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LABORATORY VERIFICATION OF THREE DIMENSIONAL IN-SITU STRESS ELEMENTS

by

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ABSTRACT

Calculation of 3-dimensional in-situ stresses using overcoring methods typically requires the use of a single set of elastic constants, Young's modulus (E) and Poisson's ratio (ν), and the assumption of linear elastic isotropy.

Two experiments using the CSIR strain cell were conducted to examine the validity of the basic in-situ stress calculation method. The first assessed a method of using the overcored strain gauge cell itself to obtain the elastic constants. The second investigated a method of measuring in-situ stress from overcored sections without using elastic constants.

Deriving elastic constants for each CSIR cell rosette while uniaxially loading and unloading the overcore produced E and ν values which were more representative of the overcore's inhomogeneous and nonisotropic nature. These elastic constants were derived from the CSIR cell strain gauges, measuring the stress/strain behaviour of the overcored rock itself, not strain gauges on core obtained from several inches or feet away. Elastic constants obtained in this manner should allow more accurate in-situ stress calculation.

The simulation of in-situ stress by triaxially compressing the overcore yields valid results only if the

assumption is made that the hole is drilled parallel to the direction of one of the principal stresses. This method should find its optimal application in measuring stress when core drilling perpendicular to bedding in sedimentary formations.

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Chapter 1

INTRODUCTION

Strain gauge overcoring using a CSIR strain cell (Appendix 1) is one of several methods available for determining 3-dimensional in-situ stresses in rock. Current practice requires determination of the two elastic constants, Young's modulus (E) and Poisson's ratio (ν), in order to calculate the in-situ state of stress using the strain cell data recorded during overcoring. The constants chosen for calculation of the principal stresses have a significant effect on the resulting magnitudes and orientations of σ_1, σ_2, and σ_3.

In measuring the state of stress in Division One at the White Pine Copper Mine, White Pine Michigan (Appendix 2), M. A. Balcar and Associates, Inc. (MAB&AI) wished to determine which of two rock testing methods would more accurately measure Young's modulus and Poisson's ratio. The decision was also made to attempt to develop a method for determining in-situ stress which does not rely on elastic constants.

Typically, E and ν are determined by crushing a segment of core similar to the overcored section in a uniaxial compression test. Axial and transverse strains are recorded during the test, typically by using electrical resistance strain gauges. The slopes of the two curves, axial stress vs. axial strain, and transverse strain vs. axial strain, yield E and ν respectively

Unfortunately, the piece of core tested to obtain E and ν will almost never be identical mechanically to the overcored section, and the calculated stress field will not, therefore, be exactly the same as the actual in-situ stress field.

To avoid using elastic constants obtained from a dissimilar sample, E and ν can be obtained from the overcore section itself by recording stress and strain while uniaxially loading and unloading the overcored section in a hydraulic press.

It is theoretically possible to measure in-situ stresses without using elastic constants. If external stresses of the correct magnitudes and orientations are applied to the overcore, cancellation of the strains produced during overcoring should result. In practice, the measured overcoring strains were cancelled by placing the overcores in a triaxial compression cell and applying axial and transverse stresses to individually cancel the axial and transverse overcore strains for each of the three strain gauge rosettes.

An elliptical elastic rosette solution was then used to calculate the principal and minor secondary transverse stresses. Adding the average applied vertical cancellation stress yielded a three dimensional approximation of the in-situ stress field, without using elastic constants (Appendix 3).

To claim that the second method (simulation) gives a good approximation of principal in-situ stress requires assuming that the overcore drilling was done in a direction parallel to one of the in-situ principal stresses. This assumption is most easily made for holes drilled vertically through flat-lying, horizontally bedded strata, such as those at the White Pine Copper Mine.

Chapter 2

LITERATURE REVIEW

Leijon (1), obtained significantly different elastic constants from the same overcoring sample if he used confined (constant 10MPa axial load) rather than unconfined biaxial loading. Values of E were 20% higher and values of ν were 50% lower when derived from the confined biaxial test.

Herget (2), used both axial loading and biaxial loading to obtain elastic constants from four overcored CSIR cells. The mean E value from the axial loading test was 4.1% higher, and the values of ν were 20% lower than those from the biaxial loading test.

The American Society for Testing and Materials (ASTM) specifies the standard procedure for determining the Young's Modulus for rock (3). This standard is for testing solid cores and therefore requires that strains be measured on the exterior of the core. The strain measurements from the overcored CSIR cell, however, were obtained from the inner wall of a hollow cylinder. The inner surface of the overcore is more restricted in its movement than the overcore exterior, perhaps resulting in dissimilar strain measurements, and thus elastic constants, between solid and hollow rock cylinders.

Chapter 3

TRADITIONAL DETERMINATION OF THE ELASTIC CONSTANTS

Elastic constants were first obtained by uniaxial compression testing solid pieces of core recovered from the same drill holes and rock units as the overcored sections. The solid cores were cut to length and surface ground to meet ASTM standards (4).

One vertical and one horizontal strain gauge were attached to each sample, and the cores were incrementally compressed to failure in a rock testing machine.

Compressive stress, axial strain, and transverse strain were recorded at intervals during testing. The elastic constants were derived as tangent values from the straight-line portions of the respective stress/strain and strain/strain curves. Elastic constants thus obtained are shown in Table 1.

The majority of the stress/strain and strain/strain curves were linear for most of their length, and provided easily measured, rational tangential values of E and ν (Figures 1,2).

Several of the curves, however, were distinctly non-linear (Figures 3,4). To obtain rational Young's moduli and

Table 1

Elastic Constants of the Solid Cores

Hole #	Rock Type	E (10^6psi) (weighted)	ν (weighted)
TH-01V	UZV	4.20	0.253
"	Widely	5.92	0.318
"	Paper Shales	5.74	0.221
TH-02H	Upper Sandstone	4.51	0.300
"	Brown Massive	9.54	0.195
TH-03V	Stripey	6.69	0.313
"	Paper Shales	5.49	0.326
TH-04H	UZV	9.65	0.148
TH-05H	Widely	9.46	0.313
TH-07H	Upper Sandstone	6.04	0.220
TH-08H	Upper Sandstone	No sample	No sample
TH-09H	Upper Sandstone	7.88	0.310

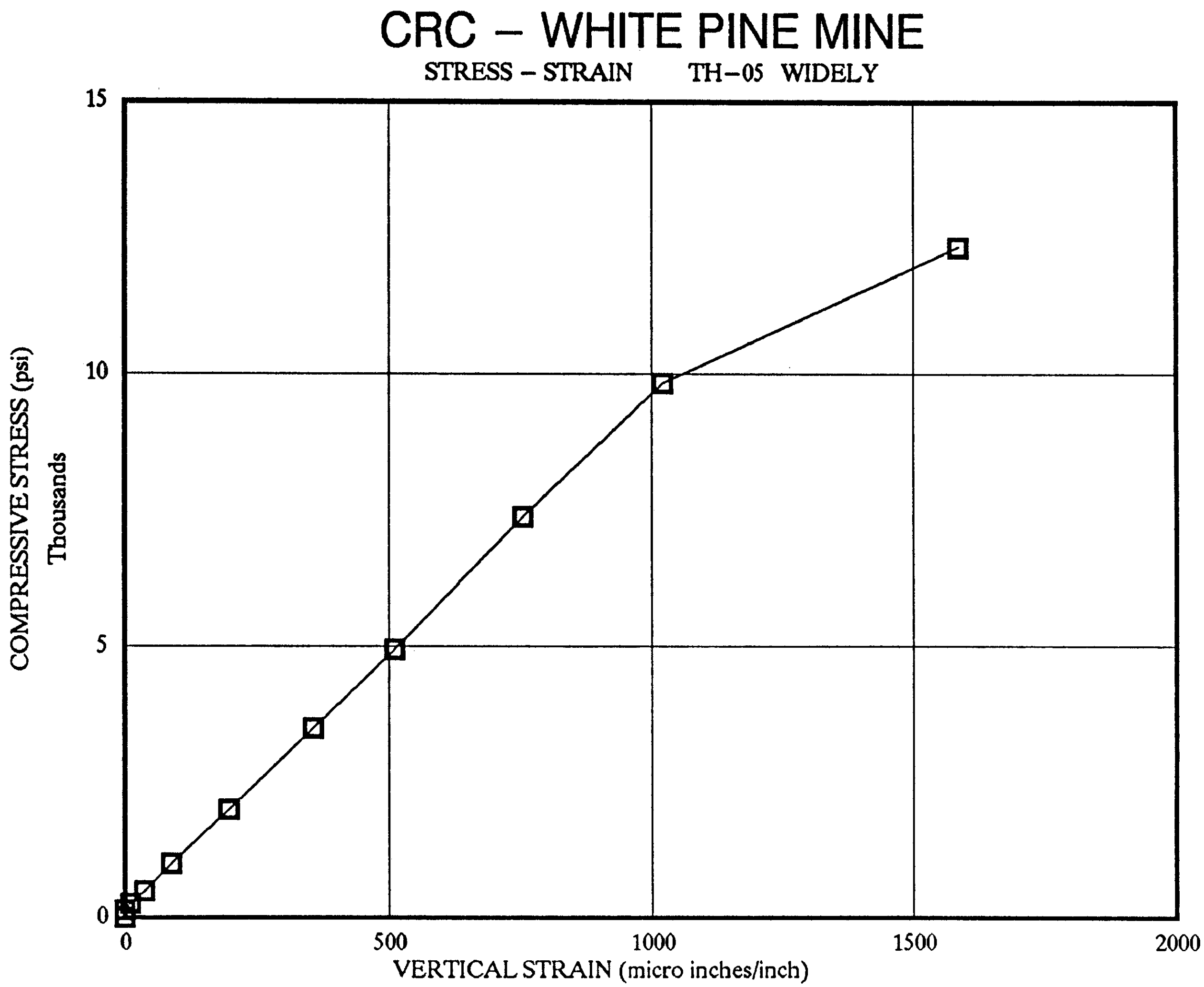


Figure 1

Typical Stress/Strain Curve for a Solid Core.

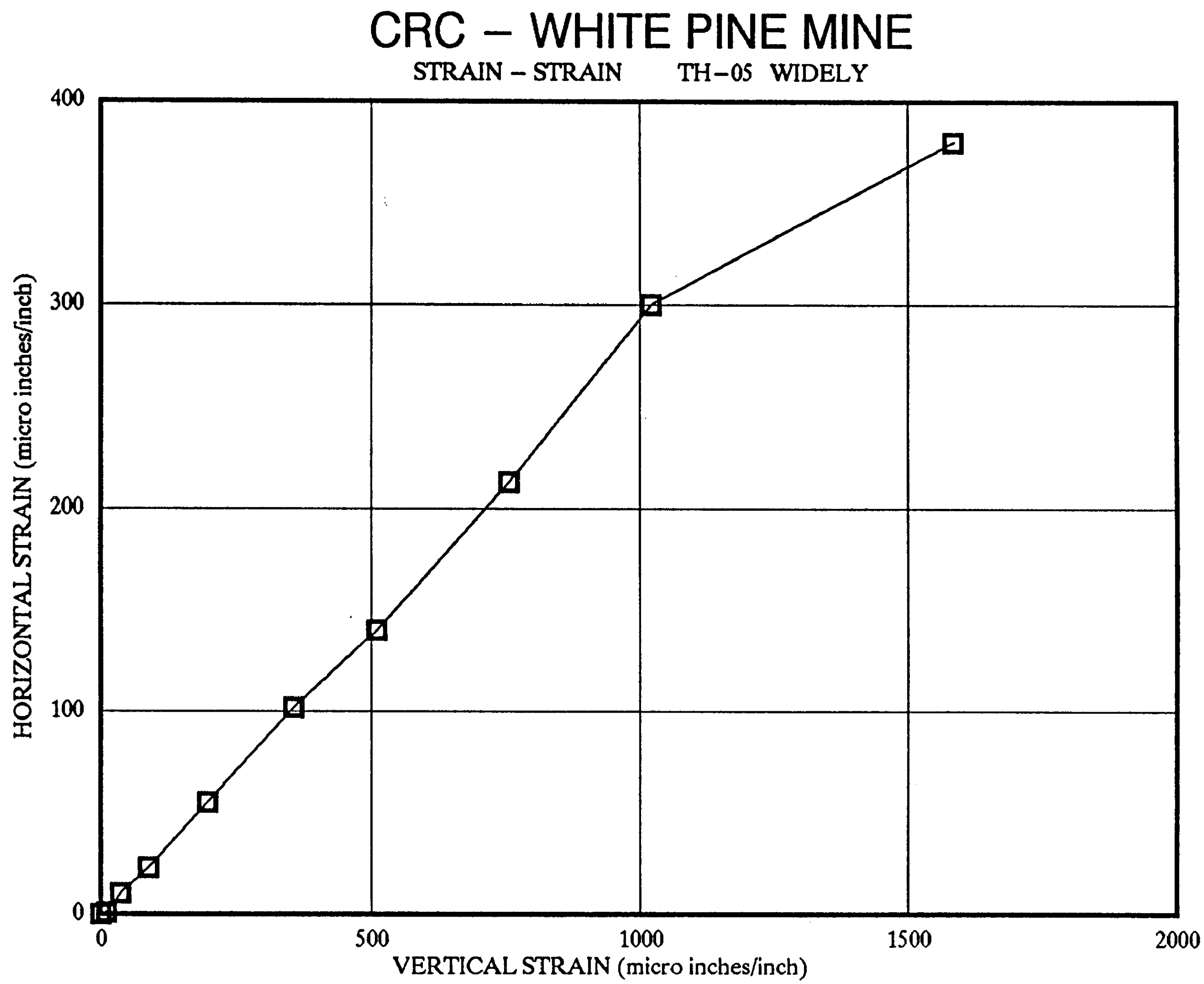


Figure 2

Typical Strain/Strain Curve for a Solid Core.

