FCP Report No. 12

MATERIAL CHARACTERIZATION OF USS-T1; MONOTONIC AND CYCLIC STRESS-STRAIN BEHAVIOR AND STRAIN-LIFE RESPONSE

by

D. F. Dittmer and M. R. Mitchell
Department of Theoretical and Applied Mechanics

ABSTRACT

Monotonic and cyclic stress-strain behavior and strain-life resistance of USS-T1 are reported. The material exhibits a minimum monotonic yield strength of 105 ksi but, due to strain softening, develops a cyclic yield strength of 78 ksi. Initial precycling of fatigue specimens has little effect on their life when compared to non-precycled results. However, periodic incremental overstraining of specimens which did not fail in approximately 10^7 reversals reduces life by a factor of about 10.

A Report of the
FRACTURE CONTROL PROGRAM

College of Engineering, University of Illinois
Urbana, Illinois
July, 1974

FOREWORD

This is the first in a series of reports on the evaluation of materials of interest to sponsors of the Fracture Control Program. Characterization of USS-T1* specimens supplied by Deere & Co. is contained in this report. Results are arranged in a way to enable the reader to use the reduced materials characterization sheets or, if deemed desirable, the original laboratory records. Also, at the back of the report are additional characterization sheets which may be removed for distribution to design personnel.

PROCEDURE

Specimens of the design shown in Fig. 1 were removed from 5/8" thick plate parallel to the rolling direction. They were machined to a surface finish of approximately 10 rms. All testing was performed at a ± 20 kip closed-loop, electrohydraulic materials test system at Talbot Laboratory of the University of Illinois. The ASTM E-9.08 tentative specification for low cycle fatigue testing served as a guide for these tests.

RESULTS

Stress-Strain Behavior

The data sheet for material characterization lists the results of both monotonic and cyclic stress-strain tests. Note the 0.2% yield strength is 105 ksi, which is fairly high, but the material has a low strain hardening exponent (n = 0.088). If a part made of this material were monotonically loaded beyond the yield strength by only a few percent increase in load, a significant amount of plastic deformation would result. In a cyclic loading environment the material softens and has a 0.2% yield strength of 78 ksi. From the plot of the monotonic and cyclic stress-strain curves

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* United States Steel's trade name for a high strength, low alloy, tempered martensitic steel

note that the cyclic "flow" strength is about one-half the monotonic (i.e. 50 ksi as compared with about 90 ksi). Thus, cyclically loading a component designed on the basis of being "fully elastic" at 90 ksi would cause failure by fatigue since the cyclic softening would result in significant plastic strains (i.e. $\epsilon_p \simeq 0.001$) being developed.

Strain-Life Resistance

In preliminary tests, the strain controlled fatigue specimens were initially precycled at a strain of ±0.01 for 4 reversals followed by 40 reversals of incremental decrements of straining to zero stress and strain. This precycling procedure is not included in ASTM E-9.08. As indicated in the tabulated results, there was no pronounced difference in lives between comparable precycled and non-precycled specimens (Group I vs Group II). However, specimens DT1-13 and 17, which received a periodic overstraining, failed at least an order of magnitude in life before the comparable constant amplitude specimens. The results of these periodic overstrain tests are not included in the "best-fit" curve shown on the characterization sheet but appear on the original strain-life curve in the middle of this report.

CONCLUSIONS

From monotonic and cyclic stress-strain results it is concluded that the USS-T1 is not unlike other steels of comparable hardness. The strain-life fatigue resistance is also comparable. However, particular attention is called to the decrease in life from periodic overstraining since a periodic overstrain is common in most ground vehicular components.

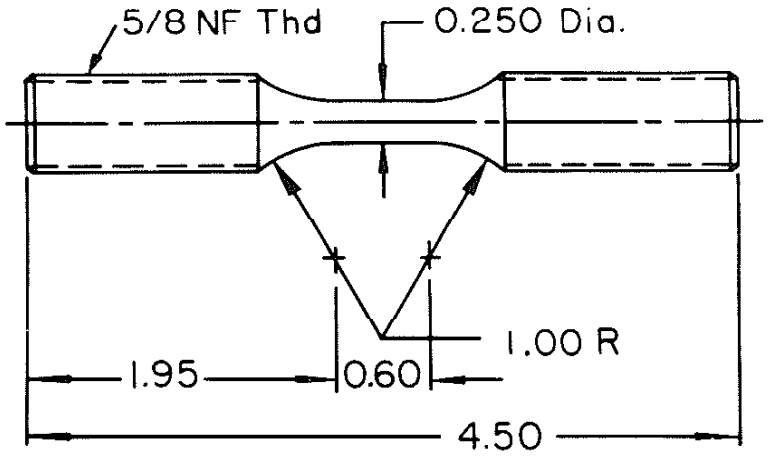


FIGURE 1 - SPECIMEN DESIGN

MATERIAL CHARACTERIZATION SHEETS

DATA SHEET FOR MATERIAL CHARACTERIZATION

Material: U.S.S. T-1 (Deere and Company)

Condition: as rec'd

Matrix Hardness: 256 BHN

Converted from: ----

Monotonic Properties:

Modulus of Elasticity, E	30.2	x 10^3 ksi
Yield Strength, 0.2% S_y	105	ksi
Ultimate Strength, S_u	117	ksi
Red. in Area, % RA	66	
True Fracture Strength, σ_f	176	ksi
True Fracture Ductility, ϵ_f	1.08	
Strain Hardening Exponent, n	0.088	
Strength Coefficient, K	160	ksi
True Toughness, U_p	160,000	in-lb/in^3
Poisson's Ratio	-----	

Cyclic Properties:

Yield Strength, 0.2% S_y'	78	ksi
Strain Hardening Exponent, n'	0.136	
Strength Coefficient, K'	182	ksi
Fatigue Strength Coefficient, σ_f'	174	ksi
Fatigue Ductility Coefficient, ϵ_f'	1.02	
Fatigue Strength Exponent, b	-0.076	
Fatigue Ductility Exponent, c	-0.688	
Transition Fatigue Life, $2N_t$	5000	rev

Microstructure: Tempered Martensite

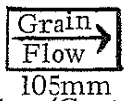
Magnification:

Comments:

1) Average compressive 0.002 offset = 110 ksi
2) Specimens removed from 5/8" plate parallel to rolling direction
3) Boron is not present in composition
4) Initial precycling had little effect on fatigue life as compared with non-precycled results
5) Periodic overstraining of a specimen run at a constant strain amplitude (0.0017) results in failure at 1.8 x 10^6 rev's. whereas runout occurs at a constant amplitude

Composition:

w/o C	=	0.228	w/o Mo	=	0.27
w/o Si	=	0.20	w/o Cu	=	----
w/o P	=	0.039	w/o Ni	=	0.98
w/o S	=	0.023	w/o Va	=	0.06
w/o Mn	=	0.73	w/o Al	=	----
w/o Cr	=	0.48	w/o B	=	*see comments

Grain Size: 

90 mm

Eutectic Cell Size (Cast irons):

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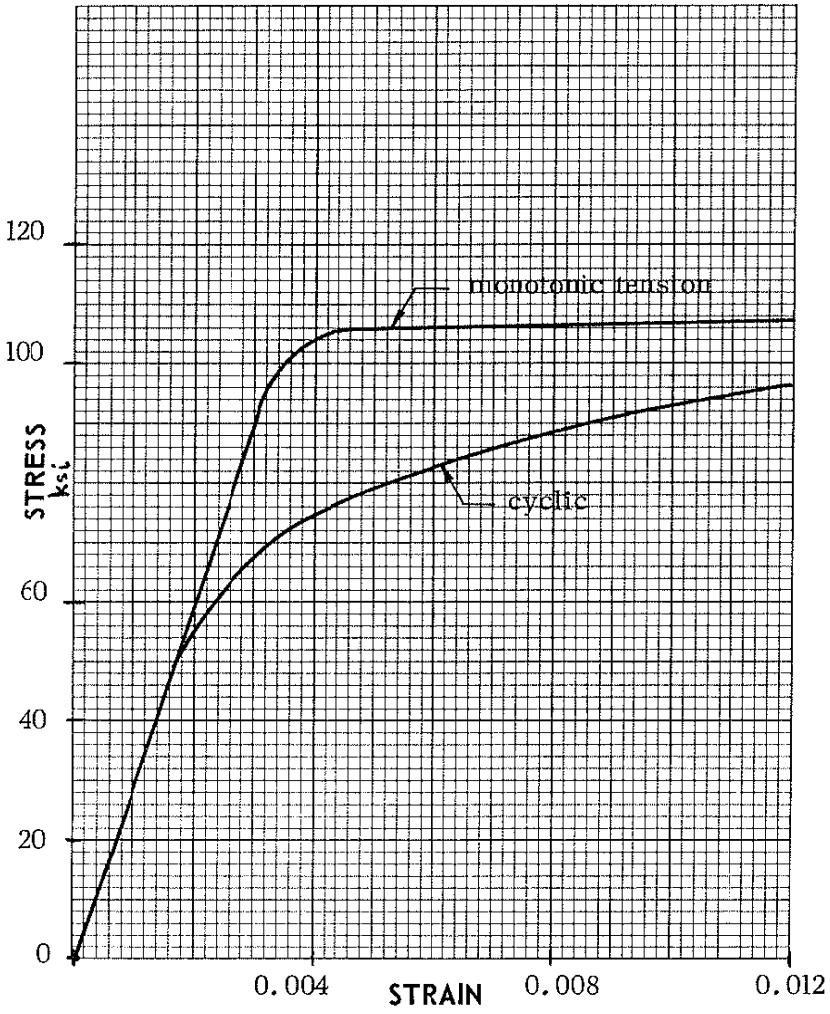
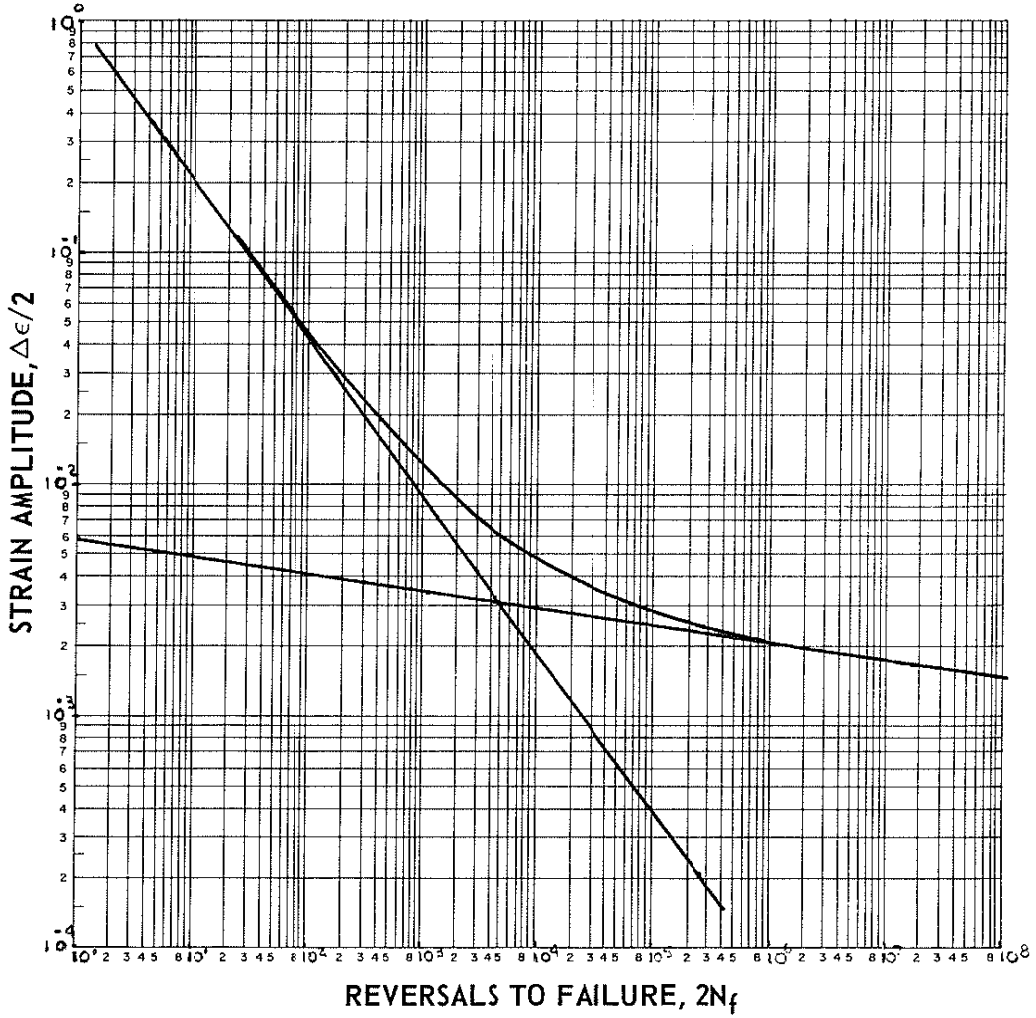
DFD 6/24/74

