tested). The system used for the small cores is shown in Fig. 7A. The input signal is a single cycle square wave. This is amplified and used to drive a 1 MHz piezoelectric transmitting transducer. The signal transmitted through the rock is received by a similar transducer and displayed on a dual beam oscilloscope through an internal variable delay line. This signal is compared with the input signal, and the variable delay line adjusted to achieve coincidence. The elapse time is then read from the delay line. The system delay is easily measured by removing the rock specimen and placing the transducers face to face. Figure 7B shows the system used for the 32-in. and 36-in. dia cores. A mechanical delay line was introduced to allow the use of rapid sweep rates, and a preamp boosted the received signal. The operating frequency ranged from 300 kHz for the large cores to 1 MHz for the small specimens. A check was made to determine if the frequency response of the rock influenced the apparent time of arrival by making measurements on a single 2-in. dia specimen at frequencies between 10 kHz and 2 MHz. The results are plotted in Fig. 8, and indicate no variation in time of arrival across the entire frequency range. The amplitude of the received signal is, of course, strongly dependent on input frequency.

The anisotropy of the Indiana limestone was investigated by evaluating the three 36-in. dia cores. The 45 individual acoustic velocity tests on these cores had a mean value of 4.021 km/sec, with 95% confidence levels at ± 0.017 km/sec and a standard deviation of 0.058 km/sec. This value of 4.021 ±

Table 2 SHORE SCLEROSCOPE SUMMARY

Core Dia.	Indiana Limestone		Charcoal Black Granite	
	Mean	Number	Mean	Number
2 in.	12	36	64	21
4 in.	15	30	83	15
12 in.	14	45	-	-
32 in. (36 in.)	14	54	75	54
All Specimens	14	165	74	90