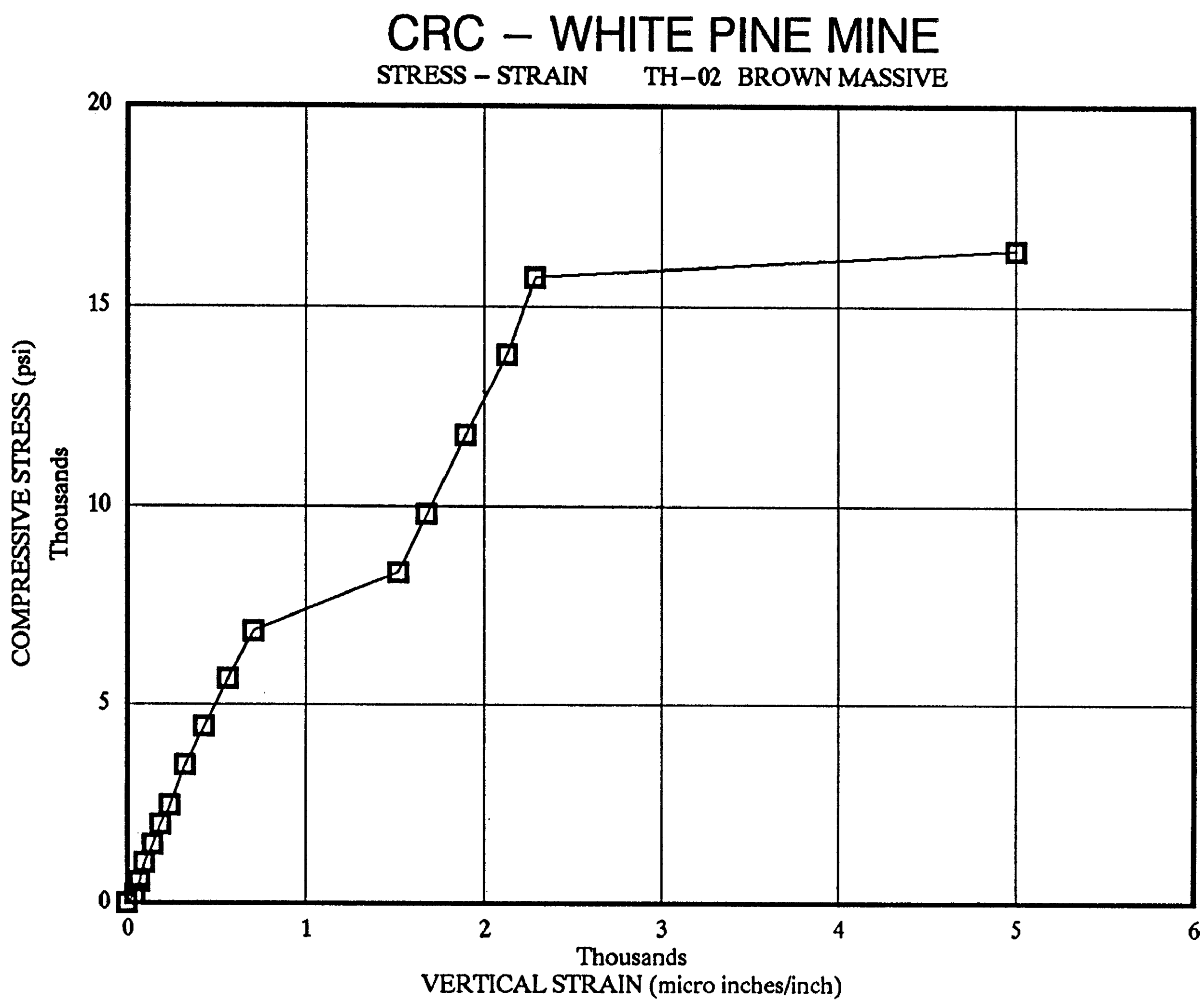


Figure 3

Atypical Stress/Strain Curve for a Solid Core.

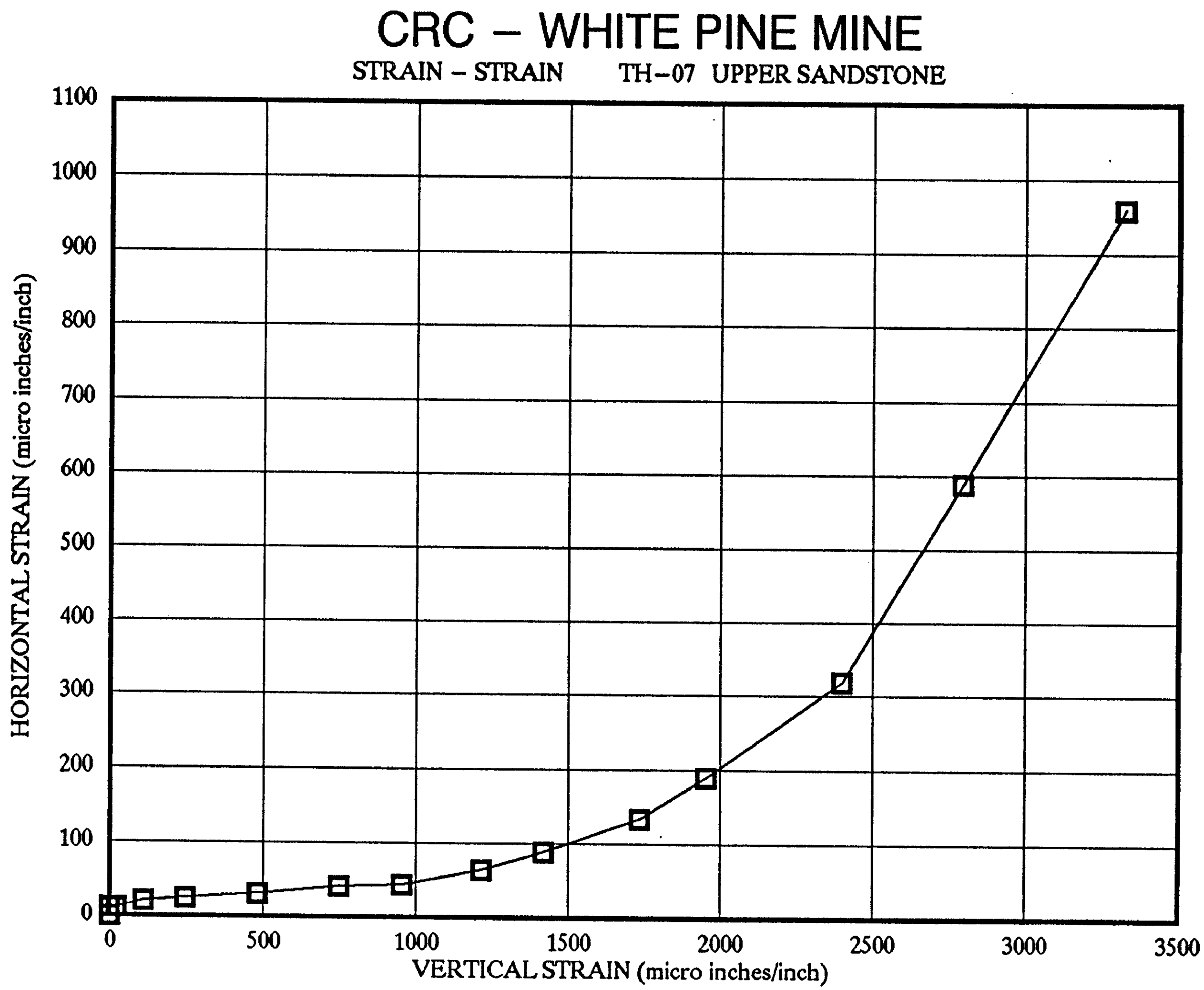


Figure 4

Atypical Strain/Strain Curve for a Solid Core.

Poisson's ratios from these curves, only the rational linear or near-linear segments of the curves were used. If more than one segment of a curve gave plausible values, the slopes of those segments were weighted, then averaged, using a computer program (5).

Chapter 4

DETERMINATION OF THE ELASTIC CONSTANTS FROM OVERCORED SECTIONS

To determine E and ν from the rock which was actually overcored, the strain gauges of the CSIR cell itself were used to obtain strain measurements while the overcore was being uniaxially compressed.

The cores containing the CSIR cells were examined for soundness, those with discing or cracks over the rosettes were not tested. Fourteen overcores were found to be suitable for testing in the press.

The acceptable cores were cut as closely as possible to the desired length of seven inches, then surface ground to meet ASTM standards (4). The prepared overcores were then placed in a rock testing machine and loaded uniaxially, not exceeding 80% of the measured compressive strength determined in the earlier testing of the solid cores (Chapter 2). Two of the overcore sections failed while being loaded.

The overcores were loaded uniaxially rather than radially or triaxially to obtain results more comparable to the uniaxial testing done on the solid core sections.

Strain recordings from all twelve gauges in the CSIR cell were made at various stress levels while loading and unloading the samples. Examination of the stress/strain and strain/strain curves generated by loading and unloading the overcore helped to identify strain gauges giving irrational readings. The values of E and ν were obtained from the tangents to their respective unloading curves. Constants from the unloading curves were assumed to more accurately reflect the rock's behaviour during overcoring. Elastic constants for the two failed overcores were calculated from the loading curves.

Just as with the stress/strain and strain/strain curves made from testing the solid cores, most of the overcore loading and unloading curves were roughly linear (Figures 5-10). In determining slopes of the non-linear unloading curves (Figures 11-16), the same methods were used as for the solid cores (Chapter 3).

The MAB&AI computer program (6) for calculating in-situ stress uses an average Young's modulus and Poisson's ratio for the CSIR cell. The values from each rosette, and the strain cell averages with their standard deviations, are shown in Table 2.

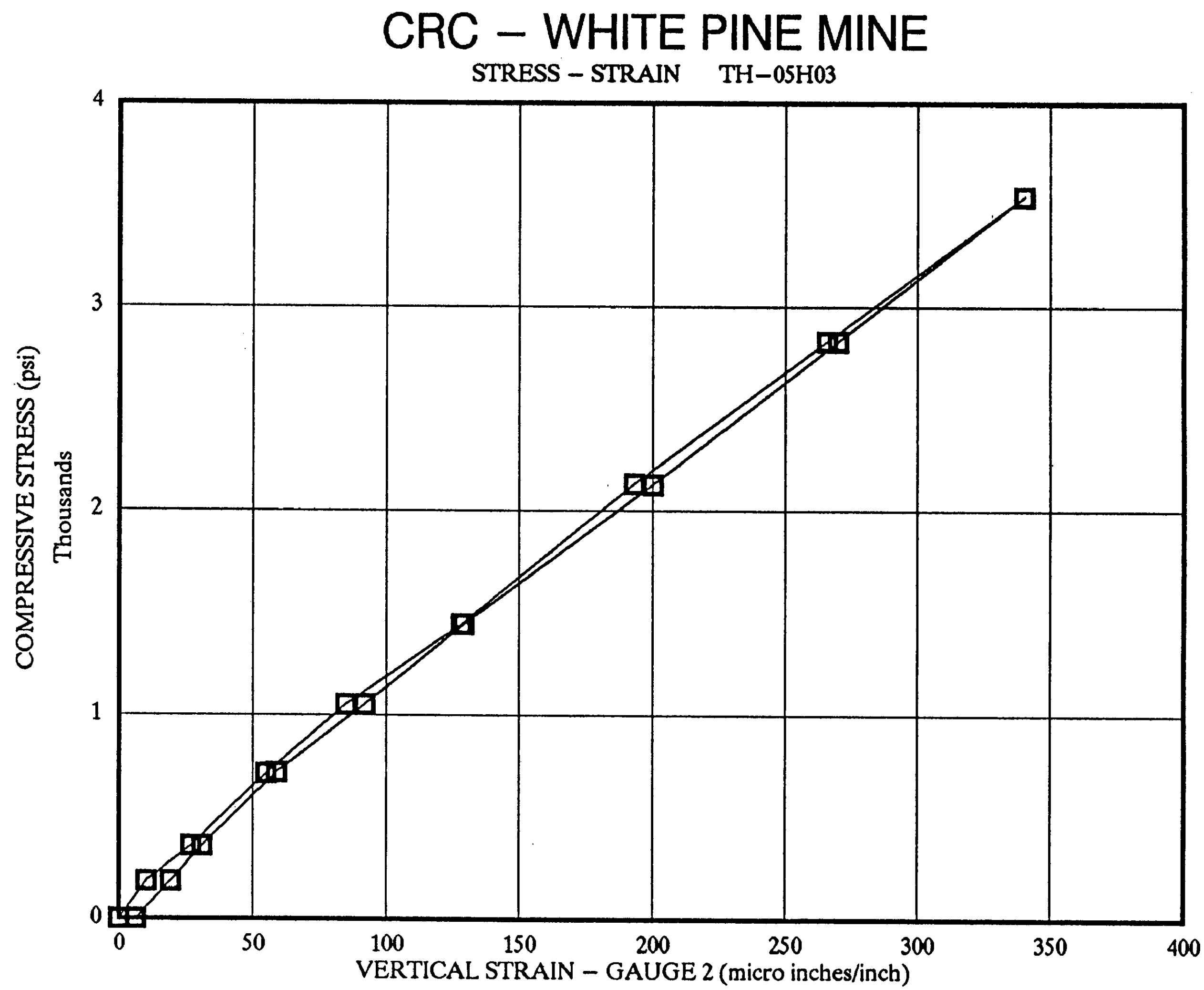


Figure 5

Typical Stress/Strain Curve for an Overcore.