Material: U.S.S. T-1 (Deere and Company) **Hardness:** 256 BHN

Condition: as rec'd





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MONOTONIC STRESS-STRAIN RESULTS

D-T1-CL

Monotonic Tension

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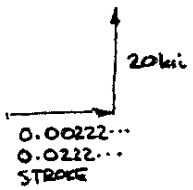
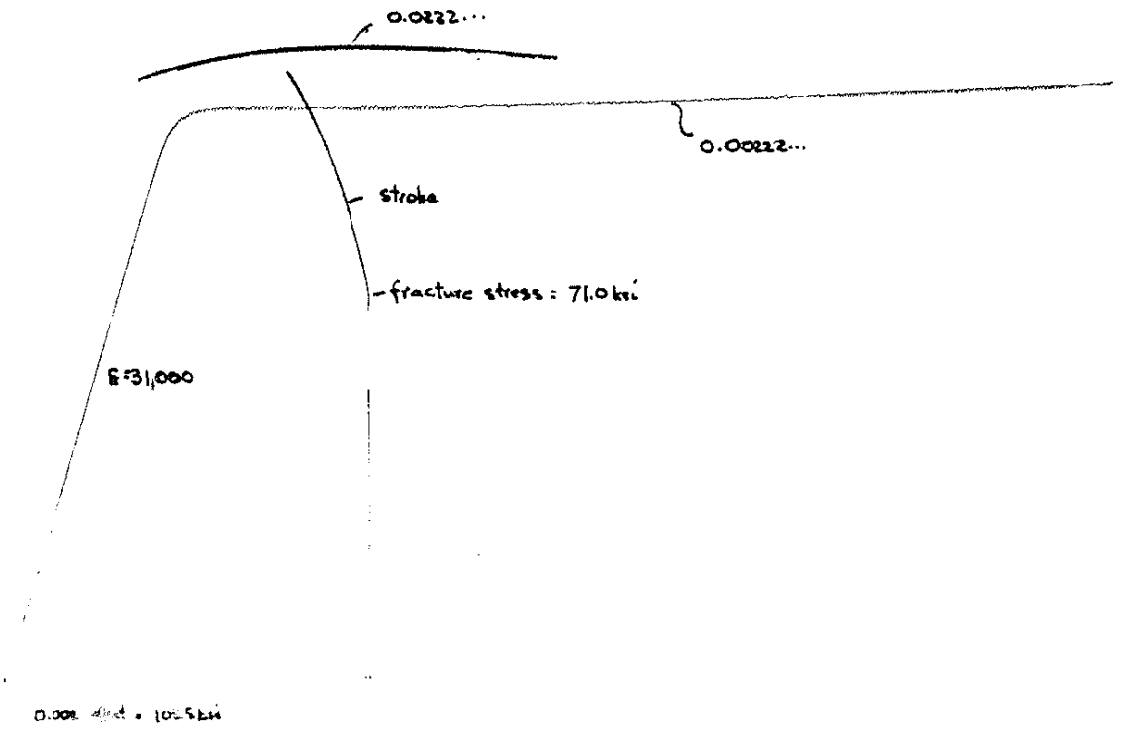




0.008 dia. = 102.5 ksi

```
**********************************************************************
********************** D-T1-01 MONOTONI **********************
**********************************************************************
```

REF	TRUE STRESS	TRUE STRAIN	PL. TRUE STRAIN
1	20.0135	0.000677	0.000014
2	40.0529	0.001321	-0.000006
3	60.1186	0.001975	-0.000017
4	80.2088	0.002607	-0.000051
5	100.3288	0.003283	-0.000041
6	105.3966	0.003770	0.000279
7	106.1579	0.004323	0.000806
8	106.4935	0.006533	0.003005
9	106.6278	0.008739	0.005207
10	107.2671	0.010940	0.007386
11	107.8068	0.013135	0.009563
12	108.7540	0.015326	0.011723
13	109.6026	0.017512	0.013880
14	110.4539	0.019693	0.016033
15	111.5123	0.021870	0.018176
16	113.1583	0.027399	0.023650
17	116.3314	0.031714	0.027859
18	118.0990	0.037081	0.033168
19	119.8790	0.042420	0.038449
20	121.2515	0.047731	0.043714
21	122.6319	0.053014	0.048951
22	123.4899	0.058268	0.054177
23	124.2437	0.063495	0.059379
24	125.1057	0.068696	0.064551

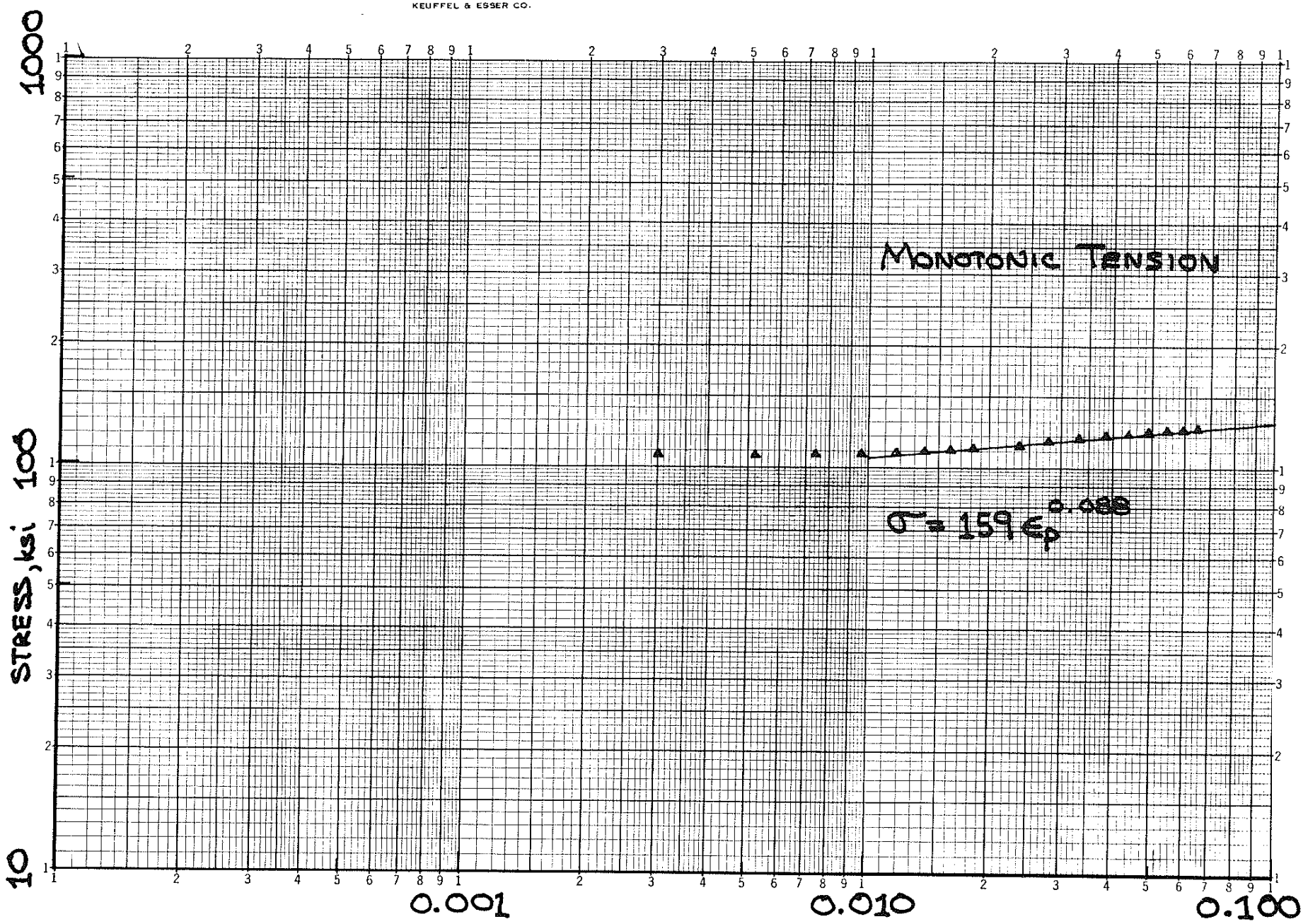
```
********************** LEAST SQUARE FITS ************************

LEAST SQUARE FIT 1
******************

IS NORMAL FIT TO BE MADE?
?Y
INPUT REF #'S FOR FIT
?8,24
EXCLUSIONS
?N

************************
* N( 1)=+6.2050890E-02 *
* K( 1)=+1.4596470E+02 *
************************

PLOT?
?
```

```
LEAST SQUARE FIT ?
******************

IS NORMAL FIT TO BE MADE?
?Y
INPUT REF #'S FOR FIT
?12,24
EXCLUSIONS
?N


************************
* N( 2)=+8.7992250E-02 *
* K( 2)=+1.5936600E+02 *
************************

PLOT?
?
 Y

SAME AXES
?Y
MIN. STRAIN LST SQ
?.01
MAX. STRAIN LST SQ
?.1
PLOT-
***AXES
?N
***CURVE DRAWN
?Y
***DATA POINTS
?N
PLTL
REPEAT LEAST SQUARE FIT?
?N


INPUT INIT & FINAL AREA
?.0484,.0165
INPUT DIV & SCALE OF STRESS -LAST POINT
?71,1
YIELD PTS. FROM LST SQ FITS
?N
```