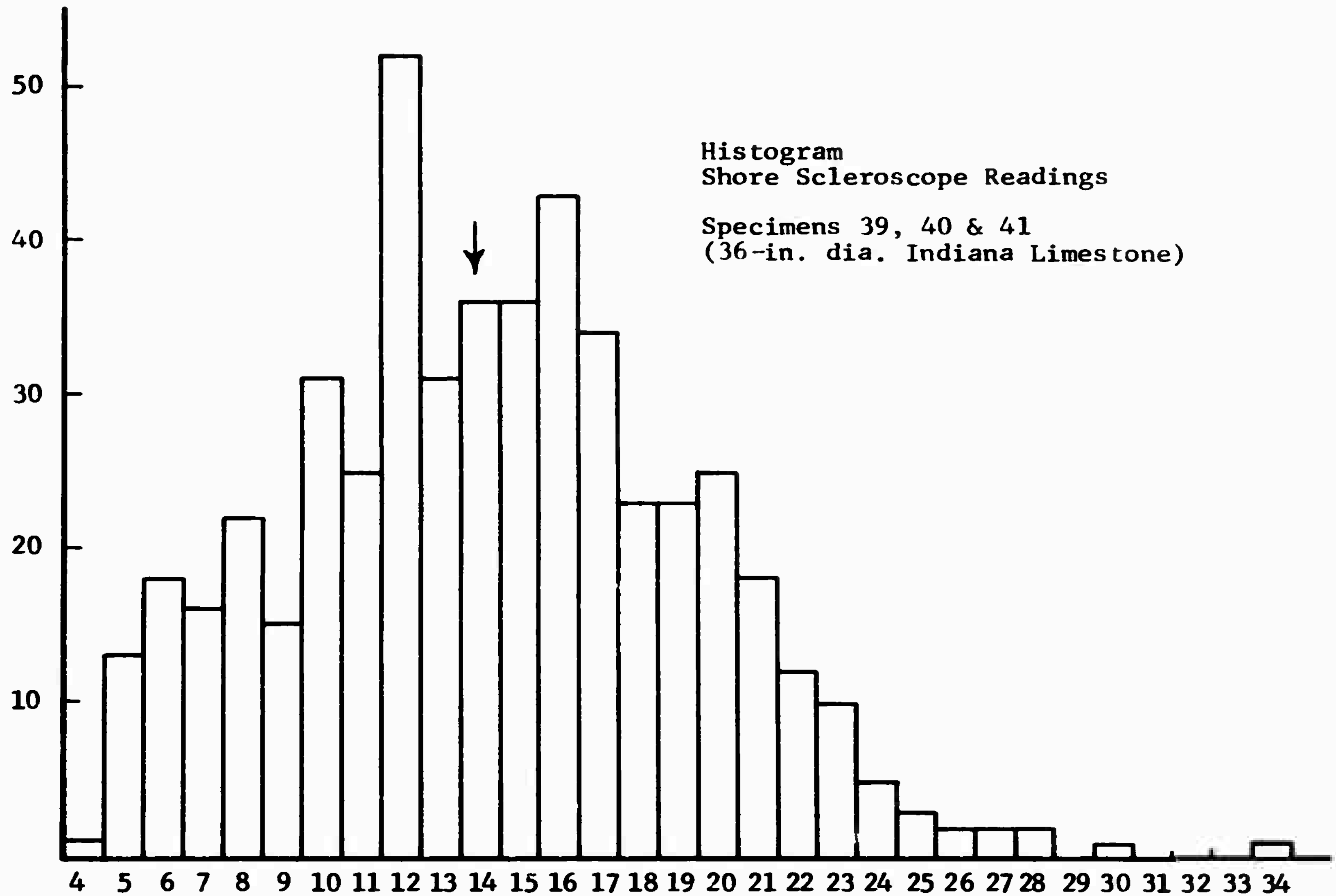


Fig. 6 DISTRIBUTION OF SHORE SCLEROSCOPE READINGS ON 36-IN. DIA. INDIANA LIMESTONE

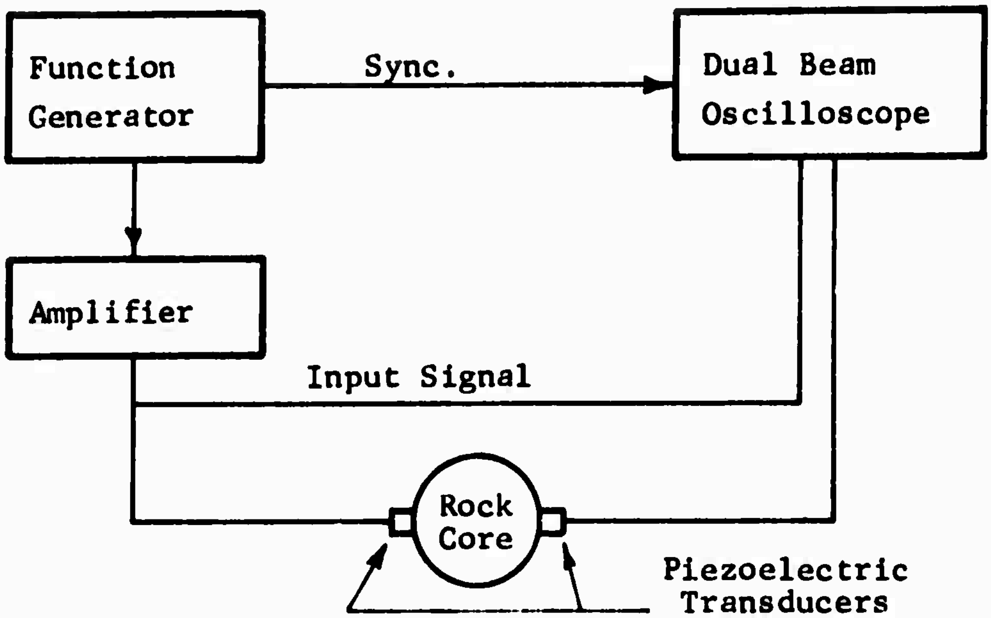


Fig. 7A ACOUSTIC VELOCITY SYSTEM FOR SMALL CORES

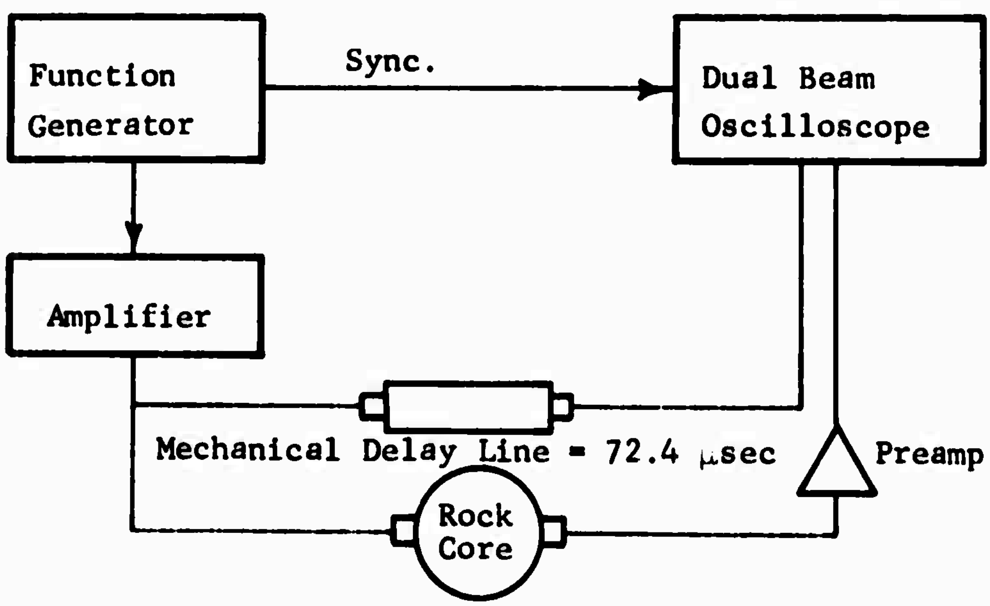


Fig. 7B ACOUSTIC VELOCITY SYSTEM FOR LARGE CORES

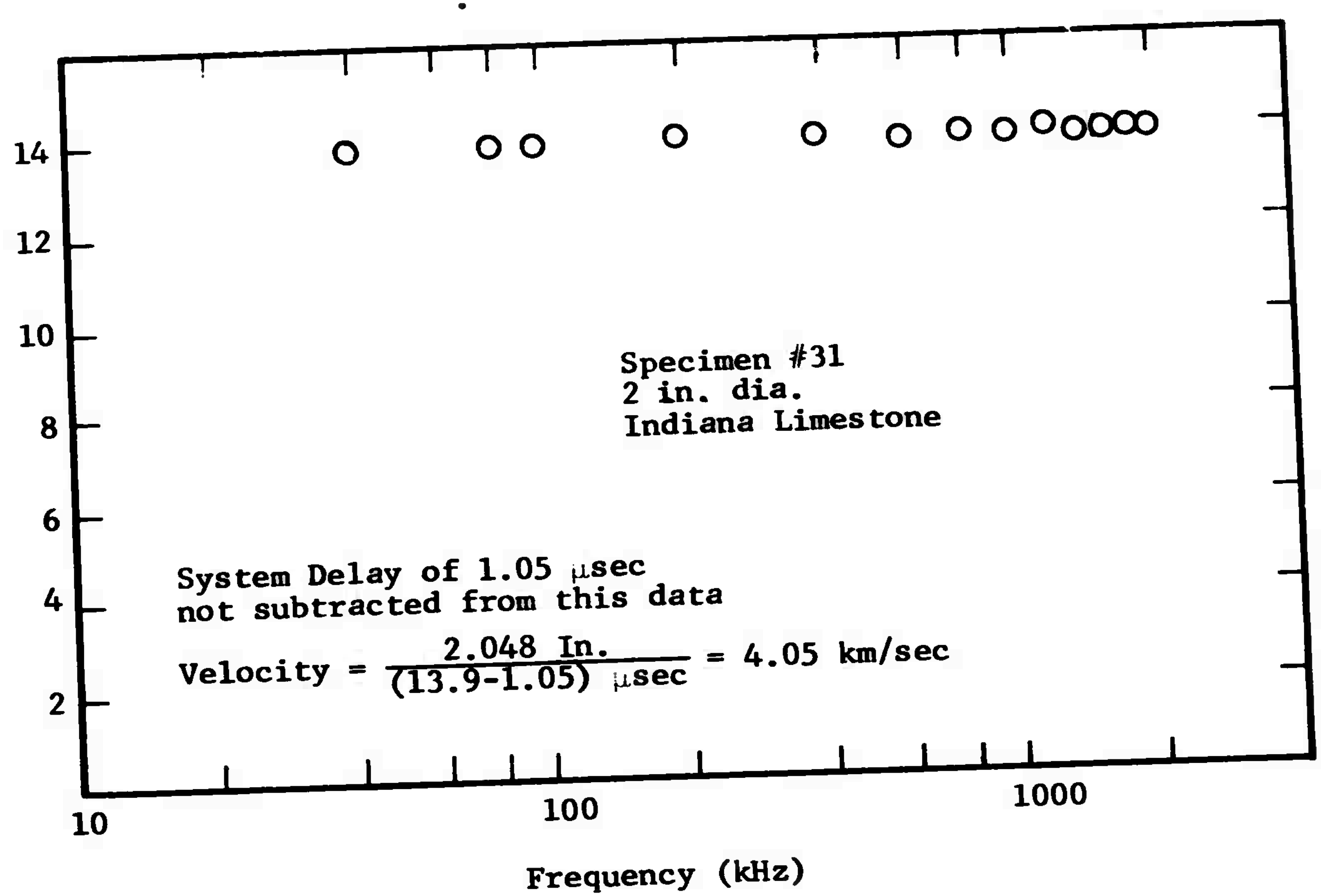


Fig. 8 TIME OF ARRIVAL MEASUREMENTS FOR A SINGLE SPECIMEN AT SEVERAL FREQUENCIES

0.017 km/sec is taken as the acoustic velocity in Indiana limestone. These 45 readings may be separated into 3 groups of 15 readings, each group spaced at 60 degree intervals around the axis of the core, or as 5 groups of 9 readings, each group spaced at 10 in. intervals down the length of the core. In this fashion we can consider the variation in acoustic velocity as a function of direction in the horizontal plane, or as a function of the vertical depth in the bedding plane. This nonemclature, and the variation of acoustic velocities as a function of direction and depth are indicated in Figure 9. Note that in all cases, the 95% confidence levels for the individual subgroups include the mean value of 4.021 km/sec computed for the entire 45 reading group.

Looking at the variation of acoustic velocity, it appears that the maximum velocity would be measured along a diameter between 2-5 and 3-6, along a quarry bearing of N-80°-W, and the lowest velocity would lie along a bearing of N-10°-E. The maximum variation is on the order of 1 1/2 percent of the mean value. Considering the variation of acoustic velocity with depth, there may exist a trend of increasing velocity with depth. The slight reversal of this trend at row #5 may be a real effect caused by the presence of the bedding plane in the formation. In any case, the variation is on the order of 1% or less. The acoustic velocities for all subgroups lie near or within the 95% confidence levels for the entire group of measurements.

Unconfined Compression Tests

Unconfined compression tests were conducted on three specimens each of Indiana limestone and Charcoal Black granite. These specimens were instrumented and the following plots are included as an appendix to this report:

deviator stress vs. shear strain
mean stress vs. volumetric strain

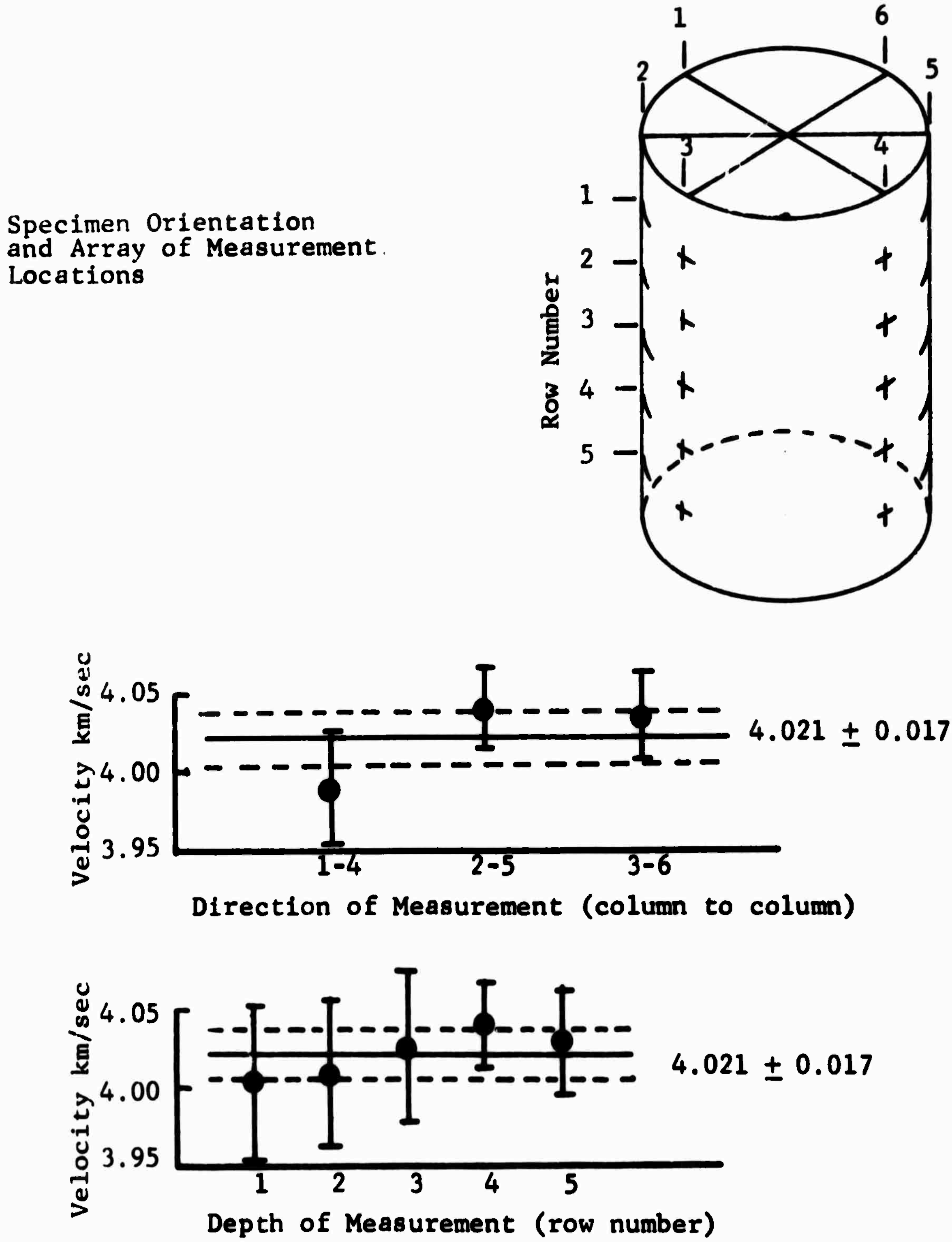


Fig. 9 ACOUSTIC VELOCITIES IN 36-IN. DIA INDIANA LIMESTONE

axial stress vs. axial and lateral strains

The failure stresses for the individual tests are indicated in Table 3.

The orientation directions of the 32-in. dia and 12-in. dia Charcoal Black granite cores were not marked by the quarry. In all, 102 acoustic velocity determinations were made on the 2-in., 4-in. and 32-in. dia granite specimens. These tests had a mean value of 4.661 km/sec with 95% confidence levels of ± 0.047 km/sec with 95% confidence levels of ± 0.047 km/sec and a standard deviation of 0.240 km/sec. The value 4.661 ± 0.047 km/sec is taken as the acoustic velocity in Charcoal Black granite. Additional insight into anisotropy can be gained by evaluating the acoustic data from the 2-in. dia and 4-in. dia cores, which were cut at IITRI from a single piece of granite, and were orientated with respect to an arbitrary direction marked on the parent core. This evaluation will be carried out in the future.

Triaxial Tests

Triaxial tests at confining pressures of 2000 psi and 4000 psi were conducted on Indiana limestone. These data have been keypunched, but not yet run on the data reduction program.

Table 3 UNCONFINED COMPRESSIVE STRENGTH

Granite		Limestone	
Test	Failure Stress	Test	Failure Stress
14	17.4 ksi	20	4.18 ksi
15	23.1 ksi	21	4.38 ksi
17	18.2 ksi	22	4.00 ksi
Mean	19.5 ksi	Mean	4.19 ksi

The data reduction for the unconfined tests is identical with that which will be used for the triaxial tests.

REFERENCES

1. Finlayson, L. A., Large Segmented High Pressure Chamber Design, IITRI Internal Report dated March 4, 1970, p. 9.
2. Cornish, R. H. and Finlayson, L. A., Reaction Frame for Restraining High Loads, U. S. Patent No. 3,476,281, Issued November 4, 1969, p. 4.