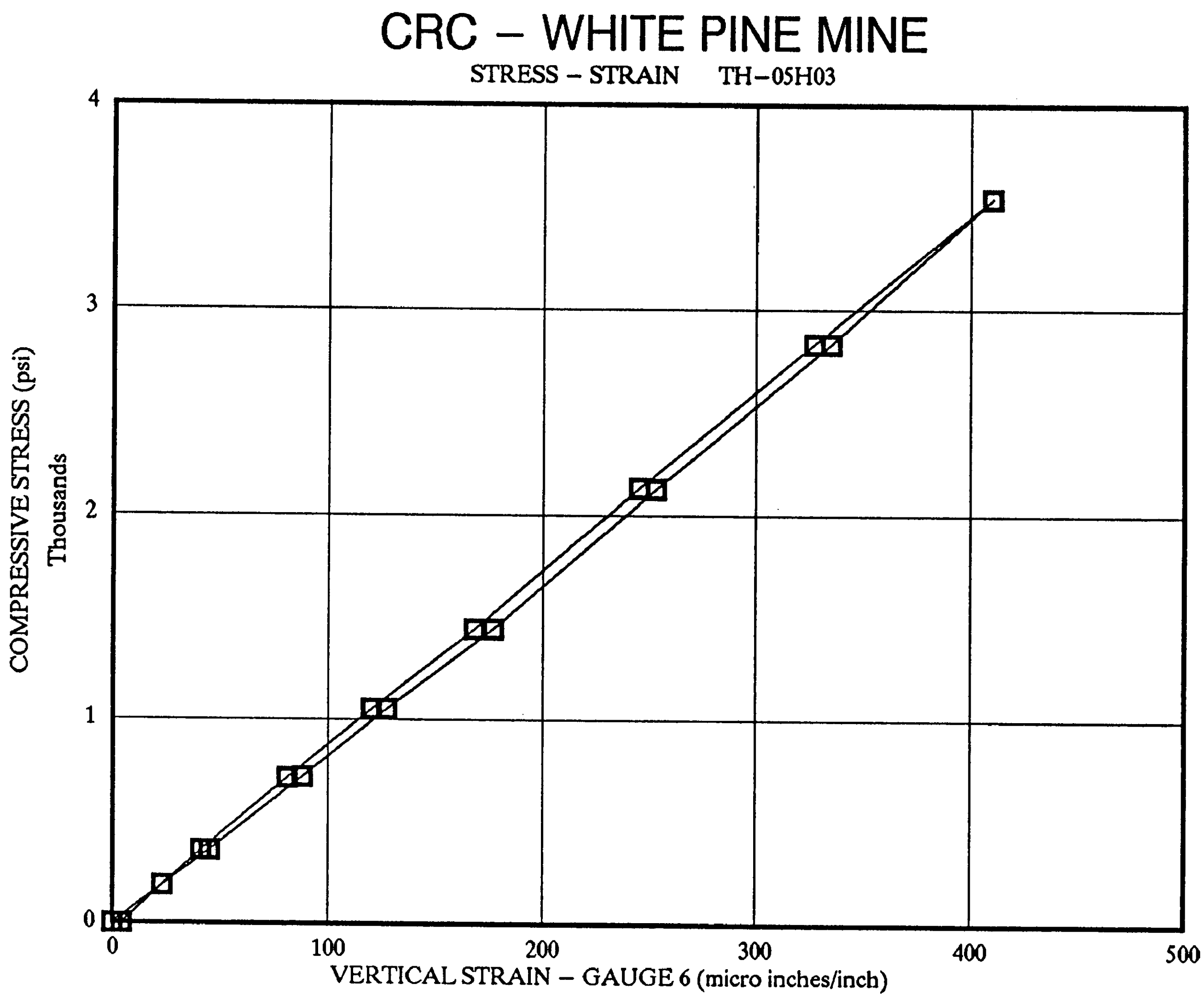


Figure 6

Typical Stress/Strain Curve for an Overcore.

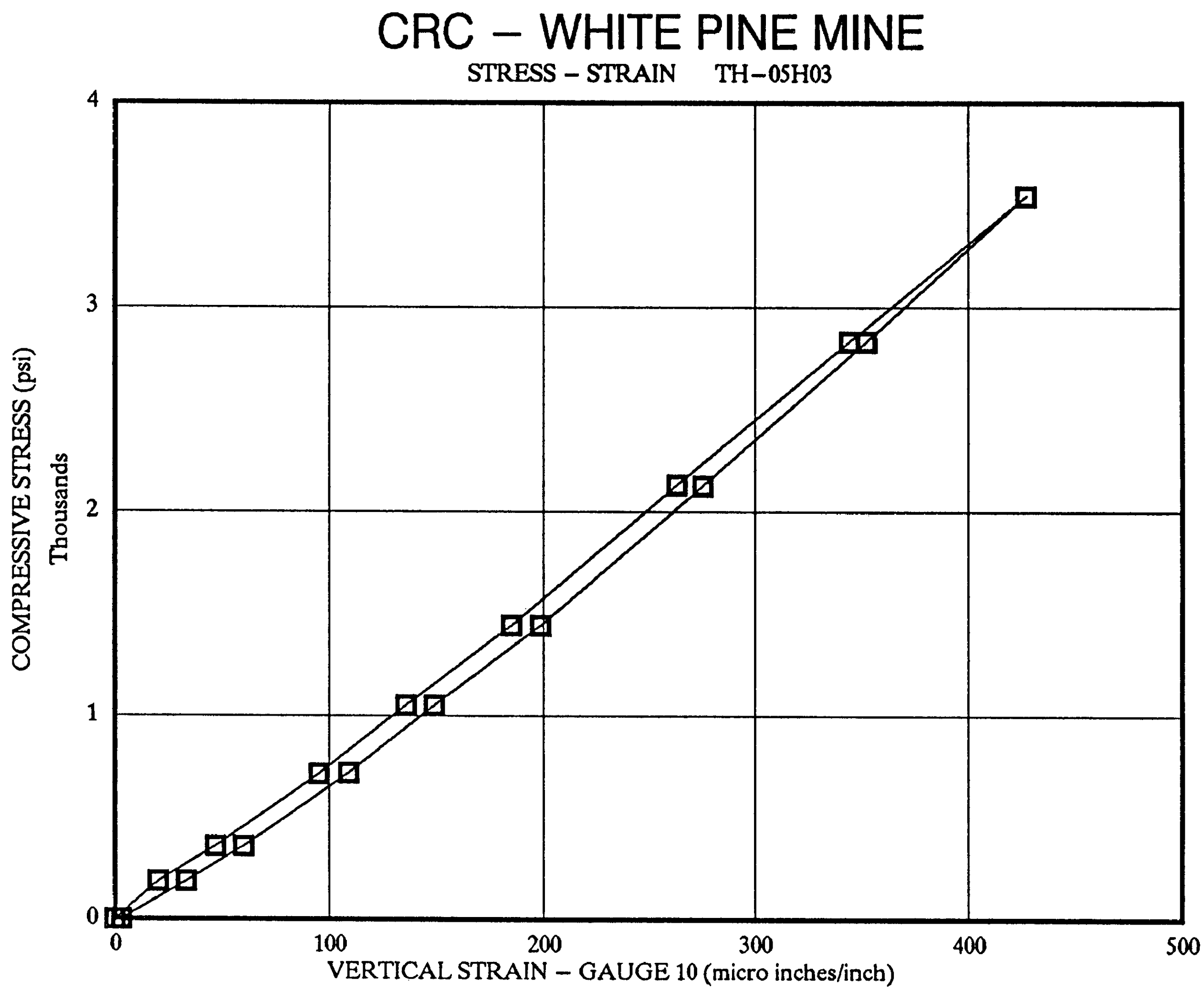


Figure 7

Typical Stress/Strain Curve for an Overcore.

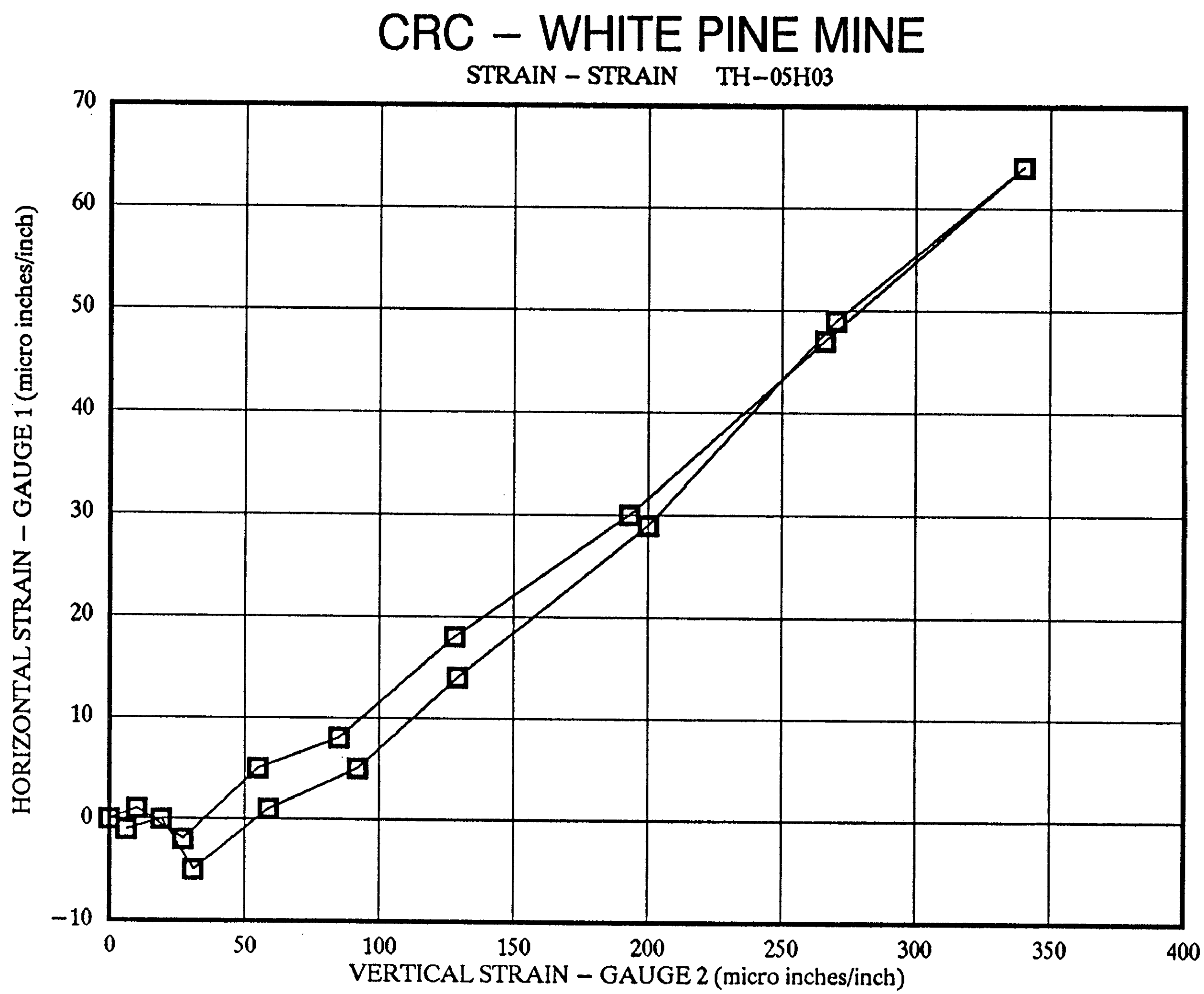


Figure 8

Typical Strain/Strain Curve for an Overcore.

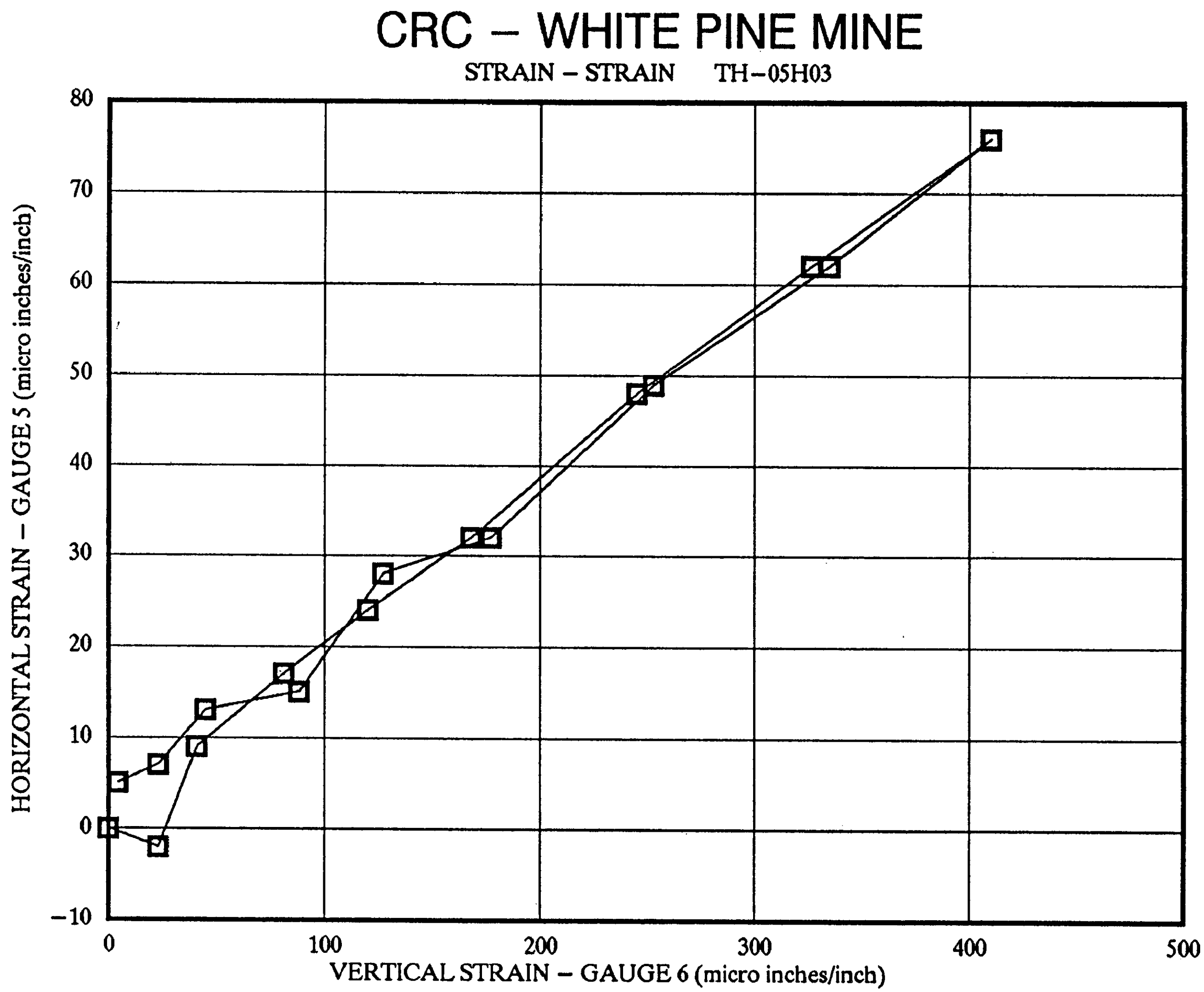


Figure 9

Typical Strain/Strain Curve for an Overcore.

