TENNESSEE VALLEY AUTHORITY
Division of Engineering Design
Civil Engineering and Design Branch

BELLEFONTE NUCLEAR PLANT
ANALYSIS OF TENDON JACKING TESTS FOR BEHAVIOR OF ROCK FOUNDATION

James H. Coulson
November 6, 1973

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1. Description of Test

The purpose of this testing program was twofold: 1) To determine the adequacy of two types of tendons to resist uplift forces on the reactor building foundations, and 2) to determine the in situ moduli of deformation for the foundation rock. Three Inland-Ryerson button-head tendons and three Stressteel strand tendons were tested. Each manufacturer installed two 40-foot tendons with the bottom 20 feet grouted for anchorage, and one 20-foot tendon with a 7-foot anchorage. The ultimate capacity of each tendon was approximately 2000 K.

For each tendon type one long tendon was instrumented between the top of the anchorage and the surface of the test pad to observe foundation deformation characteristics, and the other long tendon was instrumented along the anchorage to help determine the stress distribution in the rock adjacent to the anchorage.

Figure 1 shows the layout of the test pad along with anchorage depths for the instrumentation. The pad was located 800 feet from the center of reactor 1 on a line N 39° E. All instruments were single and double position mechanical borehole extensometers which measured between the surface of the concrete pad and the indicated anchor depth with a sensitivity of 0.001 inch.

The loading sequence for the A tendons, instrumented for rock modulus, and the B tendons, instrumented for anchorage behavior, are shown below:

A Tendons		B Tendons	
0% → 80% → 0% → 80% → 70%	10% of ultimate increments	0% → 80%	10% of ultimate increments
		80% → 60%	
		60% ⇅ 70%	100 cycles

Each step load was held for two to three minutes to read the extensometers, except during the cycling phase of the B tendons where each cycle took approximately 30 seconds. After testing, each tendon was blocked off at 70 percent of ultimate. Photographs of the Inland-Ryerson and Stressteel setups are shown in Figures 2 and 3 respectively.

2. Geology

Bedrock below the test pad is in the Chickamauga formation - a complex sequence of interbedded limestones and shales. The bedding strikes N 48° E, parallel to the long axis of the test pad, and dips 17° SE. Figure 4 shows the core from a 50-foot NX hole drilled through the test pad, and the following table gives an engineering description of the core:

Depth	Limestone	Shale	Average Percent Shale
0-17.7 ft	Medium to coarse grained	Irregular partings, t = hairline to 1/4", spacing = 0.01 ft to 0.3 ft	12
17.7 ft to 50.4 ft	Fine grained with several bands coarse grained	Nodular partings, t = hairline to 0.15", spacing = 0.02 ft to 0.3 ft	20

Figure 2 shows a joint plane behind the test pad. The joint is perpendicular to the bedding and strikes parallel to the test pad. Its surface is iron stained and shows evidence of very slight solution, especially where it crosses shale horizons.

3. Test Results

Figures 5 through 9 show the shapes of the deformation curves for the Inland-Ryerson A tendon. The deformation shown in each figure is for the interval from the surface of the concrete pad to the anchor depth indicated.

Each curve is characterized by an increase in stiffness with load to 20 to 30 percent of ultimate, above which stiffness remains nearly constant. The curved lower segment of each plot is a manifestation of bedding plane closure and tightening of horizontal fissures within the shale horizons. The rebound and reloading curves show normal hysteresis for this type of rock. The creep measured over a 34-day period at 70 percent of ultimate indicates a tendency for continued closure of micro-cracks and consolidation within the shale beds.

Data from the Stressteel A tendon are shown in Figures 10 through 15. As expected, the characteristics of these curves are the same as for the Inland-Ryerson tendon. At the time of this report, creep readings were not yet available.

Figure 16 shows the results of instrumentation adjacent to the tendon B anchorages. Each plot gives relative movement between the point of interest and the bottom of the tendon anchorage at 40 feet: For the Inland-Ryerson tendon, relative movement increases up to 30 percent of ultimate, at which time bond failure tends to increase the effective free length of the tendon and decrease relative displacements. At 80 percent of ultimate a large percentage of the tendon force has been transferred to the anchor head at 40 feet and much of the original relative deformation is lost.

The Stressteel tendon shows a progressive increase in relative deformation to 80 percent, indicating that a large transferral of force to the bottom of the tendon does not occur.

The B tendon data is difficult to analyze and interpret by itself. The finite element method should be used to fully evaluate the stress distribution in each type of tendon anchorage. Various stress distributions can be assumed and the resulting deformations compared with those in Figure 16 until the computed and measured deformations agree. As shown in the next section, assumptions made in the finite element analysis for stress distribution at the jack pad will have no effect on stresses in the zone of tendon anchorage.

4. Analysis of Data

4.1 Determination of Stresses at Depth. Since the volume of rock between the jack base plate and the top of the anchorage is under the stress influence of both the jack base plate and tendon anchorage, and since the stress distribution from the anchorage is unknown, it is necessary to establish a zone in the upper part of the rock mass where anchorage stresses have a relatively insignificant influence on stresses. This allows the deformation moduli of the rock mass to be calculated in a zone of known stresses. To determine the stress distribution imposed by the jack base plate the following assumptions are made:

1. The behavior of the one-foot-thick concrete pad is similar to that of a bed of limestone, and as a result,
2. Stresses can be calculated using the bottom of the steel jack base plate as the point of load application.
3. The Boussinesq stress distribution is valid.

Newmark's charts for stress distribution (Newmark, 1940) were used for the calculation of stresses. The resulting influence curves for the 20 inch by 20 inch Inland-Ryerson pads and the 24 inch by 24 inch Stressteel pads are shown in the upper part of Figure 17.

To determine the maximum probable influence of the anchorage, two stress distributions were calculated using 1) the entire anchorage reaction as a point load at a depth of 25 feet, and 2) one-half the reaction at 25 feet and one-half at 30 feet. Stresses were calculated using the equations for stress distribution below a vertical point load on the surface of a half space. These stresses were divided by two since the points of load application are within the half space (Terzaghi, 1943; Mindlin, 1936). The resulting influence curves are shown in the bottom half of Figure 17. As shown by the figure, between the surface of the concrete pad and a depth of ten feet it can be assumed that the influence of the anchorage on stress is negligible. Accordingly, all moduli are calculated in this zone.

4.2 Deformation Modulus of the Rock. The deformation modulus is defined as the modulus which includes elastic, plastic, and creep deformations. Since these tests were performed in situ, the effects of joints, bedding planes, weak seams, and time dependence of consolidation of the saturated shales were all included.

Deformations measured by the extensometers were interpreted using Boussinesq theory. If a portion of the surface of a half space is loaded, the displacement of any point, d_z, on the surface or within the half space can be described by:

$$d_z = \frac{qI}{E}$$

where q describes the loading conditions, I is an influence factor dependent on geometry and Poisson's ratio, and E is the modulus of the half space. For relative displacements between any two extensometer anchor points:

$$d_{z1} - d_{z2} = \frac{q\,(I_1 - I_2)}{E}$$

and

$$E = \frac{q\,(I_1 - I_2)}{d_{z1} - d_{z2}}$$

This equation was used for all calculations of deformation modulus. Newmark's charts (Newmark, 1947) were used to determine I, and Poisson's ratio was assumed to be 0.15.

Calculated values for various depth intervals and tendon forces are shown in the table below:

SUMMARY OF DEFORMATION MODULI
$E = \text{psi} \times 10^6$

Depth Interval	6" to 3'-6"		6" to 6'		6" to 10'		3'-6" to 6'		3'-6" to 10'		6' to 10'	
Tendon Type	I-R	SS	I-R	SS	I-R	SS	I-R	SS	I-R	SS	I-R	SS
Percent Ultimate												
0 to 20	.61	.23	.50	.37	.74	.40	.32	1.7	1.0	.84	-	.84
0 to 40	.46	.31	.75	.48	1.0	.56	.55	1.2	1.3	1.1	-	1.1
0 to 60	1.2	.42	.86	.60	1.2	.68	.50	2.5	1.4	1.6	-	1.6
0 to 70	1.1	.47	.91	.48	1.3	.61	.60	3.0	1.6	1.9	-	1.9
0 to 80	1.3	.48	1.0	.69	1.4	.83	.60	3.6	1.5	2.6	-	2.6
0 to 70 with creep	1.1	-	.74	-	1.1	-	.40	-	1.2	-	-	-
20 to 80	2.0	.74	1.4	.99	1.7	1.3	.82	2.5	1.7	2.4	-	2.4
80 to 40	7.6	3.0	10.2	4.7	4.0	4.2	.94	-	2.3	6.4	-	6.4

5. Recommendations for Choice of Deformation Modulus and Evaluation of Differential Settlement

5.1 Design Deformation Moduli. The following considerations are taken into account for determining pertinent moduli for design:

1. The longer the extensometer measuring interval, the more representative the values.
2. E values are a function of stress level.
3. When the concrete-rock interface is included, Stressteel values are lower than Inland-Ryerson values. Bleeding was observed around the Stressteel end of the pad during testing, but not around the Inland-Ryerson end, indicating better cleanup and less rock disturbance under the pad on the Inland-Ryerson end.