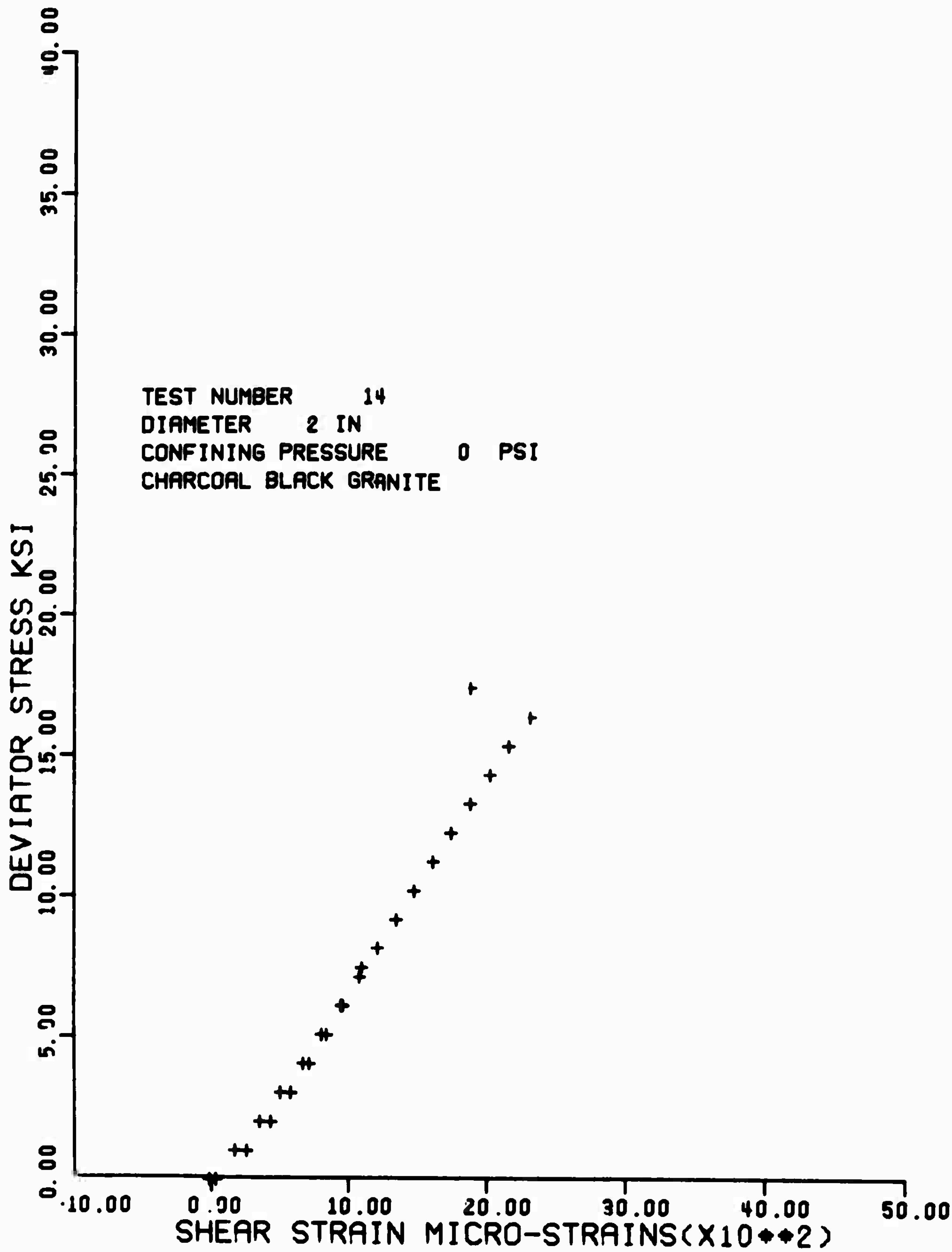
APPENDIX

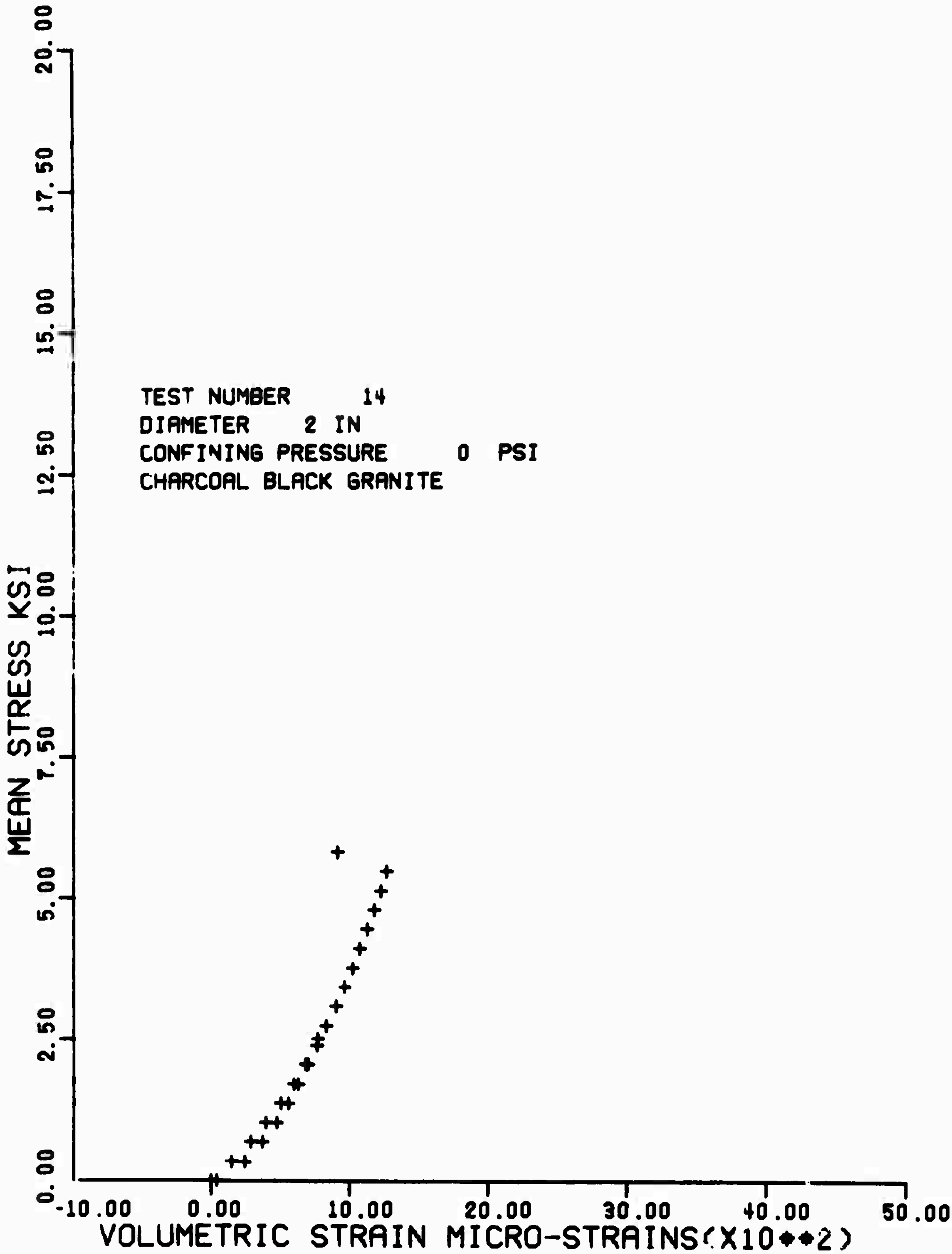
Data from Unconfined Compression Tests

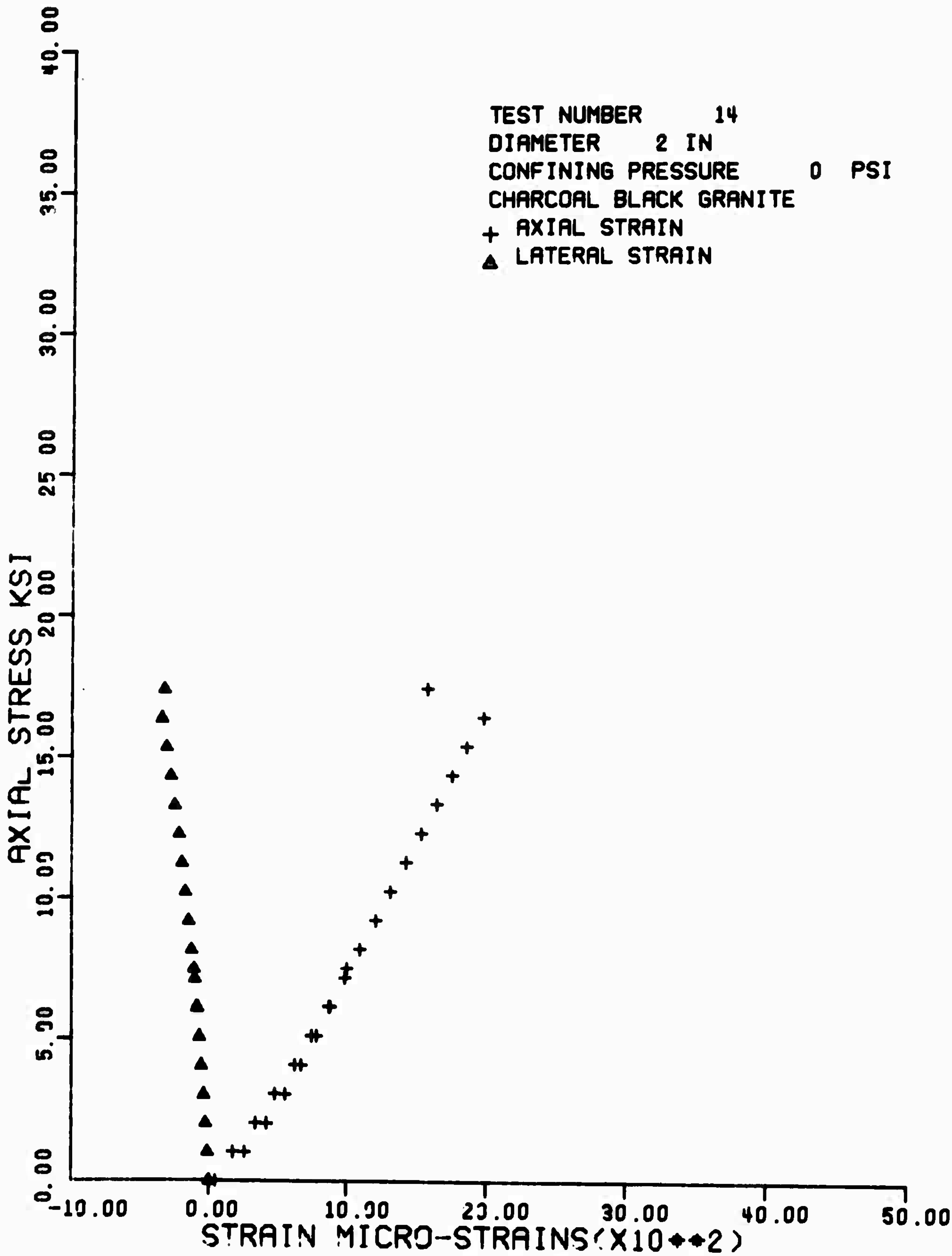
The plotted output for the six unconfined compression tests is included on the following pages. Each test includes the following plots:

deviator stress vs. shear strain
mean stress vs. volumetric strain
axial stress vs. axial and lateral strains

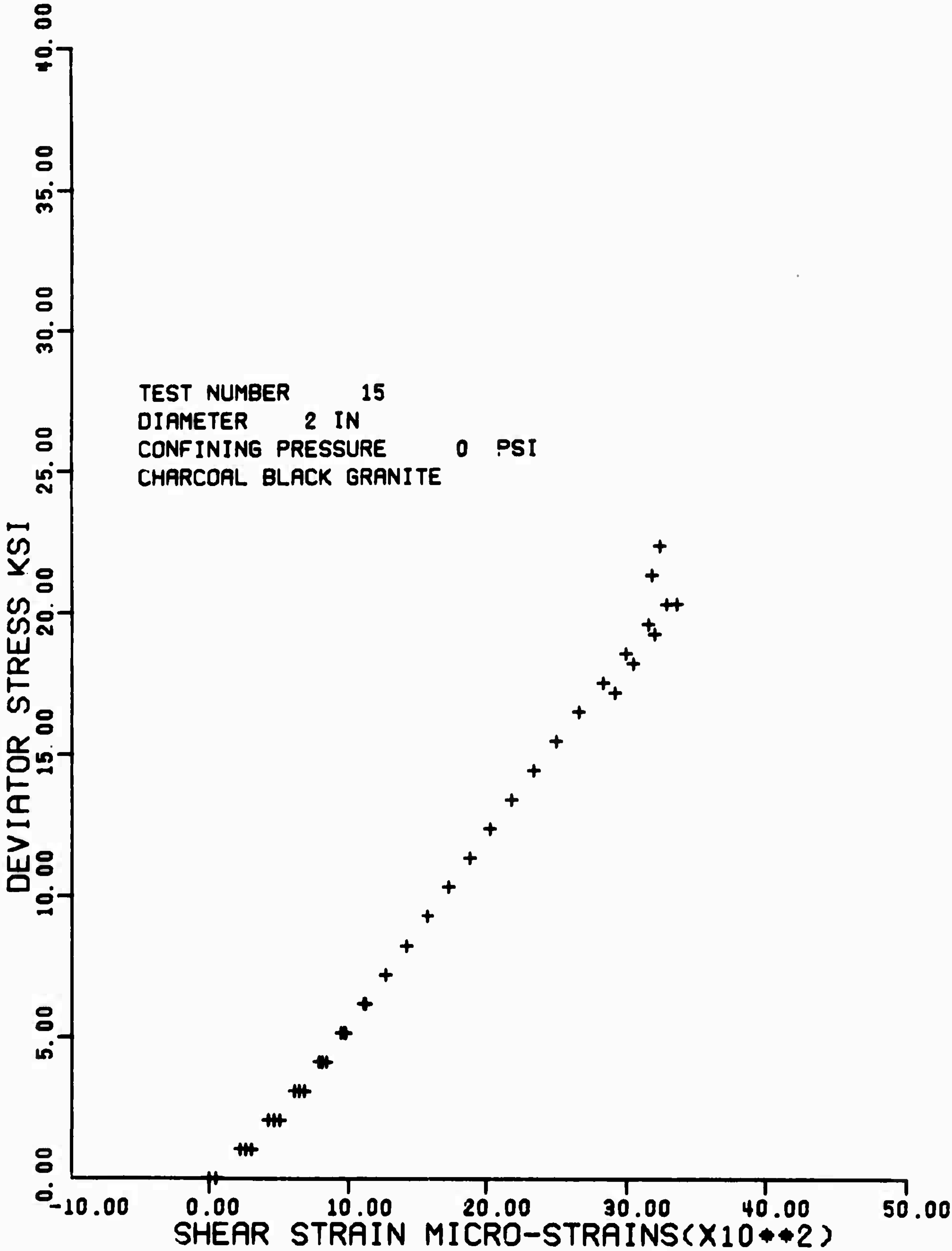
The pertinent identification data are noted on each plot.