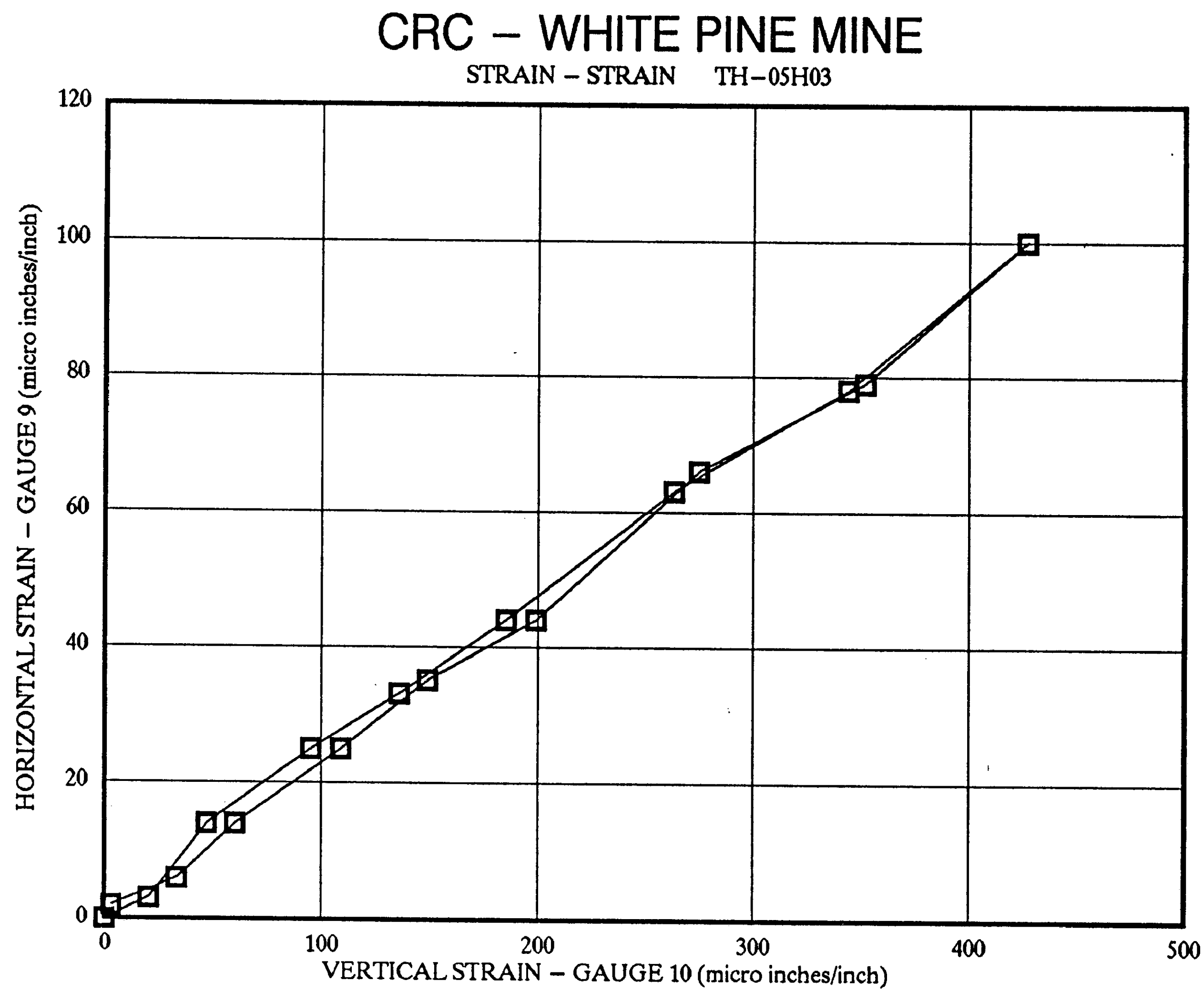


Figure 10

Typical Strain/Strain Curve for an Overcore.

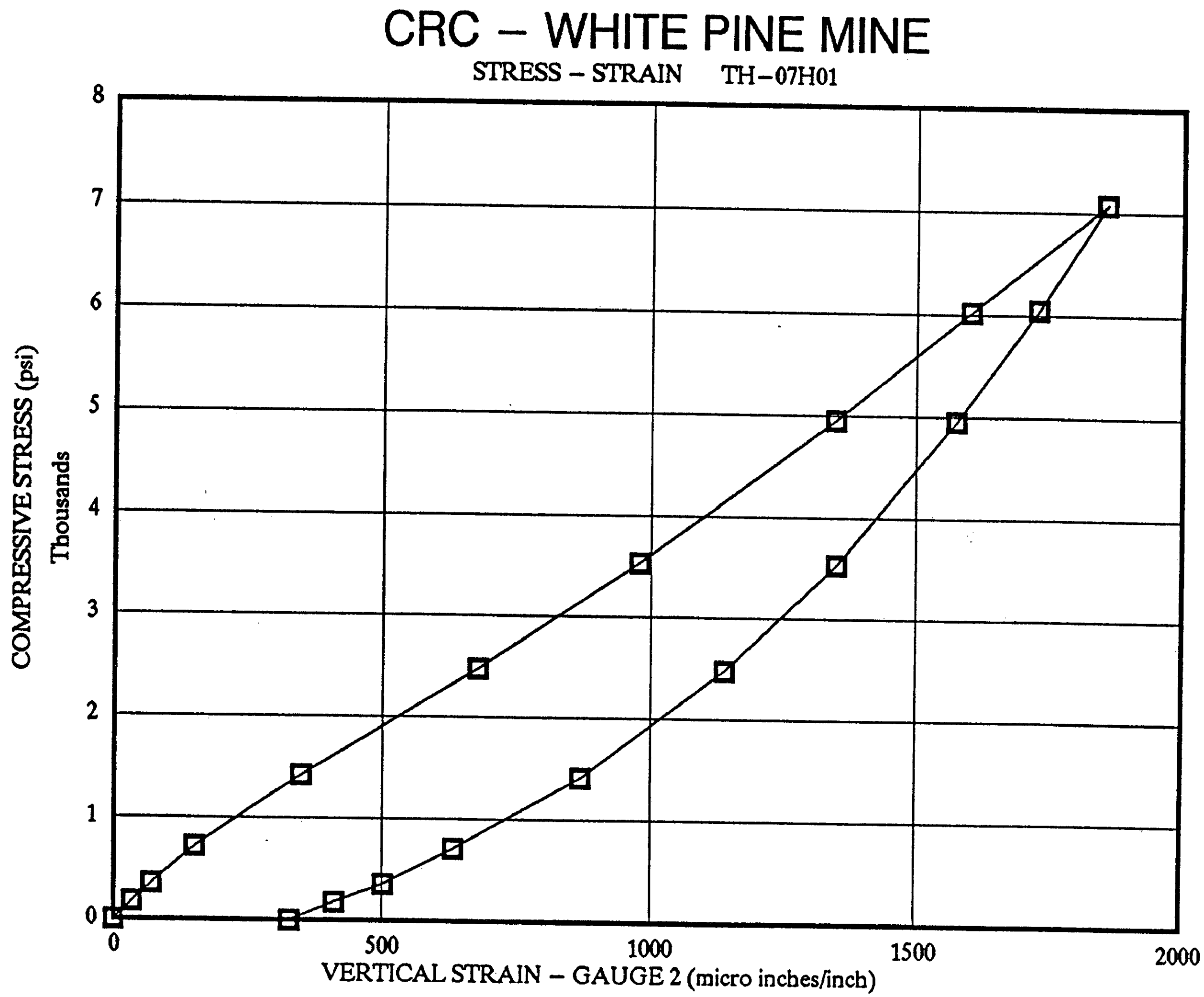


Figure 11

Atypical Stress/Strain Curve for an Overcore.

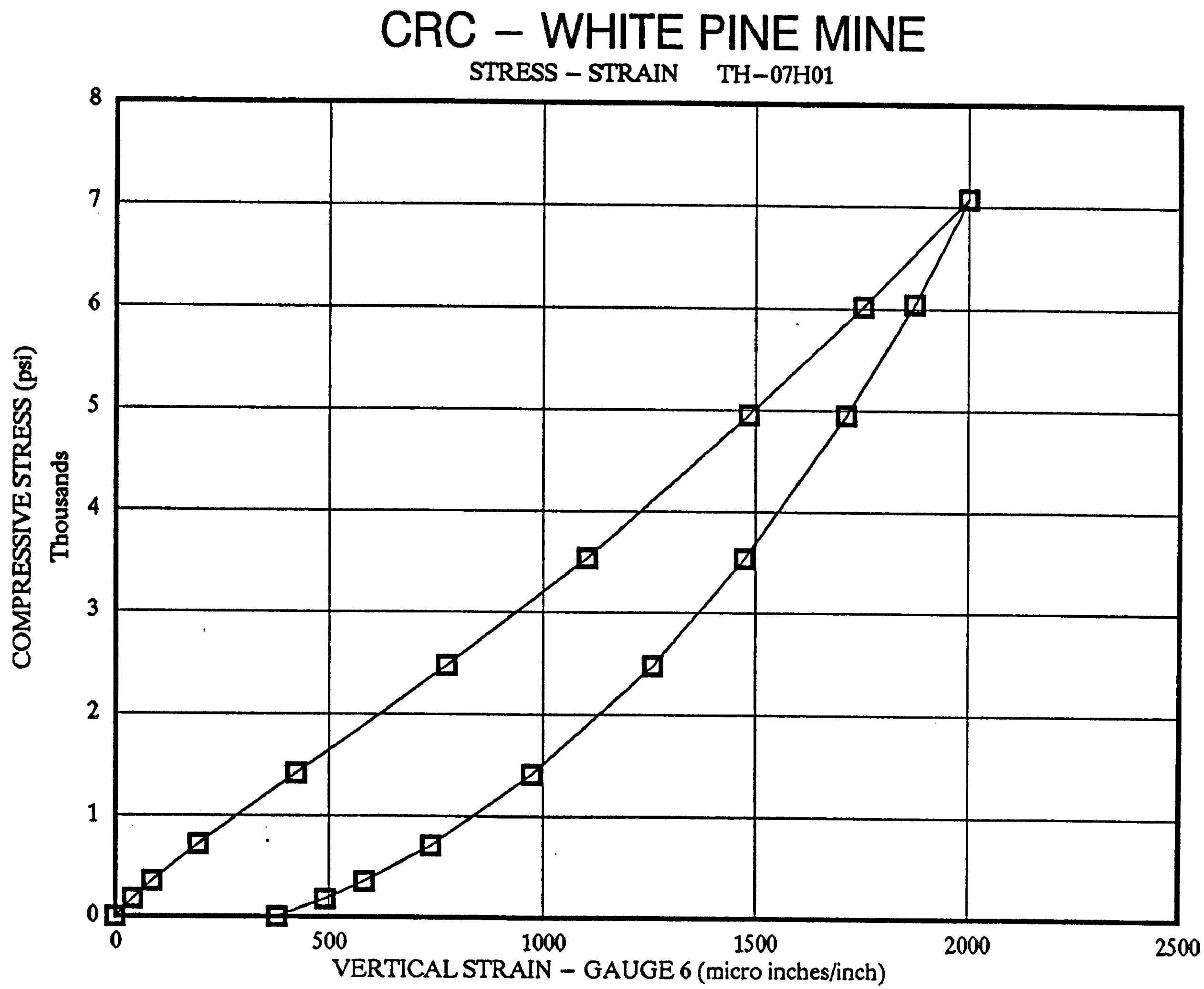


Figure 12

Atypical Stress/Strain Curve for an Overcore.

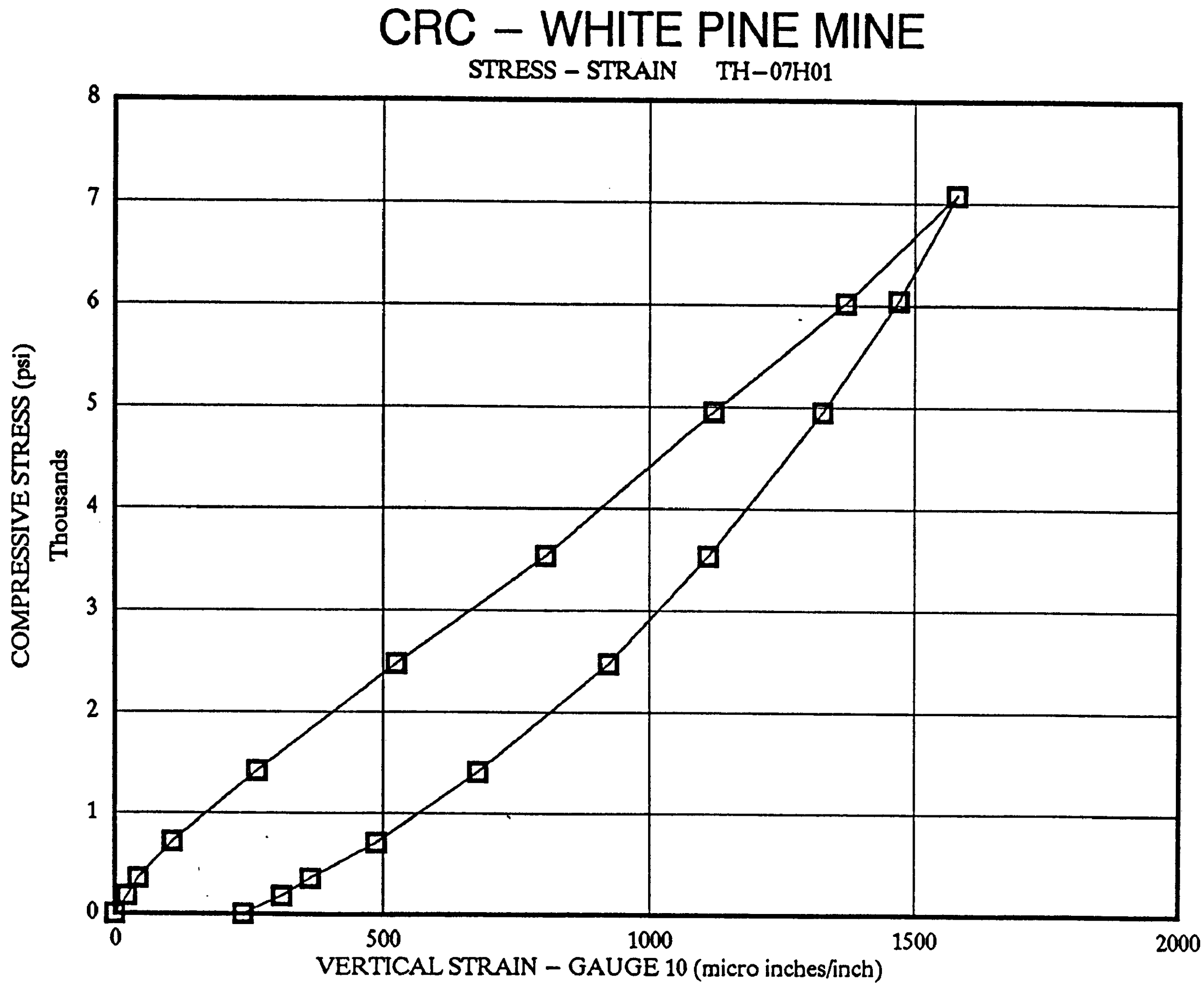


Figure 13

Atypical Stress/Strain Curve for an Overcore.