0.002 offset = 105.5 ksi

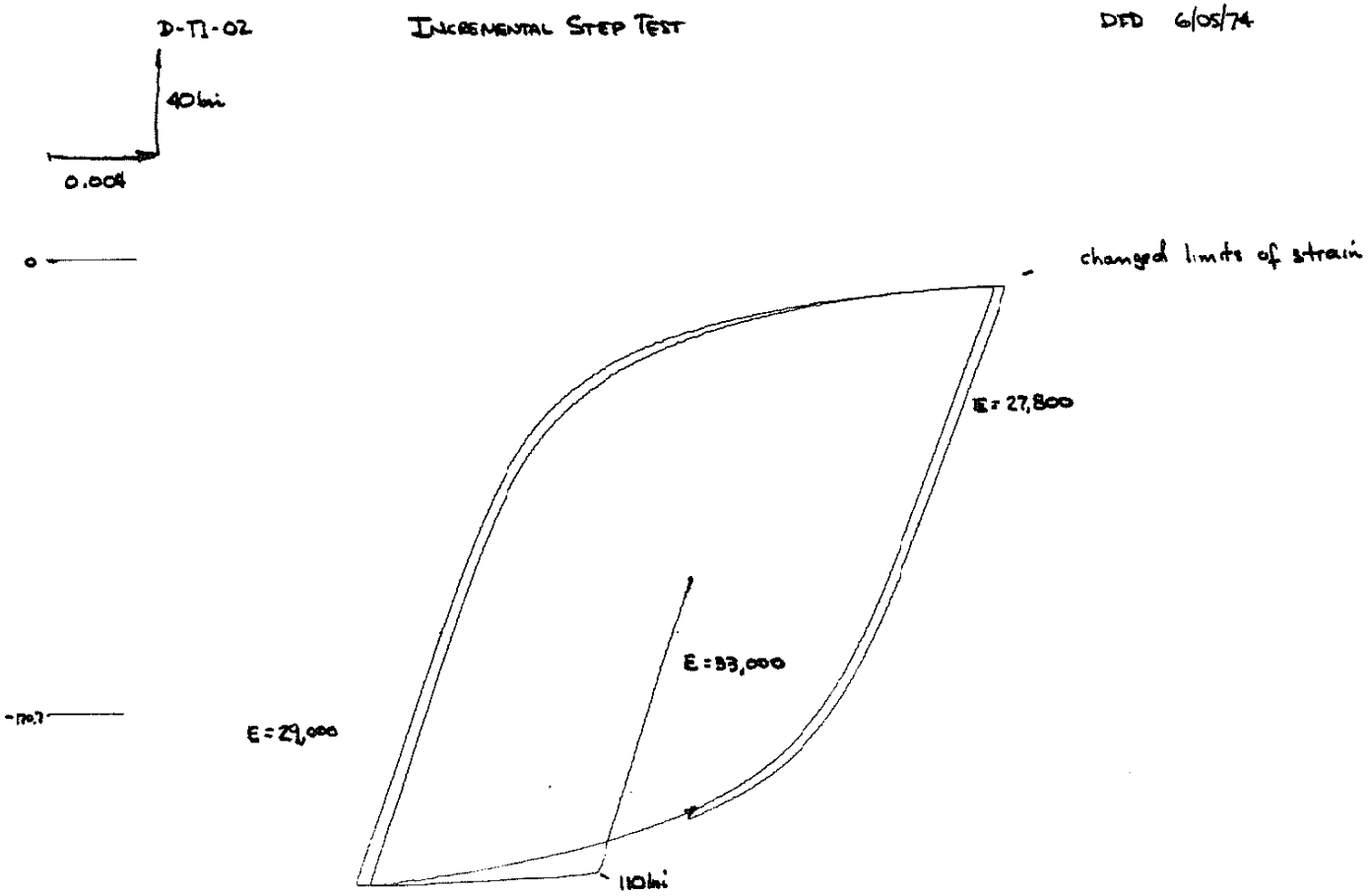
* ELASTIC MODULUS	=	3.02E+04	KSI *
* ULTIMATE STRENGTH	=	116.80	KSI *
* TRUE FRACTURE DUCTILITY	=	1.08	IN/IN*
* TRUE FRACTURE STRENGTH (UNCORRECTED)	=	208.27	KSI *
* TRUE FRACTURE STRENGTH (CORRECTED)	=	175.99	KSI *
* PER CENT REDUCTION IN AREA	=	65.91	% *

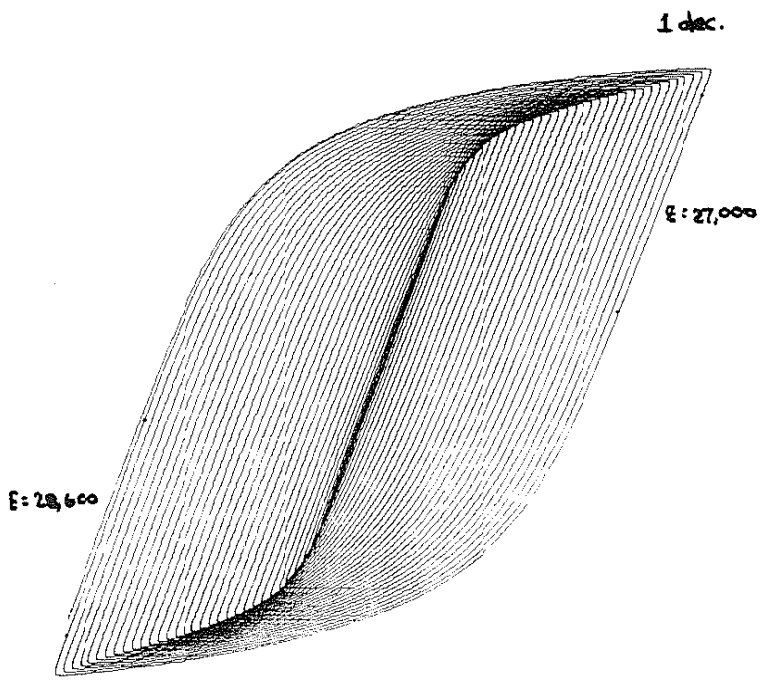
2.79 SEC 0.12 SERVICE UNITS

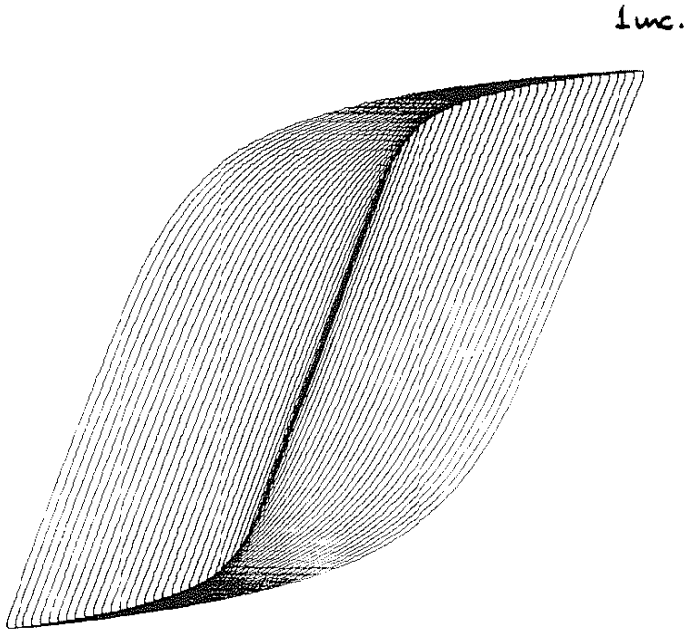

K&E LOGARITHMIC 46 7323
2 X 3 CYCLES MADE IN U.S.A.
KEUFFEL & ESSER CO.
1000
100
10
STRESS, ksi
0.001
0.010
0.100
MONOTONIC TENSION
σ = 159 εp^0.088

