EVALUATION OF ENERGY ABSORBING MATERIAL FOR PIPE WHIP RESTRAINTS

Commonwealth Edison Company
Byron and Braidwood Station, Units 1 and 2
Project 4391/4392/4683/4684

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1.0 INTRODUCTION

1.1 Introduction

A test program was conducted to evaluate the dynamic crush strength of the Energy Absorbing Material (EAM) due to impact loadings in angular configurations. A total of 15 tests were performed at the HEXCEL/MCI test facilities in Los Angeles, California, per Sargent & Lundy's Specification No. 117. The corresponding HEXCEL document (TR No. 489) describes the detailed requirements of the test program. The results of the test program are presented in this report. A summary of the results is given in Section 1.2, and the conclusions reached are presented in Section 1.3.

The balance of this report is divided into five sections. Section 2 describes test specimens in terms of dimensions, shear strength and mounting configurations.

Section 3 describes the specified test conditions and required dynamic and static measurement items. They include: load angularity, drop weight, drop height, impact velocity and specimen temperature, saddle-plate displacement and EAM crash distance.

Section 4 describes the test equipment and instrumentation.

Section 5 describes the procedures used to reduce the acquired force data to obtain kinetic energies and displacements of the test specimens. Also, the procedures used to evaluate the "Energy Absorbed per Unit Volume (EAUV)" are also presented. The quantity EAUV is also defined as E_a, where appropriate, in this report. The calculation of E_a is documented in SAD Calculation No. 8.15.1-9. Finally, the results of the qualification tests are also presented in this section.

The results of the test program are summarized in Section 1.2.

1.2 Summary

A summary of test results is presented in Table 1. This table presents the values of the essential test parameters in Columns 1 through 4, the measured data in Columns 5 through 7, and the calculated data in Columns 8 and 9. A summary of test data on EAUV is plotted in Figure 1.

The key findings of the tests may be summarized as follows:

a. The E_a in the strong-shear direction at 90° impact varies from a minimum of 5.51 IN-KIP/IN^3 to a maximum of 8.43 IN-KIP/IN^3.

b. The E_a in the weak-shear direction at 90° impact varies from a minimum of 4.47 IN-KIP/IN^3 to a maximum of 7.18 IN-KIP/IN^3.

c. The E_a in the strong-shear direction at 120° impact is 8.43 IN-KIP/IN^3.

d. The E_a in the weak-shear direction at 120° impact is 6.27 IN-KIP/IN^3.

e. The E_a in the bolted configuration at 90° impact is 6.49 IN-KIP/IN^3.

f. The test data on 4x4x3 SS were not recorded. However, test data obtained from the remaining EAM specimens are considered adequate to provide information on EAUV. Consequently, the missing test record does not have an adverse impact on the test results.

1.3 Conclusions

The conclusions drawn from the results of the EAM test program are as follows:

a. The average value of E_a at 50% strain is 5.91 IN-KIP/IN^3 with a range of 4.47 IN-KIP/IN^3 to 7.18 IN-KIP/IN^3. The corresponding qualification test samples average were

6.57 IN-KIP/IN^3 with a range of 5.32 IN-KIP/IN^3 to 7.80 IN-KIP/IN^3.

b. A comparison of the values of E_a indicates that under similar strains there is no apparent scaling effect on the behaviors of the EAM.

c. From a comparison of the test results of 90° vs. 120° impacts, it is concluded that there is no apparent loss in the energy-absorbing capacity of the EAM specimens due to load angularities.

d. From the results of 4x4x4 specimens, it is shown that there is no significant difference in E_a between the bolt and non-bolt test configurations.

2.0 TEST SPECIMENS

Two specimens were used in each dynamic crush test. All the specimens were sawed from core block No. 1182-556 with an average EAUV of 5.46 IN-KIP/IN^3 at 150°F when tested in a straight drop configuration (zero angularity). The core material was sandwiched between a top and a bottom plate by brazing. A typical arrangement of the specimen is shown in Figure 2.

The test specimens were designated in terms of their physical dimensions (length x width x depth) and shear strengths. The shear strength of each specimen was specified either as "strong shear (SS)" or "weak shear (WS)" depending on the orientation of the specimen mounted on the test fixtures. The designations of the test specimens are presented as follows:

3x3x3	WS
3x3x3	SS
4x4x2	WS
4x4x2	SS
4x4x2 5/16	WS
4x4x2 5/16	SS

4x4x3	WS
4x4x3	SS
4x4x4	WS
4x4x4	SS
5x5x4	WS
5x5x4	SS
6x6x3	WS
6x6x3	SS
4x4x4	BT

The designation "BT" refers to the last test in which the EAM specimens were bolted to the fixtures with two ASTM A193, Grade B7 bolts in an orientation similar to that found in pipe whip restraints. The test configuration for the BT test is shown in Figure 3.

3.0 TEST CONDITIONS

The conditions specified in the tests are listed as follows:

- Load Angularity - This was achieved by introducing slanted impact surfaces on the hammer. 90° and 120° load angularities were specified.

- Drop Weight - The drop weight varied with test specimens.

- Drop Height - A nominal drop height of 120 inches was specified.

- Impact Velocity - An impact velocity of 25 feet per second was specified.

- EAM Temperature - A test temperature of 120°F was specified for each specimen prior to impact.

A listing of test specimens and their corresponding test conditions is presented in Table 1.

3.2 Measurements

In addition to the specified test conditions that were recorded for each test, measurements were also made on the

static and dynamic quantities as described below:

- Dynamic Measurements

  a. Force vs. time output from the instrumented tup (force gauge): The output was recorded on a TEAC FM cassette recorder.

  b. Impact velocity: The impact velocity was obtained from the outputs of the light-sensitive limit switches of the ETI 300 Instrumented Impact System.

- Static Measurements

  a. Saddle Plate Displacement: The saddle plate displacement is defined as D_S, as shown in Figure 4. The distances between the bottom center point of the saddle plate and the top of the reaction mass were measured before and after impact. The quantity D_S was obtained as the difference between the two measurements.

  b. EAM Crush Distance: The EAM crush distance is defined as D_E, as shown in Figure 4. The depths of each specimen were measured before and after impact. The quantity D_E was obtained as the difference between the two measurements.

4.0 TEST EQUIPMENT AND INSTRUMENTATION

4.1 Test Equipment

The equipment used in the tests is depicted schematically in Figure 2. The test set-up consisted of the following four elements:

a. Drop Weight Assembly: The assembly consisted of an impact weight, an instrumented tup and an impact hammer. The hammer has two impact surfaces which are parallel to those of the anvils. The impact angles of the hammer specified in the test were 90° and 120°, respectively.

b. Saddle Plate: The saddle plate is made of 3/4 inch steel plate. It was shaped to conform with the bottom contour of the hammer and was welded to the tops of the EAM specimens.

c. Anvils: Two anvils were used in each test. The EAM test specimens were either welded or bolted to the anvils. In addition, two sets of anvils were used in the test program. The impact angles of these sets were 45° and 60°, respectively.

d. Reaction Mass: The reaction mass weighs 44,000 lbs. It

was used to anchor the anvils.

4.2 Instrumentation

The instrumentation used to acquire the test data consisted of an ETI-300 Instrumented Impact System (IIS) and additional instruments as depicted in Figure 5.

The IIS is comprised of the following components:

a. Instrumented Tup: The instrumented tup is a force gauge. It produces electrical voltage which is proportional to the magnitude of an impact force. Two different tups were used in the tests. The capacities of these tups were rated to be 350,000 lbs and 1,000,000 lbs, respectively. The latter tup was used for testing the EAM specimens with dimensions of 4"x4"x4" (BOLT), 5"x5"x4" and 6"x6"x3".

b. Optical Velocity Sensor: The sensor consisted of photoelectric limit switches and a universal timer. The information was used to compute the velocity of the hammer prior to impact.

c. Computer-Based Impact Analyzer: The analyzer accepts the outputs from the force gauge and optical velocity sensor. These signals were then digitized and analyzed

to provide:

o Load - Energy vs. Displacement plot

o Load - Energy vs. Time plot

These plots were not used in the analysis.

In addition, the analog output signal from the force gauge could also be tapped from the analyzer.

Additional instrumentations provided for the test program consisted of the following items:

a. Accelerometers: They were used to acquire acceleration signals of the hammer during impact. Three accelerometers (Bruel & Kjaer Type 4370) and three charge amplifiers (Bruel & Kjaer Type 6250) were used for each test. The accelerometers were mounted on the hammer. The mounting details are shown in Figure 7.

b. FM Recorder: A TEAC R71 FM recorder was used to record the output signals from the force gauge and the accelerometers.

c. Oscillograph Recorder: A SOLTEC 5M28 Osillograph Recorder was used to display the recorded signal immediately after each test.

4.3 Remarks

The displacement data which were required in computing the crush energy of EAM specimens were obtained from the force data. The output from the instrumented tup was recorded by an FM cassette recorder. The recorded data would then be digitized and used to obtain displacement by double integration.

As a backup for the load cell, three accelerometers (Bruel & Kjaer Model 4370) were added to the test program to acquire acceleration data. These accelerometers were mounted on mechanical filters (Bruel & Kjaer Model UA 0559) so that high-frequency spurious signals due to metal-to-metal impacts could be filtered and saturation of the charge amplifiers could be avoided. The arrangement was considered adequate for a maximum acceleration of 1000 g. The system was checked out satisfactorily for trial EAM specimens subject to normal impacts without using the saddle plate and the anvils.

However, the mechanical filters used in the tests could not accommodate the high-frequency contents of impact signals. Thus, the results from the first few production tests showed that the charge amplifiers were saturated. Efforts to eliminate this problem by switching to high-g impact accelerometers did not improve the situation. Consequently,

accelerometer data were not used in the evaluation. The loss of accelerometer data has no impact on the test program.

5.0 DATA REDUCTION

5.1 Displacement and Energy

The force data, which were recorded by an FM Cassette Recorder (TEAC R71), were digitized and used to compute the displacements and kinetic energies of the test specimens according to the approach as outlined below.

In Figure 8, the drop-weight assembly is represented by a free-body diagram, in which M_1 and M_2 represent the masses of the assembly. Since the stiffness of the instrumented tup is about 60,000 kips per inch, it is reasonable to assume that the displacement of M_1 is essentially the same as M_2. As the tup is measuring the reaction force between M_1 and M_2, the acceleration of the assembly could be represented by Equation 5.1.

$$a(t) = P(t)/M_1 \qquad (5.1)$$

where: $P(t)$ = force sensed by the tup

M_1 = mass of the drop weight

t = time

The velocity at time t is given by Equation 5.2.

$$V(t) = V_o - \int_o^t a(t)\, dt \qquad (5.2)$$

Where V_o is the impact velocity.

The displacement is given by Equation 5.3.

$$D(t) = V_o \cdot t - \int_o^t \left[\int_o^t a(t)\, dt \right] dt \qquad (5.3)$$

The energy absorbed up to time t is

$$E(t) = \int_o^t P(t) \cdot V(t)\, dt \qquad (5.4)$$

The test data was evaluated on the basis of the measured displacement at the midpoint of the saddle plate and the kinetic energy of the drop-weight assembly. The deviation between the calculated and the measured data was used to determine the validity of the test results.

In reducing the test data obtained from the 1,000,000 lbs. tup for EAM specimens 4x4x4 (BOLT), 5x5x4 and 6x6x3, it was necessary to reduce the levels of recorded force data by 30% so that the deviations in displacement and kinetic energy could be brought in line with those obtained from the other tests.

The computed displacements and kinetic energies for 14 tests are summarized in Table 2. Notice that the calculated displacements are in good agreement with the measured, with deviations ranging between 2% and 13%, whereas the deviations in the calculated kinetic energies range between 5% to 15%. The Energy-vs-Displacement plots are shown in Appendix A.

5.2 ENERGY ABSORBED PER UNIT VOLUME

The EAUV of an EAM test specimen is, by definition, computed by Equation 5.5 below:

$$E_a = \frac{E_e}{\Delta V_e} \qquad (5.5)$$

where

E_a = The cumulative energy absorbed per unit volume of crushing strain e.

ΔV_e = The change in volume corresponding to strain e and is equal to $(D_e \cdot A)$.

A = The cross-sectional area of the specimen.

D_e = Crush distance at strain e.

The final adjusted values of E_a, as shown in Table 1, vary between 4.47 IN-KIP/IN^3 to 8.43 IN-KIP/IN^3.

5.3 Qualfication Tests

A total of five qualification tests was performed by HEXCEL to establish EAUV under the normal impact condition. The five specimens were designated as G, H, X, Y and Z. The test conditions and results are summarized in Table 3.

The tests on specimens G and H were performed per Sargent & Lundy's specification No. FL-2409. Additional tests were performed on specimens X, Y and Z to obtain the information on crush strain.

The values of E_a obtained from the qualification tests vary from 5.32 IN-KIP/IN^3 to 7.80 IN-KIP/IN^3.