TEST NUMBER 14
DIAMETER 2 IN
CONFINING PRESSURE 0 PSI
CHARCOAL BLACK GRANITE
DEVIATOR STRESS KSI
0.00
5.00
10.00
15.00
20.00
25.00
30.00
35.00
40.00
-10.00
0.00
10.00
20.00
30.00
40.00
50.00
SHEAR STRAIN MICRO-STRAINS(X10**2)


TEST NUMBER 14
DIAMETER 2 IN
CONFINING PRESSURE 0 PSI
CHARCOAL BLACK GRANITE
MEAN STRESS KSI
0.00
2.50
5.00
7.50
10.00
12.50
15.00
17.50
20.00
-10.00
0.00
10.00
20.00
30.00
40.00
50.00
VOLUMETRIC STRAIN MICRO-STRAINS(X10**2)



TEST NUMBER 14
DIAMETER 2 IN
CONFINING PRESSURE 0 PSI
CHARCOAL BLACK GRANITE
AXIAL STRAIN
LATERAL STRAIN
AXIAL STRESS KSI
STRAIN MICRO-STRAINS(X10**2)
0.00
5.00
10.00
15.00
20.00
25.00
30.00
35.00
40.00
-10.00
0.00
10.00
20.00
30.00
40.00
50.00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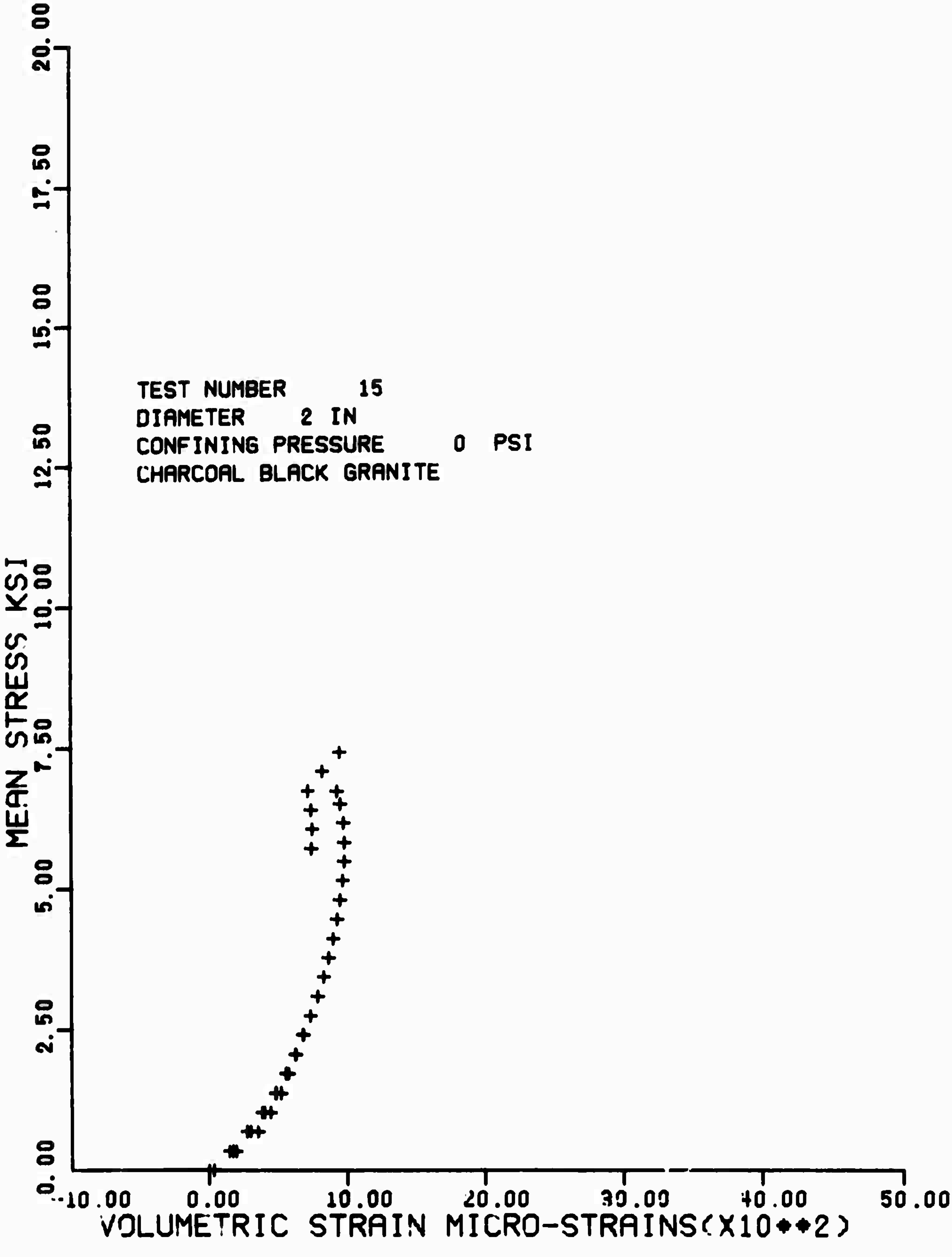
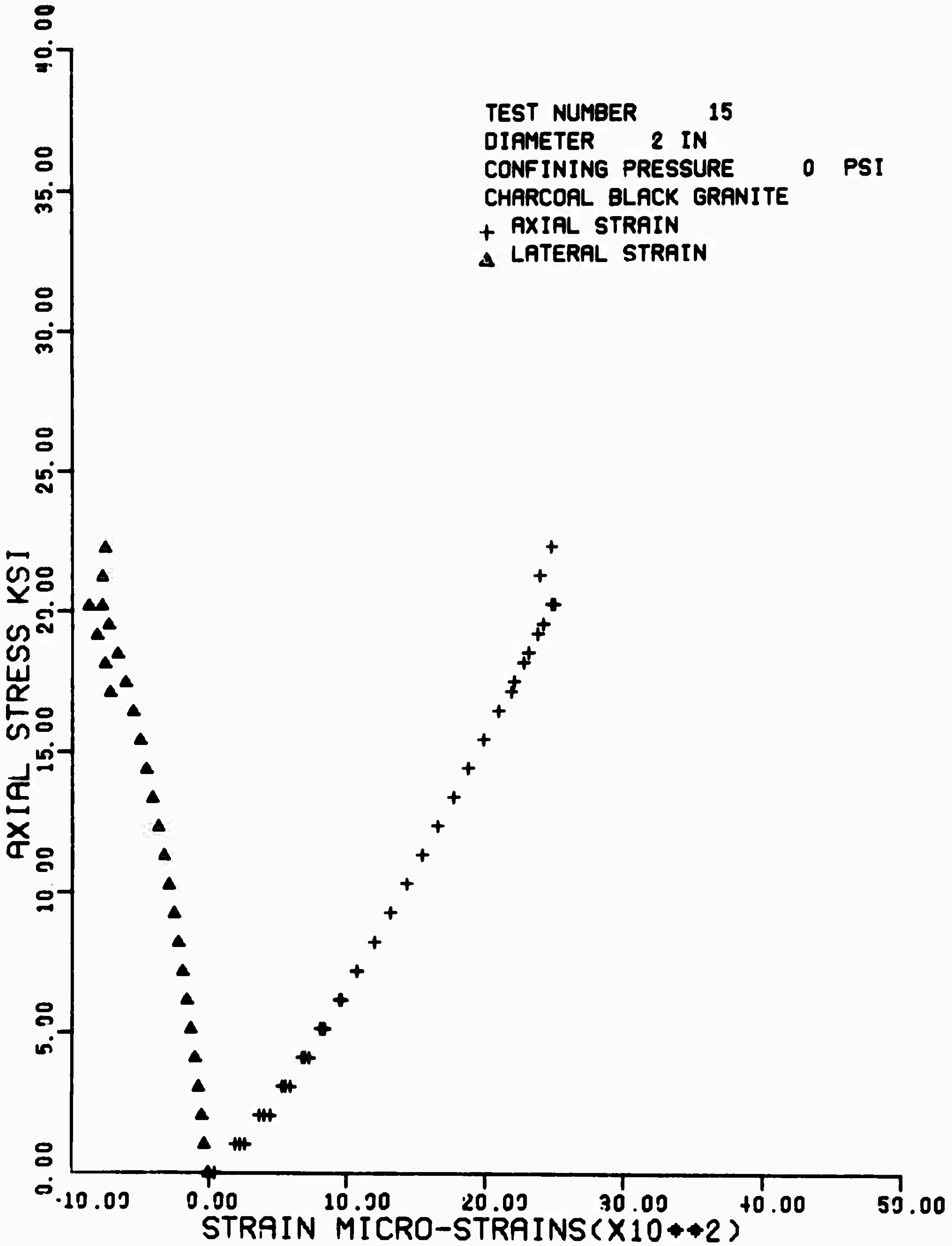
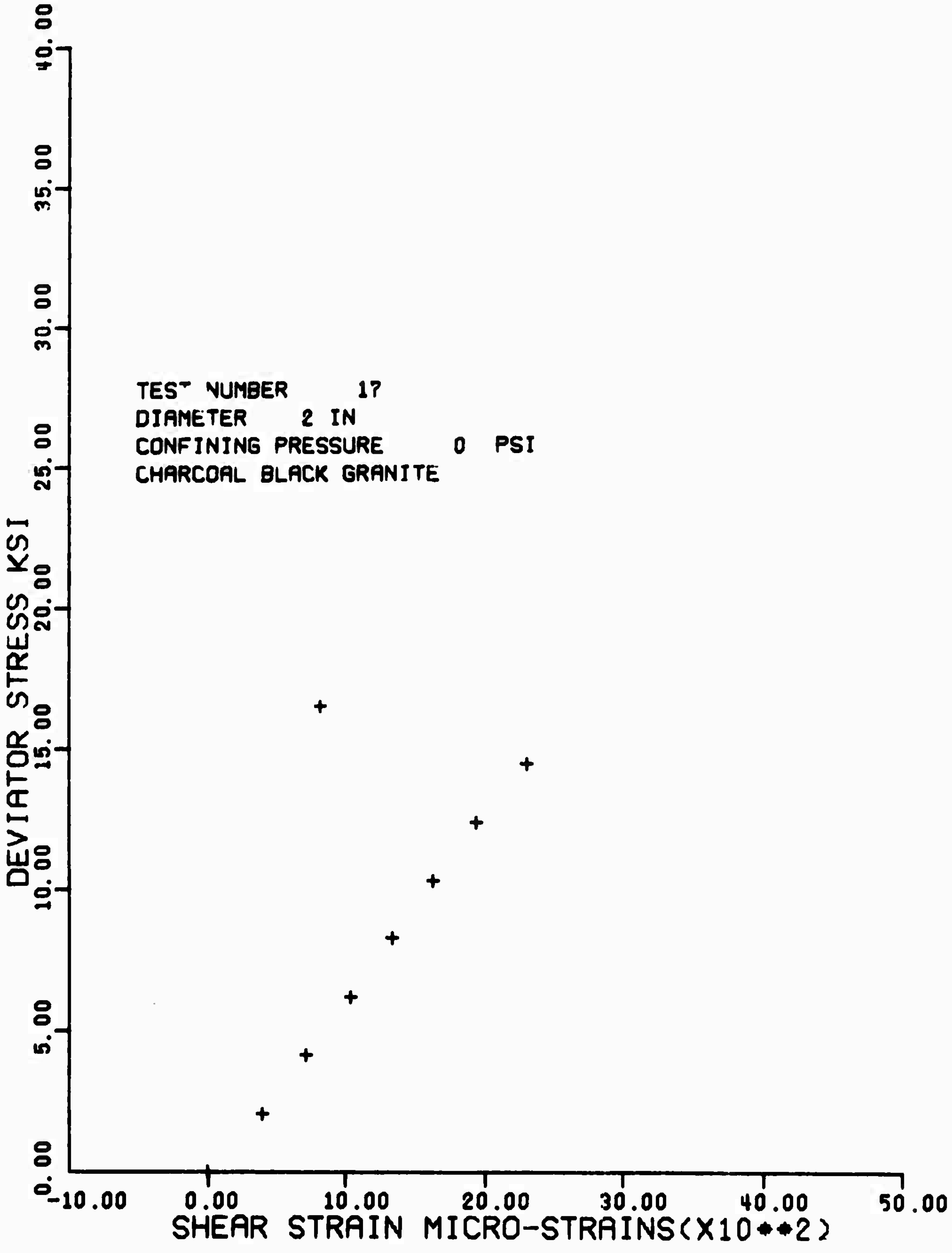
DIAMETER 2 IN
CONFINING PRESSURE 0 PSI
CHARCOAL BLACK GRANITE
DEVIATOR STRESS KSI
SHEAR STRAIN MICRO-STRAINS(X10**2)
0.00
5.00
10.00
15.00
20.00
25.00
30.00
35.00
40.00
-10.00
0.00
10.00
20.00
30.00
40.00
50.00