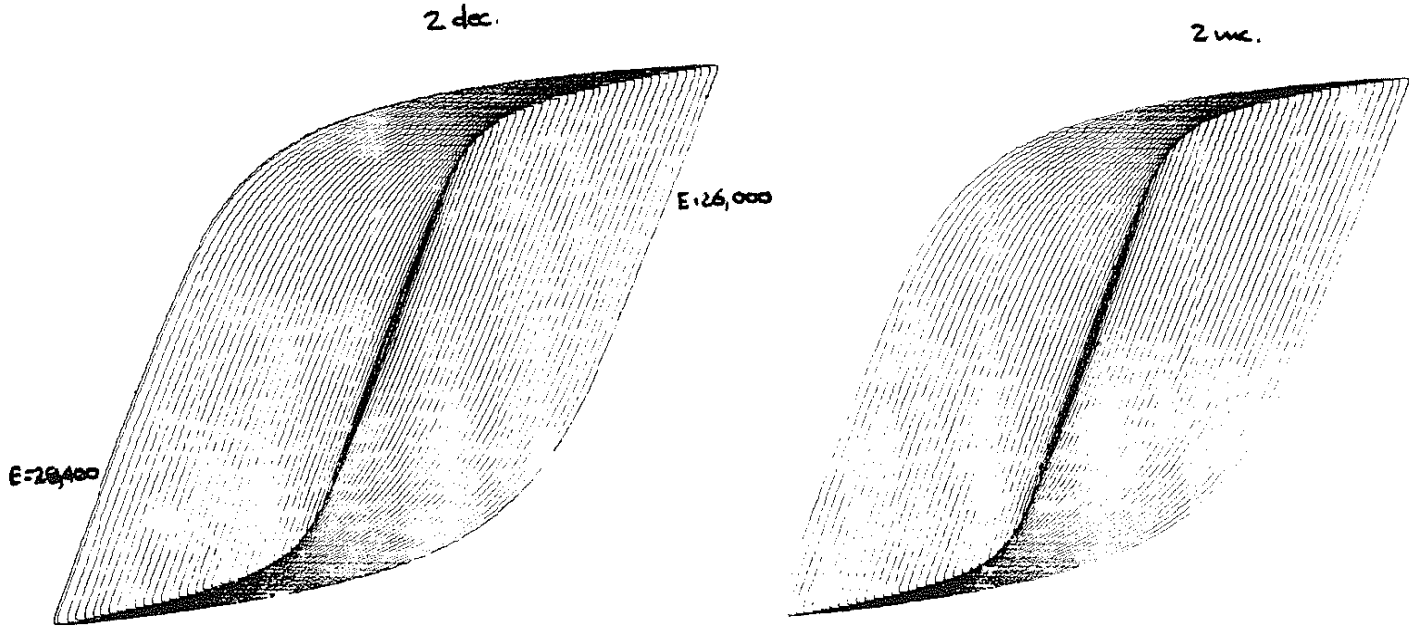
CYCLIC STRESS-STRAIN RESULTS

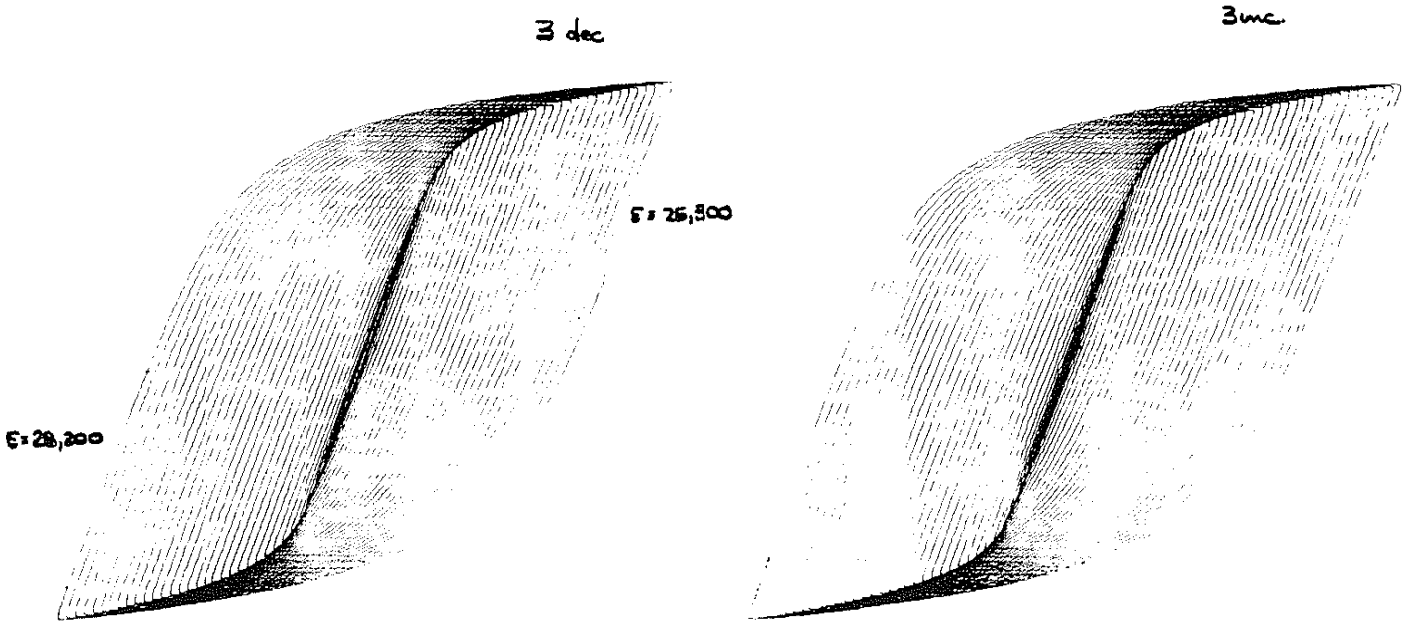
D-T1-02 INCREMENTAL STEP TEST DED 6/05/74 1 OF 7



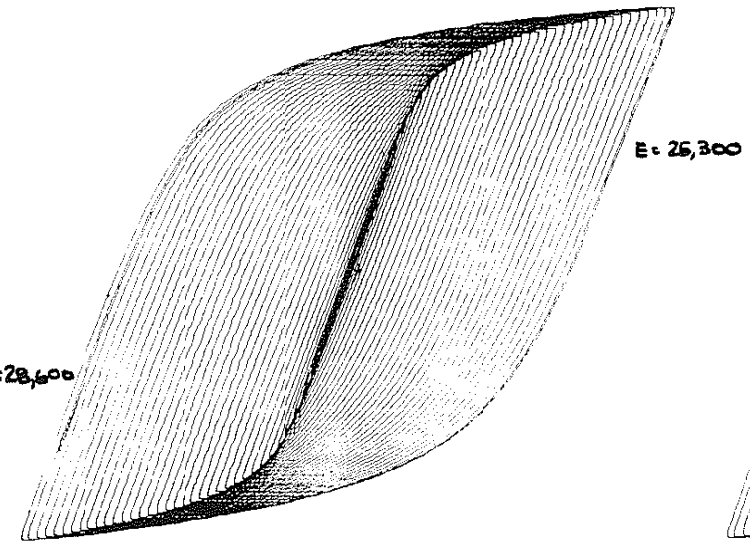

1 dec.
E: 27,000
E: 28,600


1 inc.

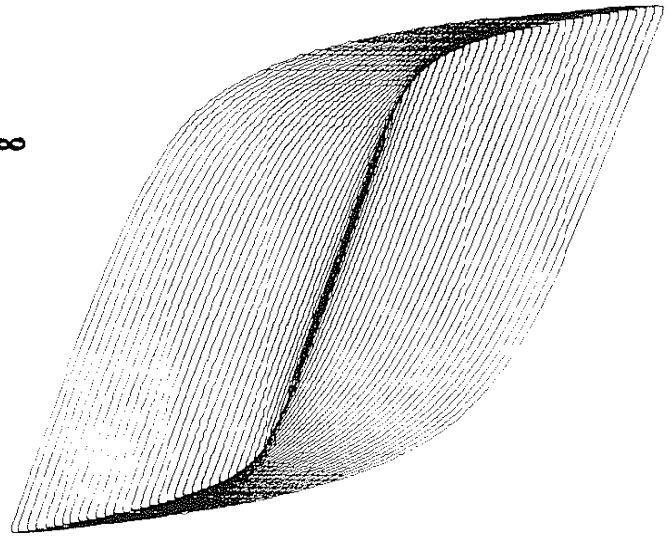

2 dec.
E=26,000
E=29,400
2 inc.