TABLE 1
SUMMARY OF TEST PARAMETERS AND RESULTS

(1) DESIGNATION OF TEST SPECIMEN	(2) ANVIL ANGLE (DEGREE)	(3) TOTAL DROP WEIGHT (LBS.)	(4) DROP HEIGHT (IN)	(5) IMPACT VELOCITY (FPS)	(6) SADDLE DIS-PLACEMENT (IN)	(7) EAM CRUSH DISTANCE (IN)	(8)* E_a IN-KIP/ IN^3	(9) ULTIMATE STRAIN (IN/IN)
3 x 3 x 3 WS	90°	1975	120	25.00	2.90	2.06	5.24	0.67
3 x 3 x 3 SS	90°	1975	120	25.03	2.85	2.00	5.51	0.66
4 x 4 x 2 WS	90°	1975	120	24.99	1.83	1.27	4.47	0.61
4 x 4 x 2 SS	90°	1975	120	25.02	1.33	0.88	8.13**	0.43
4 x 4 x 2 5/16 WS	120°	2400	120	25.07	2.13	1.33	6.27	0.55
4 x 4 x 2 5/16 SS	120°	2400	120	25.07	2.13	1.01	8.43**	0.43
4 x 4 x 3 WS	90°	3050	120	25.08	2.72	1.87	7.18	0.62
4 x 4 x 3 SS	90°	3050	120	25.11	2.18	1.77	+	0.58
4 x 4 x 4 WS	90°	4000	120	25.09	3.67	2.57	5.26	0.64
4 x 4 x 4 SS	90°	4150	130	26.04	3.52	2.35	5.89	0.58
4 x 4 x 4 BT	90°	4150	120	25.09	2.78	2.45	6.49	0.61
5 x 5 x 4 WS	90°	6550	120	25.34	3.74	2.59	5.44	0.65
5 x 5 x 4 SS	90°	6550	120	25.37	3.23	2.25	6.42	0.56
6 x 6 x 3 WS	90°	6925	120	25.32	2.35	1.54	6.15	0.50
6 x 6 x 3 SS	90°	6925	120	25.33	2.28	1.47	7.98**	0.48

Legends: * = E_a is computed based on 50% strain.

** = E_a is computed based on maximum strain obtained from the test.

+ = Data Lost

TABLE 2
VERIFICATION OF DISPLACEMENT AND KINETIC ENERGY

SAMPLE ID	DEFLECTION (IN) MEASURED	CALC.	DEV(%)	ENERGY (1000 FT-LB) $1/2\ mV_o^2$	CALC.	DEV(%)
3 X 3 X 3 SS	2.850	2.903	1.87	19.21	16.74	-12.9
3 X 3 X 3 WS	2.900	2.954	1.86	19.17	16.47	-14.1
4 X 4 X 2 SS	1.330	1.307	- 1.71	19.20	16.79	-12.5
4 X 4 X 2 WS	1.830	1.904	4.05	19.15	16.69	-12.9
4 X 4 X 2 5/16 SS	2.130	2.112	- 0.85	23.42	19.88	-15.1
4 X 4 X 2 5/16 WS	2.795	2.747	- 1.71	23.59	20.23	-14.2
4 X 4 X 3 SS*	-	-	-	-	-	-
4 X 4 X 3 WS	2.720	2.362	-13.6	29.79	25.98	-12.8
4 X 4 X 4 SS	3.515	3.607	2.62	43.70	40.11	- 8.21
4 X 4 X 4 WS	3.670	3.495	- 4.77	39.10	35.20	- 9.97
4 X 4 X 4 BT	2.780	3.070	10.40	40.57	36.06	-11.12
5 X 5 X 4 SS	3.230	3.252	0.68	65.46	60.76	- 7.18
5 X 5 X 4 WS	3.740	3.845	2.80	65.31	60.72	- 7.03
6 X 6 X 3 SS	2.280	2.326	2.01	68.99	65.27	- 5.40
6 X 6 X 3 WS	2.350	2.398	2.03	68.94	64.87	- 5.90

* Data Lost

TABLE 3
VALUES OF ENERGY ABSORBED PER UNIT
VOLUME OBTAINED FROM QUALIFICATION TESTS

(1) EAM I.D.	(2) TOTAL DROP WEIGHT (LBS)	(3) IMPACT VELOCITY (FPS)	(4) EAM CRUSH DISTANCE (IN)	(5) E_a IN-KIP/IN^3	(6) SPECIMEN TEMPTERATURE (°F)	(7) STRAIN (IN/IN)
G	6920	15.30	2.63	5.32	150	-
H	6920	15.31	2.61	5.60	150	-
X	1775	26.38	1.88	6.70	120	0.46
Y	1925	26.22	1.75	7.43	120	0.43
Z	1950	26.34	2.03	7.80	120	0.52

Notes: 1. Specimen Z was tested employing the 1,000,000 lb. force gauge. The remaining tests were conducted with the 300,000 lb. force gauge.