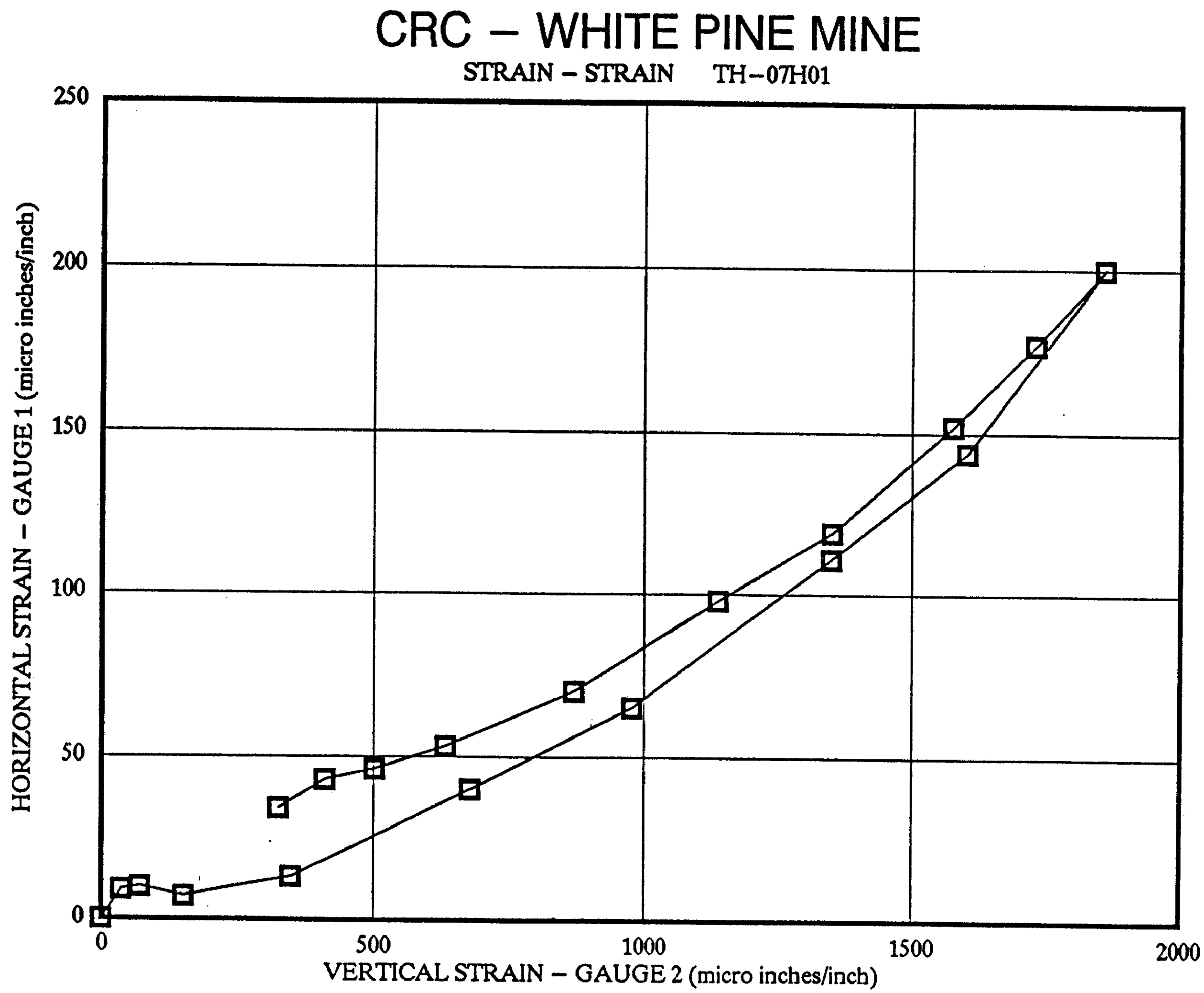


Figure 14

Atypical Strain/Strain Curve for an Overcore.

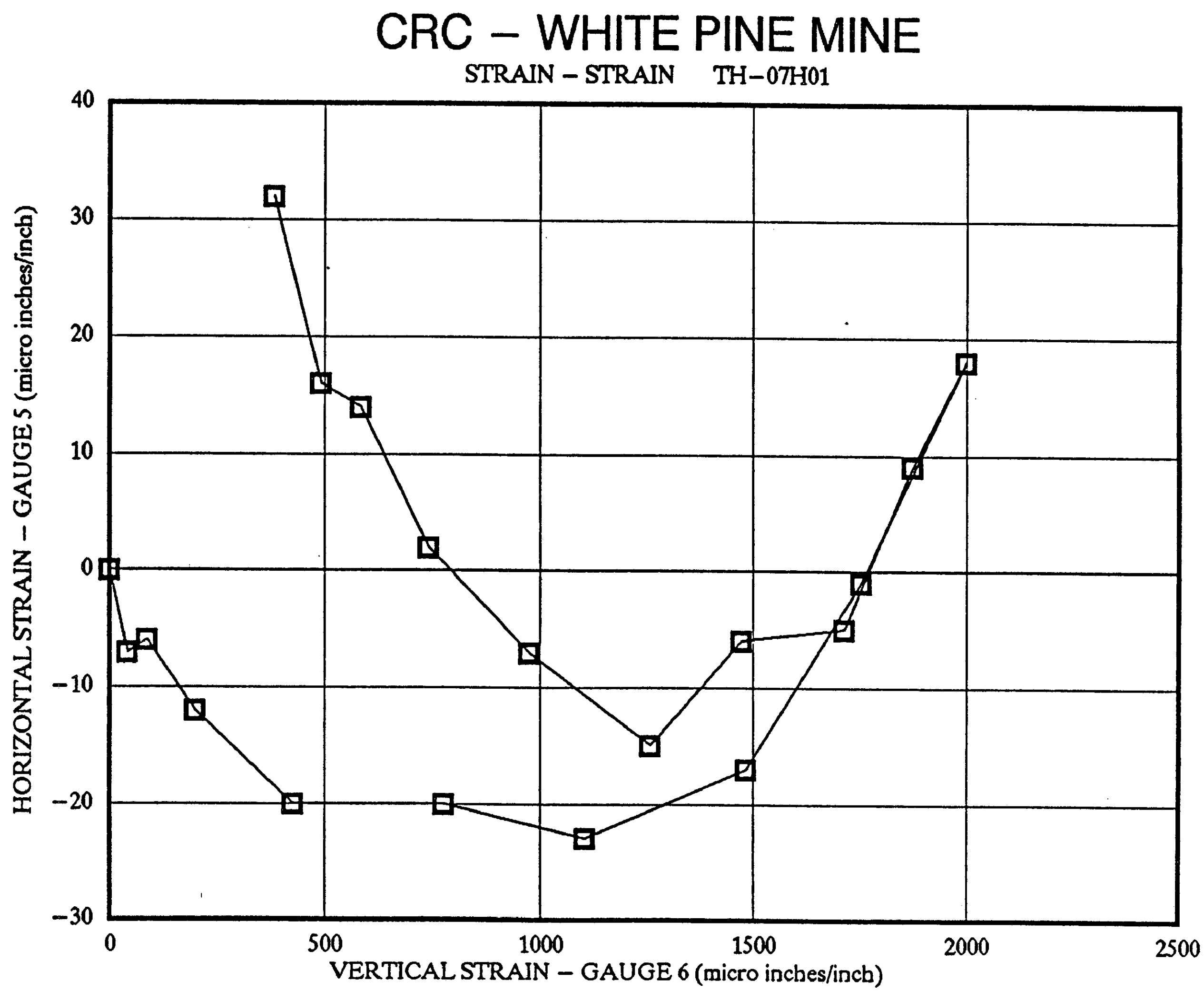


Figure 15

Atypical Strain/Strain Curve for an Overcore.

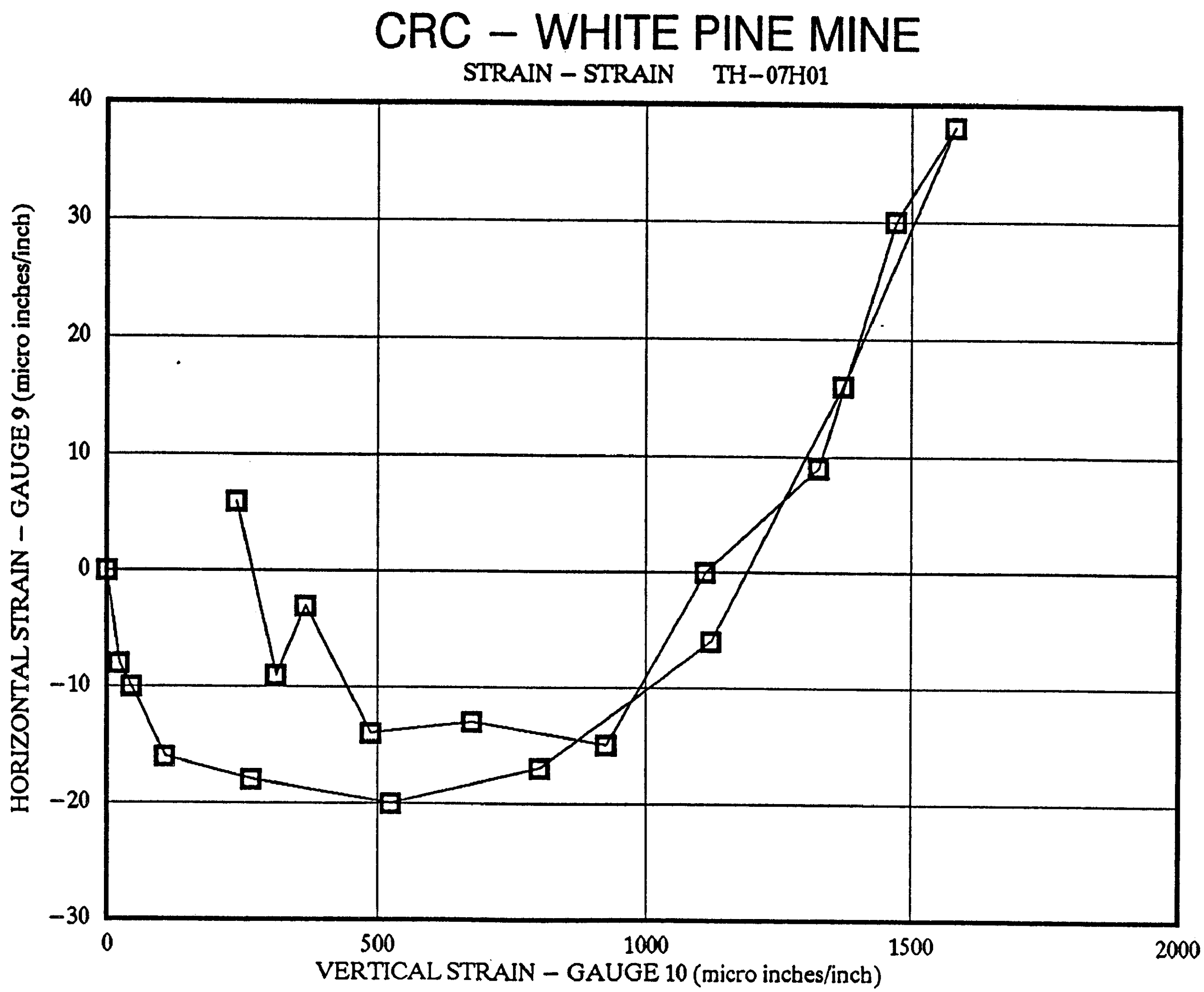


Figure 16

Atypical Strain/Strain Curve for an Overcore.

Table 2

Elastic Constants of the Overcores

Test #	Rock Type	Rosette E (10^6 psi) (weighted)	Average E std dev (10^6 psi) (weighted)	Rosette ν (wt.)	Average ν std dev (wt.)
TH-01V01	UZV	4.26 --- 3.73	4.00 0.26	0.188 --- 0.104	0.146 .044
TH-01V02	Widely	5.52 --- 5.49	5.50 0.02	0.182 0.408 0.298	0.244 .056
TH-01V07	Paper Shales	6.27 2.57 3.78	4.20 1.54	0.105 0.182 0.152	0.152 .030
TH-02H01	Upper Sand-stone	6.72 9.50 7.92	8.10 1.13	0.203 0.133 0.270	0.230 .023
TH-02H02	Brown Massive	10.62 6.69 14.70	11.12 3.15	0.215 0.251 0.236	0.232 .015
TH-03V02	Stripey	7.50 7.41 7.80	7.57 0.17	0.191 0.248 0.214	0.218 .023
TH-03V03A	Paper Shales	5.62 5.75 5.62	5.66 0.45	0.114 0.201 0.283	0.203 .071
TH-03V04	Paper Shales	9.69 5.11 5.40	6.73 2.09	--- 0.412 0.345	0.360 .171
TH-04H01	UZV	---	---	---	---

(continued)

Table 2

(continued)

Test #	Rock Type	Rosette E (10^6 psi) (weighted)	Average E std dev (10^6 psi) (weighted)	Rosette ν (wt.)	Average ν std dev (wt.)
TH-05H01	Widely	5.16 5.28 13.58	8.12 4.00	0.138 0.422 0.319	0.301 .126
TH-05H03	Widely	10.05 8.64 8.41	9.03 0.91	0.220 0.189 0.234	0.216 .019
TH-07H01	Upper Sand-stone	5.24 5.02 5.85	5.52 0.26	0.199 0.081 0.088	0.109 .032
TH-08H02	Upper Sand-stone	6.58 6.22 6.12	6.30 1.18	0.123 0.107 0.090	0.108 .036
TH-09H01	Upper Sand-stone	4.06 8.00 4.83	5.63 2.33	0.131 0.141 0.084	0.119 .042

Chapter 5

COMPARISON OF THE VALUES OF THE ELASTIC CONSTANTS

In comparing the values of E and ν determined by the two methods presented in chapters three and four (Table 3), the most obvious differences are between the Poisson's ratios.

Poisson's ratios from the overcores were lower than the Poisson's ratios obtained from the solid cores for ten of the twelve sets of test results which can be compared. The Poisson's ratio values of the overcores averaged 0.079, or 25.4%, smaller than the Poisson's ratios of the solid cores from the same test hole and rock unit. This is a significant difference, and use of the higher solid core ν values would markedly affect the calculated stresses.