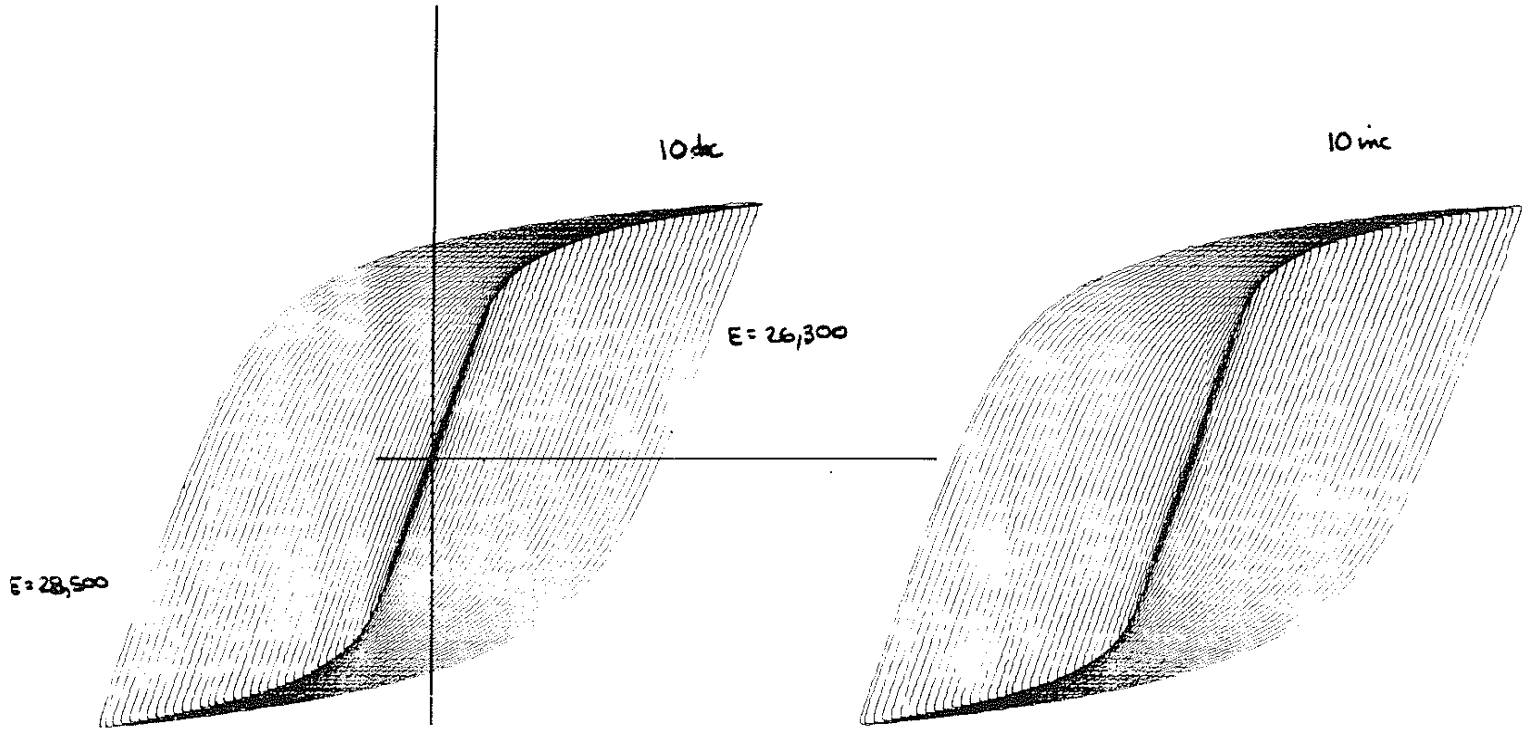

3 dec
E = 26,500
E = 28,200
3mc

5 dec.



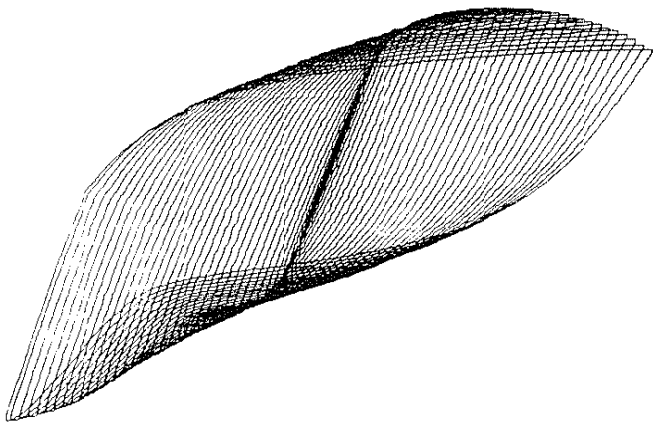
5 inc.




10 dec
E = 26,300
E = 28,500
10 inc

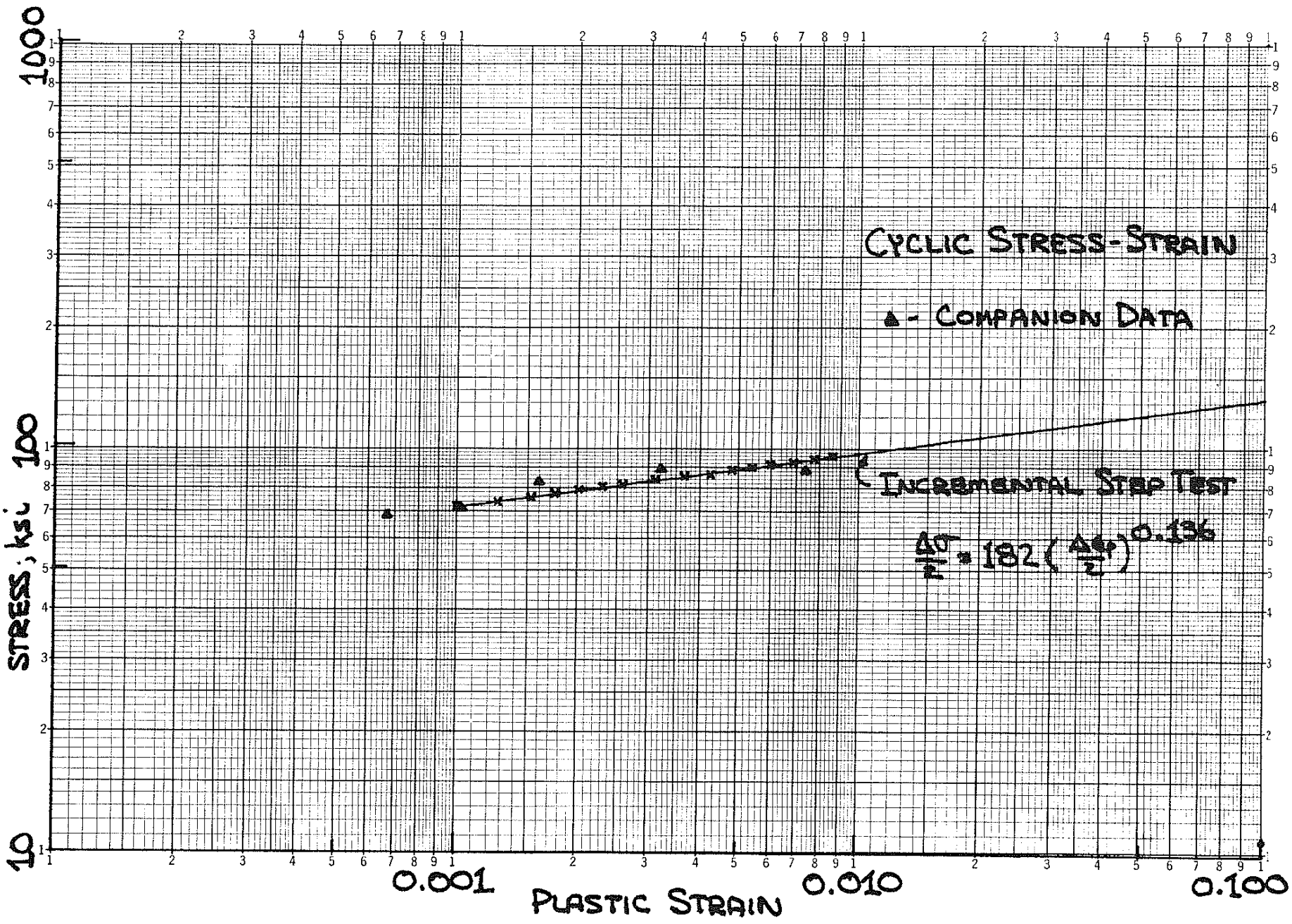
D-T1-02

14 inc



$B_f = B_T$

```
**********************************************************************
 ********************* D-T1-02 STEP 10- **********************
**********************************************************************


**********************************************************************
*  REF        AV EP          AV SG      AV PEP(E0)                   *
*   1       0.002110        57.5993      0.000190                    *
*   2       0.002480        62.3010      0.000403                    *
*   3       0.002760        66.3089      0.000547                    *
*   4       0.003100        69.2966      0.000790                    *
*   5       0.003390        71.5965      0.001003                    *
*   6       0.003720        73.5963      0.001266                    *
*   7       0.004040        75.2955      0.001530                    *
*   8       0.004320        77.0952      0.001750                    *
*   9       0.004640        78.7928      0.002013                    *
*  10       0.004970        80.0911      0.002300                    *
*  11       0.005290        81.1917      0.002583                    *
*  12       0.005900        83.5889      0.003114                    *
*  13       0.006510        85.2889      0.003667                    *
*  14       0.007140        86.0947      0.004270                    *
*  15       0.007771        88.3798      0.004825                    *
*  16       0.008391        89.7786      0.005398                    *
*  17       0.009021        91.1783      0.005981                    *
*  18       0.009960        92.5745      0.006875                    *
*  19       0.010881        94.2696      0.007739                    *
*  20       0.011811        95.9677      0.008613                    *
**********************************************************************


************************ LEAST SQUARE FITS **********************


LEAST SQUARE FIT 1
******************


IS NORMAL FIT TO BE MADE?
?Y
INPUT REF #'S FOR FIT
?5,20
EXCLUSIONS
?N


***********************
* N(1)=+1.3554700E-01 *
* K(1)=+1.8214750E+02 *
***********************


DO YOU WANT A PLOT MADE OF THIS?
?
```