2. Strains on specimens G and H are not available.

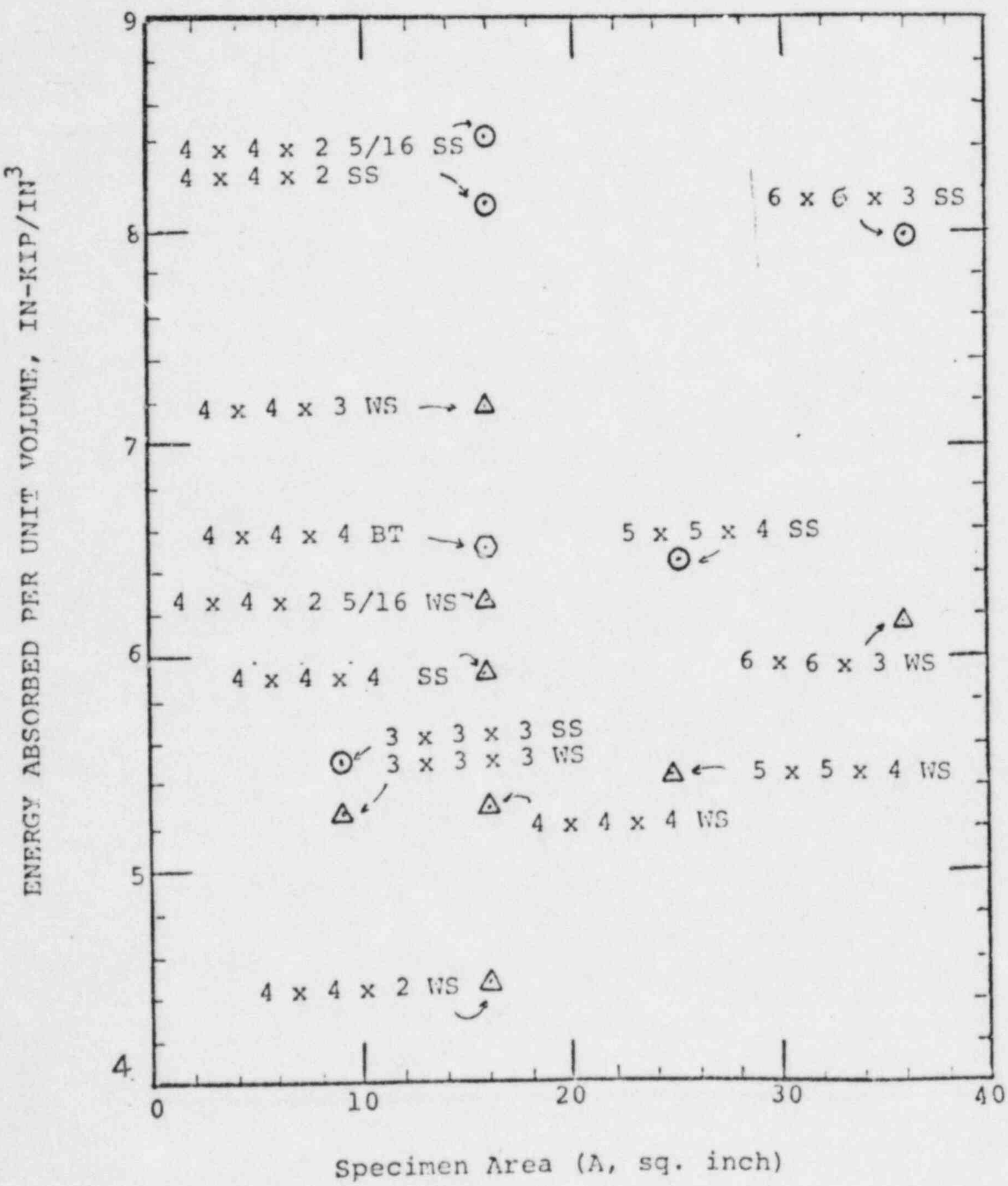


FIGURE 1: SUMMARY OF ENERGY ABSORBED PER UNIT VOLUME OF EAM SPECIMENS

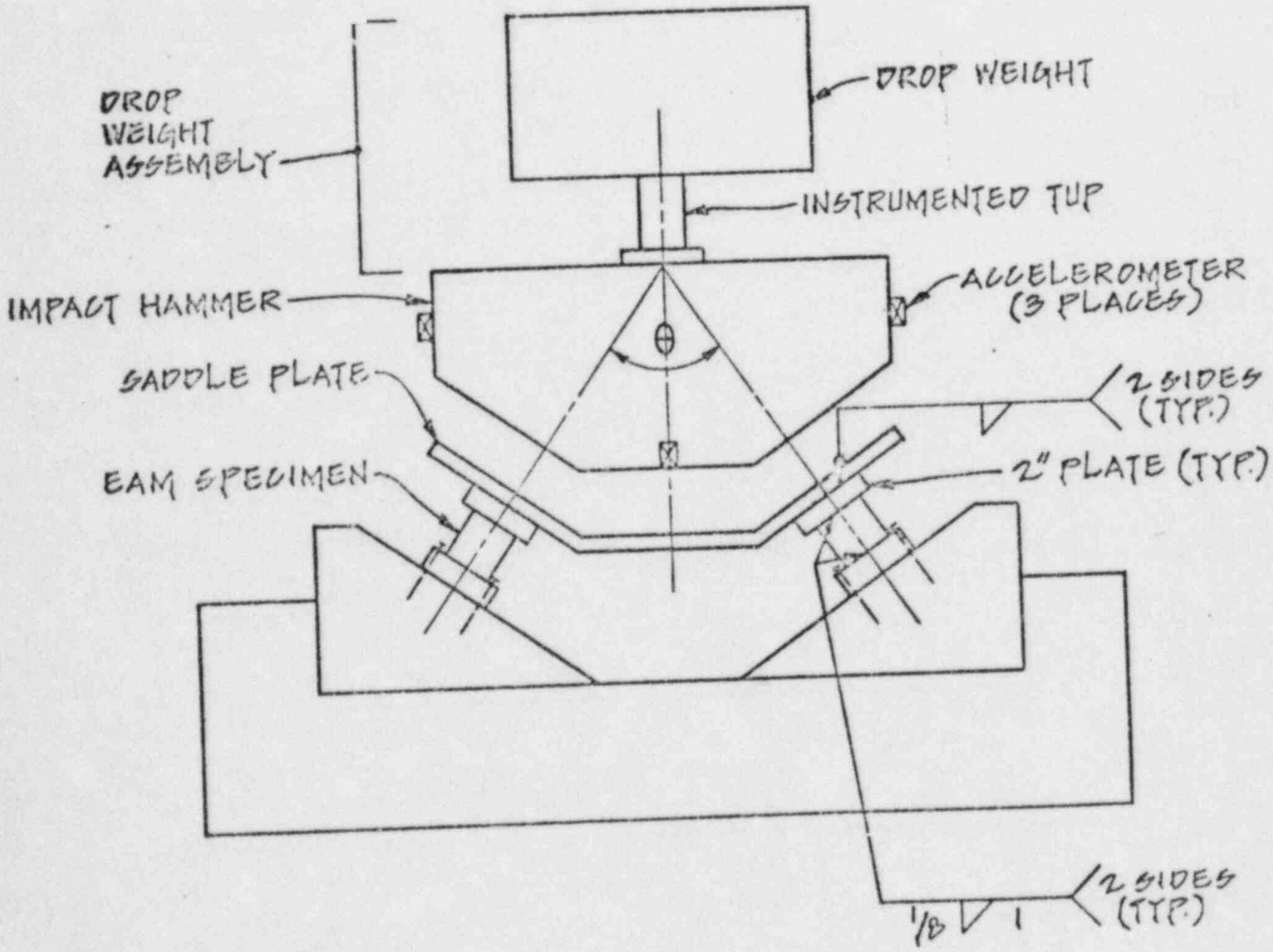


Figure 2 Test Set-Up

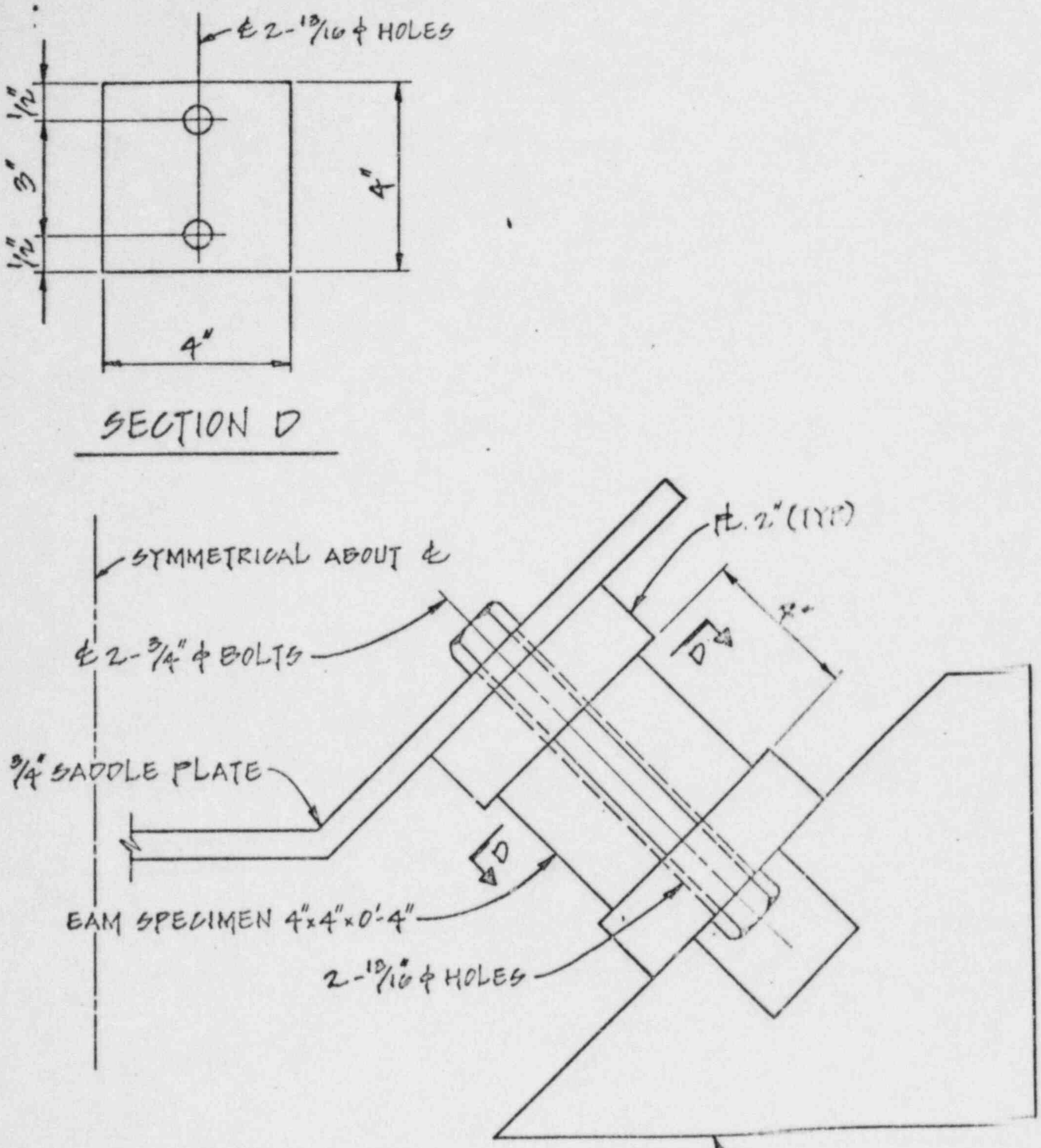
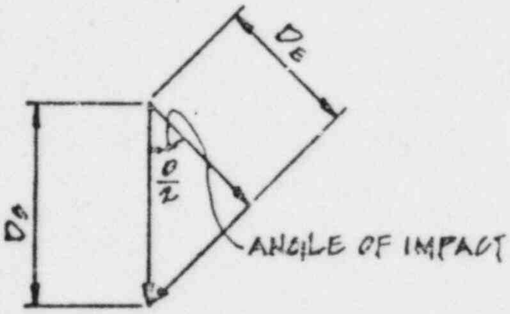