Figure 18 shows an idealized deformation curve with secant and tangent moduli for various segments of the curve superimposed. Two numbers are given for each modulus. The first is an average of the Inland-Ryerson and Stressteel results for the depth interval from 3 feet 6 inches to 10 feet, while the second is the Inland-Ryerson value from 6 inches to 10 feet, including the concrete pad and concrete-rock interface. Stressteel values are not averaged with the Inland-Ryerson values for the second set of moduli because of the apparent anomalous behavior of the concrete pad during the Stressteel test.

The design moduli chosen from Figure 18 will depend on the particular application as follows:

Application	Deformation Modulus psi x 10^6
1. Rock undisturbed and clean	First value
2. Rock disturbed by blasting or not well prepared	Second value ( )
3. Tendon prestress in reactor buildings	1.2 (1.1)
4. Construction of reactors on prestressed foundation	2.1 (1.7)
5. Unloading tangent modulus	4.3 (4.0)
6. Plant construction outside reactors. No foundation prestress, average load equivalent to 20 percent to 40 percent of ultimate during tests.	1.2 (1.0)

5.2 Differential Settlements. Possible maximum differential settlements can be estimated using two loaded areas remote enough from each other that their zones of stress influence do not coalesce. The first, which represents a reactor building, is 120 feet in diameter and is founded on a prestressed foundation with a modulus of 2.1 x 10^6 psi. The second, representing the auxiliary building, is 250 feet in diameter and is founded on rock with a modulus of 1.0 x 10^6 psi. Both areas are assumed to be loaded with an average stress of 30 psi.

Using Newmark's charts the reactor building settles 0.009 inches while the auxiliary building settles 0.088 inches. Thus, the maximum probable differential settlement between buildings is 0.08 inches - an insignificant amount. In reality this value will be much less because most settlement occurs during construction, and because the stress fields for the buildings overlap with no sudden change in foundation stress at the building interface. Both buildings will tend to settle together in the same settlement basin.

6. References

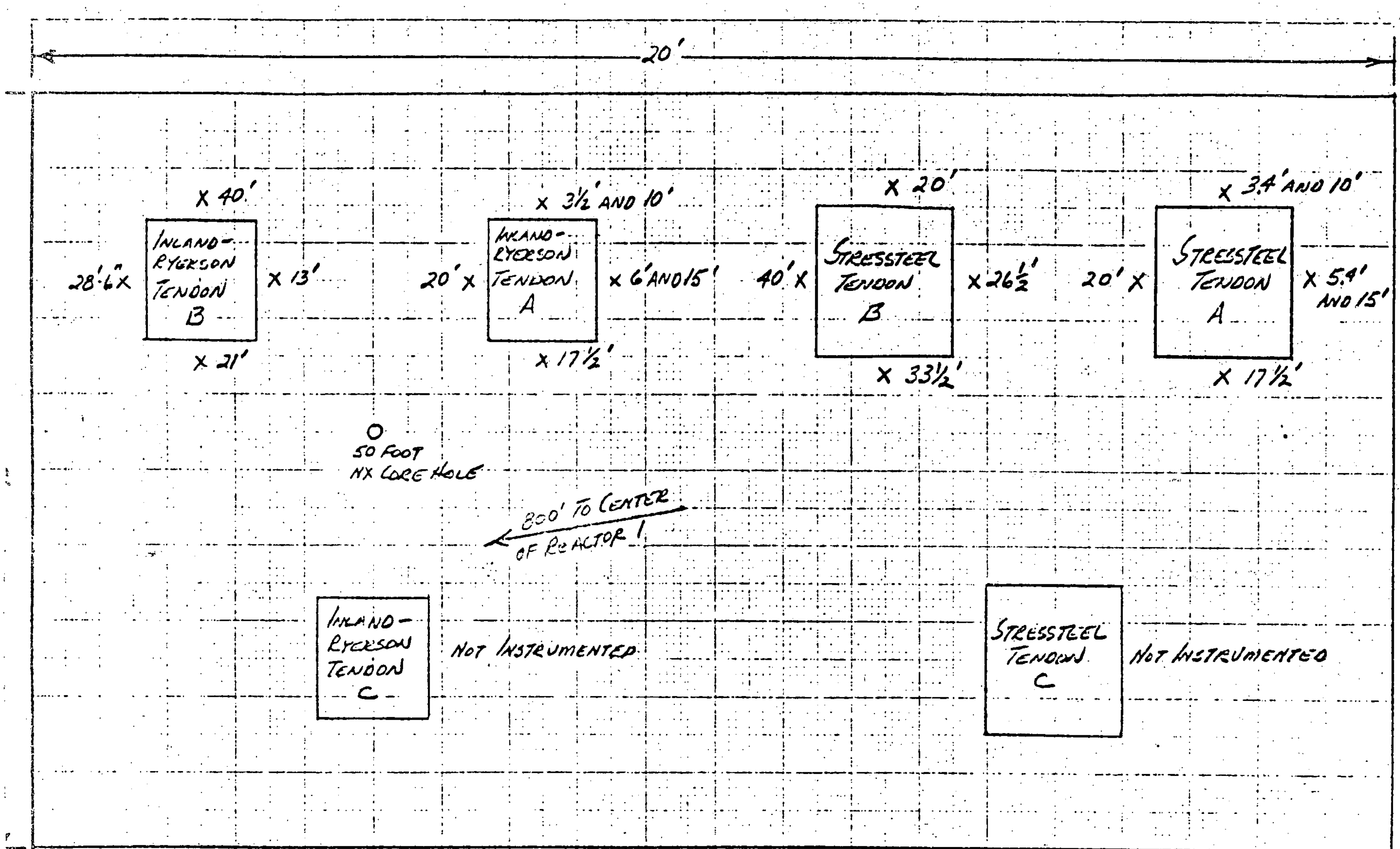
1. Mindlin, R. D., (1936), "Force at a Point in the Interior of a Semi-Infinite Solid," Physics, Volume 7, page 195.

2. Newmark, N. M., (1947), "Influence Charts for Computation of Vertical Displacements in Elastic Foundations," Engineering Experiment Station Bulletin Series 367, Volume 44, Number 45, March 23, 1947, University of Illinois.

3. Newmark, N. M., (1964), "Influenee Charts for Computation of Stresses in Elastic Foundations," Engineering Experiment Station Bulletin Series Number 338, Volume 61, Number 92, June 1964, University of Illinois.

4. Terzaghi, K. T., (1943), Theoretical Soil Mechanics, John Wiley and Sons, Incorporated.

7. Figures



KEY

SCALE 1" = 2'-0"

X 40' LOCATION AND DEPTH OF SINGLE POSITION EXTENSOMETER

X 3½' AND 10' LOCATION AND DEPTHS OF DOUBLE POSITION EXTENSOMETER

FIGURE 1 — LAYOUT OF JACK BASE PLATES AND INSTRUMENTATION ON TEST PAD

Figure 2 - Inland-Ryerson test setup.

Figure 3 - Stressteel test setup.

Dry

Wet

Figure 4 - Core from 50-foot NX hole through test pad.