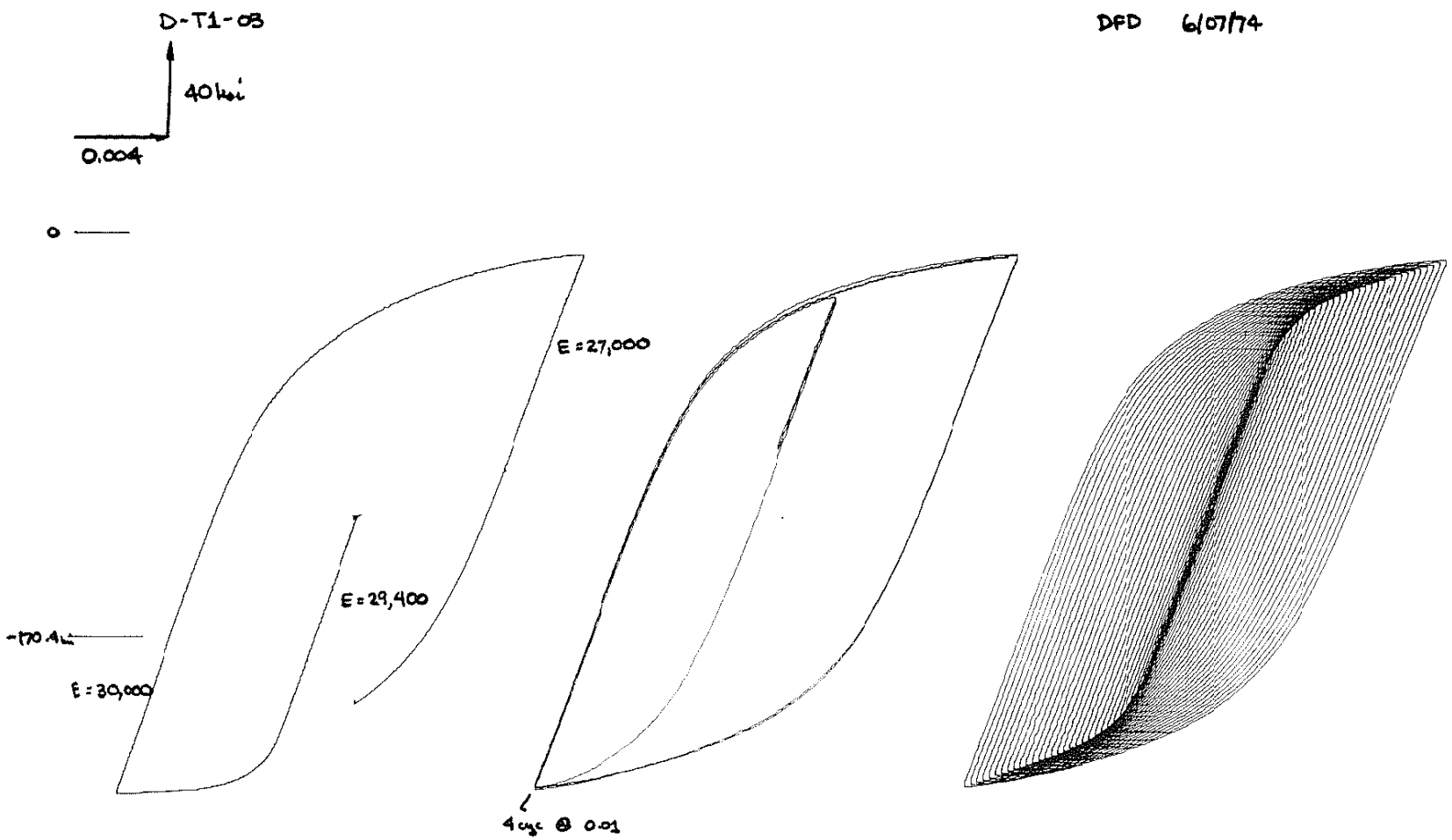

CYCLIC STRESS-STRAIN
▲ - COMPANION DATA
INCREMENTAL STEP TEST
$\frac{\Delta\sigma}{2} = 182\left(\frac{\Delta\varepsilon_p}{2}\right)^{0.136}$
STRESS, ksi
1000
100
10
0.001
0.010
0.100
PLASTIC STRAIN