Figure 3 Test Set-Up For The Bolted Configuration



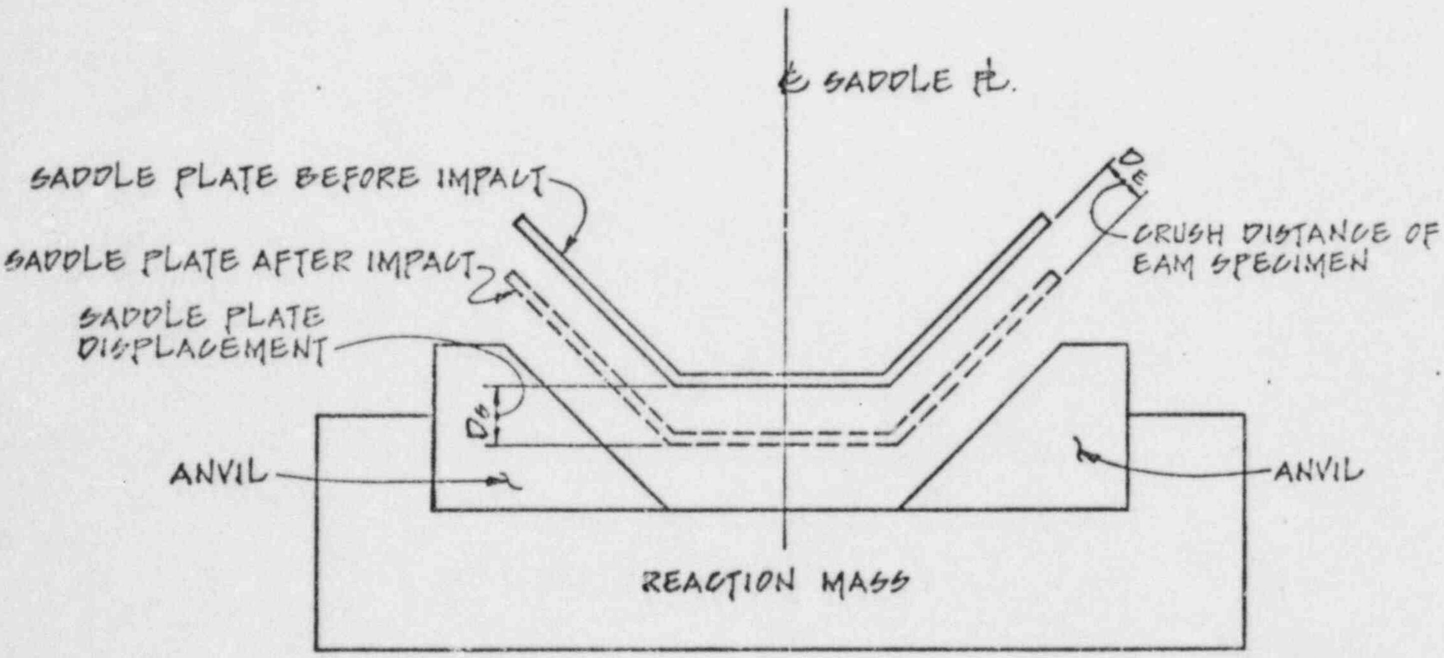


Figure 4 Displacement In Relationship Between Saddle Plate and EAM Specimen

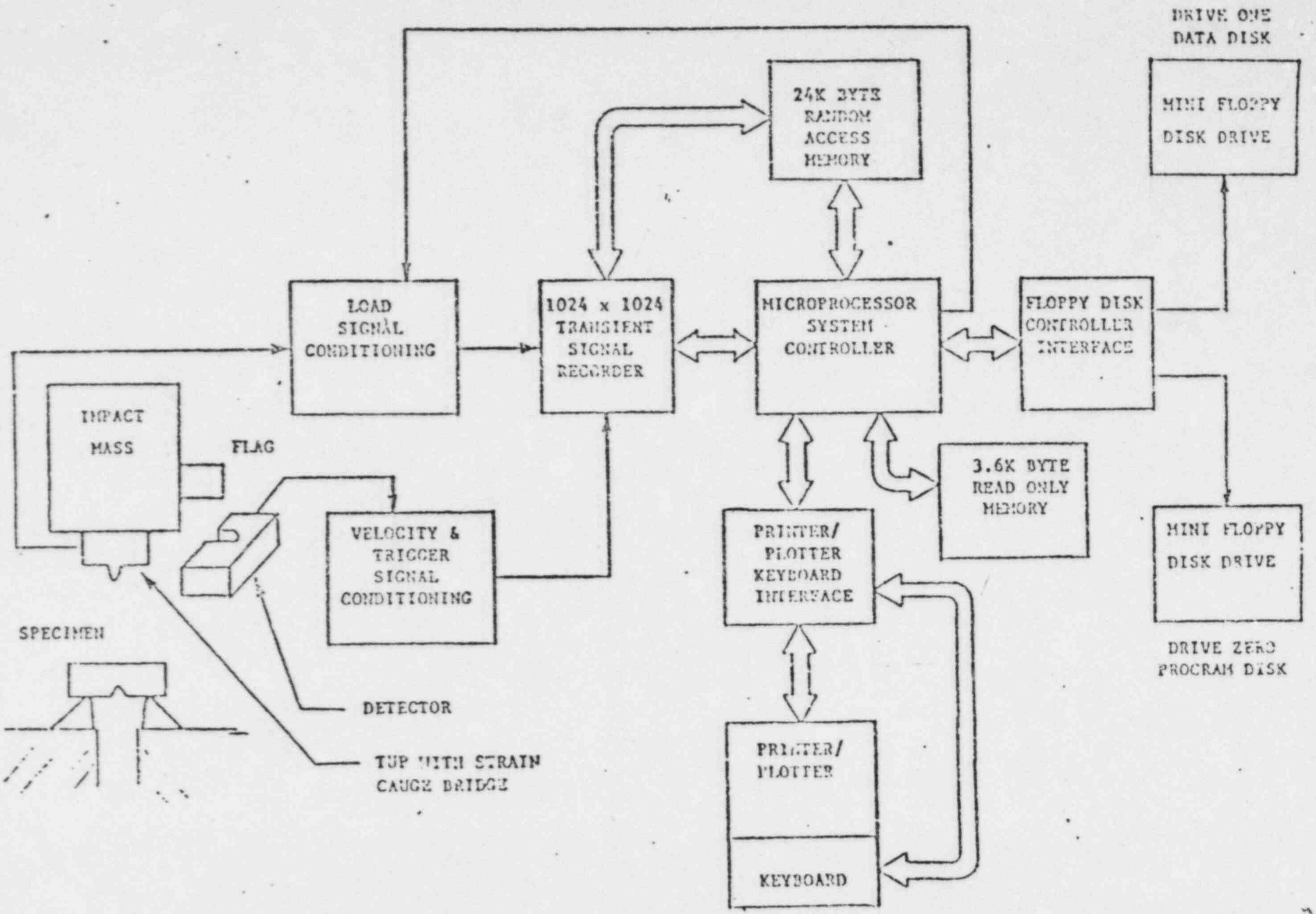


Figure 5. ETI-300 Instrumented Impact System

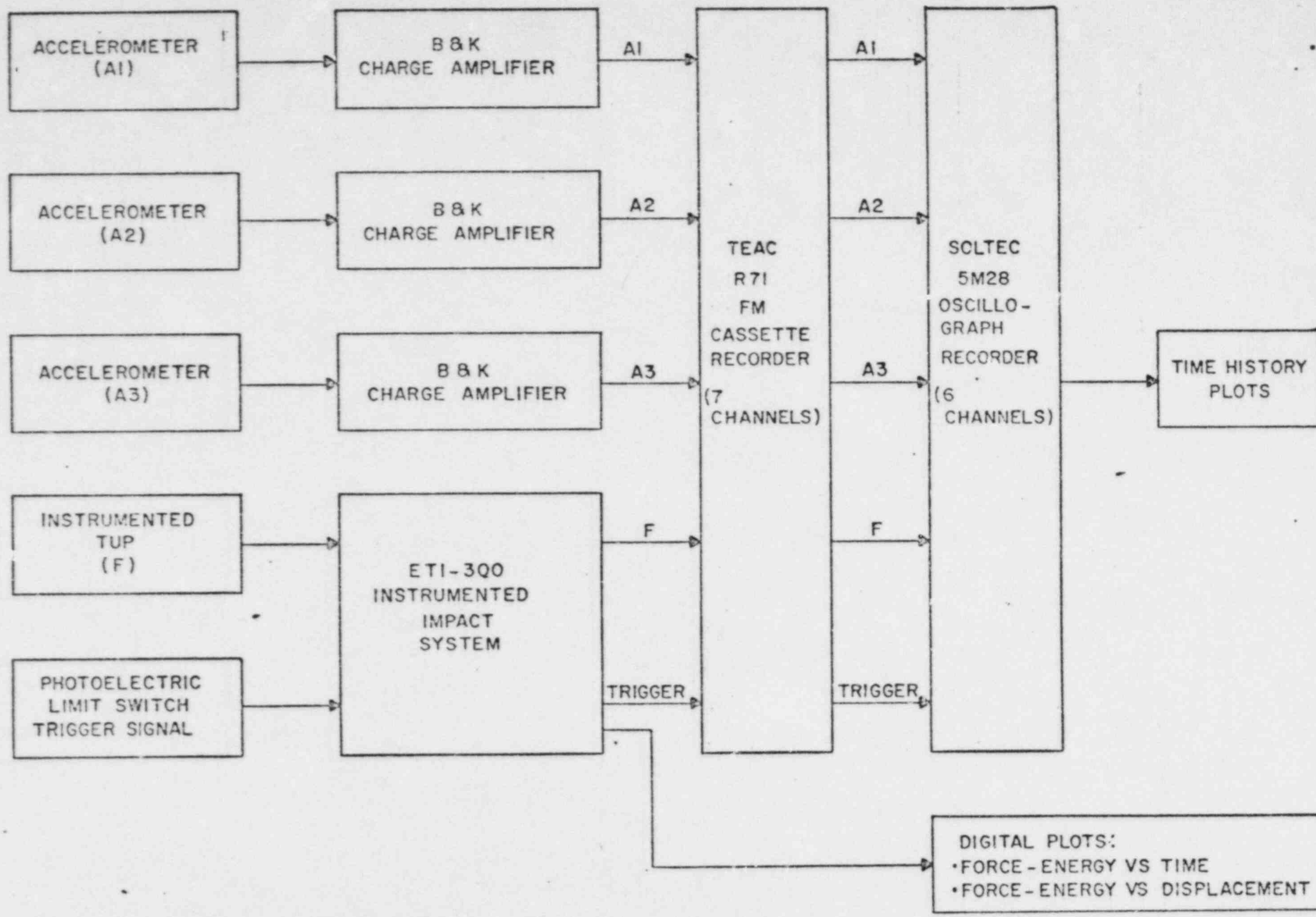


Figure 6. Instrumentation [illegible] Testing

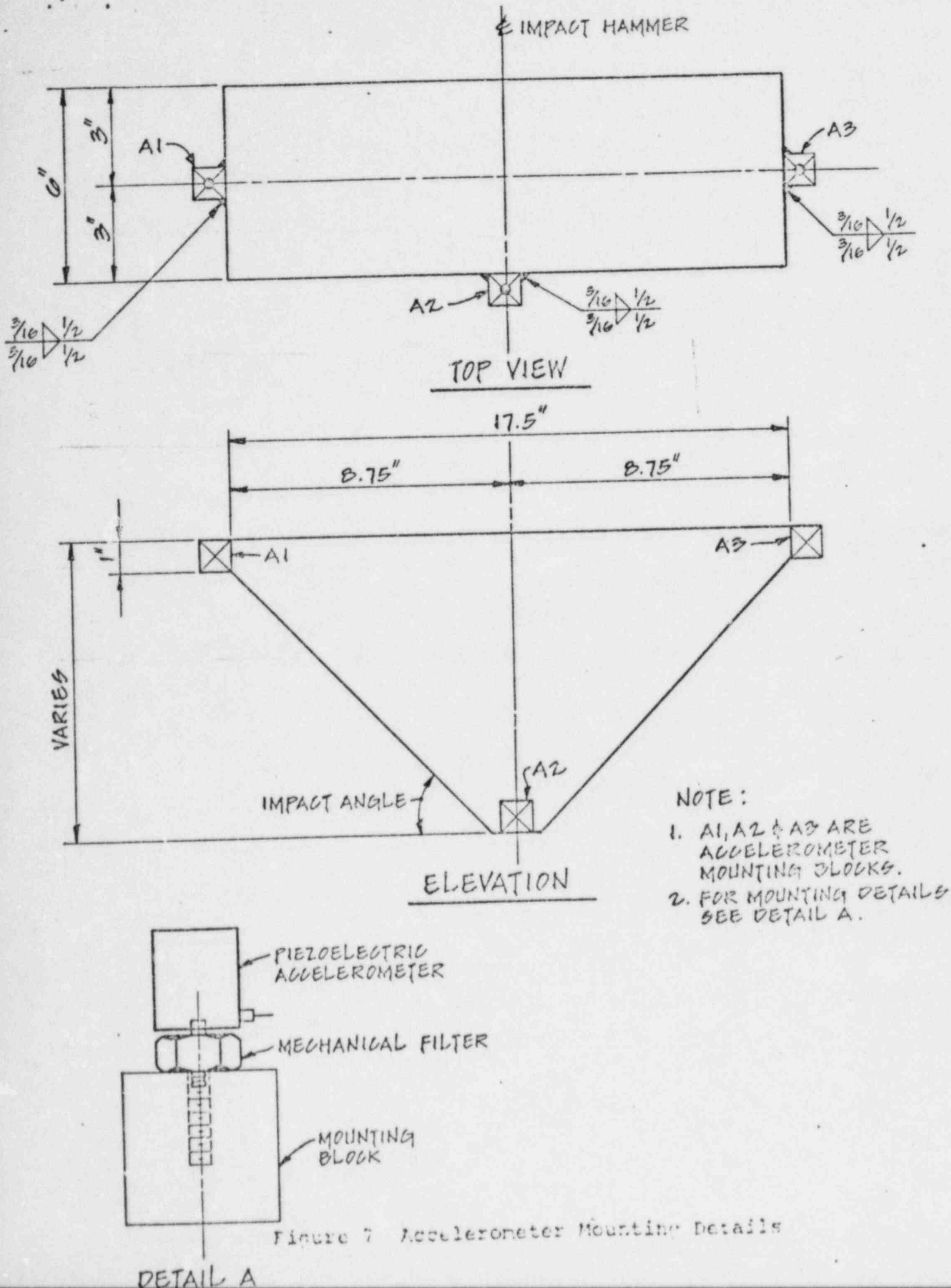


Figure 7 Accelerometer Mounting Details