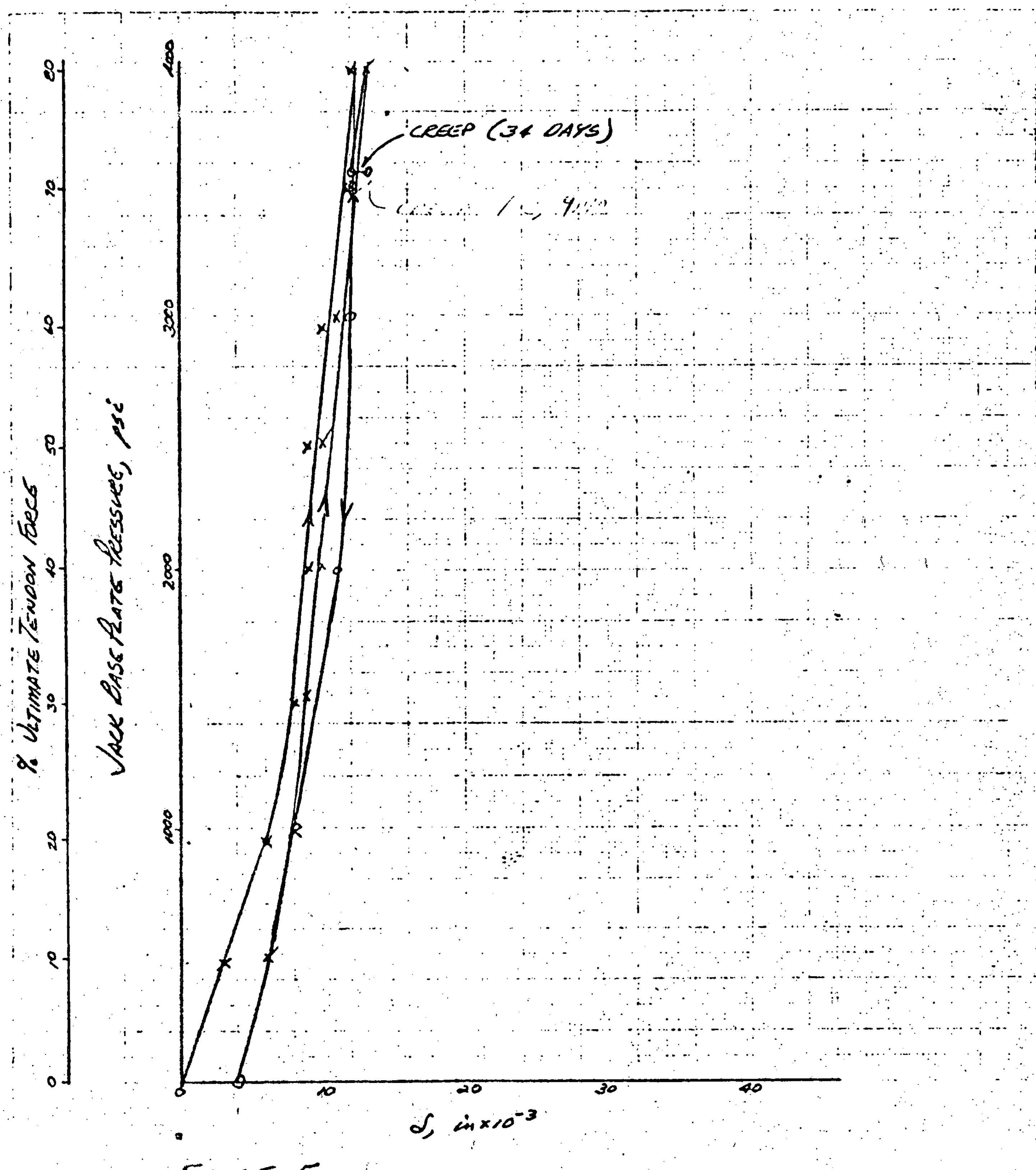


FIGURE 5

BELLEFONTE NUCLEAR PLANT
INSITU DEFORMATION MODULUS TEST

INLAND-RYERSON TENDON A
ANCHOR DEPTH 3½'

JWC

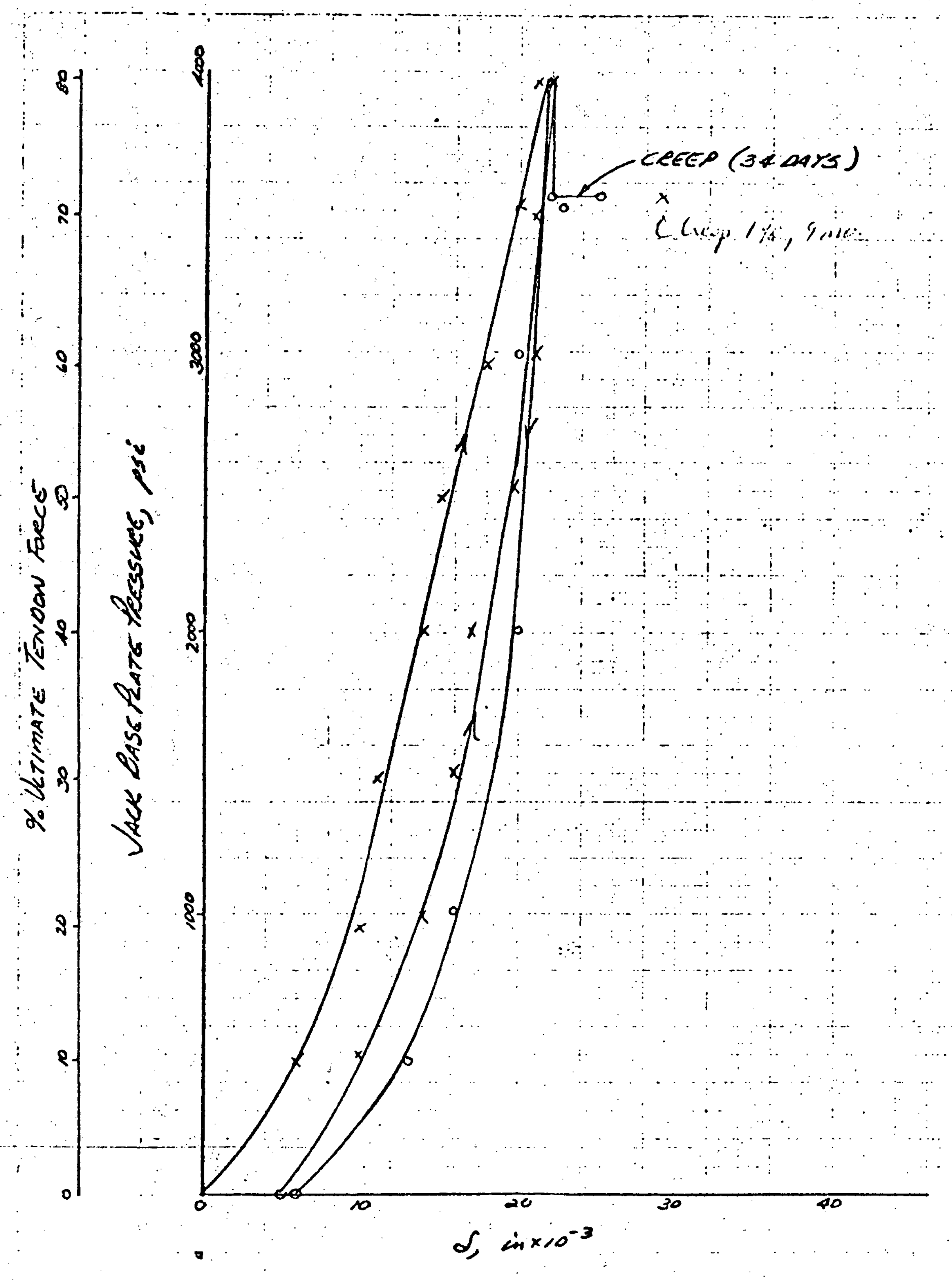


FIGURE 6

BELLEFONTE NUCLEAR PLANT
INSITU DEFORMATION MODULUS TEST

INLAND-RYERSON TENDON A
ANCHOR DEPTH 6'

JHC

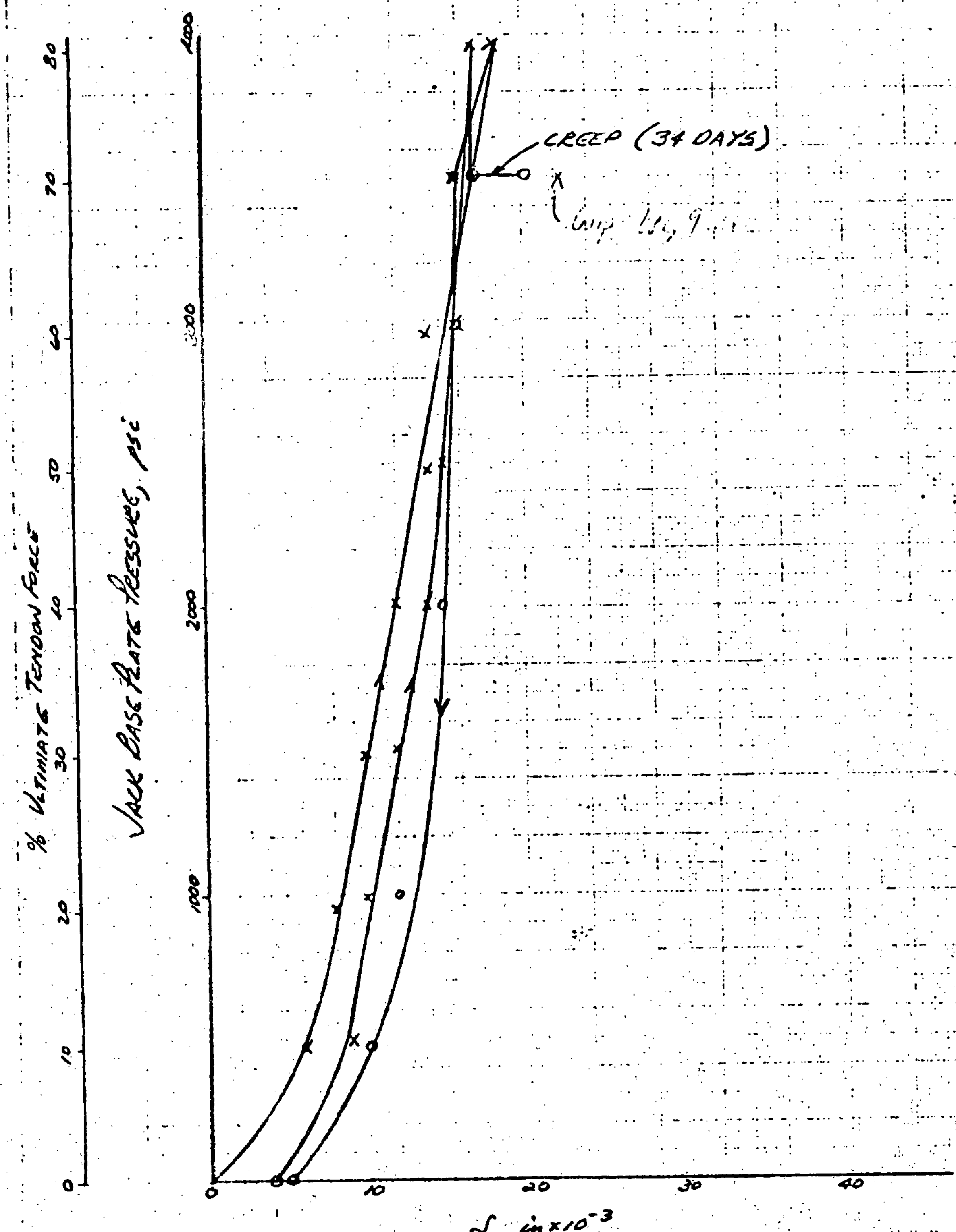


FIGURE 7

BELLEFONTE NUCLEAR PLANT
INSITU DEFORMATION MODULUS TEST

INLAND-RYERSON TENDON A
ANCHOR DEPTH 10'