The lower Poisson's ratio values from the overcores might be, in part, the result of taking strain measurements from the inner surfaces of the hollow cylinders rather than from the outer surfaces. The rock at the inner surface of the core would have more resistance to transverse movement than the rock on the outside. Such restraint would result in lower measured transverse strains for the inner surface of the overcores than would be recorded on the unrestrained outside of a cylinder, as is the case for solid cores. A lower

Table 3

Comparison of the Elastic Constants:

Overcore versus Solid Core Measurements

Test #	ΔE (10^6 psi)	Percent	Δν	Percent
TH-01V01	-0.20	-4.8	-0.107	-42.3
TH-01V02	-0.42	-7.1	-0.074	-23.3
TH-01V07	-1.54	-26.8	-0.069	-31.2
TH-02H01	3.59	78.5	-0.070	-23.3
TH-02H02	1.58	16.6	0.037	19.0
TH-03V02	0.88	13.2	-0.095	-30.4
TH-03V03A	0.17	3.1	-0.123	-37.3
TH-03V04	1.24	22.6	0.034	10.4
TH-04H01	---	---	---	---
TH-05H01	-1.34	-14.2	-0.012	-3.8
TH-05H03	-0.43	-4.5	-0.097	-31.0
TH-07H01	-0.52	-8.6	-0.111	-50.5
TH-08H02	---	---	---	---
TH-09H01	-2.25	-28.6	-0.191	-61.6

transverse strain with a constant axial strain will produce a lower Poisson's ratio.

The differences in Young's modulus between the two methods were not as marked, nor as large. Seven of the twelve E values from the CSIR cells were lower than the Young's moduli of the solid cores and five of the twelve were higher. The mean difference in Young's modulus between the overcores and solid cores was 0.06×10^6 psi, or 3.1%.

For calculating the in-situ stresses it was decided to use the average E and ν values from the overcores. The rationale for preferring the overcore values was that they were a better measurement of the elastic constants for the rock to which the CSIR cell strain gauges were attached; the elastic constants having been obtained using the same strain gauges, with the same geometrical relationship, on the same rock, as during the overcoring itself.

Chapter 6

TRIAXIAL STRESS CANCELLATION OF MEASURED OVERCORING STRAINS

Given the large variation of elastic constants determined by the two preceding uniaxial testing methods, it would be desirable to have a method for finding in-situ stress not requiring laboratory testing and calculation of E and ν.

An experiment was conducted to see if triaxial compression equipment could be used to reproduce the in-situ stresses which had been acting on the overcored sections, prior to overcoring, by applying axial and transverse stresses to cancel out the strains recorded while overcoring. An estimate of the in-situ stresses could then be made without relying on elastic constants.

The cut and ground overcored sections were placed in a Hoek - Franklin type triaxial compression cell and axially loaded in a 220,000 pound capacity rock testing machine. The top platen was a hemispherical seat, the bottom platen was a cylinder machined to allow passage of the strain meter cable to the CSIR cell in the overcore. Transverse (hydraulic) pressure was applied to the exteriors of the overcores with a 10,000 psi hydraulic pump.

The objective of placing the overcore under load was to impose a stress field simulating the magnitude and orientation of the in-situ stress on each CSIR cell rosette, assuming that core drilling had been done parallel to one of the principal in-situ stresses. Therefore, a combination of loads was sought that would produce strain gauge readings equal in magnitude but opposite in sign to those recorded after overcoring. This procedure was called 'zeroing out', or cancelling, the in-situ stresses.

Since the overcores were neither homogeneous nor isotropic, a unique combination of axial and confining loads was required to 'zero out' the horizontal and vertical strain gauges in each of the three CSIR strain cell rosettes. This resulted in three sets of axial and transverse 'zeroing' stresses for each overcore.

The three axial 'zeroing' stresses which cancelled the axial overcoring strains were averaged to derive an estimate of the in-situ stress parallel to the drillhole axis.

The three transverse 'zeroing' stresses were resolved into major (σ_p), and minor (σ_q), transverse stresses using an equiangular rosette solution (7). The angle Θ_p, measured positive counterclockwise from the orientation of σ_p to the orientation of rosette number one, was also found using the standard 60° rosette solution. Θ_q is perpendicular to and in the same plane, 90° from the overcore axis, as Θ_p.

The overcored sections containing the CSIR cells are thick walled cylinders. Therefore, the stresses applied to the overcore in the laboratory cannot be compared directly to the in-situ stresses, which are assumed to be applied to the rock mass at infinity.

The stresses σ_p and σ_q, applied at the overcore exterior, were converted to σ_p and σ_q at infinity to represent in-situ stress, using the Lamé thick-walled cylinder equation (5):

$$\sigma_{tc} = 2P_i\left(\frac{r^2}{r^2 - a^2}\right) \qquad \textbf{(1)}$$

where: σ_{tc} = tangential stress at the inner surface

P_i = pressure on the cylinder exterior

r = cylinder outside radius

a = cylinder inside radius

Since the same value of σ_{tc} (equal to the transverse gauge zeroing stress) needs to be produced by stresses applied at either the overcore surface or at infinity, σ_{tc} for r = a and σ_{tc} for r = ∞ are equal:

$$\sigma_{tc} = 2P_i\left(\frac{r^2}{r^2 - a^2}\right) = 2P_\infty\left(\frac{r^2}{r^2 - \infty^2}\right) \qquad \textbf{(2)}$$

Which simplifies to:

$$\sigma_{tc} = P_i \left(\frac{r^2}{r^2 - a^2} \right) = P_\infty \tag{3}$$

The in-situ stress required to produce the tangential stress σ_{tc} in the overcore is greater than the horizontal zeroing stresses σ_p and σ_q by a factor of :

$$\left(\frac{r^2}{r^2 - a^2} \right) \tag{4}$$

For the overcore TH-02H02, with an outside diameter of 3.185 inches (r = 1.593), and an inside diameter of 1.496 inches (a = 0.748):

$$P_i \left(\frac{1.593^2}{1.593^2 - 0.748^2} \right) = P_\infty \tag{5}$$

and

$$P_i(1.283) = P_\infty \quad or \quad P_i = 0.780 P_\infty \tag{6}$$

The stress applied to the core's circumference to cancel the overcore strains will, therefore, be 78% of the stress required at infinity to cancel the same strains. Conversely, to produce equal tangential stress at the inner wall of the overcore, the stress applied at infinity must be 28% larger than the laboratory confining stress.

Chapter 7

COMPARISON OF CALCULATED AND SIMULATED IN-SITU STRESS

To compare the in-situ stresses calculated by MAB&AI using the overcore-derived elastic constants (Table 4), to the simulated in-situ stresses (Table 5), two assumptions were made. First, that the elastic constants obtained from the overcores and used in the calculations were correct. Second, that the drillhole axis was oriented parallel to one of the principal stresses.

The assumption of drilling parallel to a principal stress would be unnecessary if independent cancellation stresses could be applied to the overcores in the directions of the principal stresses, or a method for rotation of the experimentally obtained secondary stresses were available. At this time no such method has been developed.

The test for which the assumption of drilling parallel to a principal stress was most probably true was 03V03A, since it was drilled vertically and approximately perpendicular to the bedding. The orientation of σ_3 for test 03V03A from the calculated in-situ stress model is only 4° from the vertical, supporting the assumption that the hole was drilled parallel to one of the principal stresses. It was expected that this

Table 4

Calculated In-Situ Stress*

Test #	σ_1 psi	Az deg	Inc deg	σ_2 psi	Az deg	Inc deg	σ_3 psi	Az deg	Inc deg
02H02	5851	36	-10	4126	306	2	2769	46	80
03V03A	5104	38	-1	3413	308	4	2915	298	-86
04H01	5813	14	-8	4767	285	7	2252	58	79
05H03	6971	20	-5	6035	291	4	2673	58	84
07H01[1]	10521	309	-7	8453	36	20	6741	57	-68
08H02[1]	12701	341	-2	10943	71	18	6637	78	-72
09H01[2]	7126	322	-23	4390	299	66	3072	48	8

[1] 73' by 38' pillar
[2] 115' by 28' pillar

Table 5

Simulated In-Situ Stress*

Test #	σ_1 psi	Az deg	Inc deg	σ_2 psi	Az deg	Inc deg	σ_3 psi	Az deg	Inc deg
02H02	8938	60	2	7304	330	8	2640	150	82
03V03A	9015	301	0	4997	31	0	4023	0	90
04H01	6630	335	12	6629	65	2	2236	155	78
05H03	7074	322	2	6345	52	1	763	142	88
07H01	9879	320	-19	7257	50	1	4470	140	71
08H02	5910	330	22	4215	60	1	3181	150	68
09H01	7482	52	-29	5516	142	5	4410	52	61

* Inclination above the horizontal is positive.
Azimuth is measured clockwise from magnetic north.

test would produce vertical stresses of about 2300 psi since the overcoring was done at a depth of 2000 feet and the average overburden density was reported as 165 lb/ft^3. However, significantly higher vertical in-situ stresses were obtained from both test methods.

For the 21 principal stresses, the simulation technique produced larger stresses than the calculation method in 12 instances, and smaller stresses in nine. The average difference between simulated and calculated magnitudes of stress was 6% greater for the simulated stresses. The smallest difference was 1%, and the largest difference was 77%.

Two of the tests, 02H02 and 04H01, showed vertical stresses close to the predicted 2300 psi. Test holes 07, 08, and 09 were drilled in pillars and showed vertical stresses significantly higher than the 2300 psi overburden stress, as expected due to pillar stress concentration.

The only obvious similarity in results was that for each test, with the exception of 09H01, σ_3 was always the most vertical of the principal stresses. The average inclination of σ_3 for the first six tests was 80 degrees; the average inclination for all seven tests was 77 degrees.

The azimuths for simulated σ_1 and σ_2 from test 02H02 are roughly aligned with the calculated azimuths, being rotated 24 degrees clockwise in nearly the same plane.

The same cannot be said for the azimuths of the simulated stresses σ_1 and σ_2 for tests 03V03A, 04H01, 05H03, and 09H01, which appear to have rotated 90 degrees from their calculated azimuths.

However, test 04H01 shows an insignificant difference of magnitude (1 psi) between simulated σ_1 and σ_2. If σ_1 is made σ_2, and vice-versa, then the two stresses will have rotated only 50 degrees clockwise from their calculated azimuths.

For 05H03, simulated σ_2 is 90% of simulated σ_1. If once again simulated σ_1 and σ_2 are relabeled σ_2 and σ_1 respectively, their azimuths will have rotated only 31 degrees clockwise from calculated σ_1 and σ_2.

If simulated σ_1 and σ_2 for tests 04H01 and 05H03 are relabeled as suggested, the average change in azimuths for σ_1 and σ_2 for tests 02H02, 04H01, and 05H03 from their calculated azimuths is 36 degrees clockwise.

The azimuths of σ_1 and σ_2 simulated for 07H01 and 08H02 are rotated 13° clockwise and 11° counterclockwise, respectively, from their calculated azimuths.

For tests 03V03A and 09H01 the azimuths of simulated σ_1 and σ_2 are nearly 90° different from the calculated azimuths.

The differences in orientation of the calculated and simulated stress fields may largely be due to the manner in which anisotropy was treated by the two methods. Averaging the differing measurements of E and ν from each overcore will more than likely produce a different calculated stress field than using a method which incorporates the differing elastic constants to reflect the sample's anisotropy.

The simulation method may have produced larger stress measurements due to the inclusion of residual stress. The first stress measurements after overcoring were made within minutes or hours of the overcore recovery. The measurements made immediately prior to the overcores being placed in the triaxial cell were taken two hundred or more days after overcoring, allowing the release of residual stress in the interim. Increasing the calculated stresses of Table 4 by the average measured residual stress increase (51%) and comparing the resulting predicted stresses to the recorded simulated stresses of Table 5, the predicted stresses averaged 3260 psi greater than the simulated stresses, with a standard deviation of 3910 psi. While not being a precise fit to the simulated stresses, the predicted effect of residual stress is a step in the right direction.

Chapter 8

SUMMARY

Where possible the elastic constants used in calculations of in-situ stress by overcoring should be obtained from compressively stressing the overcored strain gauges themselves. It remains to be determined whether E and ν are best found by uniaxial, biaxial, or triaxial testing.

To take full advantage of these more accurate elastic constants, a method of calculation using the individual E and ν from each CSIR cell rosette should be developed.

The simulation of in-situ stress by triaxial confinement has the advantage of not utilizing the elastic constants while using the unique behaviour of each CSIR cell rosette to reflect the anisotropy of the overcore. For now, however, the method is limited to finding secondary principal stresses, unless the hole can be drilled parallel to one of the principal stresses.

REFERENCES

1. Leijon, B. A., Stillborg, B. L., A Comparative Study Between Two Rock Stress Measurement Techniques at the Luossavaara Mine, Rock Mechanics and Rock Engineering, No. 19, 1986, p 155 - 157.

2. Herget, G., Miles, P., Zawadsky, W., Equipment and Procedures to Determine Ground Stresses In a Single Drill Hole, CANMET Report 78 - 11, 1977, p 9 - 11.

3. American Society for Testing and Materials, Standard Test Method for Elastic Moduli of Intact Rock Core Specimens in Uniaxial Compression, Annual Book of ASTM Standards Vol. 04.08, 1988, p 377 - 380.

4. American Society for Testing and Materials, Standard Practice for Preparing Rock Core Specimens and Determining Dimensional and Shape Tolerances, Annual Book of ASTM Standards Vol. 04.08, 1988, p 727 - 730.

5. Abel, J. F., Jr. MEANSD, unpublished, 1988.

6. Balcar, M. A., Program STRCELL, unpublished, 1989.

7. Meier, J. H., Strain Rosettes, Handbook of Experimental Stress Analysis, Ed. M. Hetenyi, J. Wiley & Sons, 1950, p 410 - 415.

8. Abel, J. F., Jr., Dowis, J. E., Richards, D. P., Concrete Shaft Lining Design, Proc. 20th U.S. Symposium on Rock Mechanics, 1979, p 627 - 640.

Appendix 1

CSIR STRAIN CELL DESCRIPTION AND INSTALLATION

The CSIR triaxial strain cell consists of a hollow plastic cylinder fitted with three small pistons (Figures 17, 18), with a rosette of four strain gauges set on the face of each piston (Figure 19). The pistons are spaced 120 degrees apart in a plane perpendicular to the cylinder axis.

Core drilling to the test site (Figure 20) was done using a 3.65 inch diameter bit. When the test site was reached, the end of the hole was squared using a full face diamond bit. A 1.5 inch diameter hole was cored past the squared-off face and the recovered core examined for suitability for testing. If the rock was suitable, a CSIR strain cell was installed.

For installation, each cell rosette was covered with epoxy, inserted to the test location, and the rosette pistons forced against the wall of the 1.5 inch hole. The cell was left overnight to allow adequate time for the epoxy to cure.