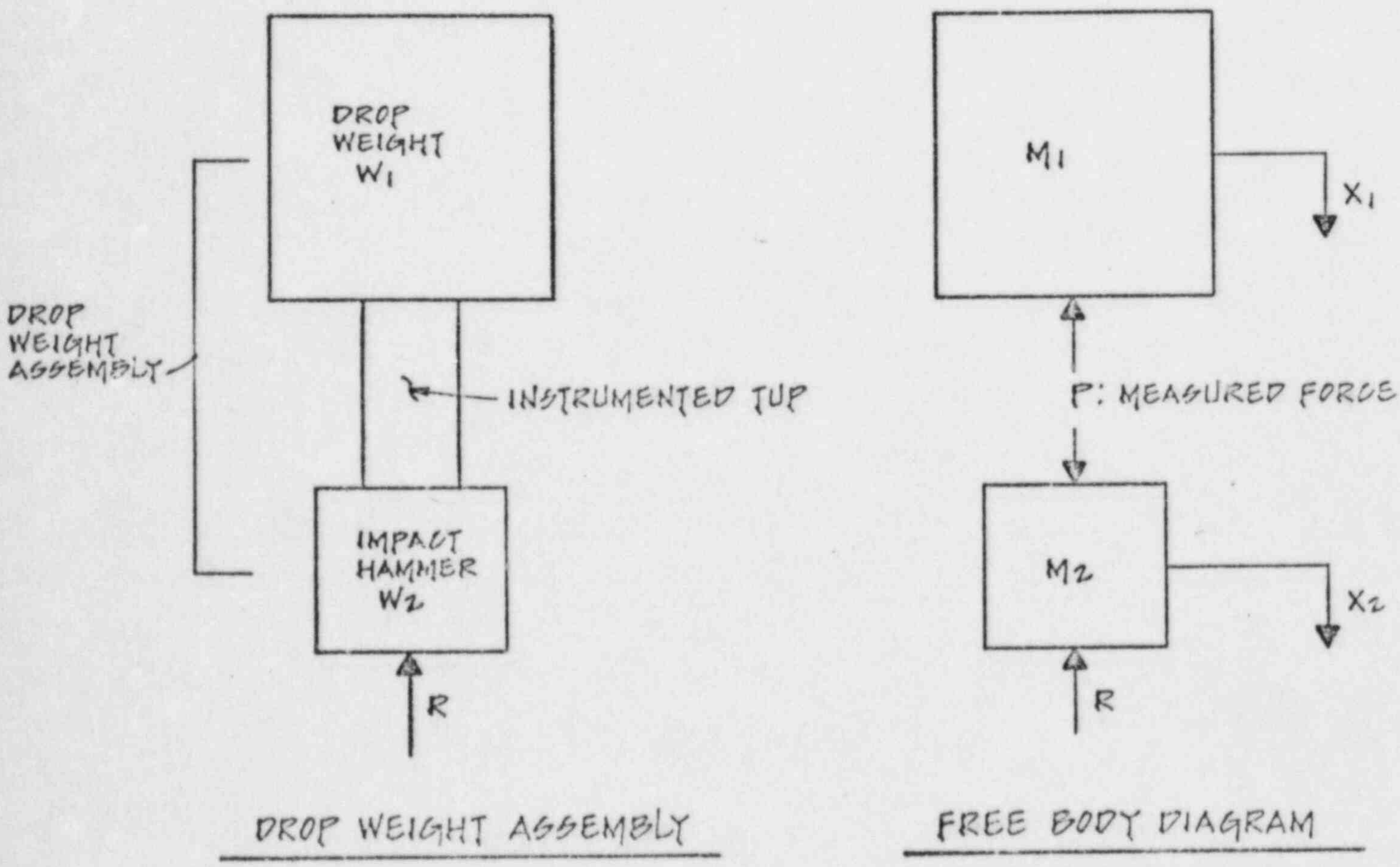


Figure 8 Analytical Model Representing the Drop-Weight Assembly

APPENDIX A

Energy-Displacement Plots

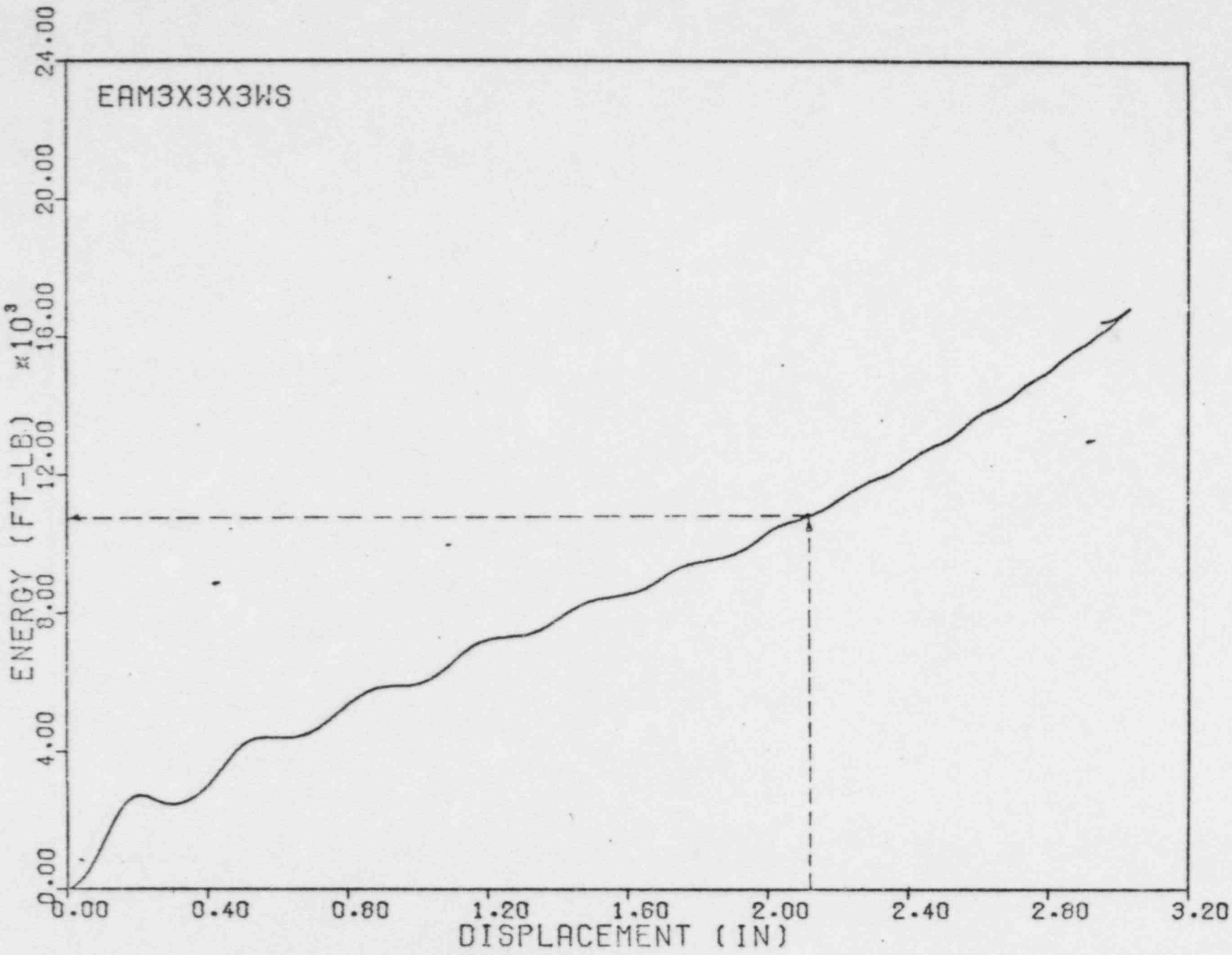


Figure A1 Energy-Displacement Plot for EAM 3 x 3 x 3 WS

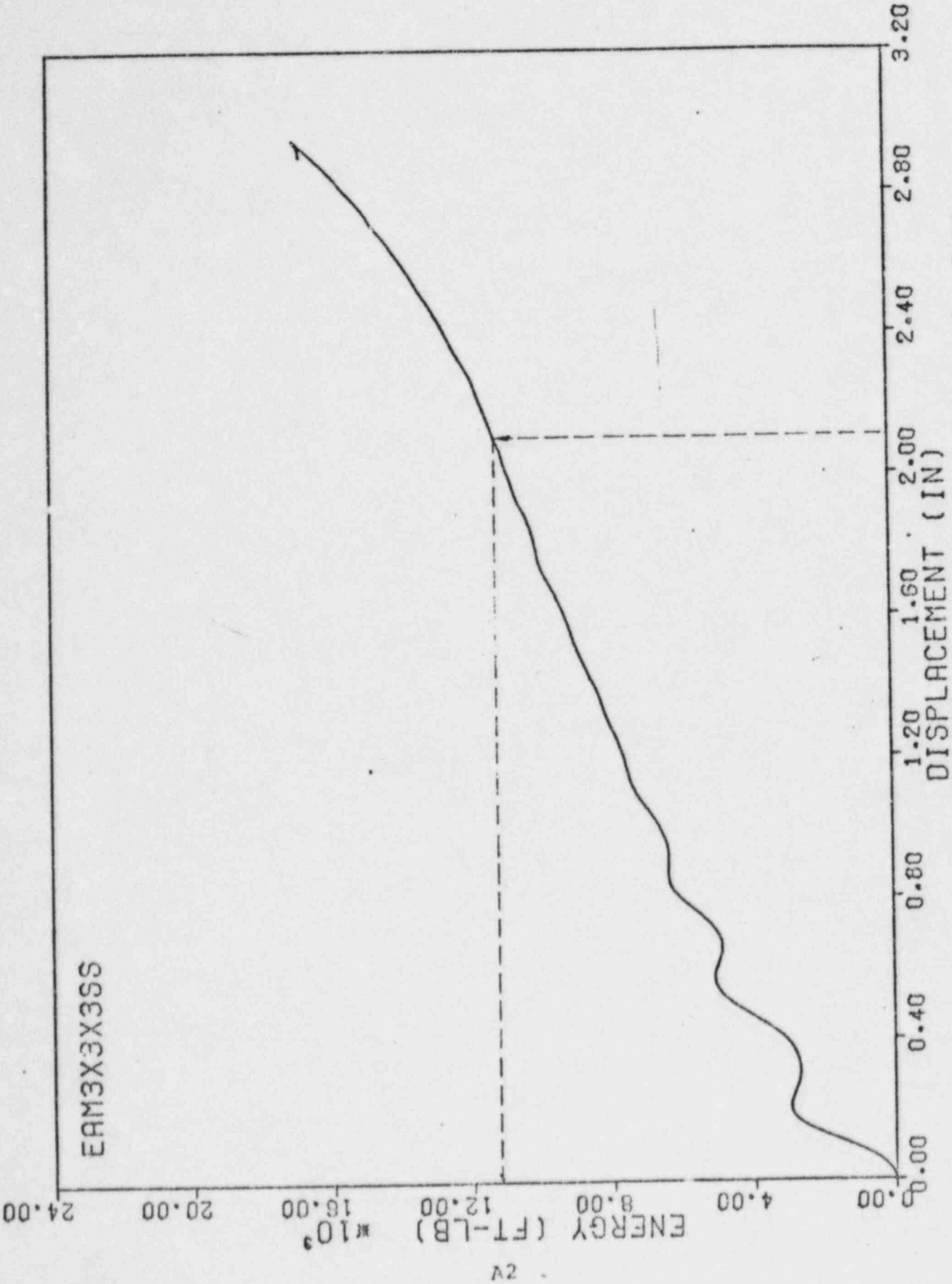


Figure A2 Energy-Displacement Plot for EAM 3 x 3 x 3 SS

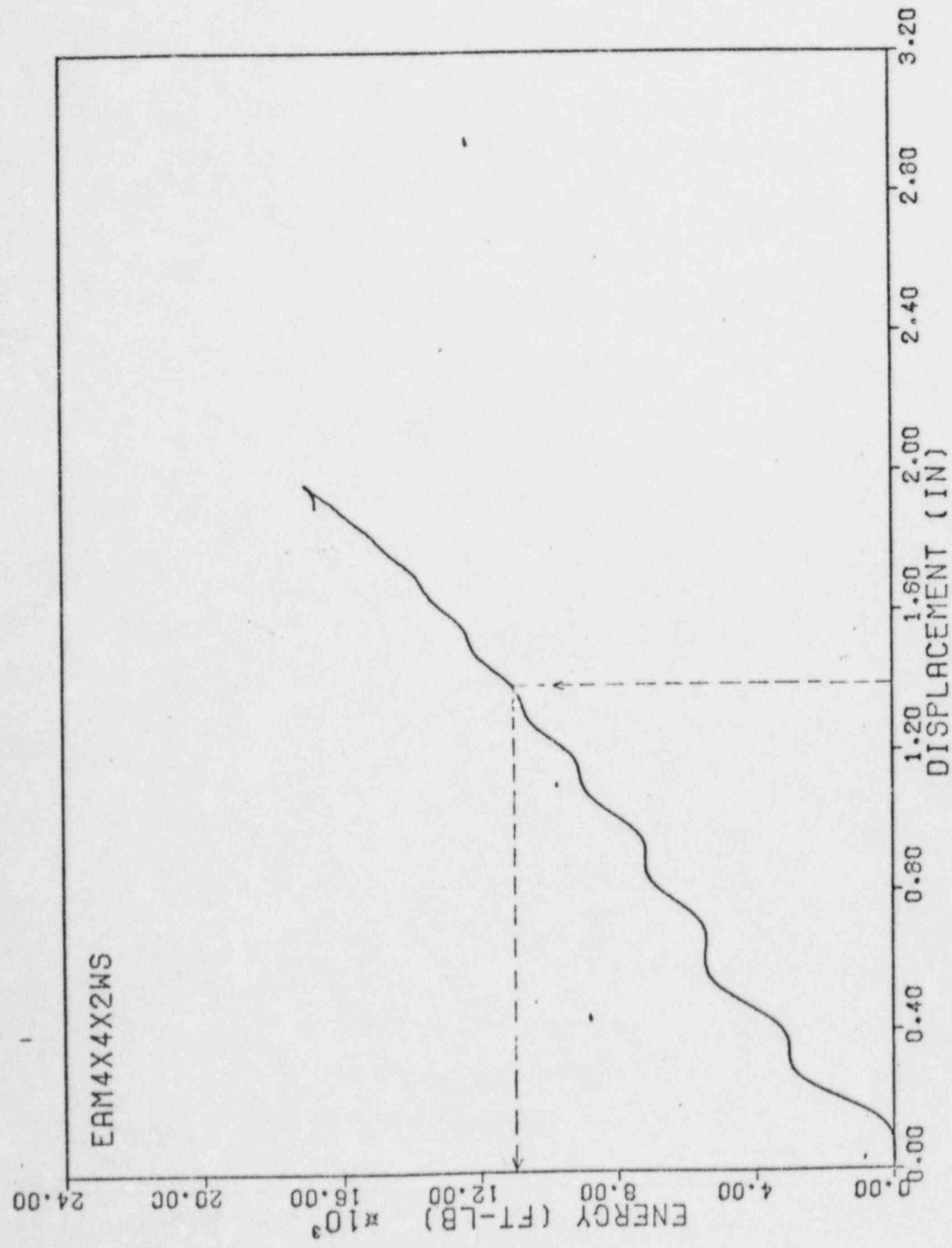