TEST NUMBER 15
DIAMETER 2 IN
CONFINING PRESSURE 0 PSI
CHARCOAL BLACK GRANITE
MEAN STRESS KSI
0.00
2.50
5.00
7.50
10.00
12.50
15.00
17.50
20.00
-10.00
0.00
10.00
20.00
30.00
40.00
50.00
VOLUMETRIC STRAIN MICRO-STRAINS(X10**2)


TEST NUMBER 15
DIAMETER 2 IN
CONFINING PRESSURE 0 PSI
CHARCOAL BLACK GRANITE
AXIAL STRAIN
LATERAL STRAIN
AXIAL STRESS KSI
0.00
5.00
10.00
15.00
20.00
25.00
30.00
35.00
40.00
-10.00
0.00
10.00
20.00
30.00
40.00
50.00
STRAIN MICRO-STRAINS(X10**2)


TEST NUMBER 17
DIAMETER 2 IN
CONFINING PRESSURE 0 PSI
CHARCOAL BLACK GRANITE
DEVIATOR STRESS KSI
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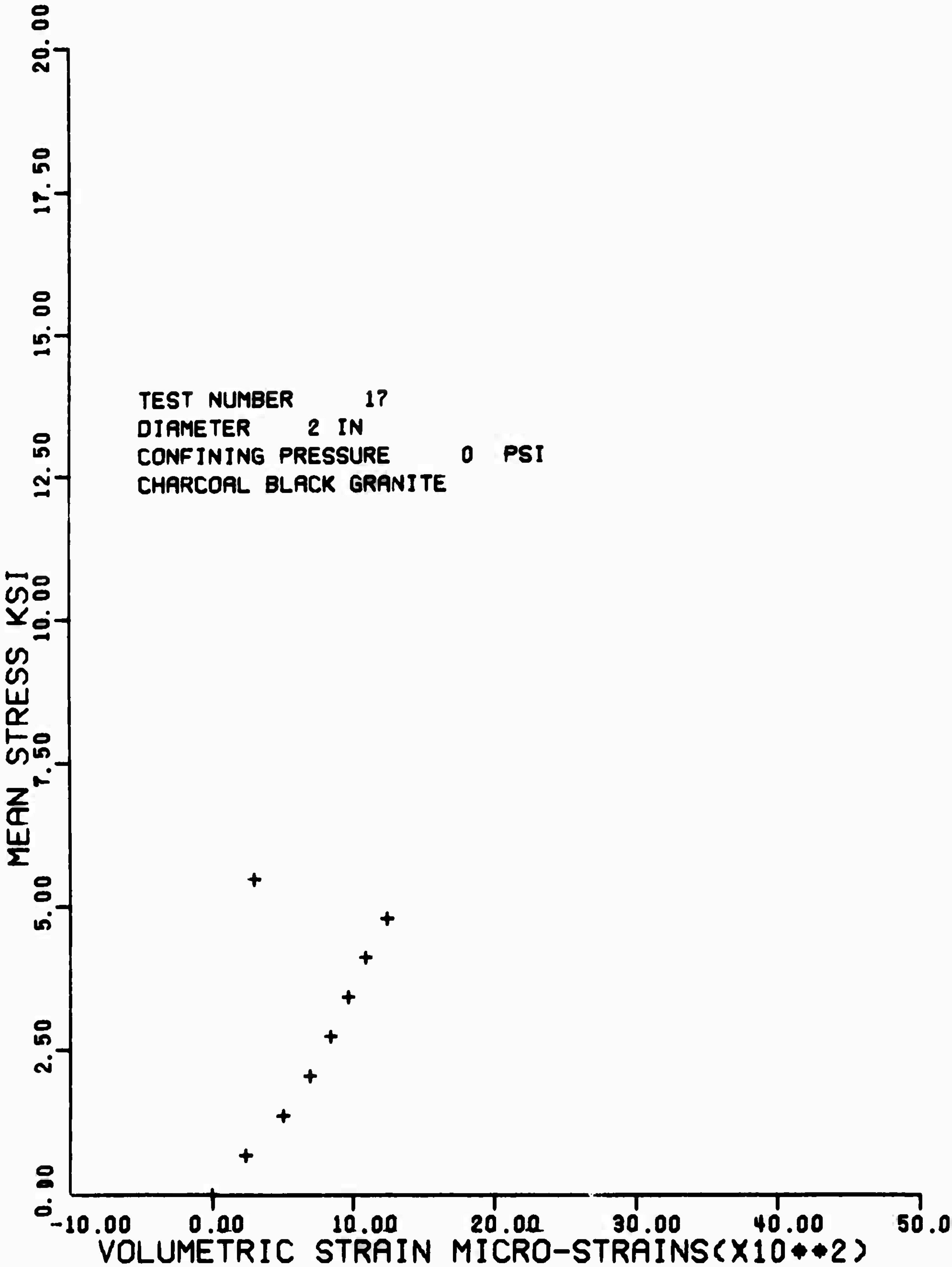
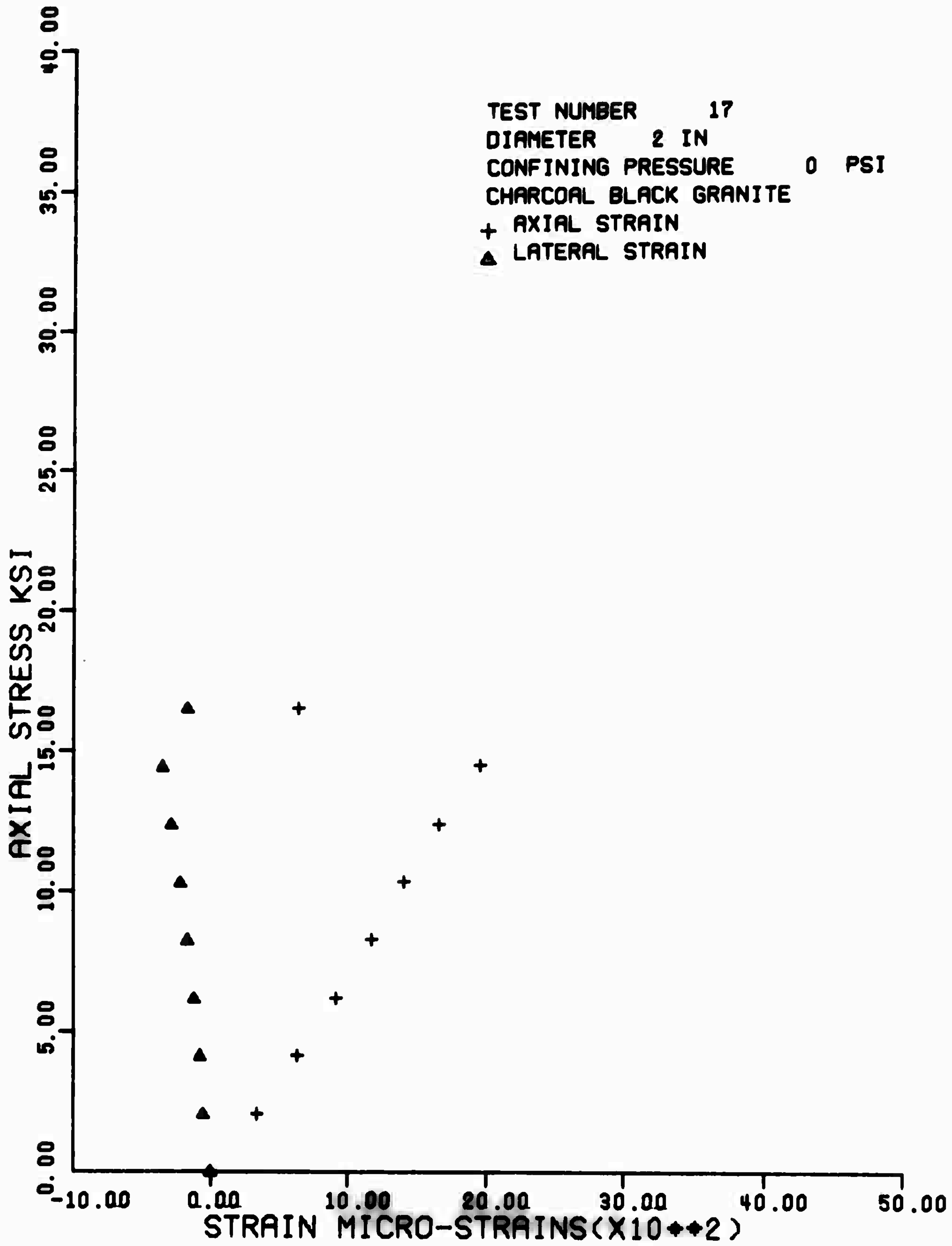
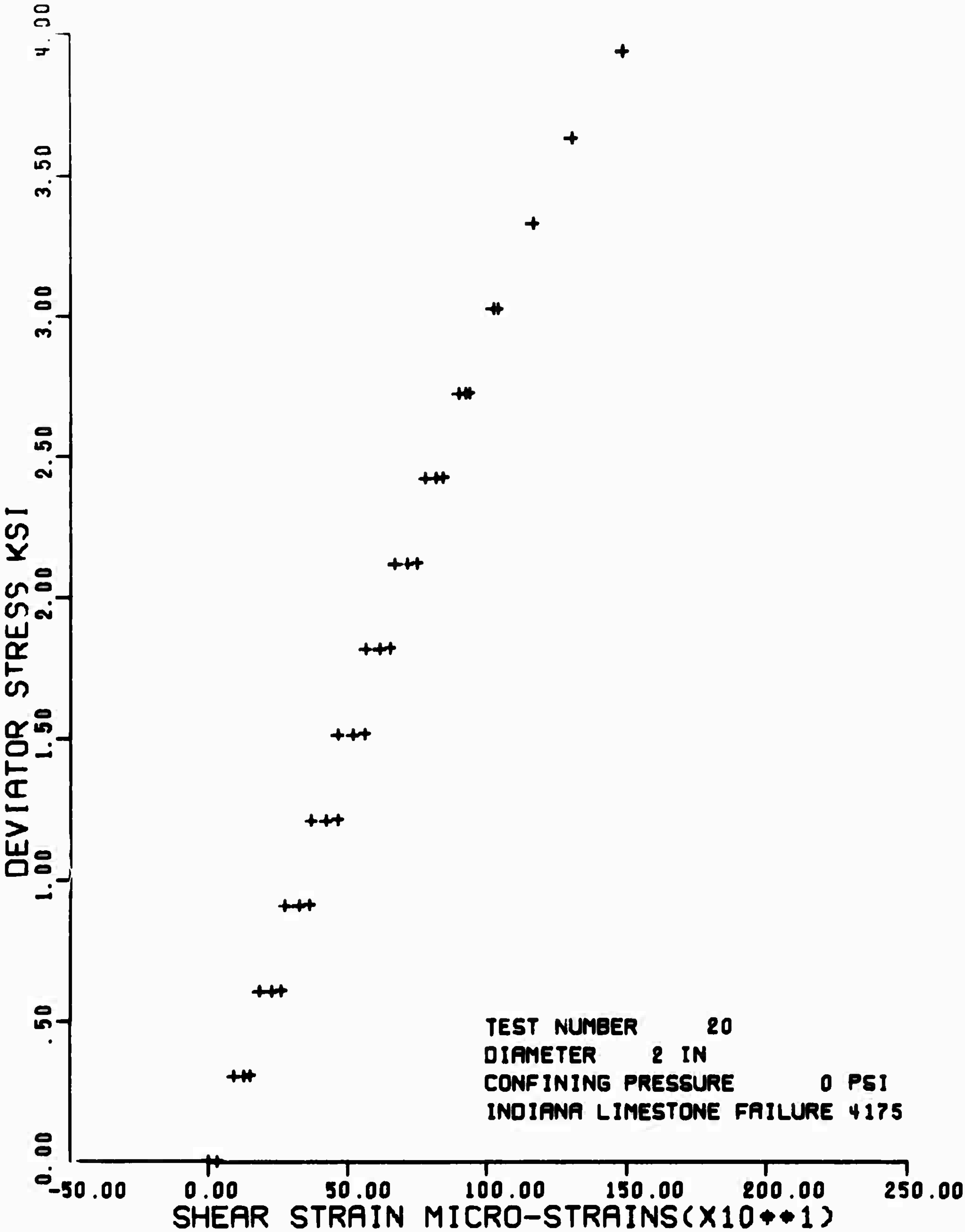
5.00
10.00
15.00
20.00
25.00
30.00
35.00
40.00
-10.00
0.00
10.00
20.00
30.00
40.00
50.00
SHEAR STRAIN MICRO-STRAINS(X10**2)