JHC

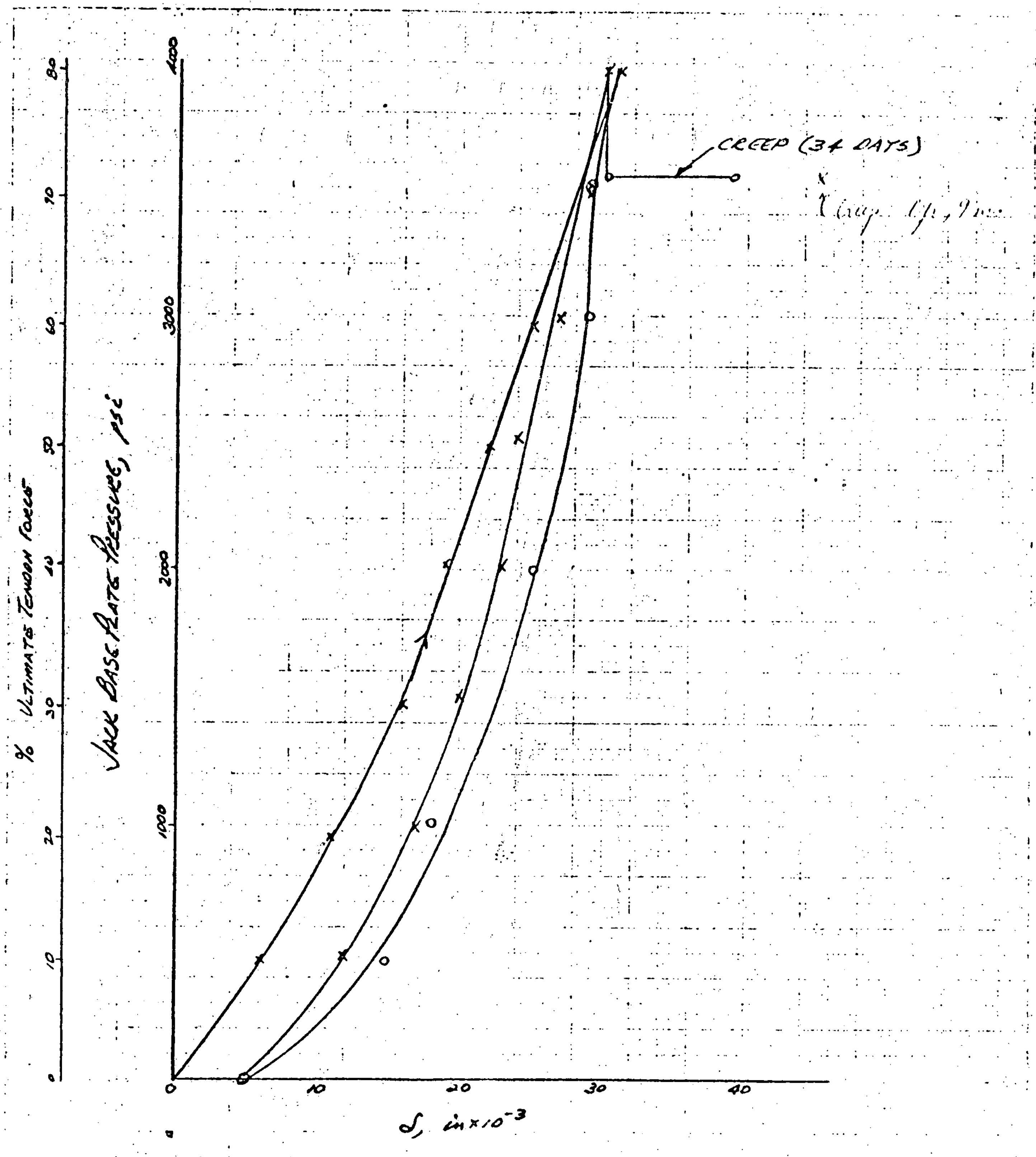


FIGURE 8

BELLEFONTE NUCLEAR PLANT
INSITU DEFORMATION MODULUS TEST

INLAND-RYERSON TENDON A
ANCHOR DEPTH 17½'

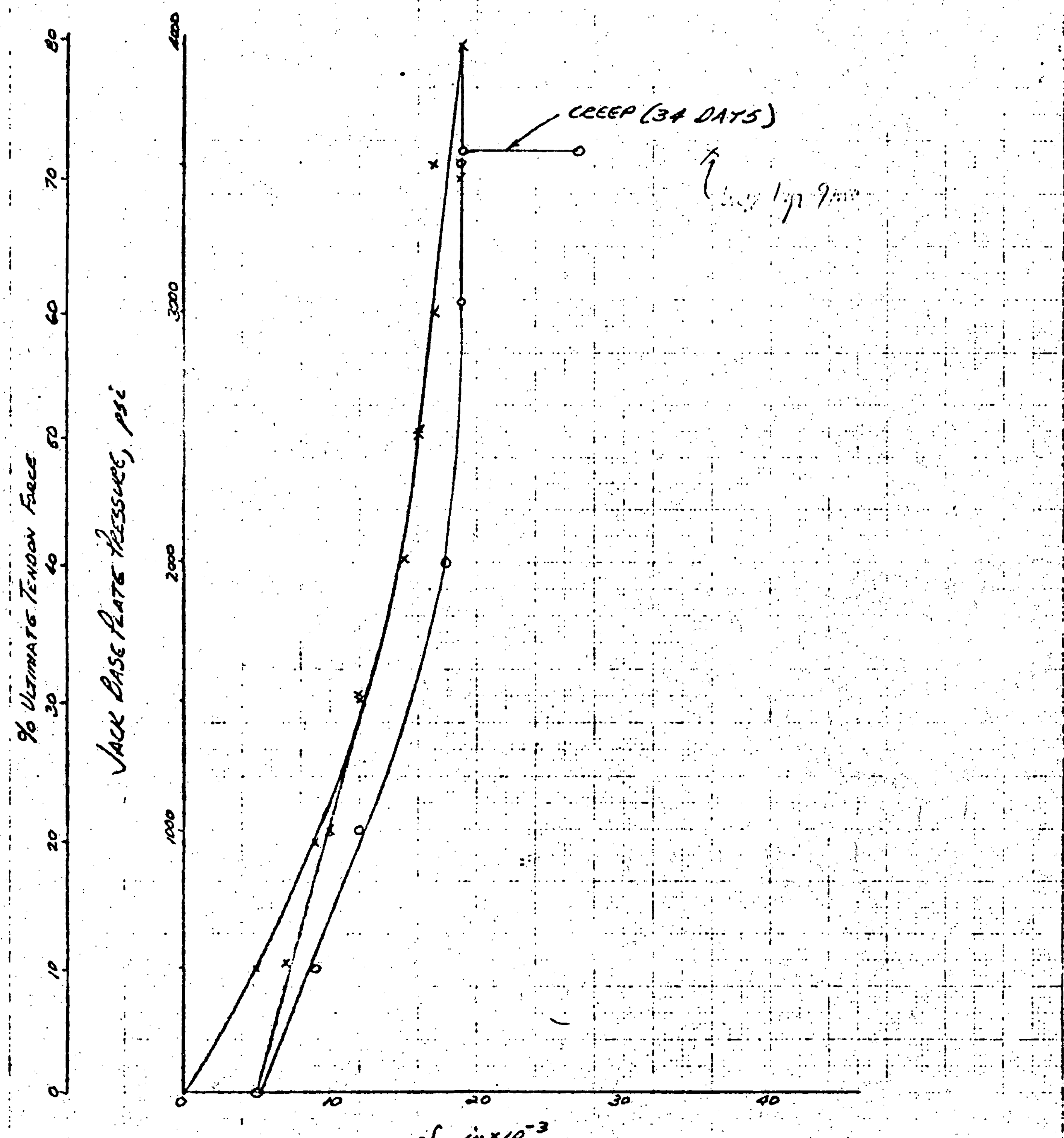


FIGURE 9

BELLEFONTE NUCLEAR PLANT
INSITU DEFORMATION MODULUS TEST

INLAND-RYERSON TENDON A
ANCHOR DEPTH 20'