Figure A3 Energy-Displacement Plots for EAM 4 x 4 x 2 WS

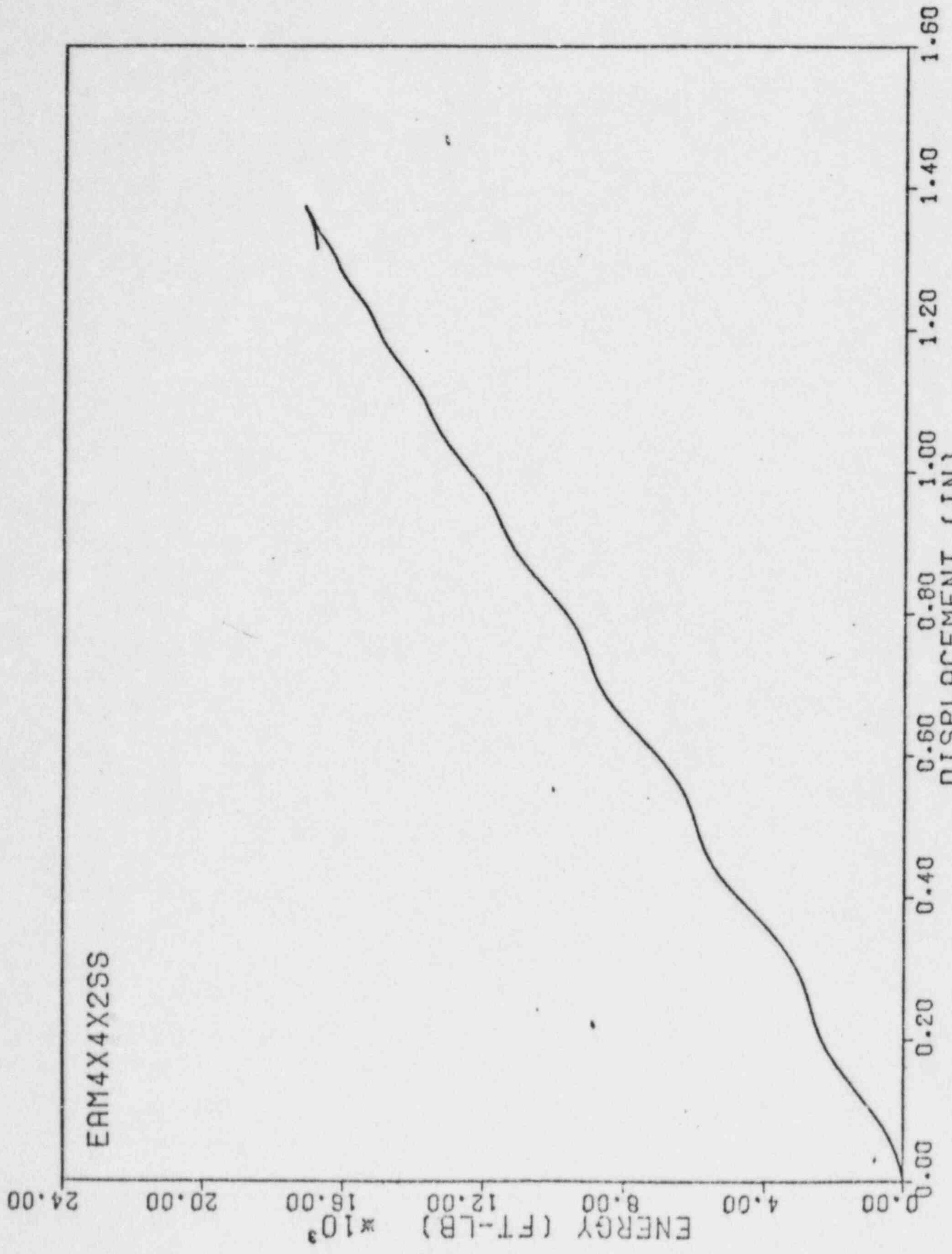


Figure A4 Energy-Displacement Plot for EAM 4 x 4 x 2 SS

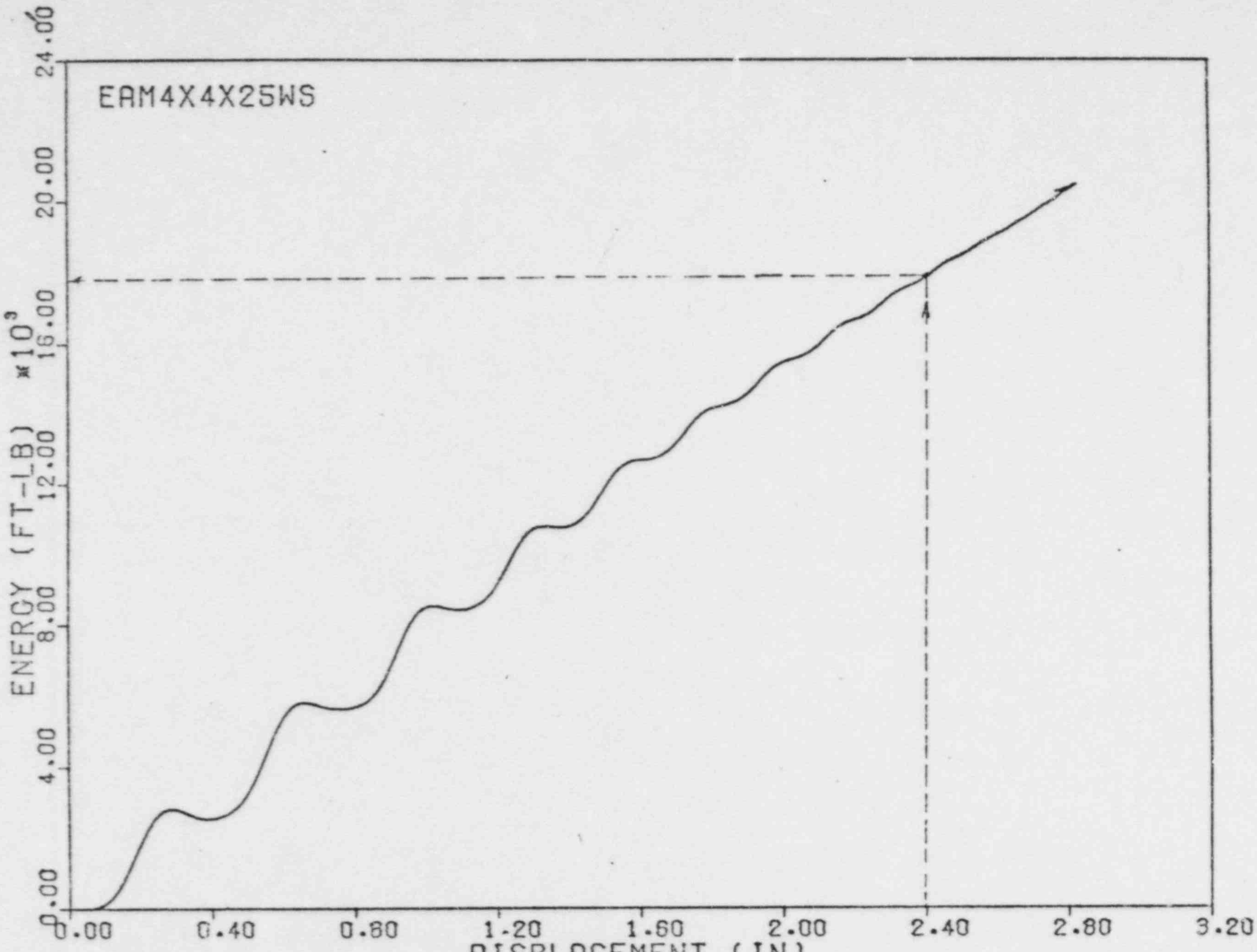


Figure A5 Energy-Displacement Plot for EAM 4 x 4 x 2 5/16 WS

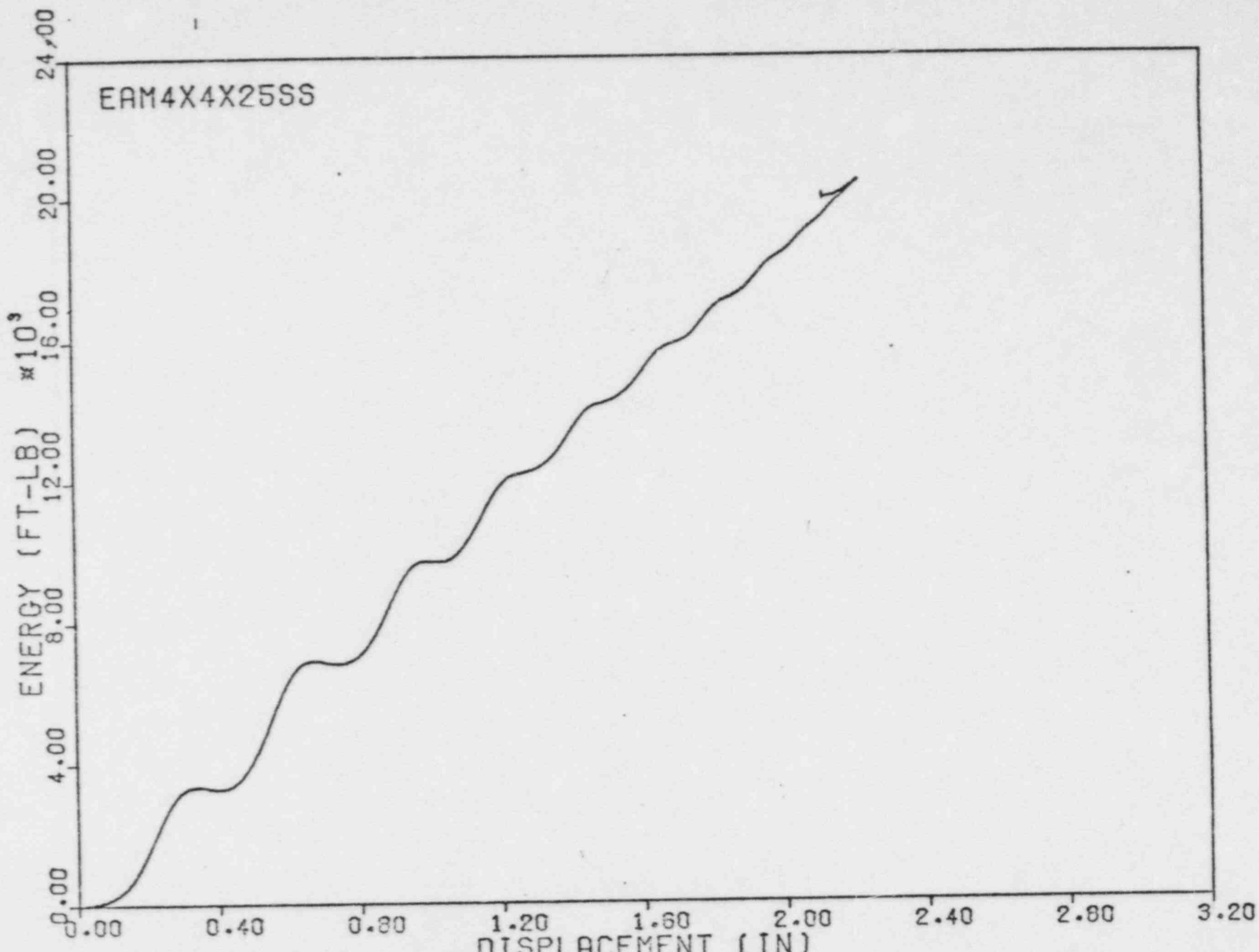


Figure A6 Energy-Displacement Plot For EAM 4 x 4 x 2 5/16 SS

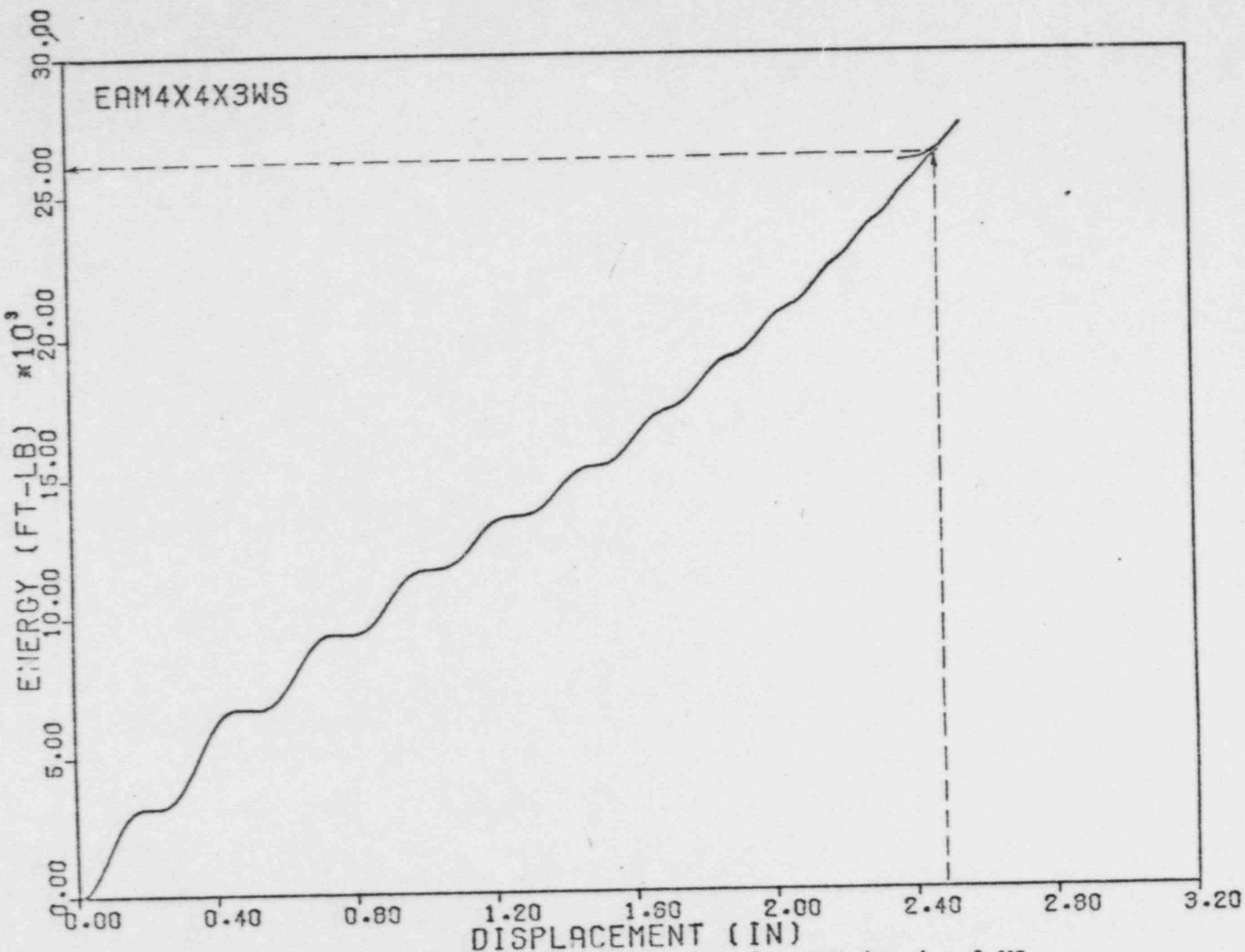