The following day, each of the strain gauges were measured for the 'zero stress' values. The installation tool was then removed and the 1.5 inch hole plugged prior to overcoring.

A narrow kerf bit was used for overcoring the strain cell, making an overcore approximately 3.20 inches in

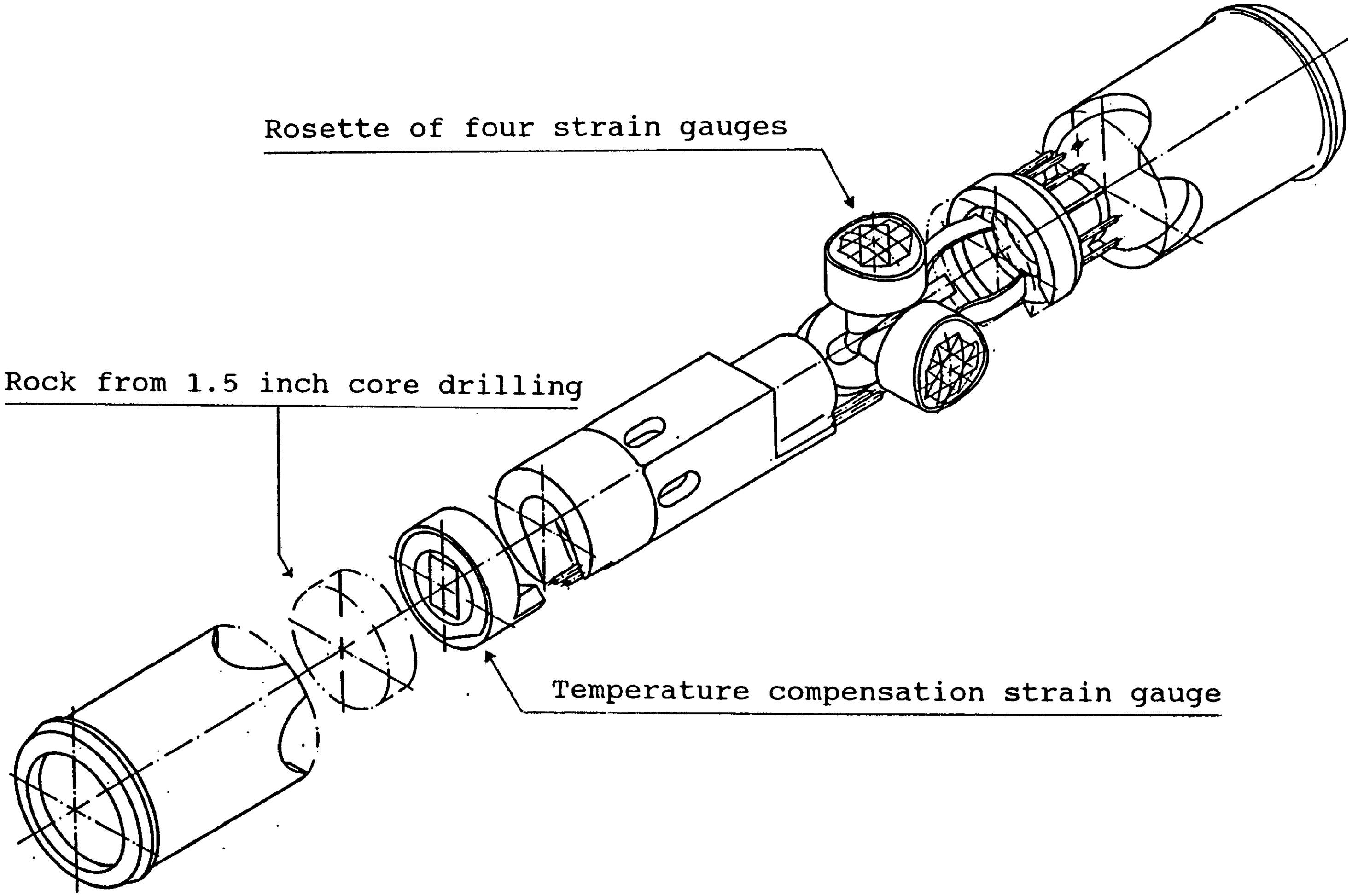


Figure 17

Exploded View of the CSIR Triaxial Strain Cell.

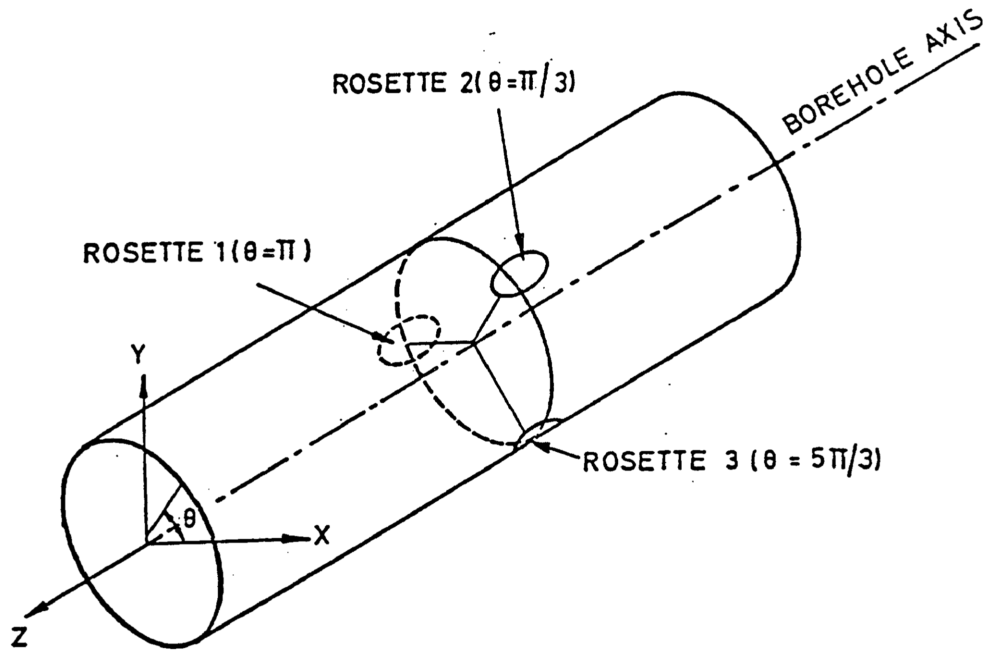


Figure 18

Orientation of the Rosettes in the CSIR Cell.

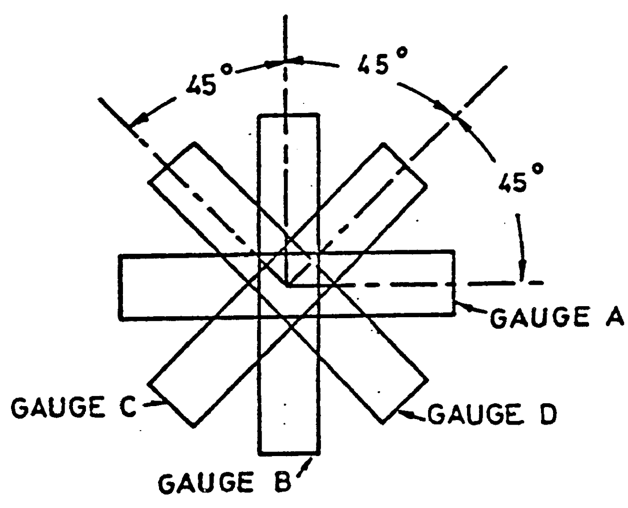


Figure 19

Orientation of the Rosette Strain Gauges.

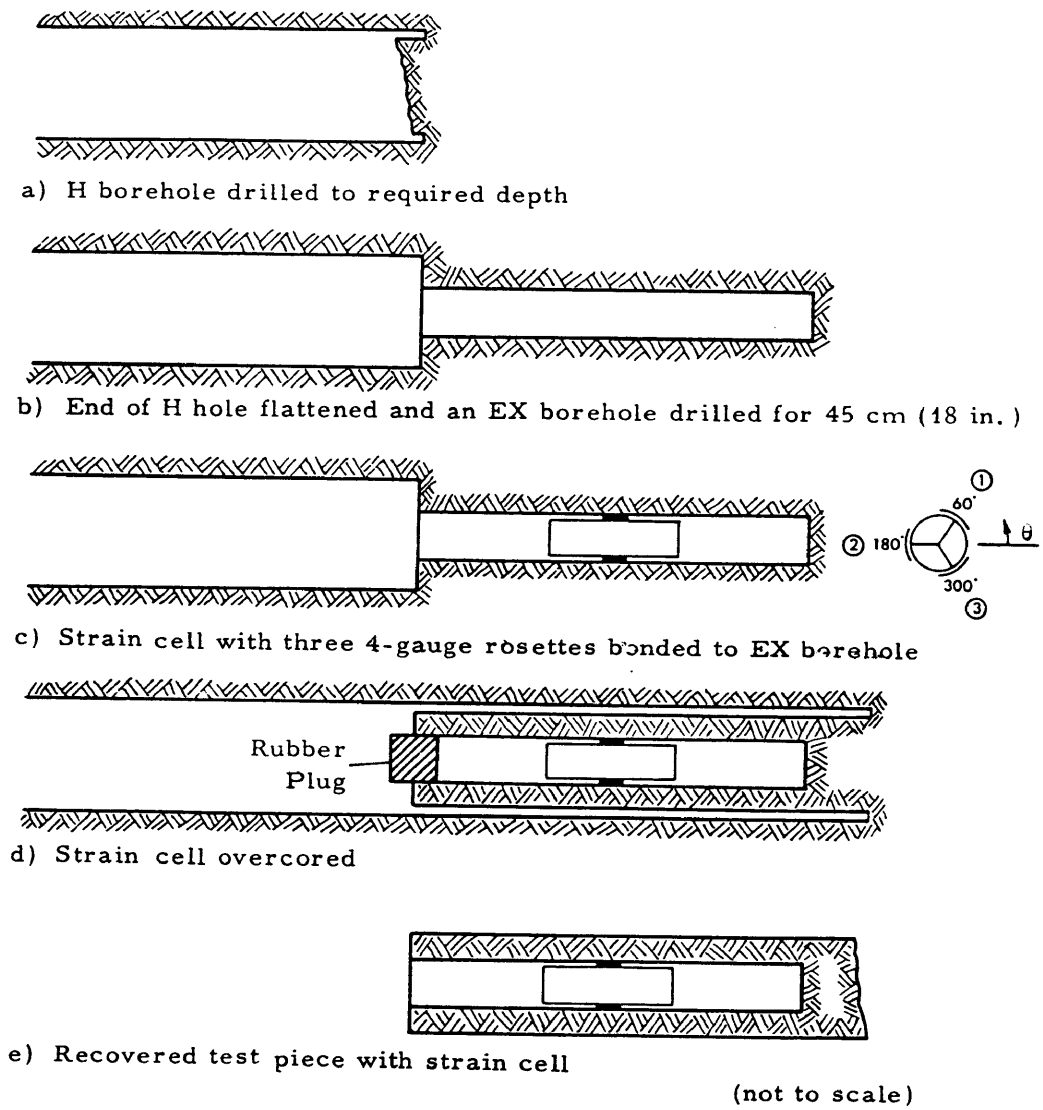


Figure 20

Sequence of Steps in CSIR Strain Cell Overcoring.

diameter. As soon as the sample was dry, the cell was connected to the strain meter, and the strain gauges were read. This measurement gave the initial, or 'elastic' stress relief. Subsequent measurements recorded the onset of strains related to the time-dependent release of 'residual' stresses.