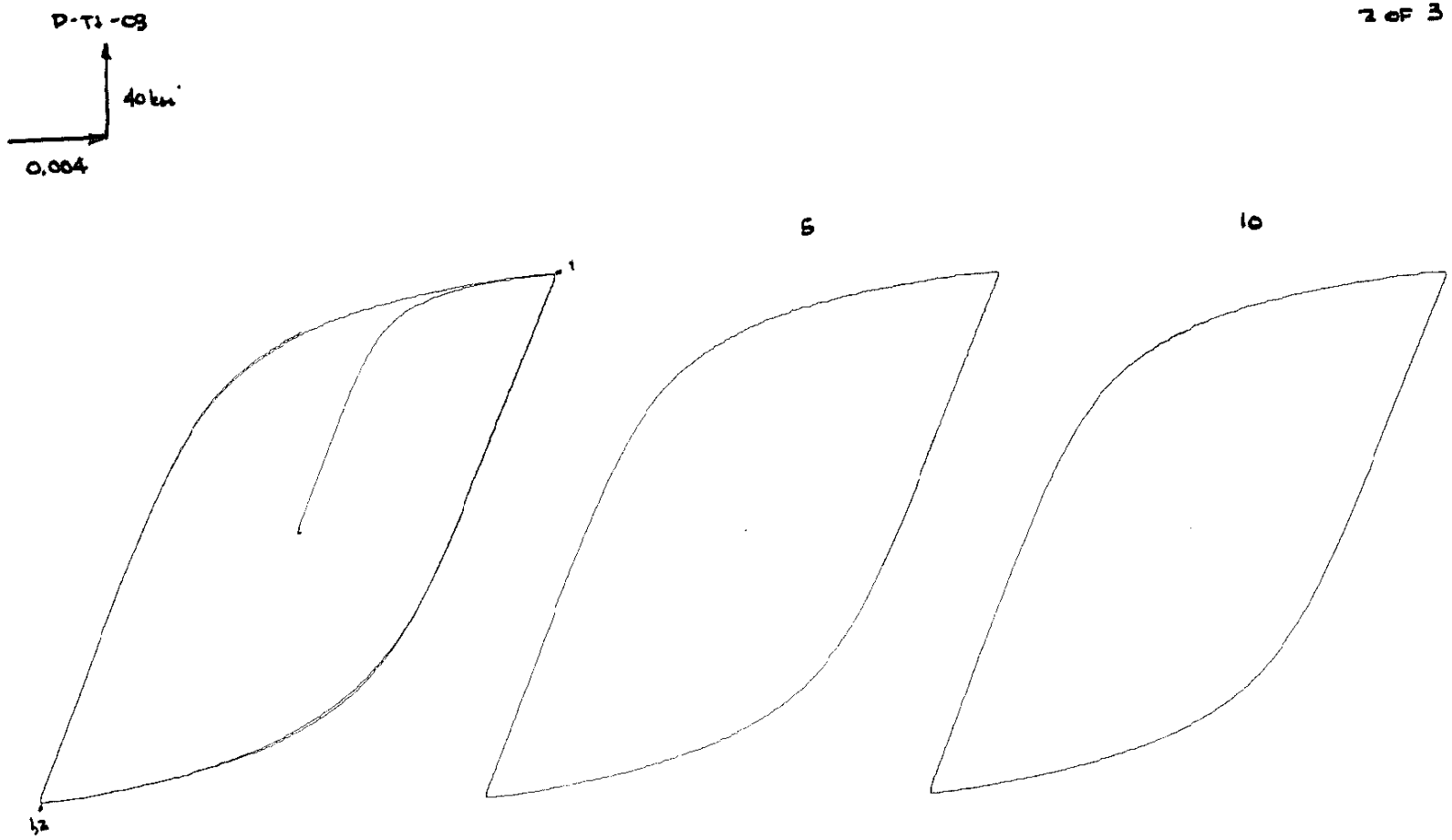
STRESS-STRAIN HYSTERESIS LOOPS

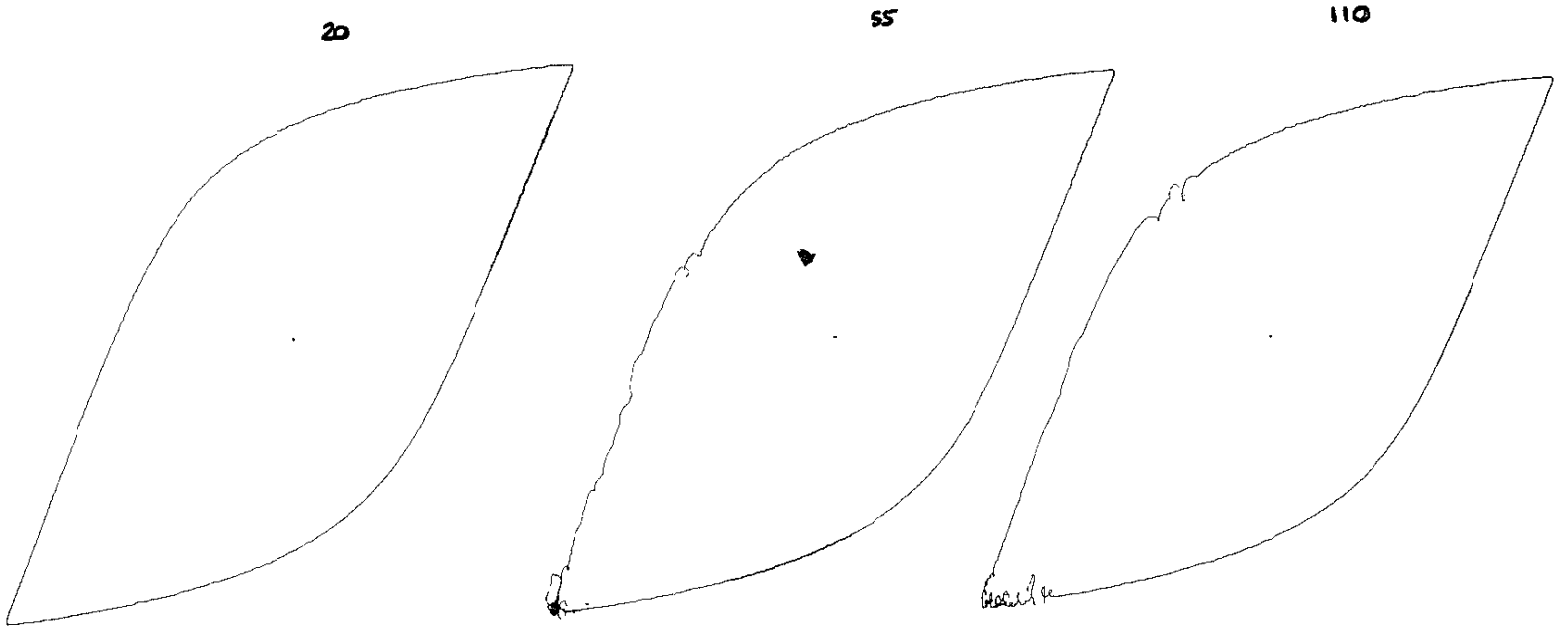
FROM CONTROLLED STRAIN FATIGUE TESTS

D-T1-03

DFD 6/07/74



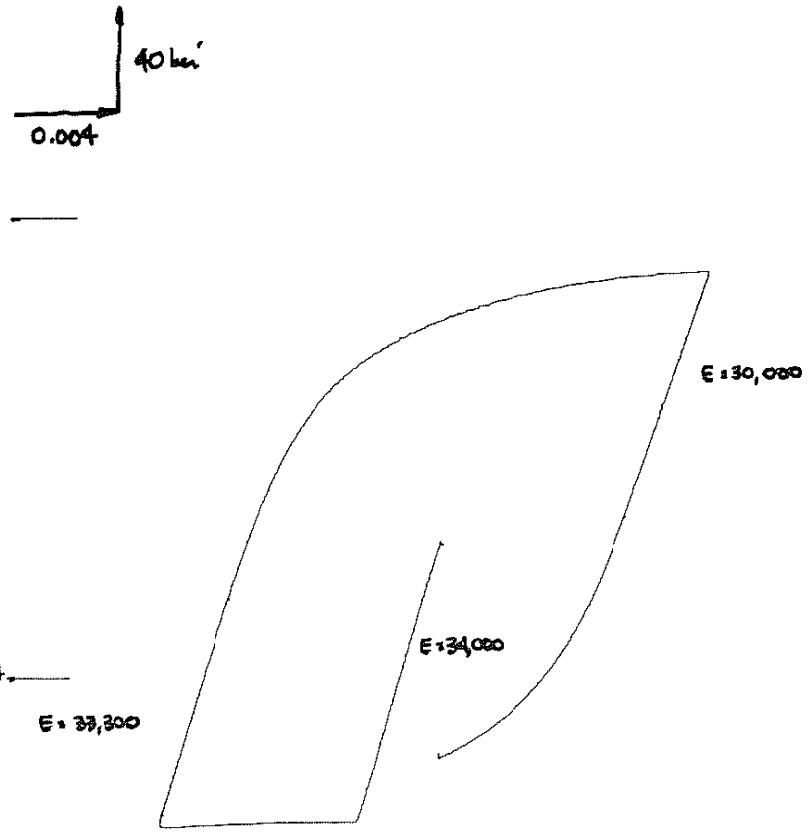

D-T1-C8
40 kN
0.004
5
10
1
1,2

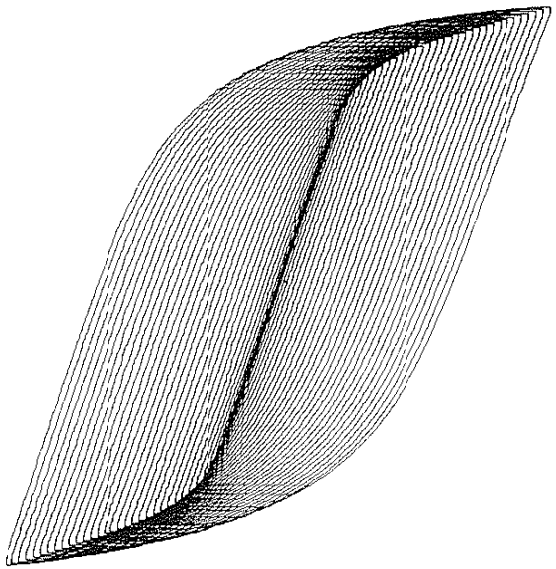


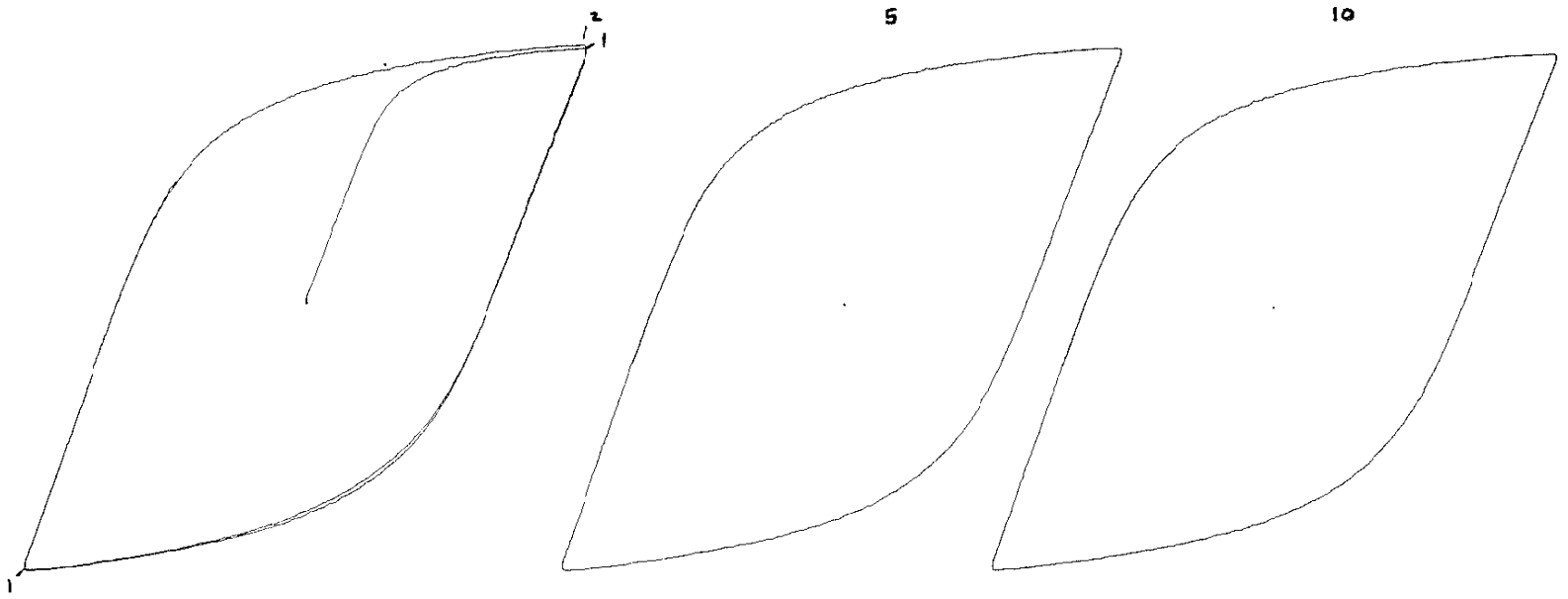
TEST STOPPED

D-T1-04