Figure A7 Energy-Displacement Plot for LM 4 x 4 x 3 WS

TEST DATA WAS NOT RECORDED

Figure A8 Energy-Displacement Plot for EAM 4 x 4 x 3 SS

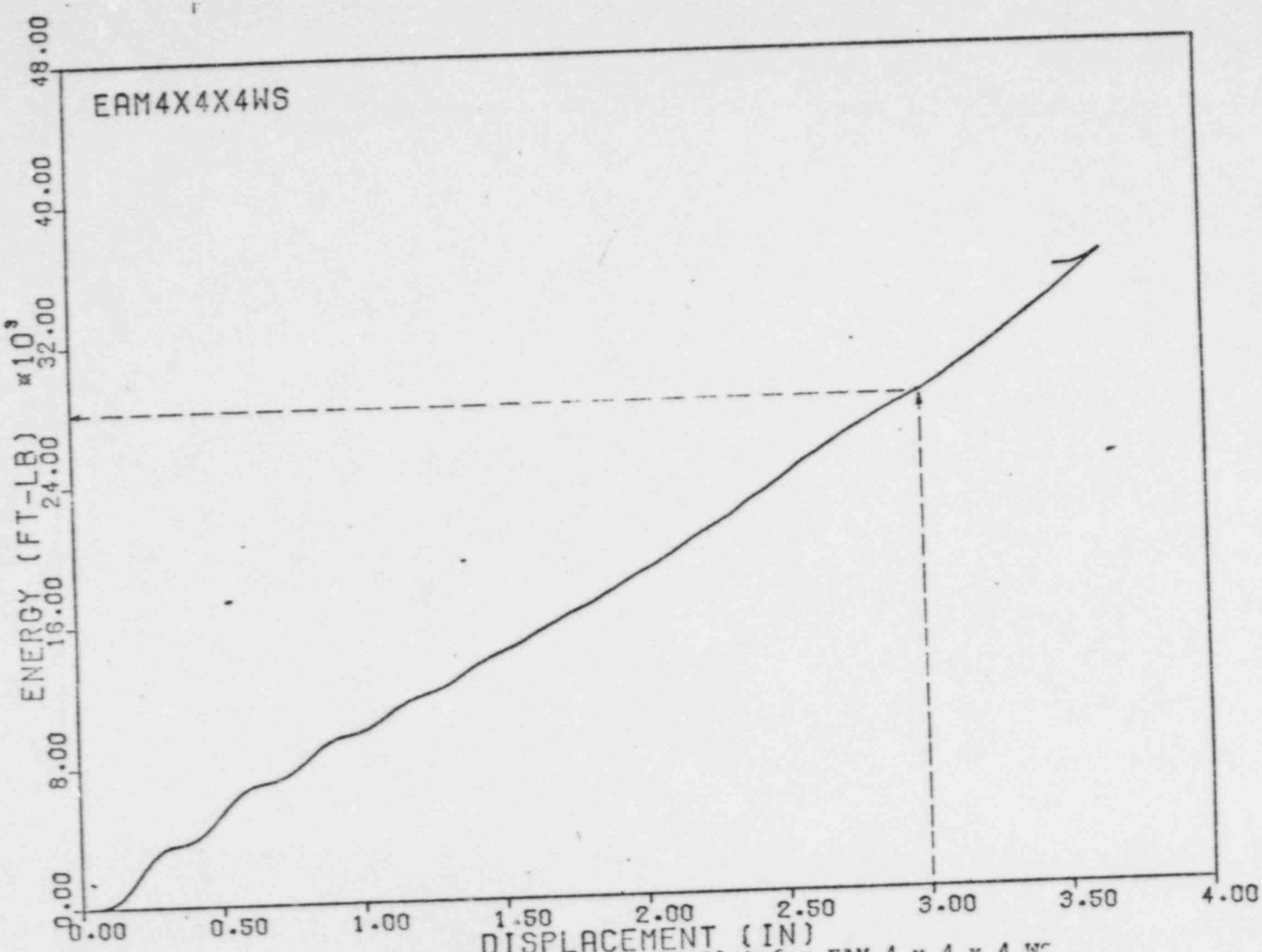


Figure A9 Energy-Displacement Plot for EAM 4 x 4 x 4 WS

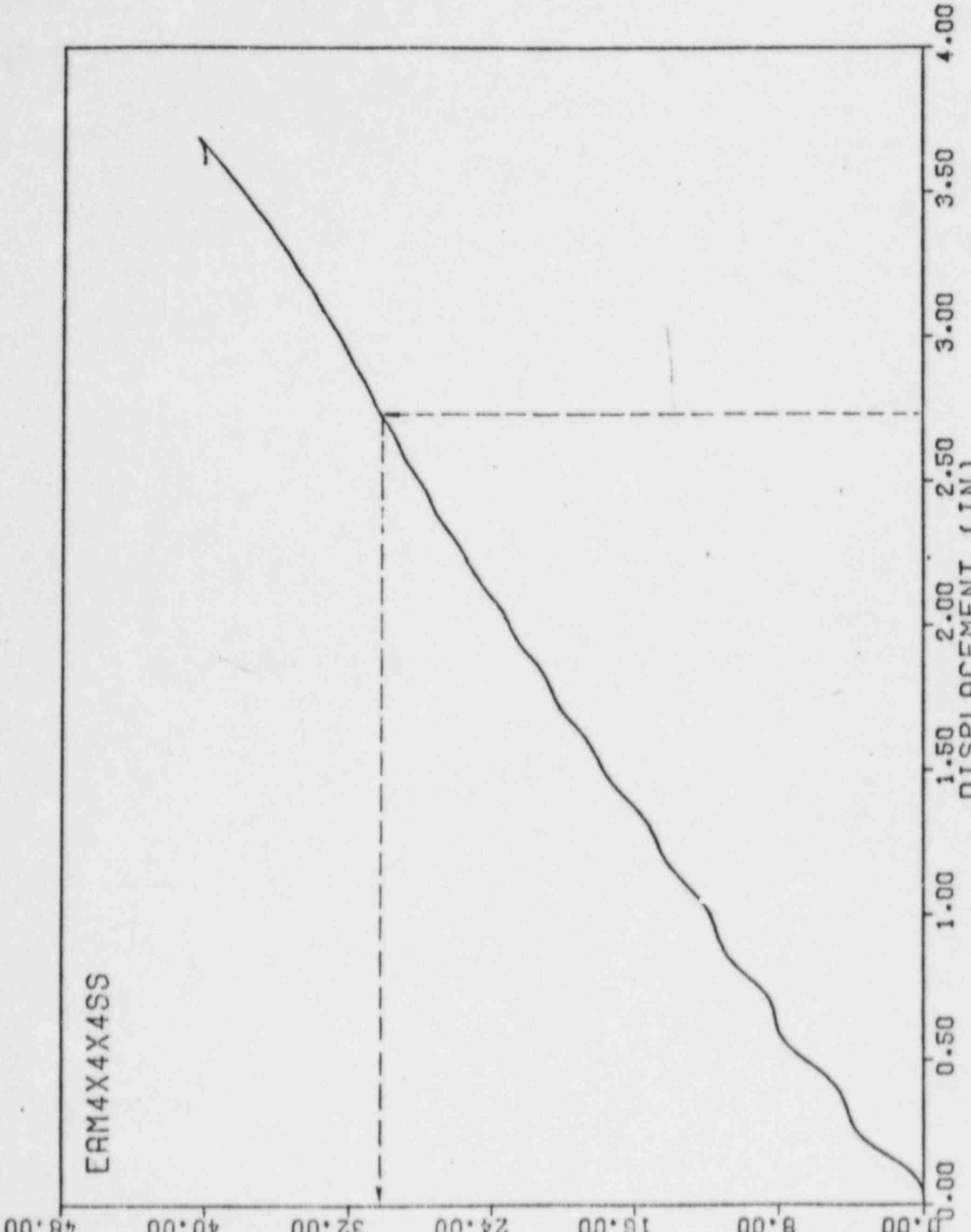


Figure A10 Energy-Displacement Plot for EAM 4 x 4 x 4 SS

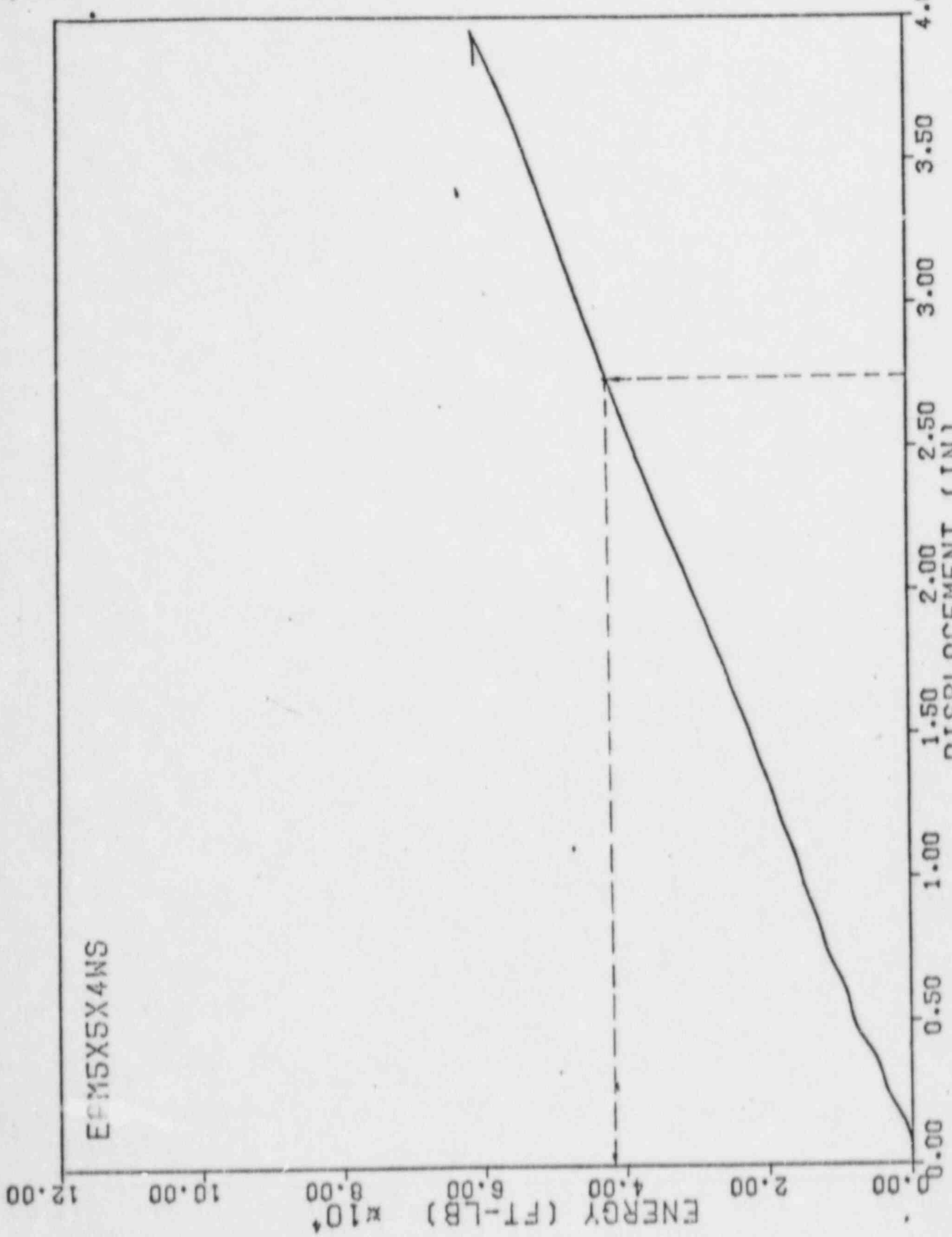


Figure A11 Energy-Displacement Plot for FAM 5 x 5 x 4 WS