Appendix 2

WHITE PINE COPPER MINE

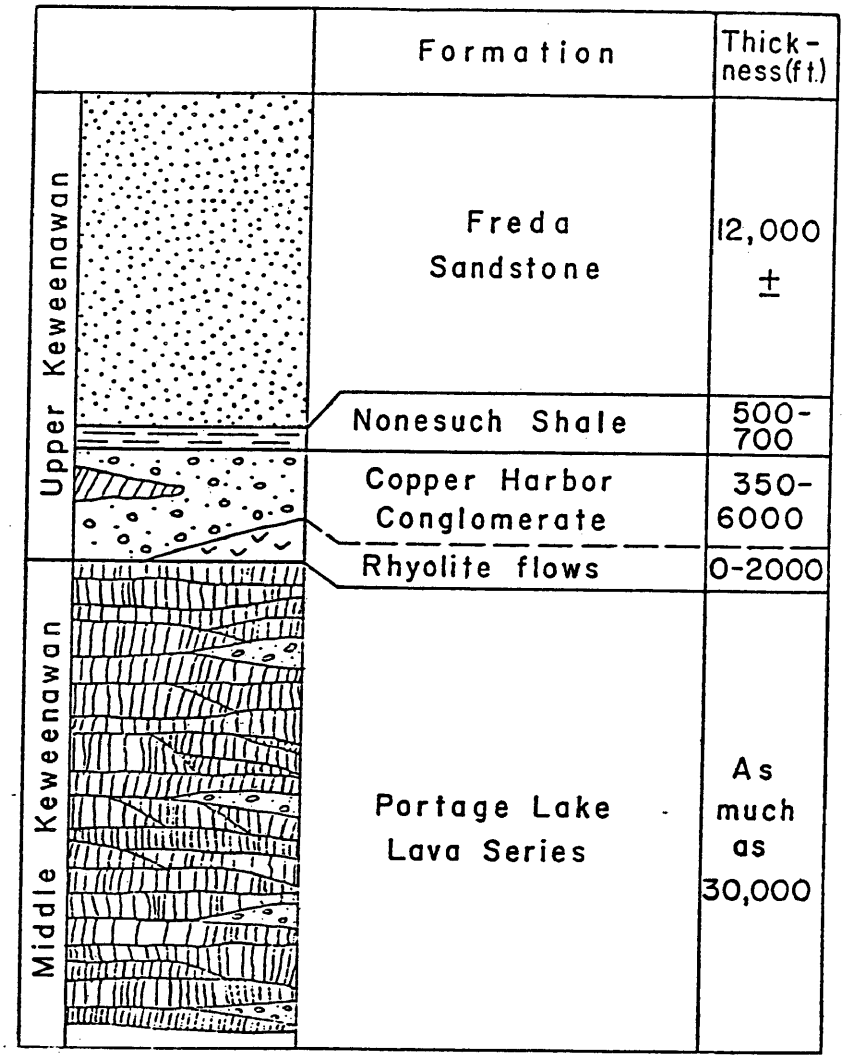


Figure 21

Columnar Section of the

Keweenawan Series in the White Pine Mine

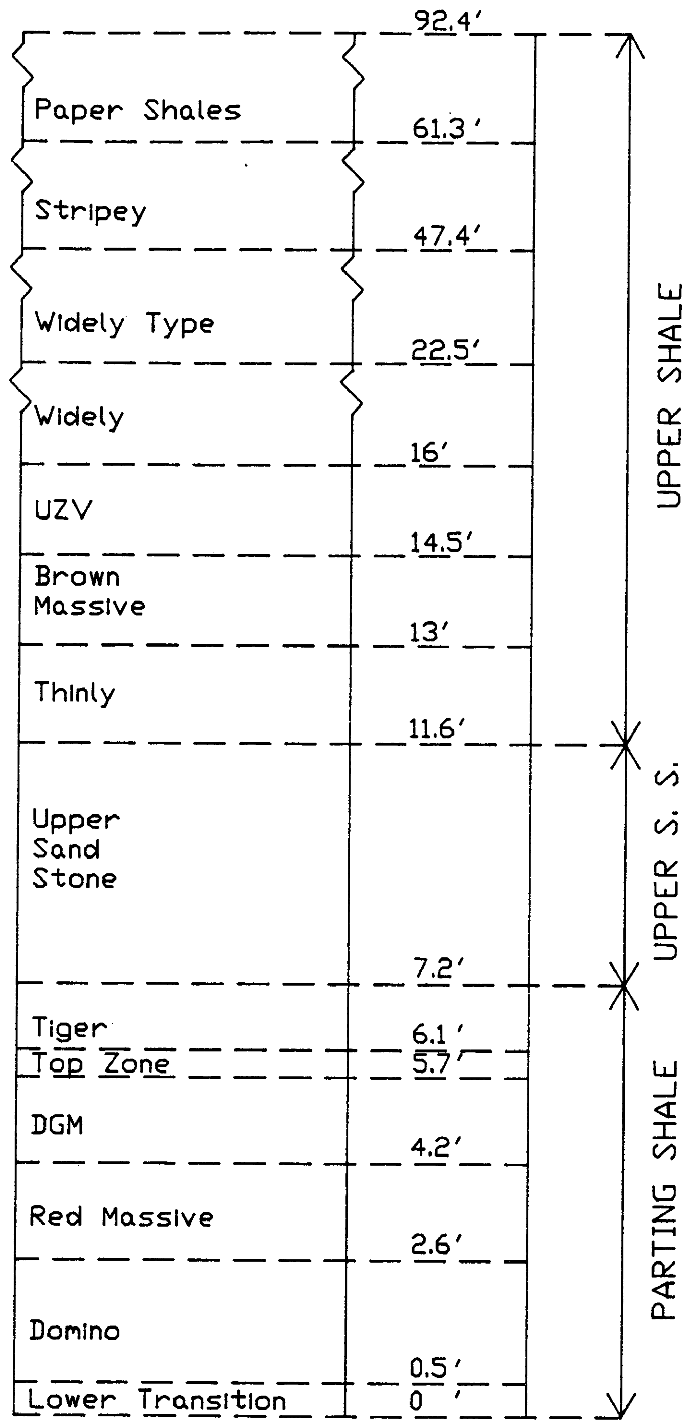


Figure 22

Typical Column in the Nonesuch Shale

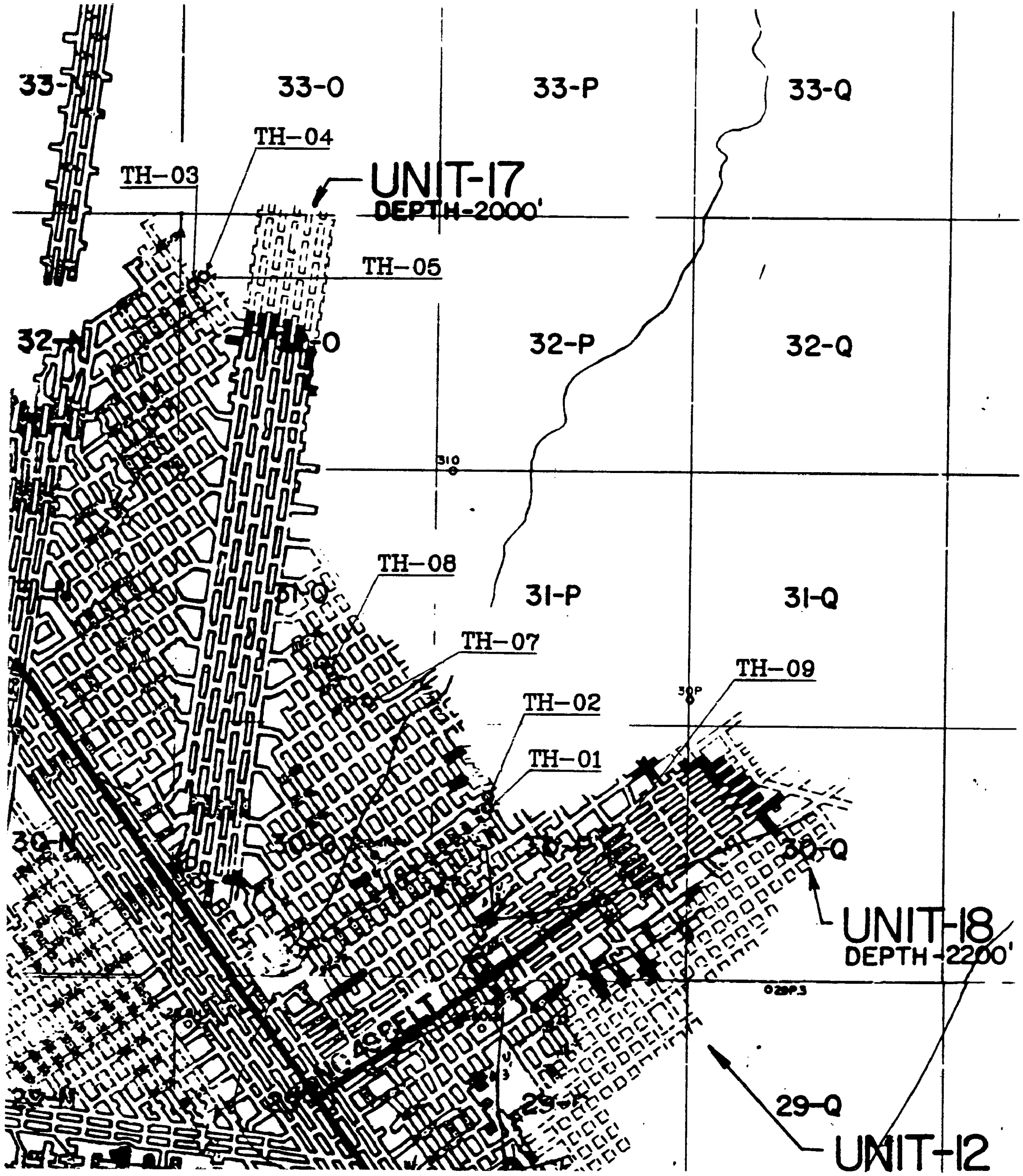


Figure 23

Map of Division One

Showing the Test Hole Locations

Appendix 3

SAMPLE CALCULATION

The calculations for TH-05H03 were as follows: Prior to placing the cut and ground overcore in the triaxial cell, the following measurements were taken:

Outside Diameter = 3.184 inches

Inside Diameter = 1.493 inches

The cylinder end area was calculated to be 6.217 in^2.

Once the overcore was in the triaxial compression cell, each of the CSIR cell rosettes were 'zeroed' in turn. The axial and transverse hydraulic pressures were recorded:

Table 6

Applied Stresses for TH-05H03

Rosette Number	Axial Stress (psi)	Horizontal Stress (psi)
1 (σ_1)	5860	600
2 (σ_2)	5860	4420
3 (σ_3)	7316	4150

Using the equation for solving equiangular (60°) rosettes (7):

$$\sigma_{p,q} = \frac{\sigma_1 + \sigma_2 + \sigma_3}{3} \pm \frac{\sqrt{2}}{3}\sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_1 - \sigma_3)^2}$$

the laboratory values of σ_1, σ_2, and σ_3 were substituted:

$$\sigma_{p,q} = \frac{600 + 4150 + 4420}{3} \pm \frac{\sqrt{2}}{3}\sqrt{(600 - 4150)^2 + (4150 - 4420)^2 + (600 - 4420)^2}$$

yielding $\sigma_p = 5518$ psi and $\sigma_q = 595$ psi.

The orientation of σ_p is found using the equation (7):

$$\tan 2\theta_p = \frac{\sqrt{3}\ (\sigma_2 - \sigma_3)}{2\sigma_1 - \sigma_2 - \sigma_3}$$

The angle theta is measured counterclockwise from the direction of σ_p to the orientation of rosette 1. Substituting the laboratory values of σ_1, σ_2, and σ_3:

$$\tan 2\theta = \frac{\sqrt{3}\ (4150 - 4420)}{2(600) - 4150 - 4420}$$

and $\Theta_p = 2$ degrees. Since Θ_q is perpendicular to Θ_p and also lies in the plane of the CSIR cell's transverse strain gauges, $\Theta_q = \Theta_p + 90°$, and $\Theta_q = 92$ degrees.

The conversion of Θ_p and Θ_q to the in-situ stresses at infinity using equation 3, with r = 1.593 inch, a = 0.747 inch:

$$\sigma_{p,q\infty} = \sigma_{p,q}\left(\frac{1.593^2}{1.593^2 - 0.747^2}\right) = 1.282\sigma_{p,q}$$

so σ_p at infinity = 1.282(5518) = 7074 psi, and σ_q at infinity = 1.282(595) = 763 psi.

The average axial stress is (5860 + 5860 + 7316)/3 = 6345 psi, oriented parallel with the borehole.

The simulated in-situ stresses are therefore:

σ_p = 7074 psi, azimuth 322°, inclination 2°,

σ_q = 763 psi, azimuth 142°, inclination 88°,

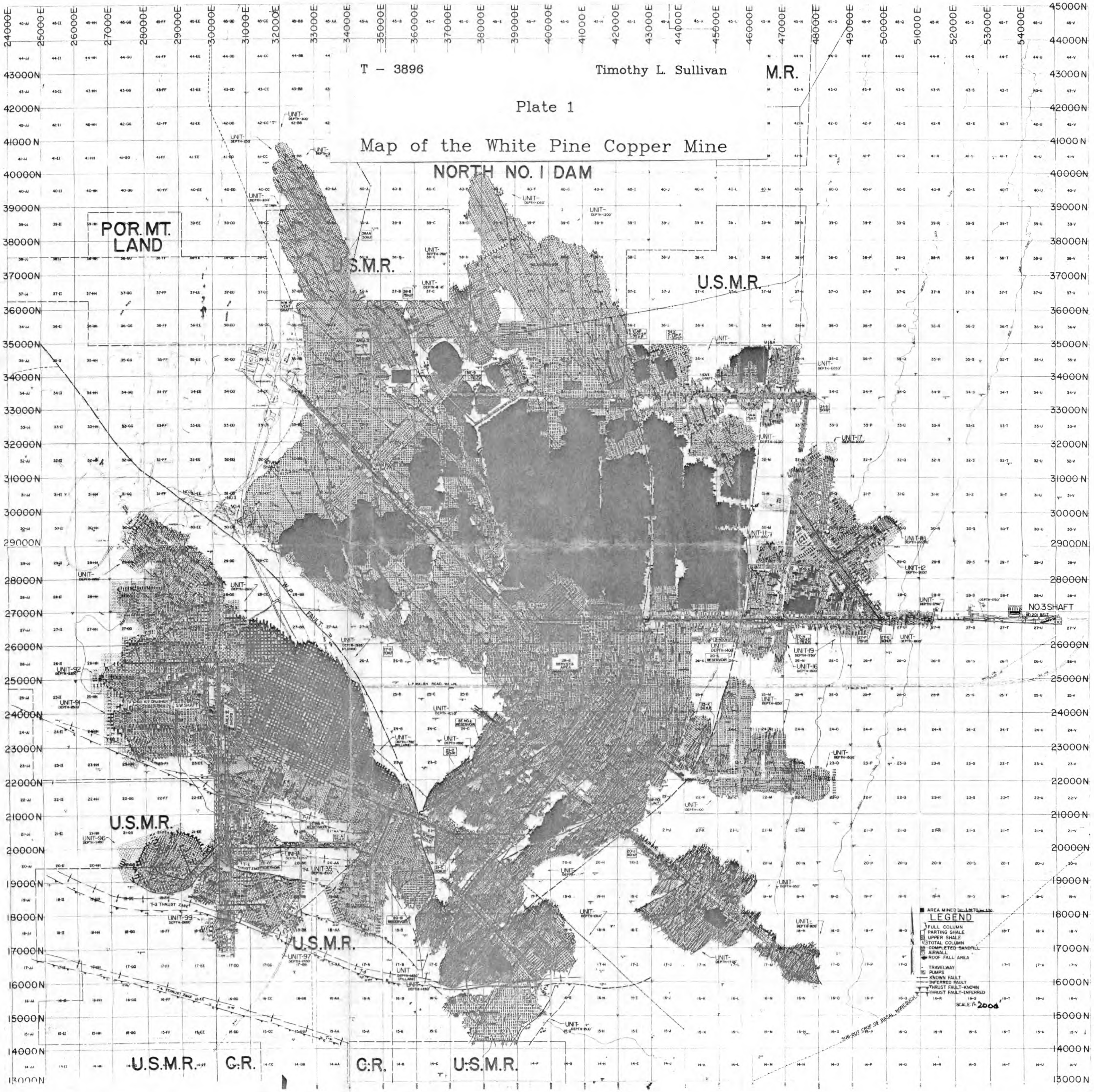
σ_{axial} = 6345 psi, azimuth 52°, inclination 1°.

or:

σ_1 = 7074 psi, azimuth 322°, inclination 2°,

σ_2 = 6345 psi, azimuth 52°, inclination 1°,

σ_3 = 763 psi, azimuth 142°, inclination 88°.



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Timothy L. Sullivan
M.R.
Plate 1
Map of the White Pine Copper Mine
NORTH NO. I DAM
POR. MT. LAND
U.S.M.R.
U.S.M.R.
U.S.M.R.
U.S.M.R.
U.S.M.R.
U.S.M.R.
C.R.
C.R.
NO.3 SHAFT
LEGEND
AREA MINED
FULL COLUMN
PARTING SHALE
UPPER SHALE
TOTAL COLUMN
COMPLETED SANDFILL
AIRWALL
ROOF FALL AREA
TRAVELWAY
PUMPS
KNOWN FAULT
INFERRED FAULT
THRUST FAULT-KNOWN
THRUST FAULT-INFERRED
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