JHC

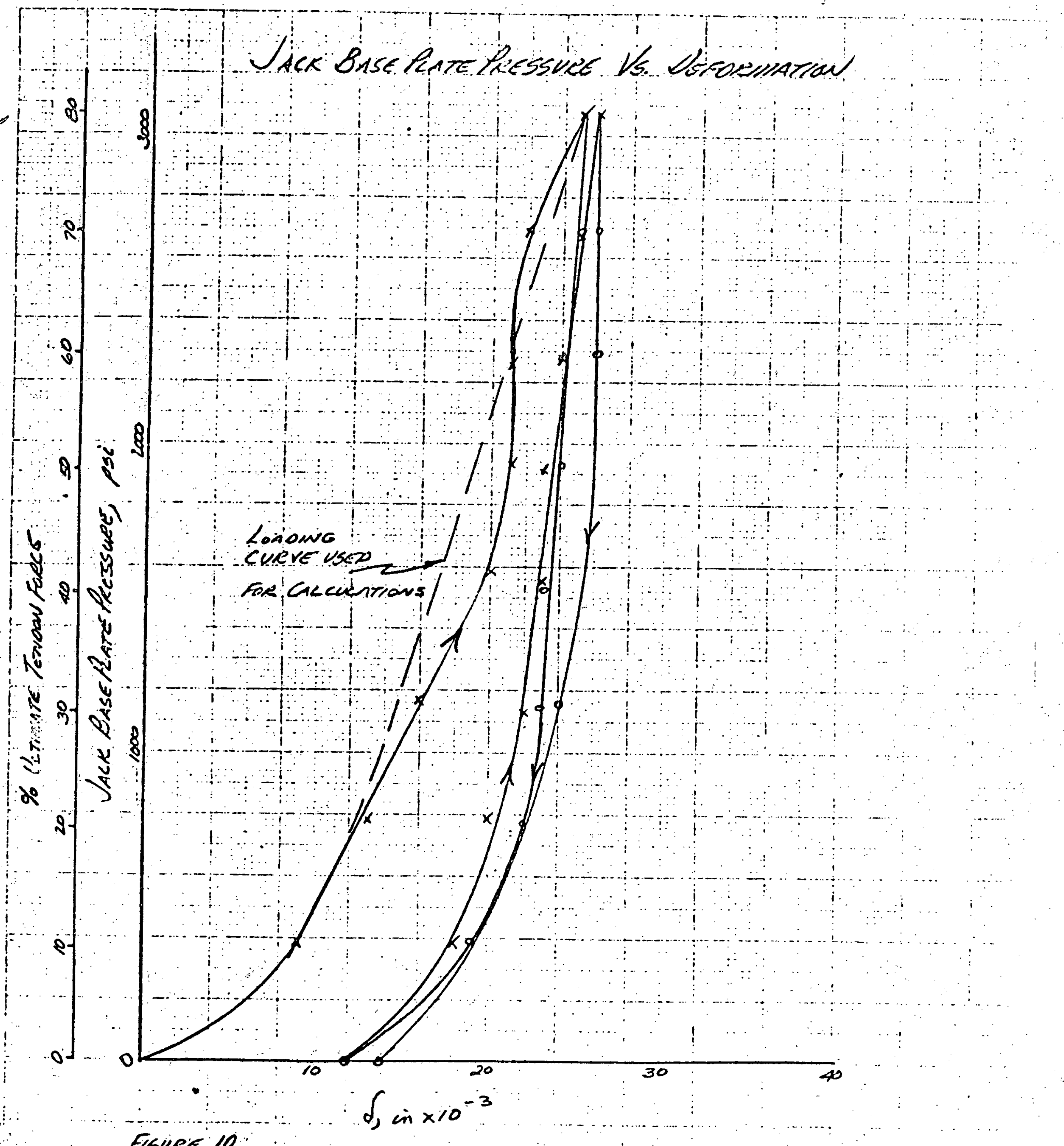


FIGURE 10
BELLEFONTE NUCLEAR PLANT
INSITU DEFORMATION MODULUS TEST

STRESSTEEL TENDON A
ANCHOR DEPTH 3.4'

MC

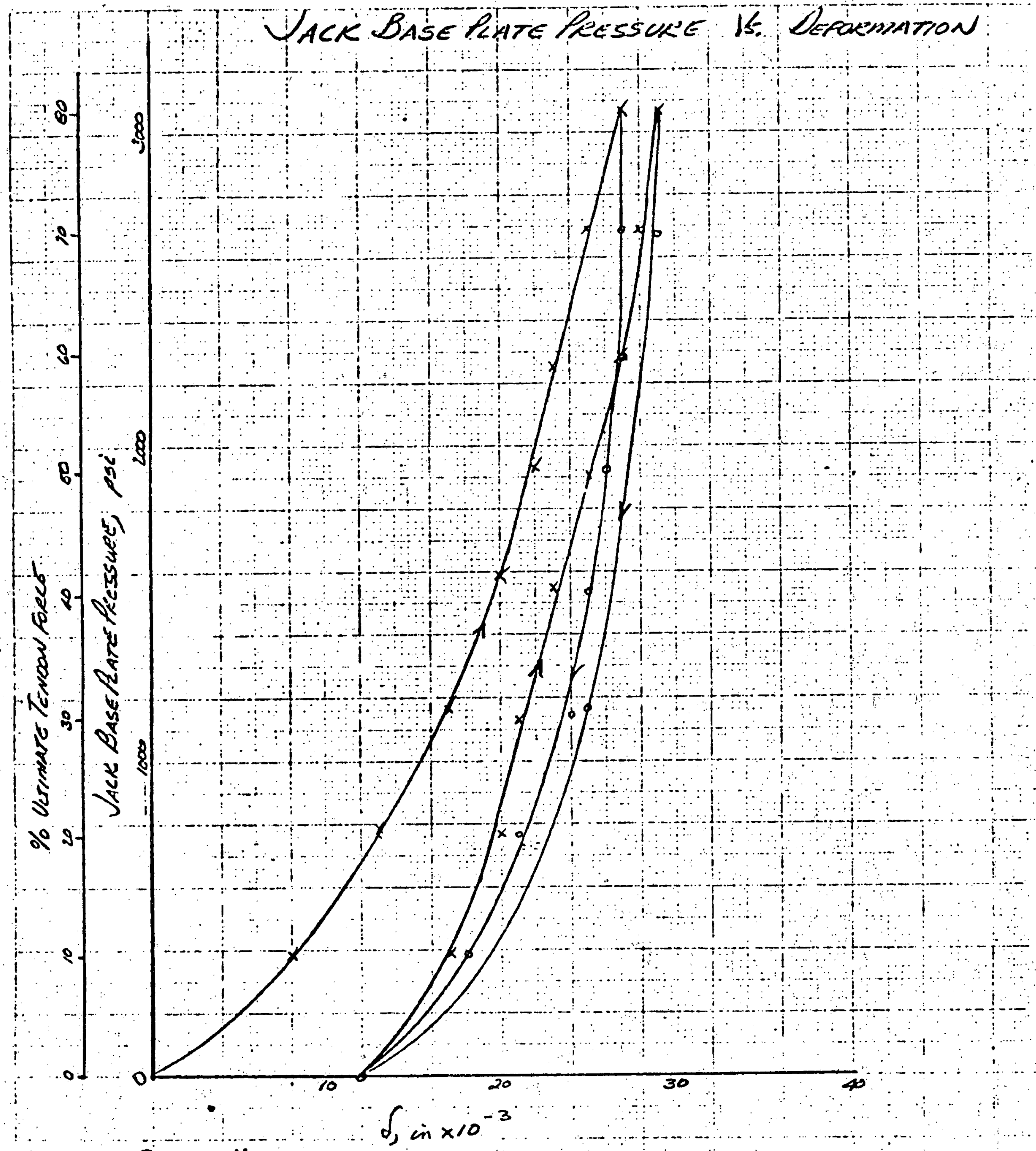


FIGURE 11
BELLEFONTE NUCLEAR PLANT
INSITU DEFORMATION MODULUS TEST

STRESSTEEL TENDON A
ANCHOR DEPTH 5.4'