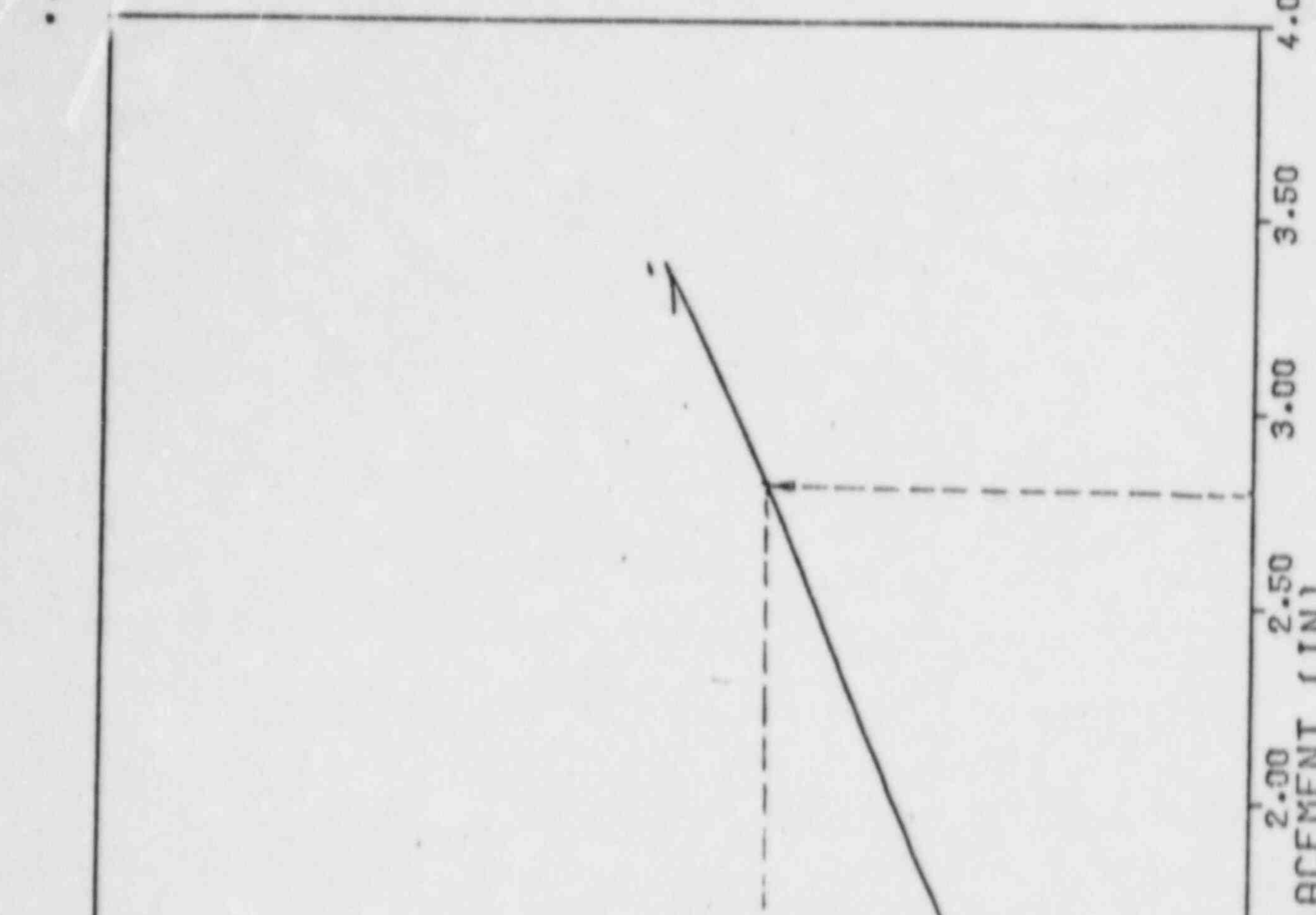


Figure A12 Energy-Displacement Plot for EAM 5 x 5 x 4 SS

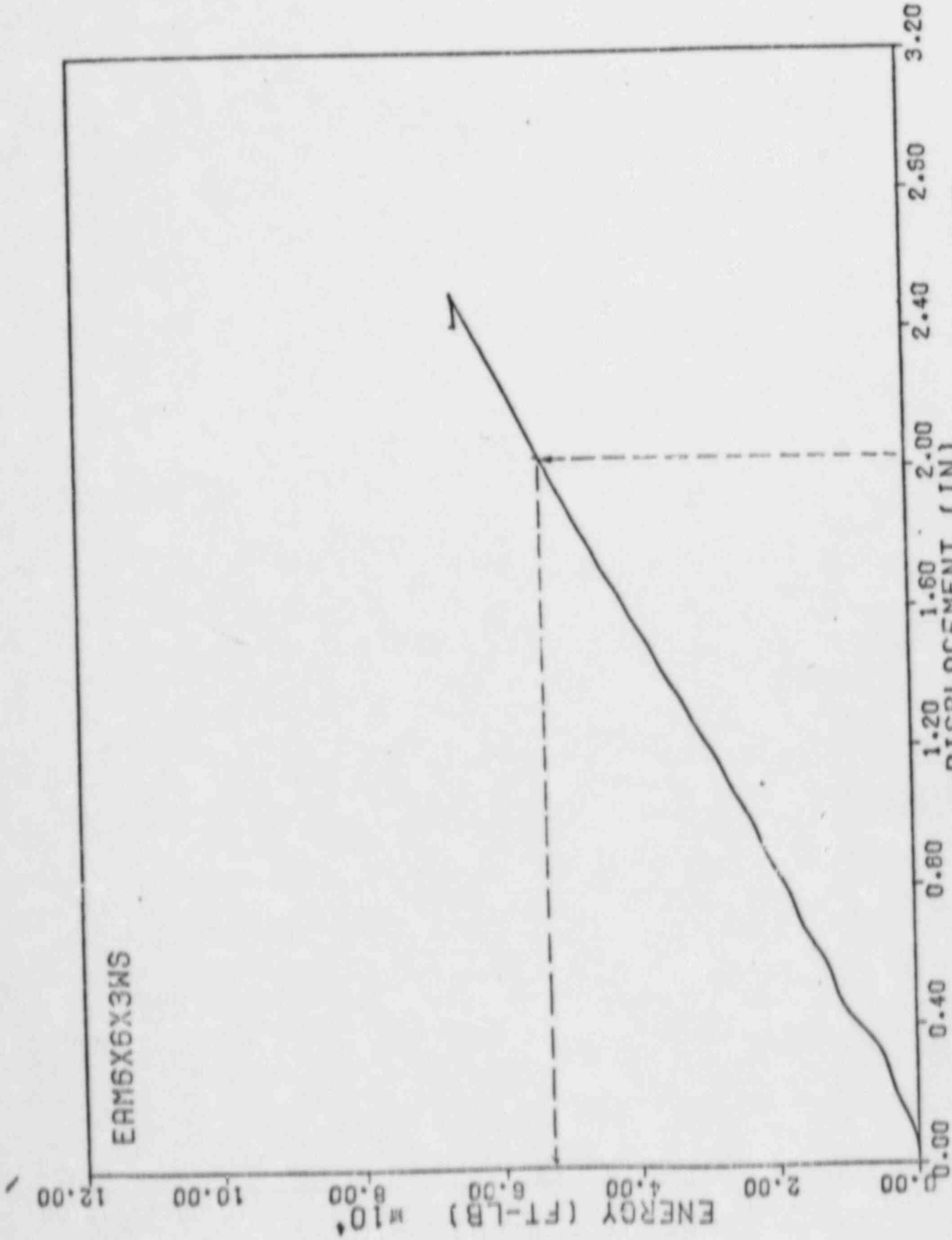


Figure A13 Energy-Displacement plot for EAM 6 x 6 x 3 WS

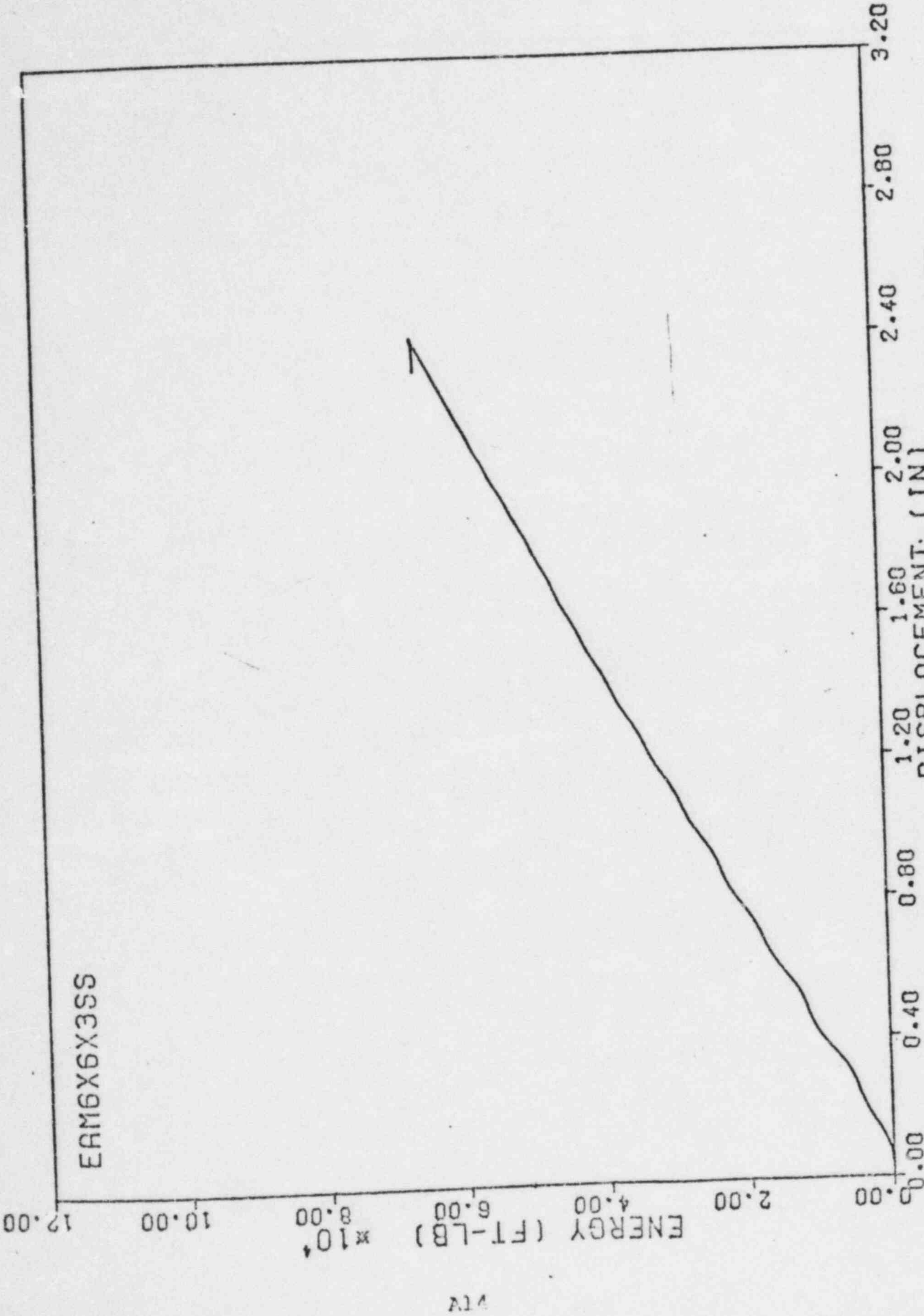


Figure A14 Energy-Displacement for EAM 6 x 6 x 3 SS

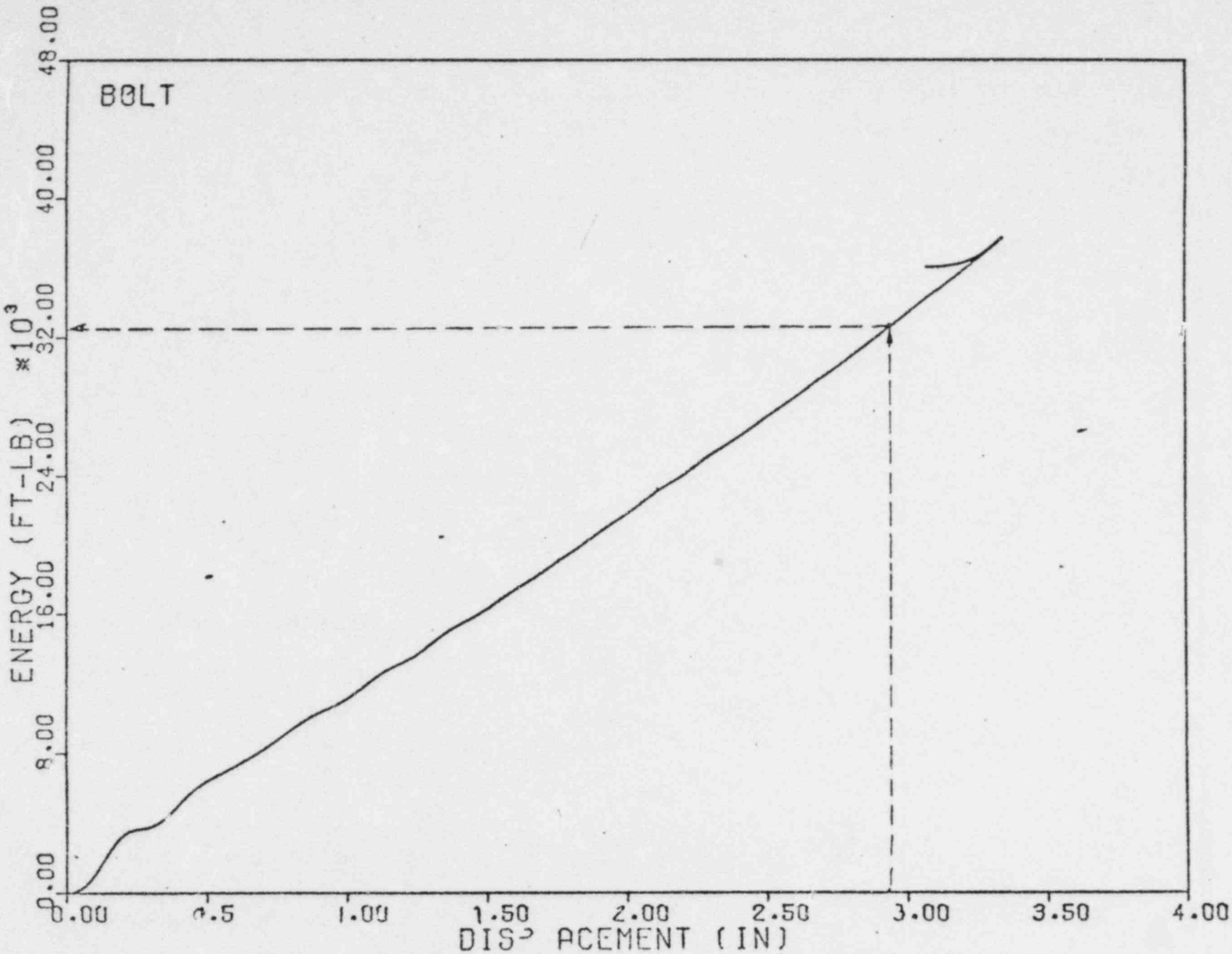


Figure A15 Energy-Displacement Plot for FAM 4 x 4 x 4 BT

End of Appendix A