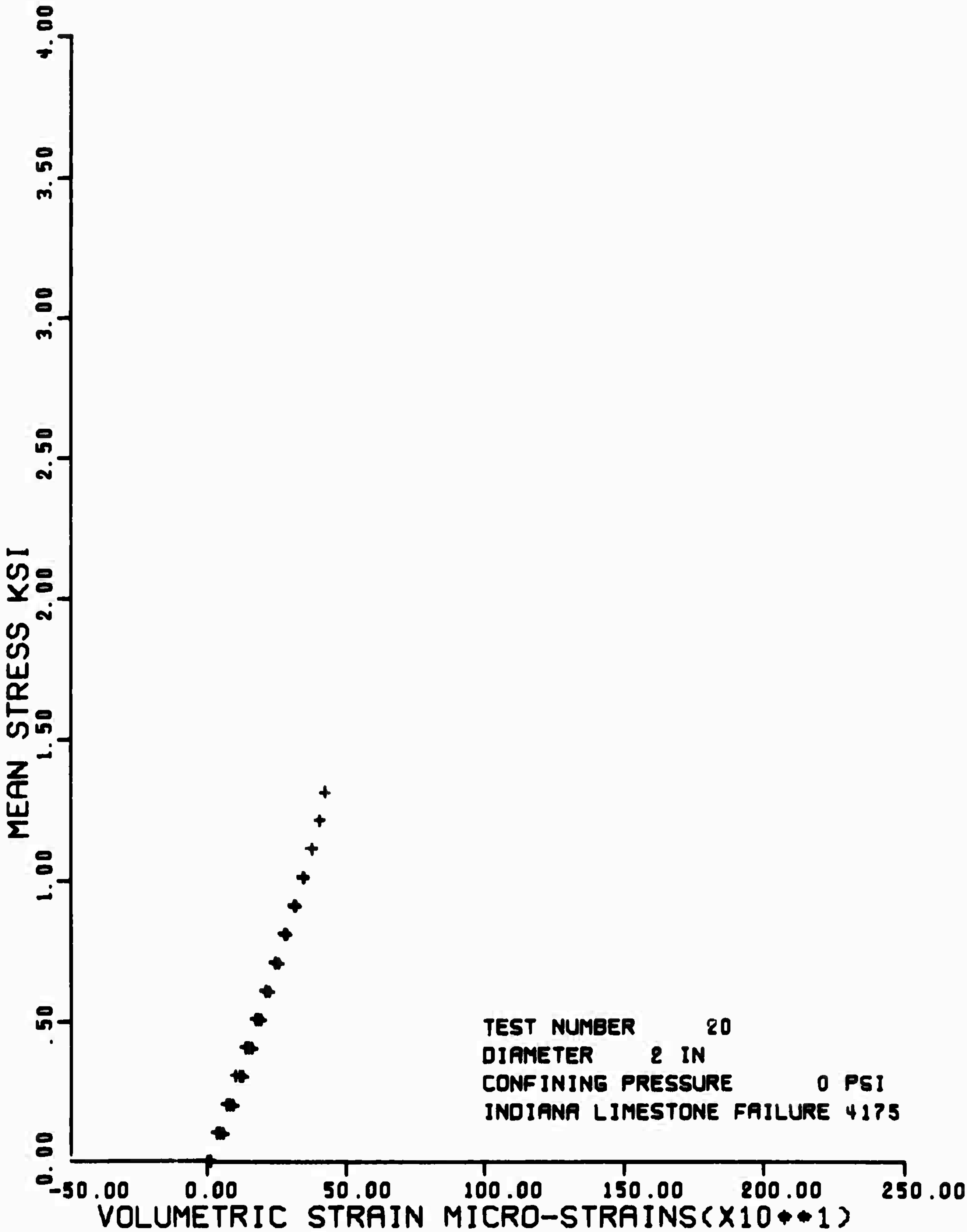

TEST NUMBER 17
DIAMETER 2 IN
CONFINING PRESSURE 0 PSI
CHARCOAL BLACK GRANITE
MEAN STRESS KSI
0.00
2.50
5.00
7.50
10.00
12.50
15.00
17.50
20.00
-10.00
0.00
10.00
20.00
30.00
40.00
50.00
VOLUMETRIC STRAIN MICRO-STRAINS(X10**2)



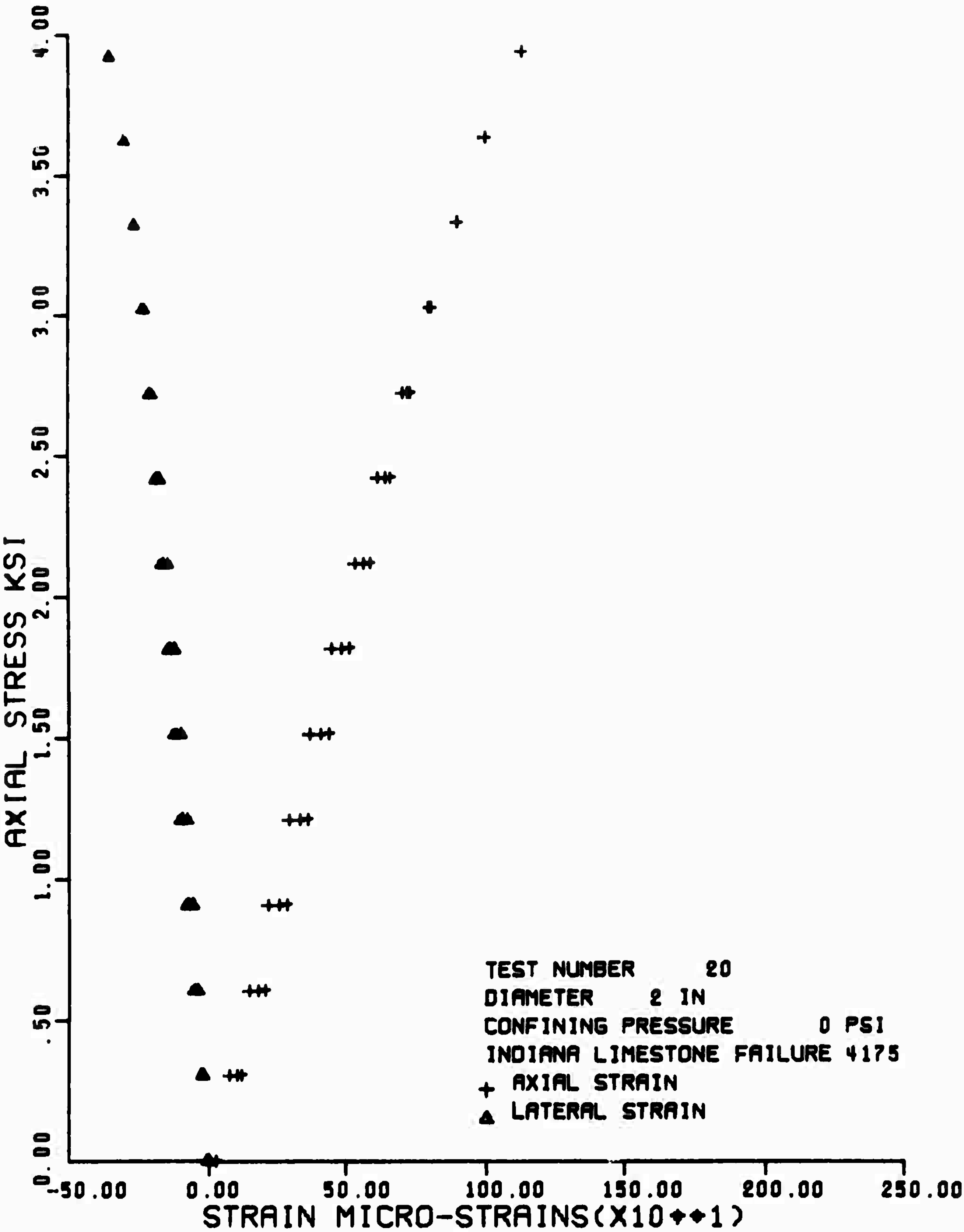
TEST NUMBER 17
DIAMETER 2 IN
CONFINING PRESSURE 0 PSI
CHARCOAL BLACK GRANITE
AXIAL STRAIN
LATERAL STRAIN
AXIAL STRESS KSI
0.00
5.00
10.00
15.00
20.00
25.00
30.00
35.00
40.00
-10.00
0.00
10.00
20.00
30.00
40.00
50.00
STRAIN MICRO-STRAINS(X10**2)