JHC

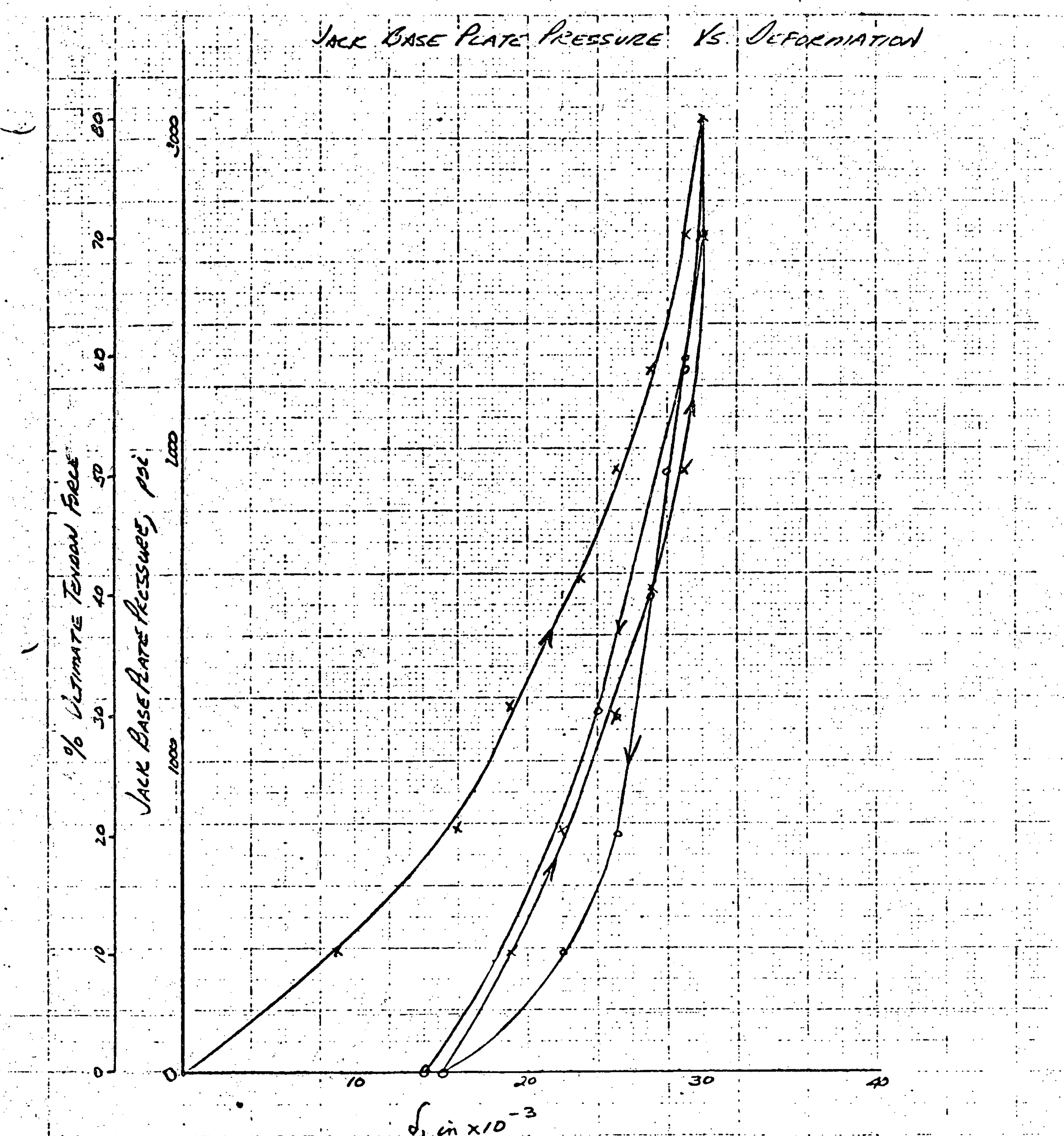


FIGURE 12
BELLEFONTE NUCLEAR PLANT
INSITU DEFORMATION MODULUS TEST

STRESSTEEL TENDON A
ANCHOR DEPTH 10'

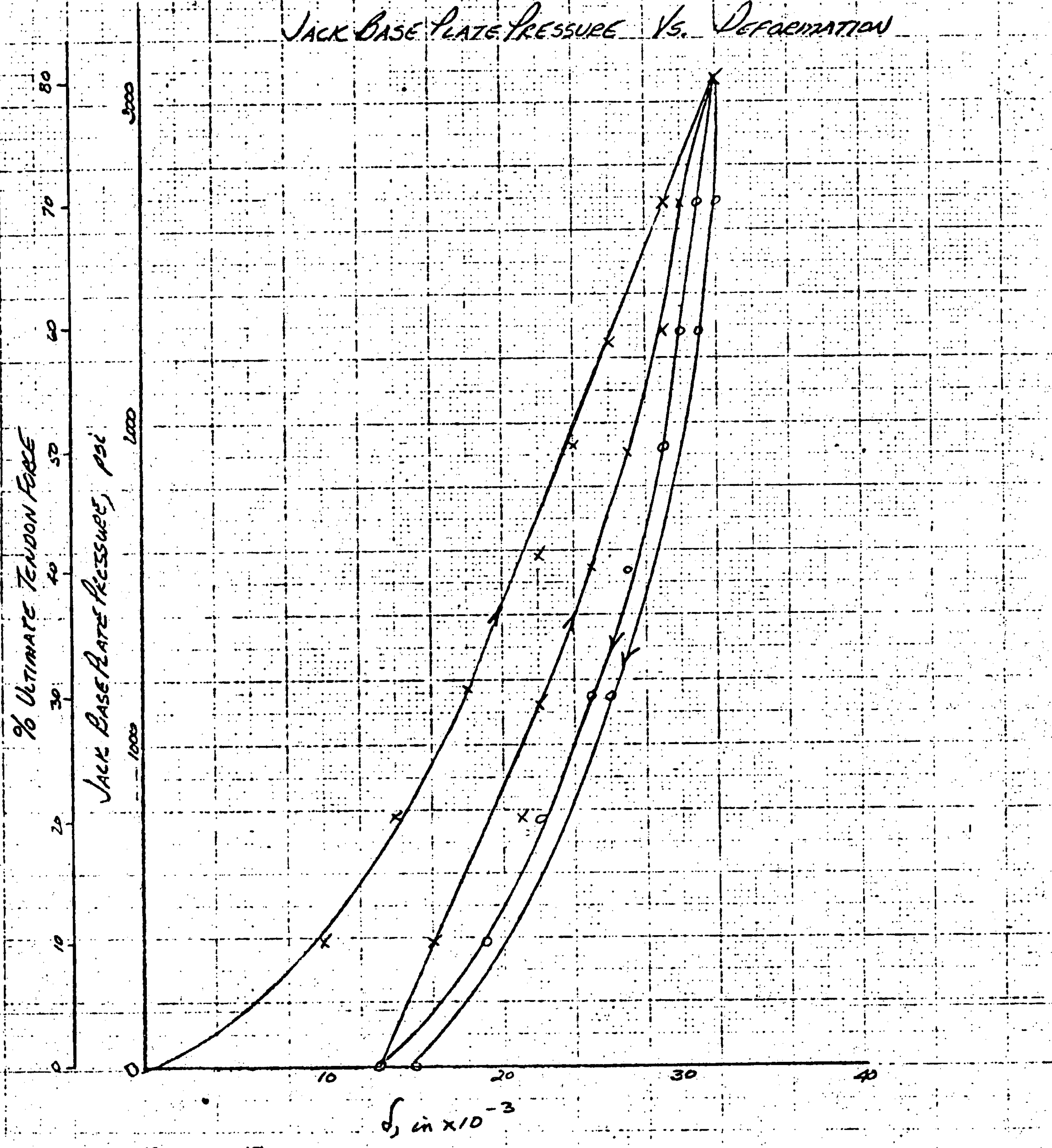


FIGURE 13
BELLEFONTE NUCLEAR PLANT
INSITU DEFORMATION MODULUS TEST

STRESSTEEL TENDON A
ANCHOR DEPTH 15'

JHC

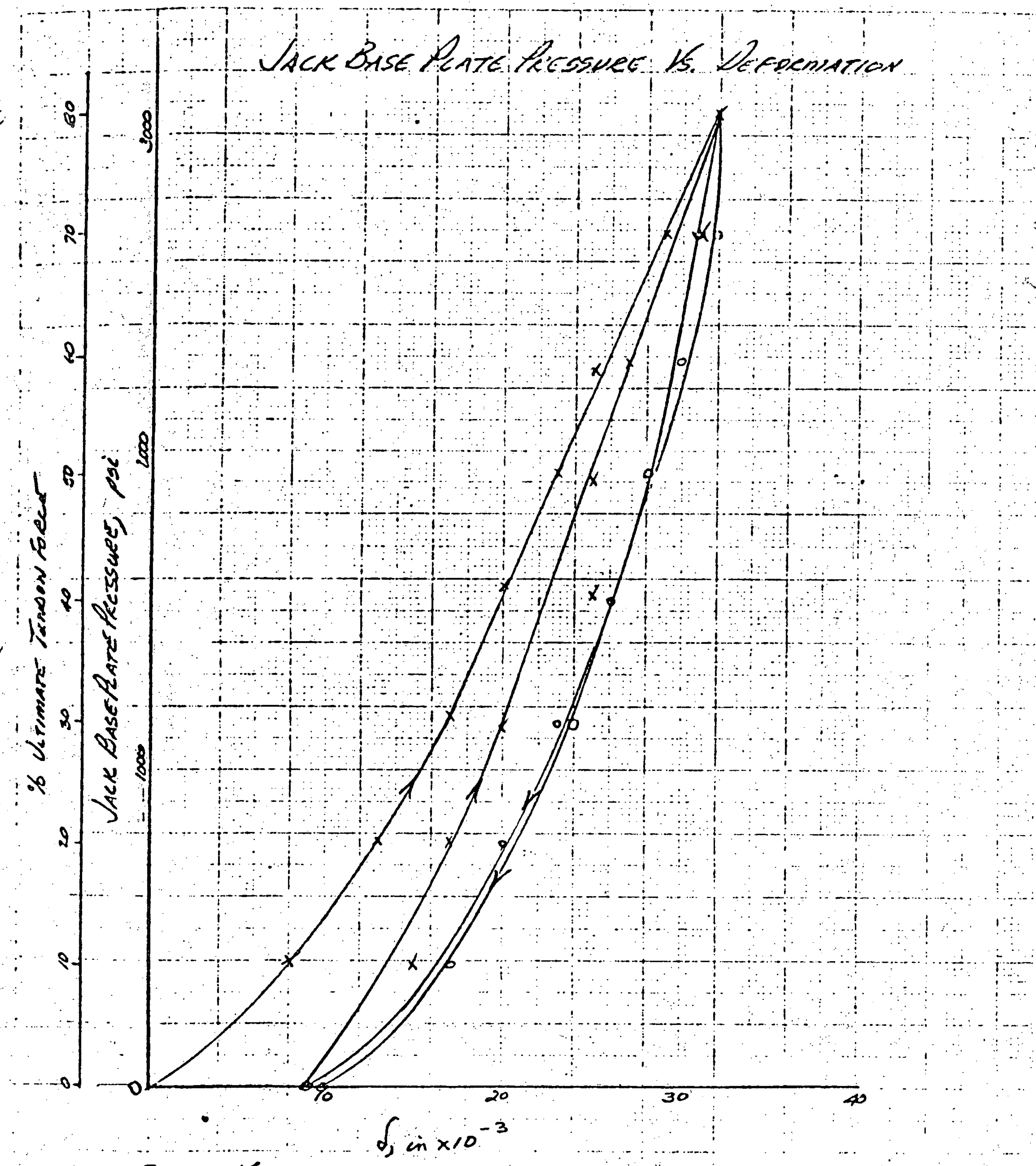


FIGURE 14
BELLEFONTE NUCLEAR PLANT
INSITU DEFORMATION MODULUS TEST

STRESSTEEL TENDON A
ANCHOR DEPTH 17½

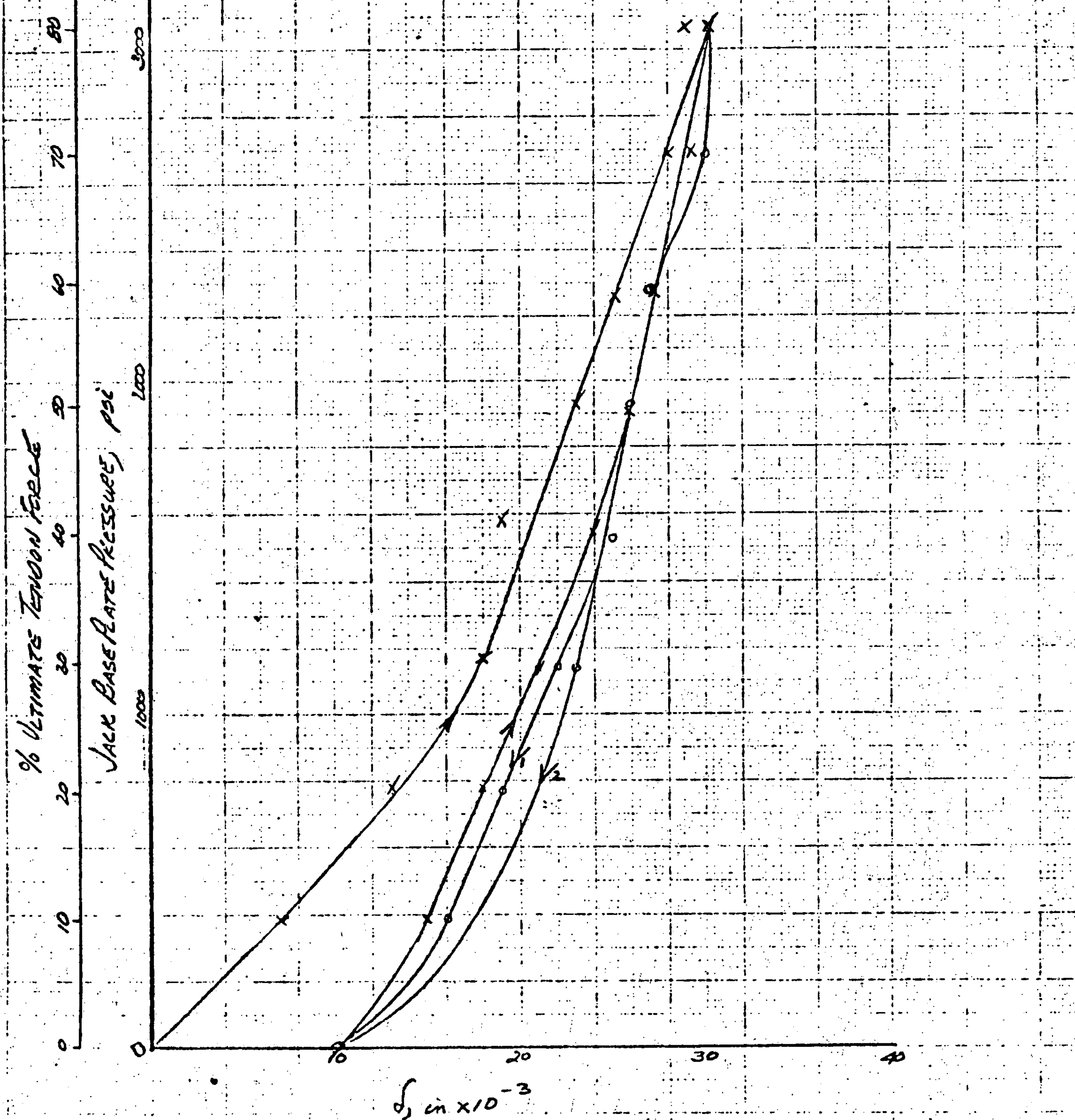


FIGURE 15
BELLEFONTE NUCLEAR PLANT
INSITU DEFORMATION MODULUS TEST

STRESSTEEL TENDON A
ANCHOR DEPTH 20'