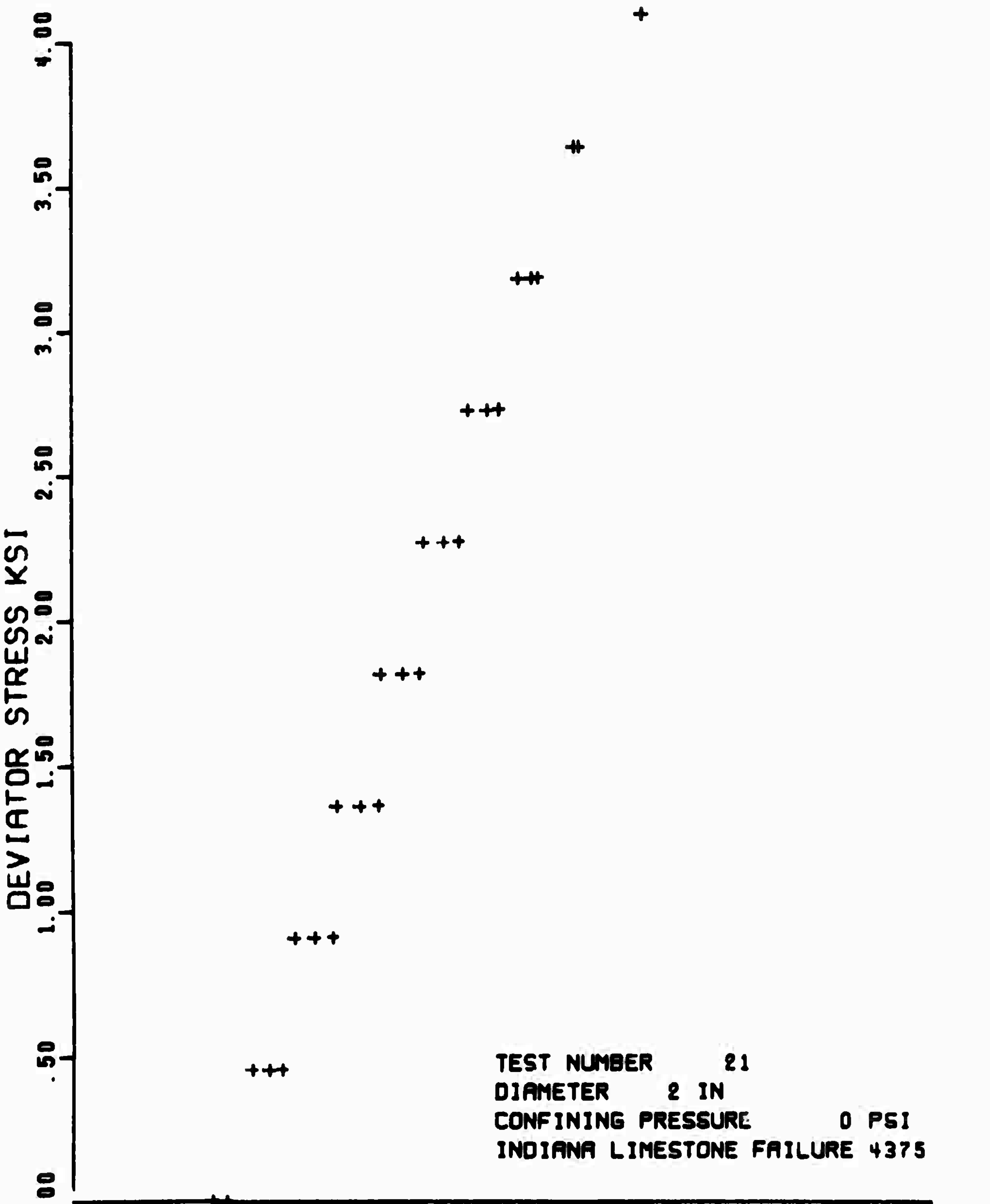


DEVIATOR STRESS KSI
0.00
.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
-50.00
0.00
50.00
100.00
150.00
200.00
250.00
SHEAR STRAIN MICRO-STRAINS(X10**1)
TEST NUMBER 20
DIAMETER 2 IN
CONFINING PRESSURE 0 PSI
INDIANA LIMESTONE FAILURE 4175

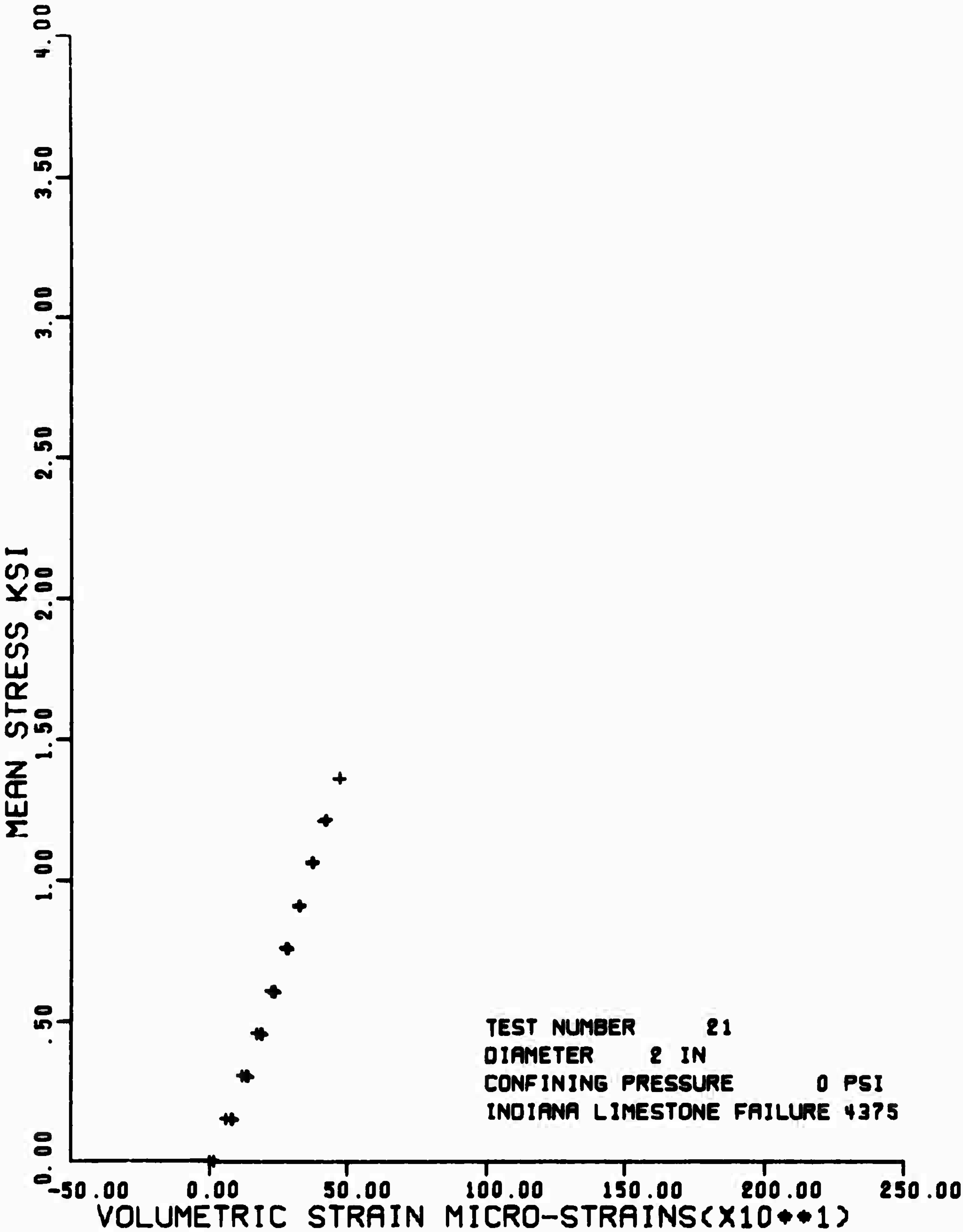


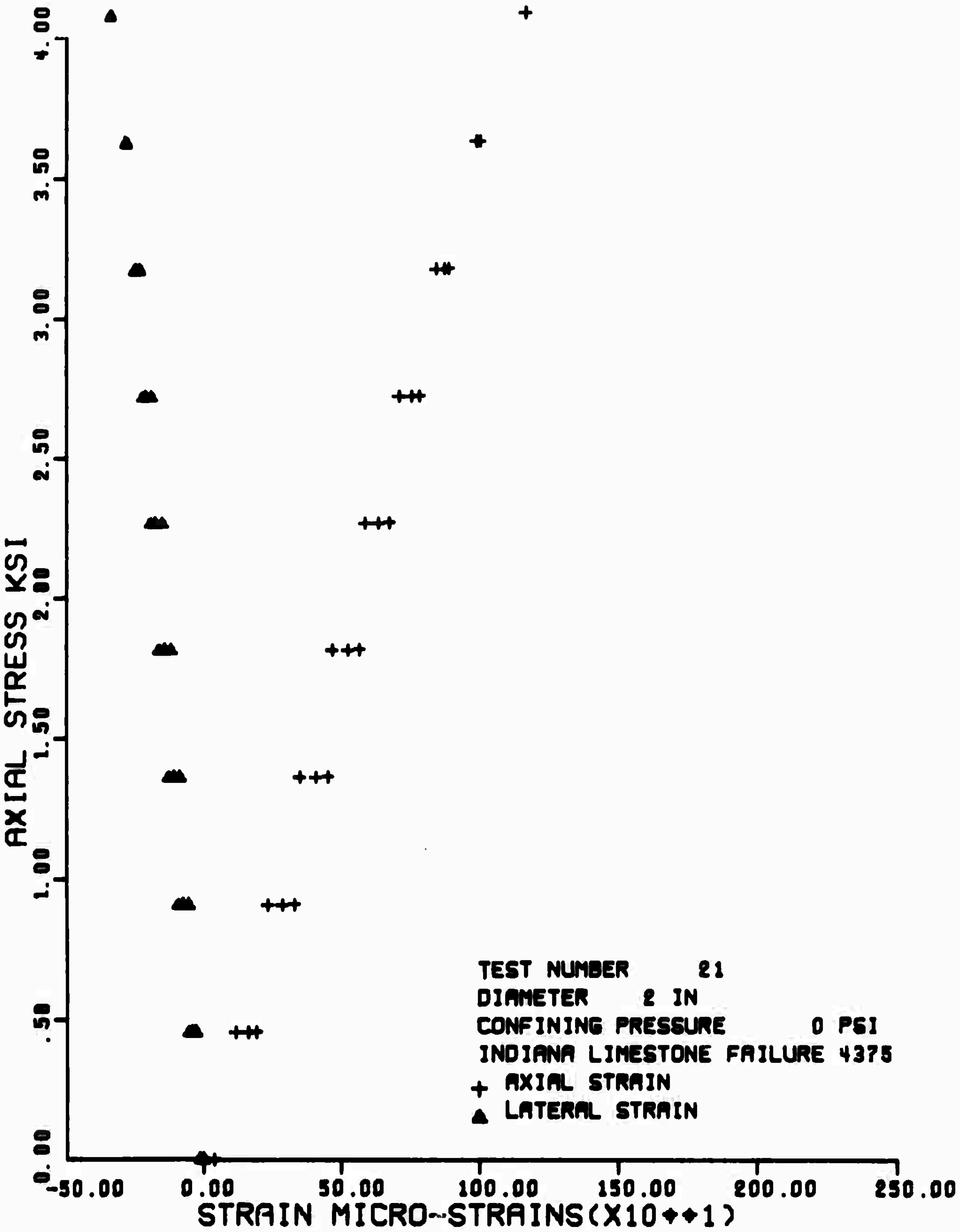
MEAN STRESS KSI
0.00
.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
-50.00
0.00
50.00
100.00
150.00
200.00
250.00
VOLUMETRIC STRAIN MICRO-STRAINS(X10**1)
TEST NUMBER 20
DIAMETER 2 IN
CONFINING PRESSURE 0 PSI
INDIANA LIMESTONE FAILURE 4175