JHC

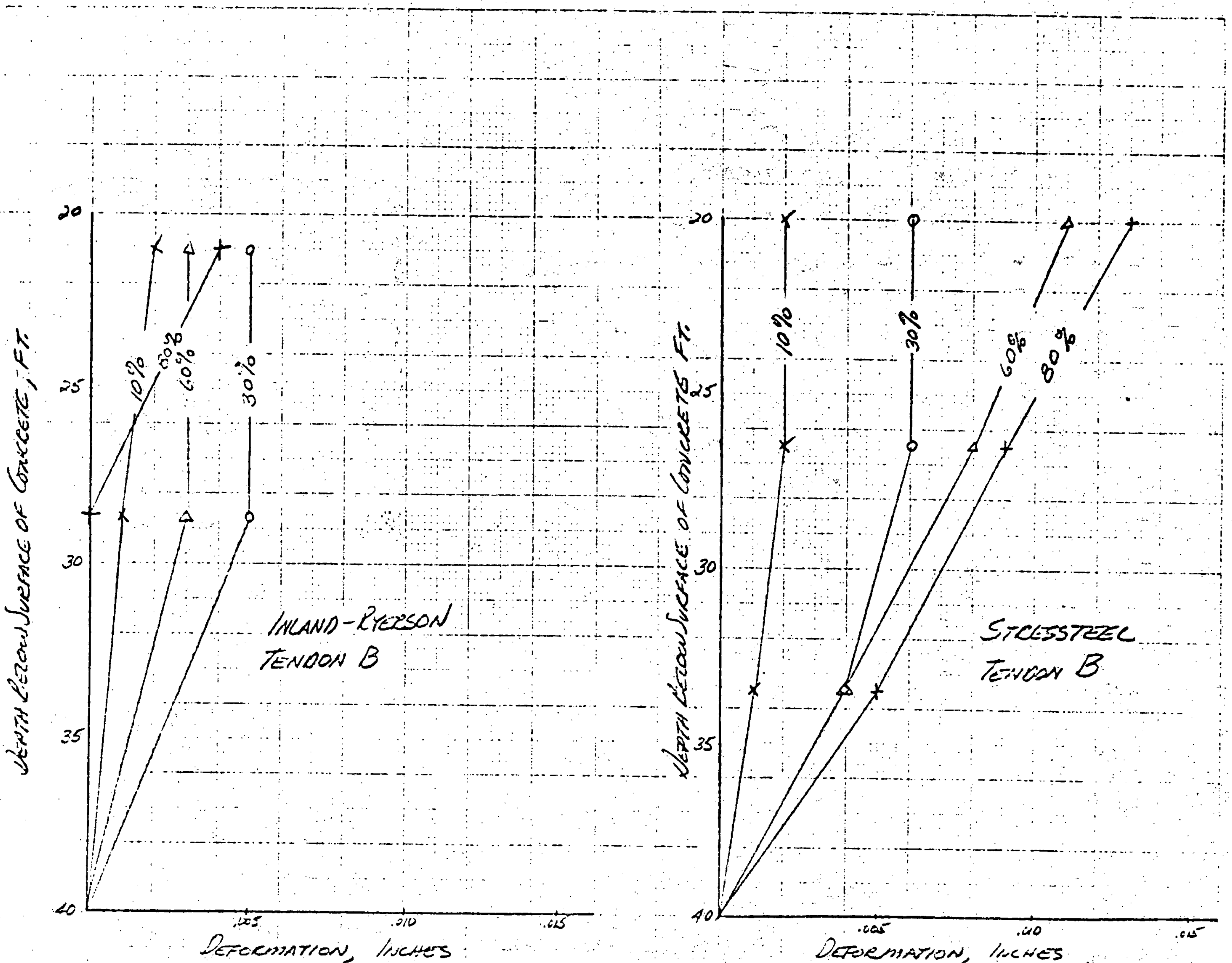


FIGURE 16 DISTRIBUTION OF DEFORMATION RELATIVE TO FORTY FEET FOR BOTH TYPES OF TENDON ANCHORAGE

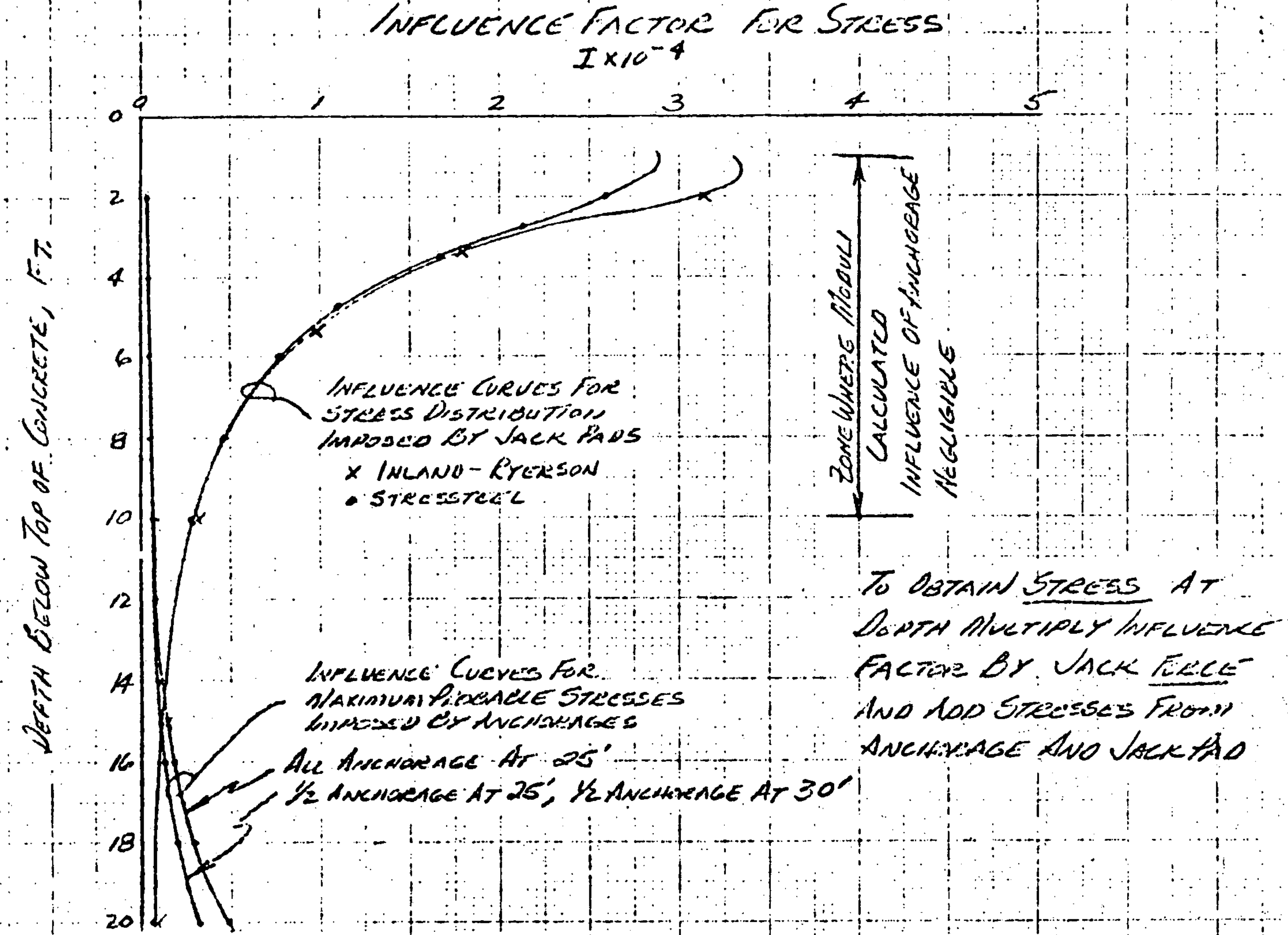
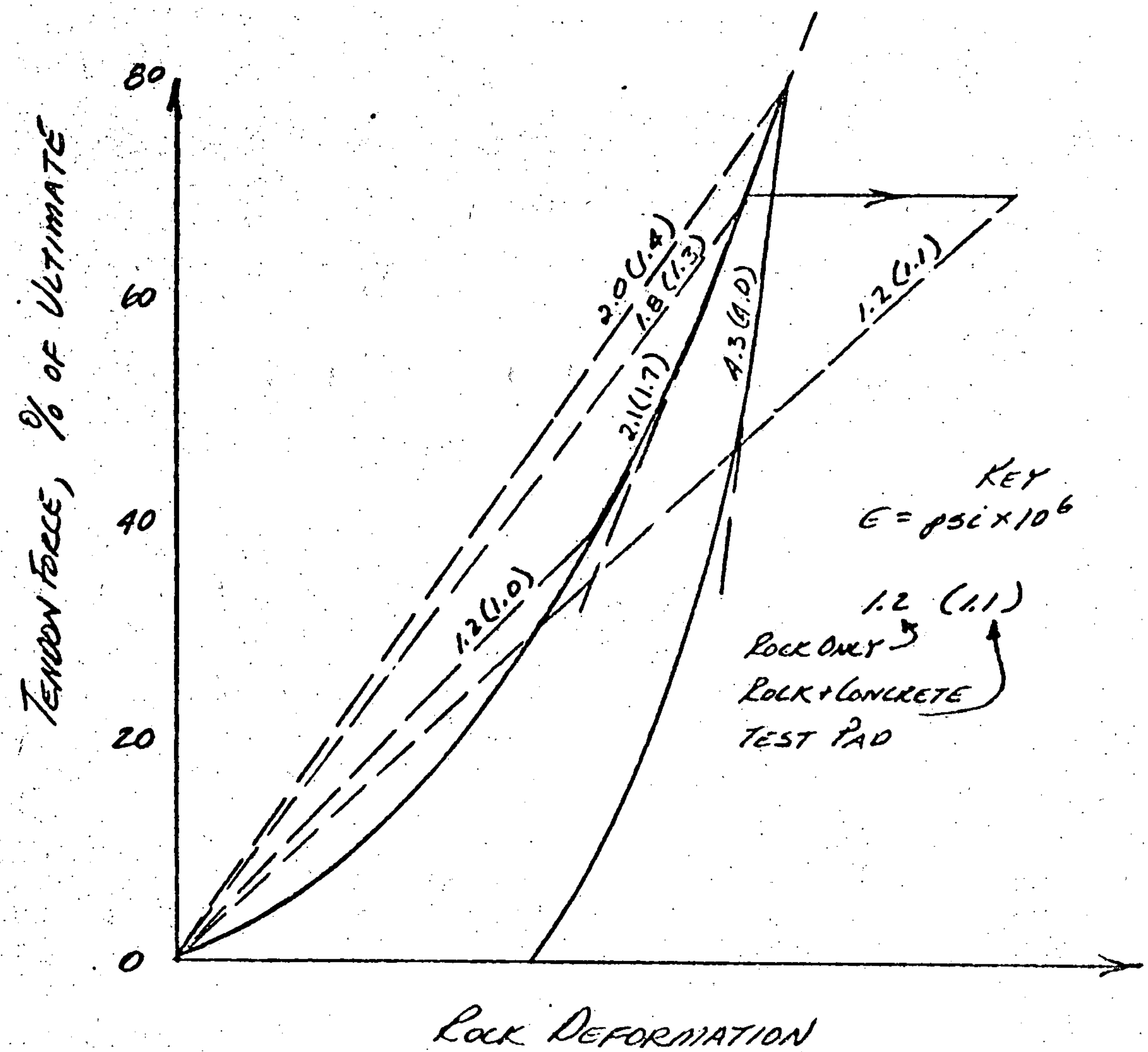


FIGURE 17 INFLUENCE FACTORS FOR DETERMINATION OF ZONE FOR MODULUS CALCULATIONS

JAK



NOTE: THIS FIGURE IS SCHEMATIC AND CANNOT BE USED TO SCALE ADDITIONAL MODULUS VALUES

FIGURE 18 CALCULATED DEFORMATION MODULI FOR A TYPICAL LOADING–UNLOADING–CREEP CURVE.