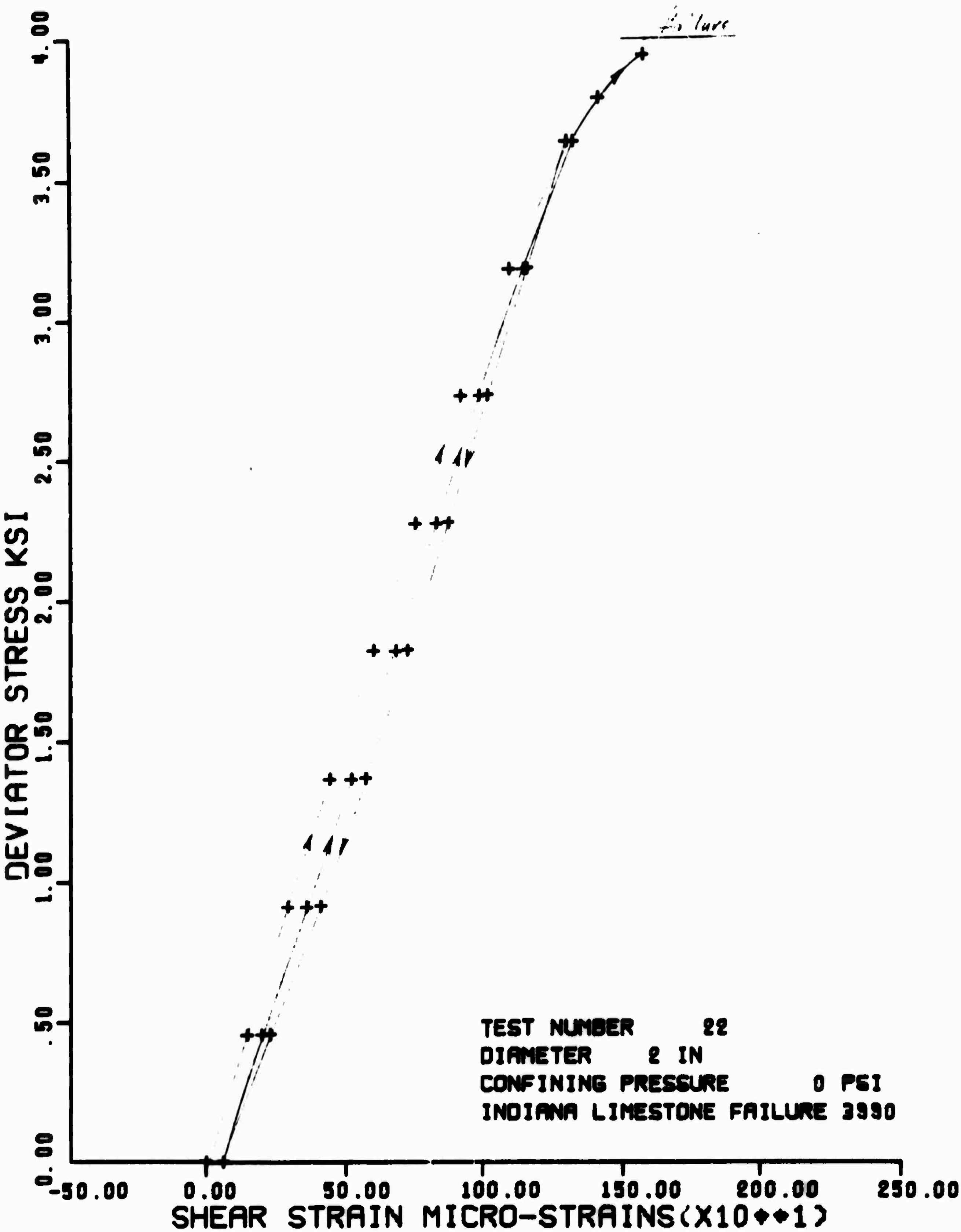

AXIAL STRESS KSI
0.00
.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
-50.00
0.00
50.00
100.00
150.00
200.00
250.00
STRAIN MICRO-STRAINS(X10**1)
TEST NUMBER 20
DIAMETER 2 IN
CONFINING PRESSURE 0 PSI
INDIANA LIMESTONE FAILURE 4175
AXIAL STRAIN
LATERAL STRAIN

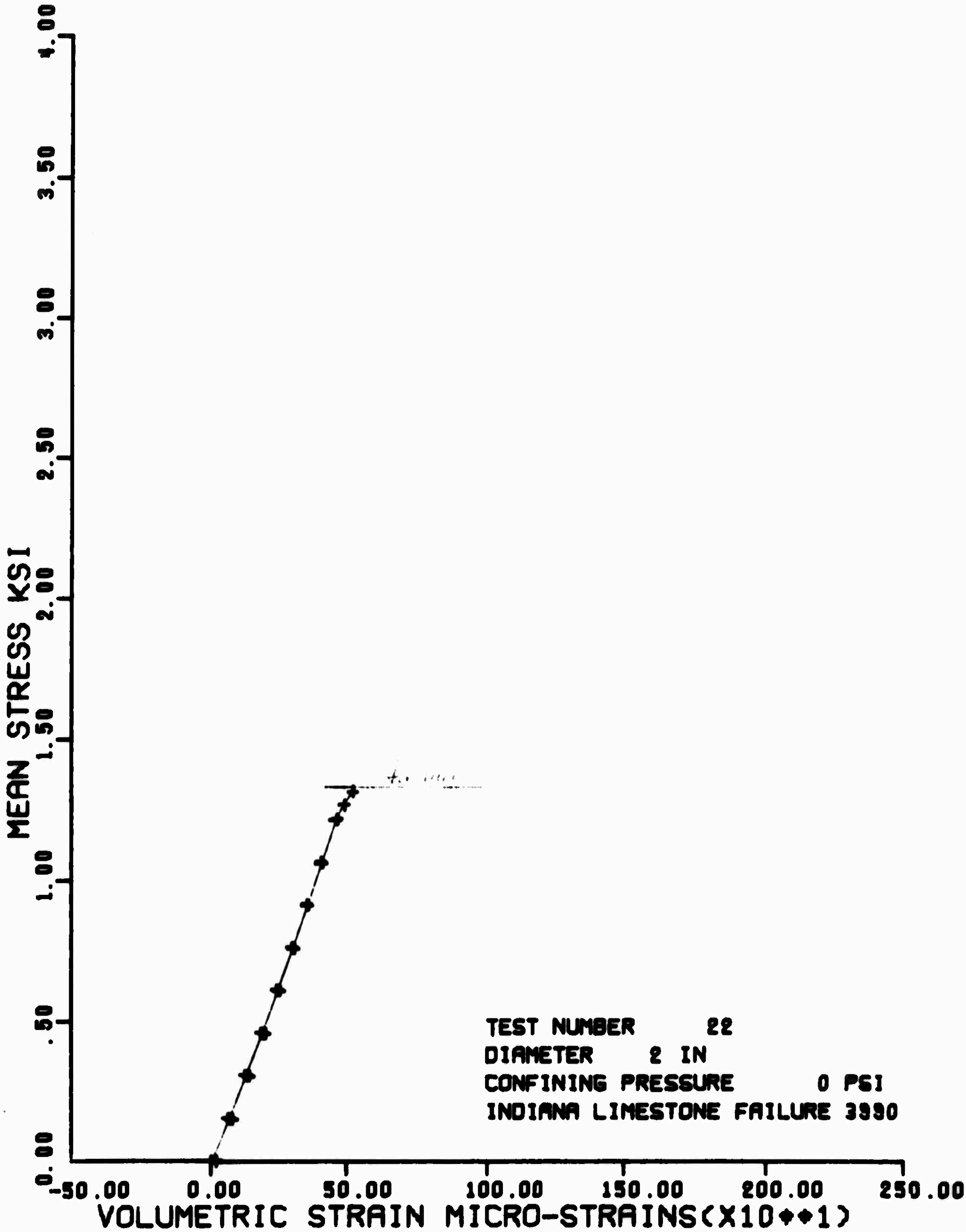


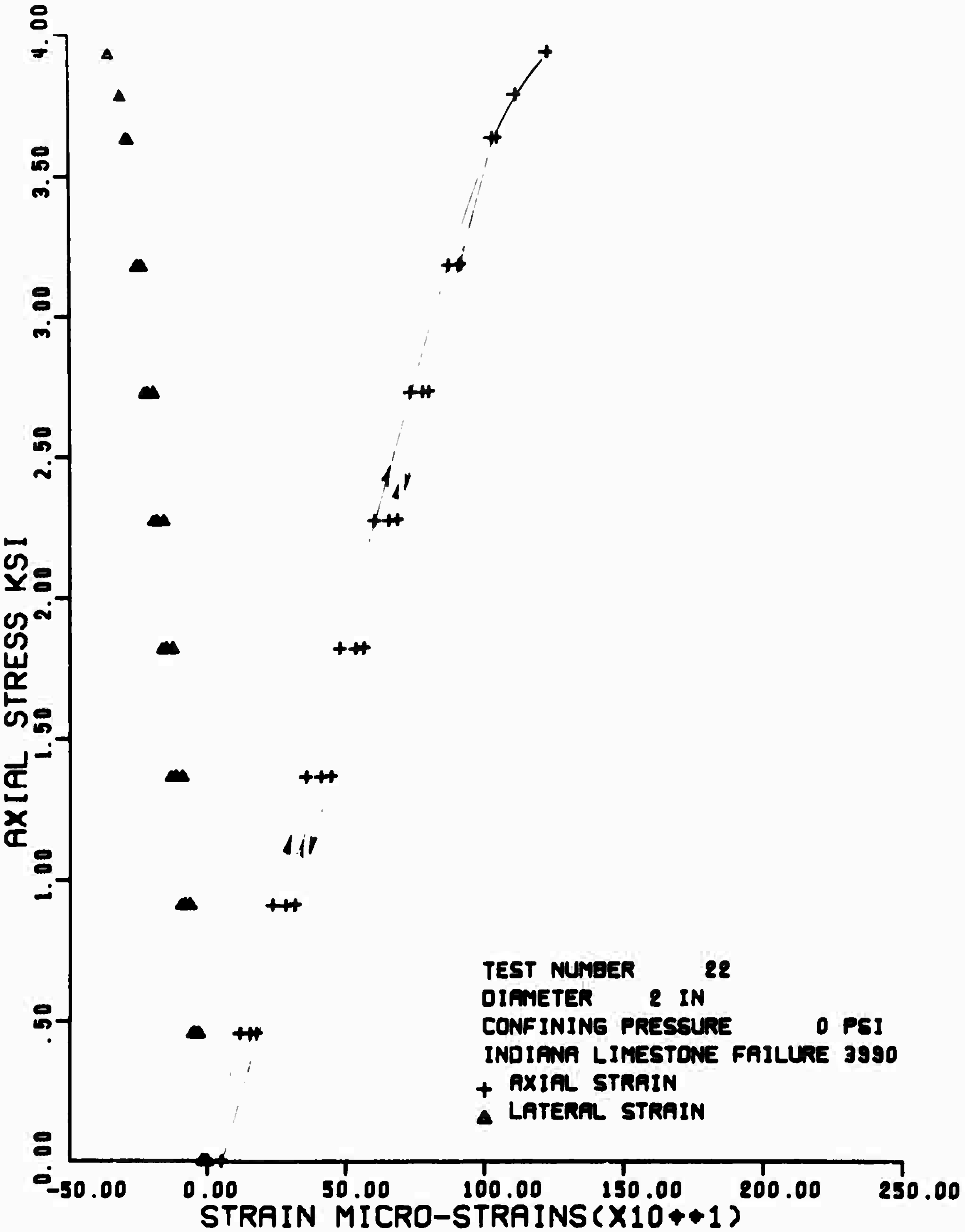
DEVIATOR STRESS KSI
0.00
.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
-50.00
0.00
50.00
100.00
150.00
200.00
250.00
SHEAR STRAIN MICRO-STRAINS(X10**1)
TEST NUMBER 21
DIAMETER 2 IN
CONFINING PRESSURE 0 PSI
INDIANA LIMESTONE FAILURE 4375


MEAN STRESS KSI
0.00
.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
-50.00
0.00
50.00
100.00
150.00
200.00
250.00
VOLUMETRIC STRAIN MICRO-STRAINS(X10**1)
TEST NUMBER 21
DIAMETER 2 IN
CONFINING PRESSURE 0 PSI
INDIANA LIMESTONE FAILURE 4375


AXIAL STRESS KSI
4.00
3.50
3.00
2.50
2.00
1.50
1.00
.50
0.00
-50.00
0.00
50.00
100.00
150.00
200.00
250.00
STRAIN MICRO-STRAINS(X10**1)
TEST NUMBER 21
DIAMETER 2 IN
CONFINING PRESSURE 0 PSI
INDIANA LIMESTONE FAILURE 4375
AXIAL STRAIN
LATERAL STRAIN


Failure
DEVIATOR STRESS KSI
0.00
.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
-50.00
0.00
50.00
100.00
150.00
200.00
250.00
SHEAR STRAIN MICRO-STRAINS(X10**1)
TEST NUMBER 22
DIAMETER 2 IN
CONFINING PRESSURE 0 PSI
INDIANA LIMESTONE FAILURE 3990


MEAN STRESS KSI
4.00
3.50
3.00
2.50
2.00
1.50
1.00
.50
0.00
-50.00
0.00
50.00
100.00
150.00
200.00
250.00
VOLUMETRIC STRAIN MICRO-STRAINS(X10**1)
TEST NUMBER 22
DIAMETER 2 IN
CONFINING PRESSURE 0 PSI
INDIANA LIMESTONE FAILURE 3990


AXIAL STRESS KSI
0.00
.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
-50.00
0.00
50.00
100.00
150.00
200.00
250.00
STRAIN MICRO-STRAINS(X10**1)
TEST NUMBER 22
DIAMETER 2 IN
CONFINING PRESSURE 0 PSI
INDIANA LIMESTONE FAILURE 3990
AXIAL STRAIN
LATERAL STRAIN