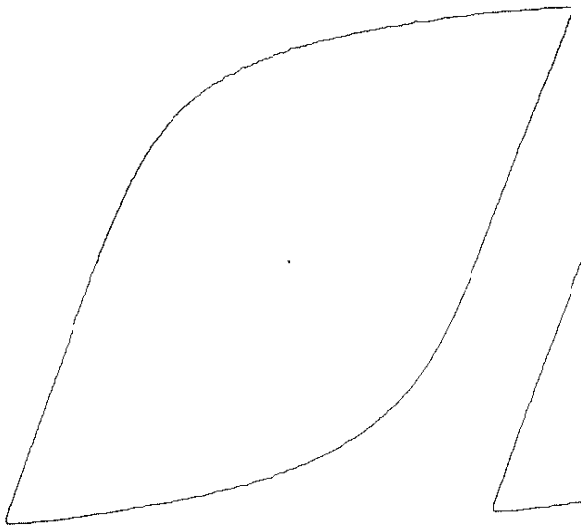
DFD 6/07/74



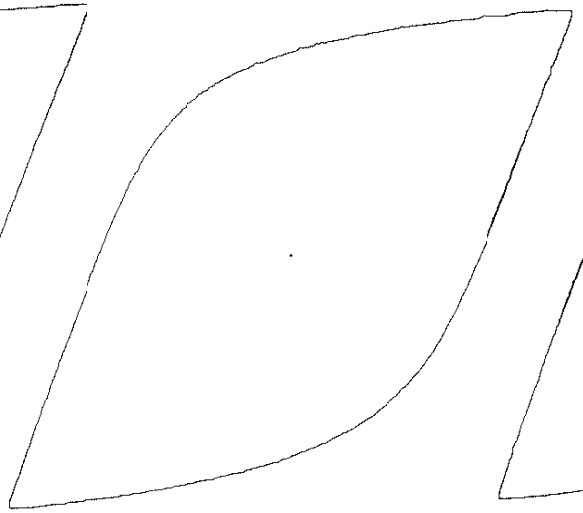



2
1
1
5
10

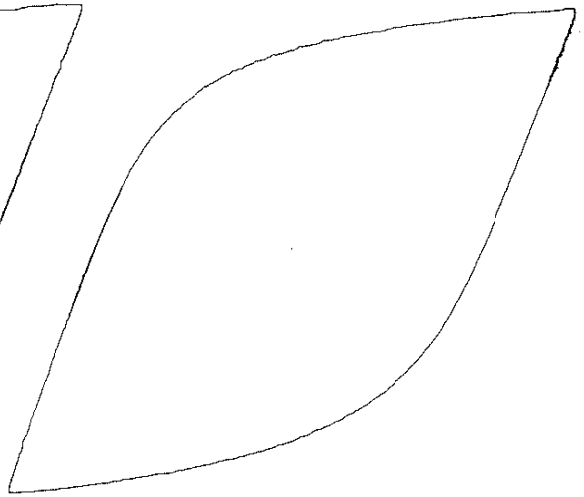
20

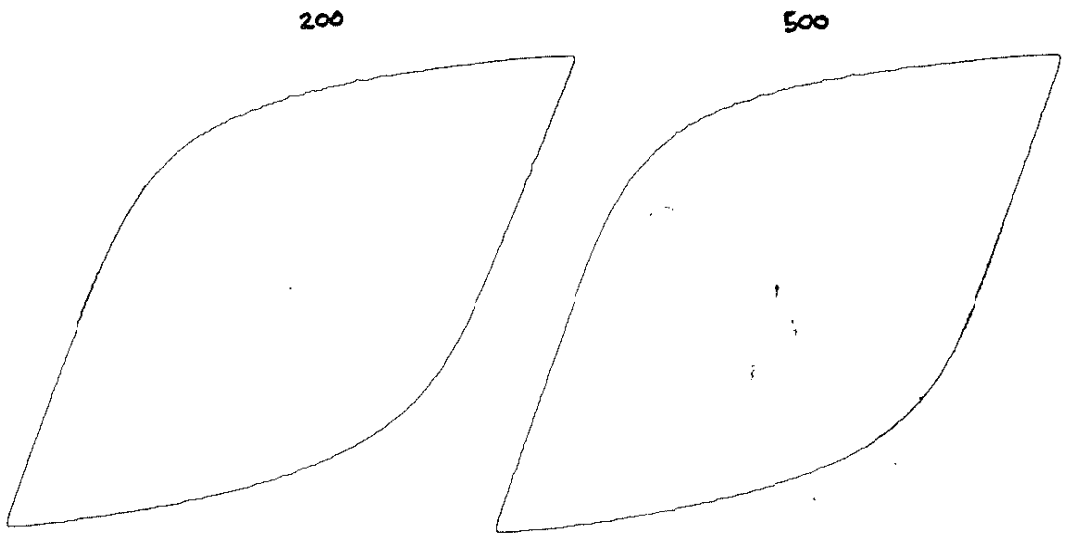


50



100

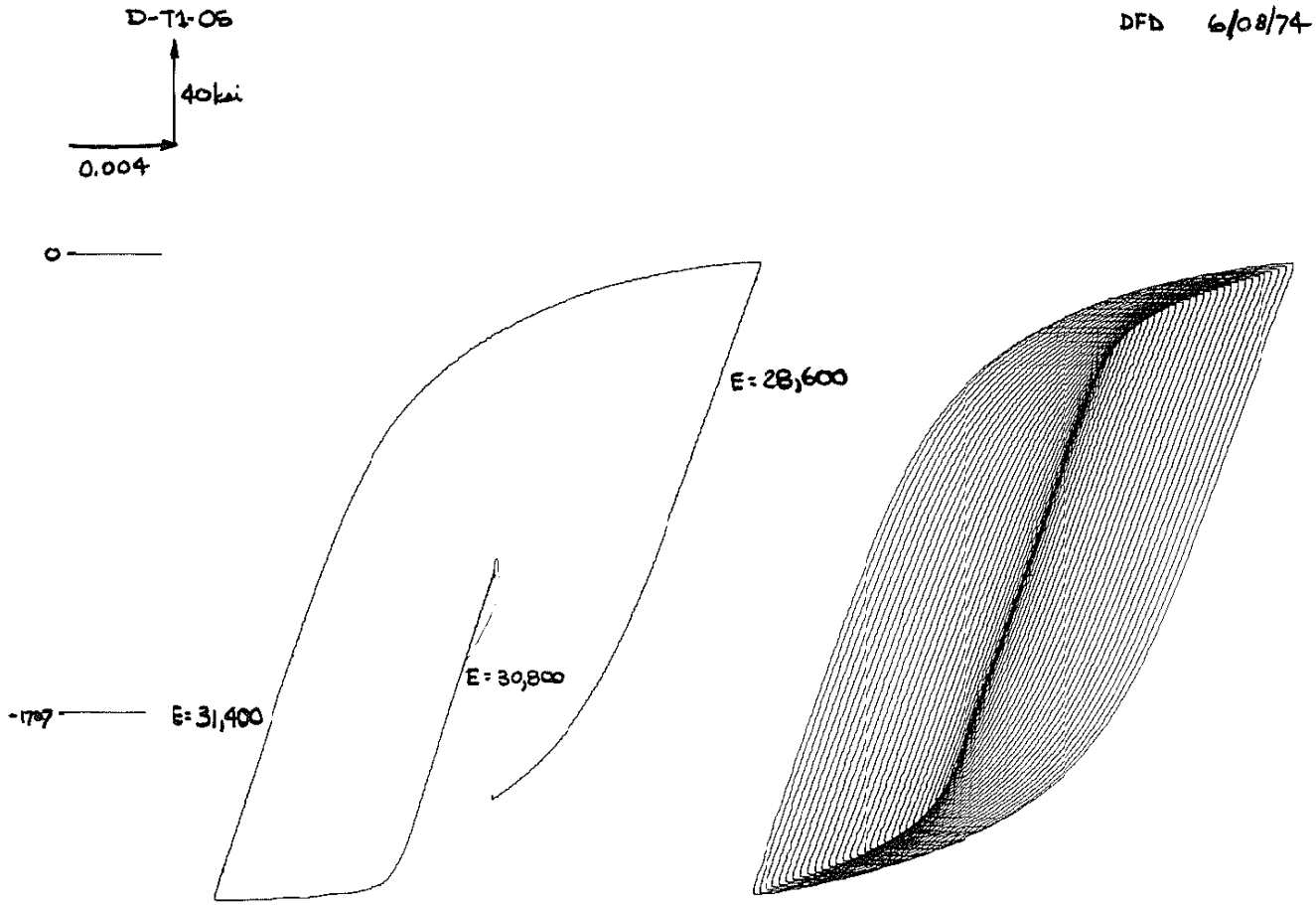


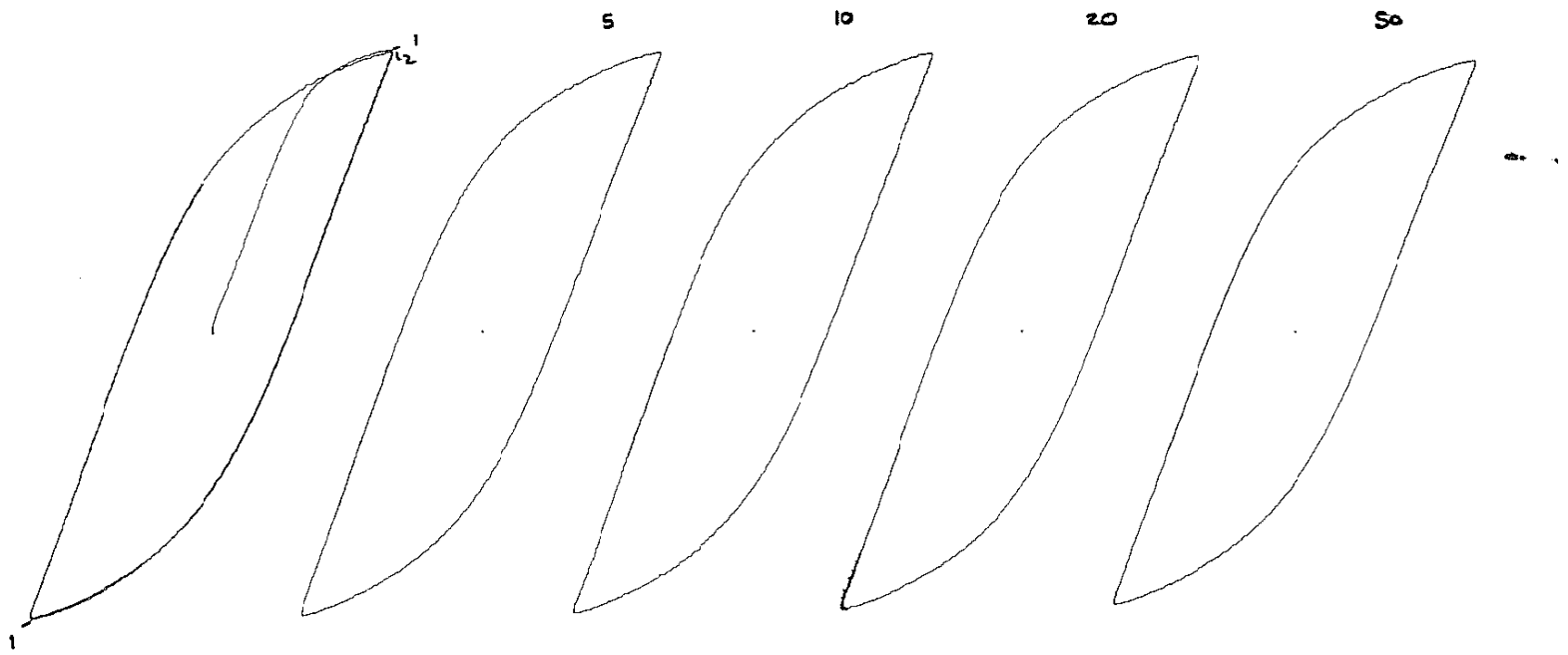


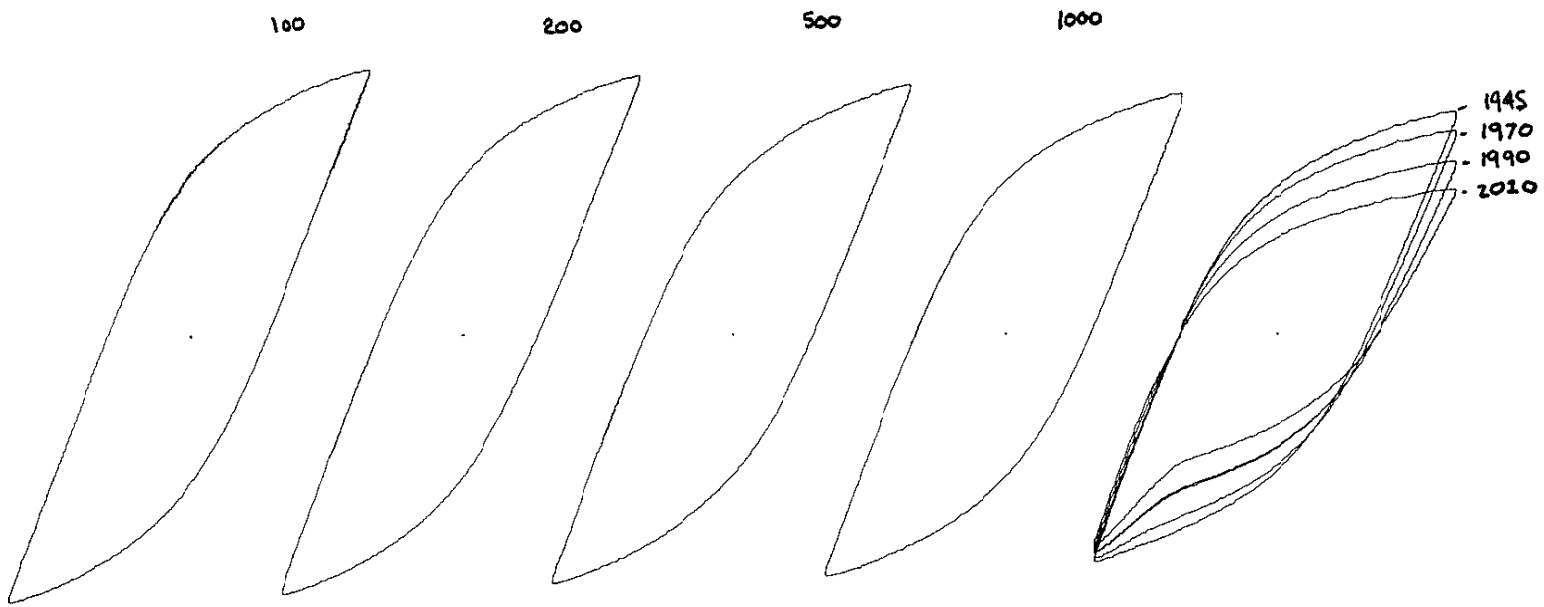
$N_f = 529$
(out of g.l.)

D-T1-06

DFD 6/08/74



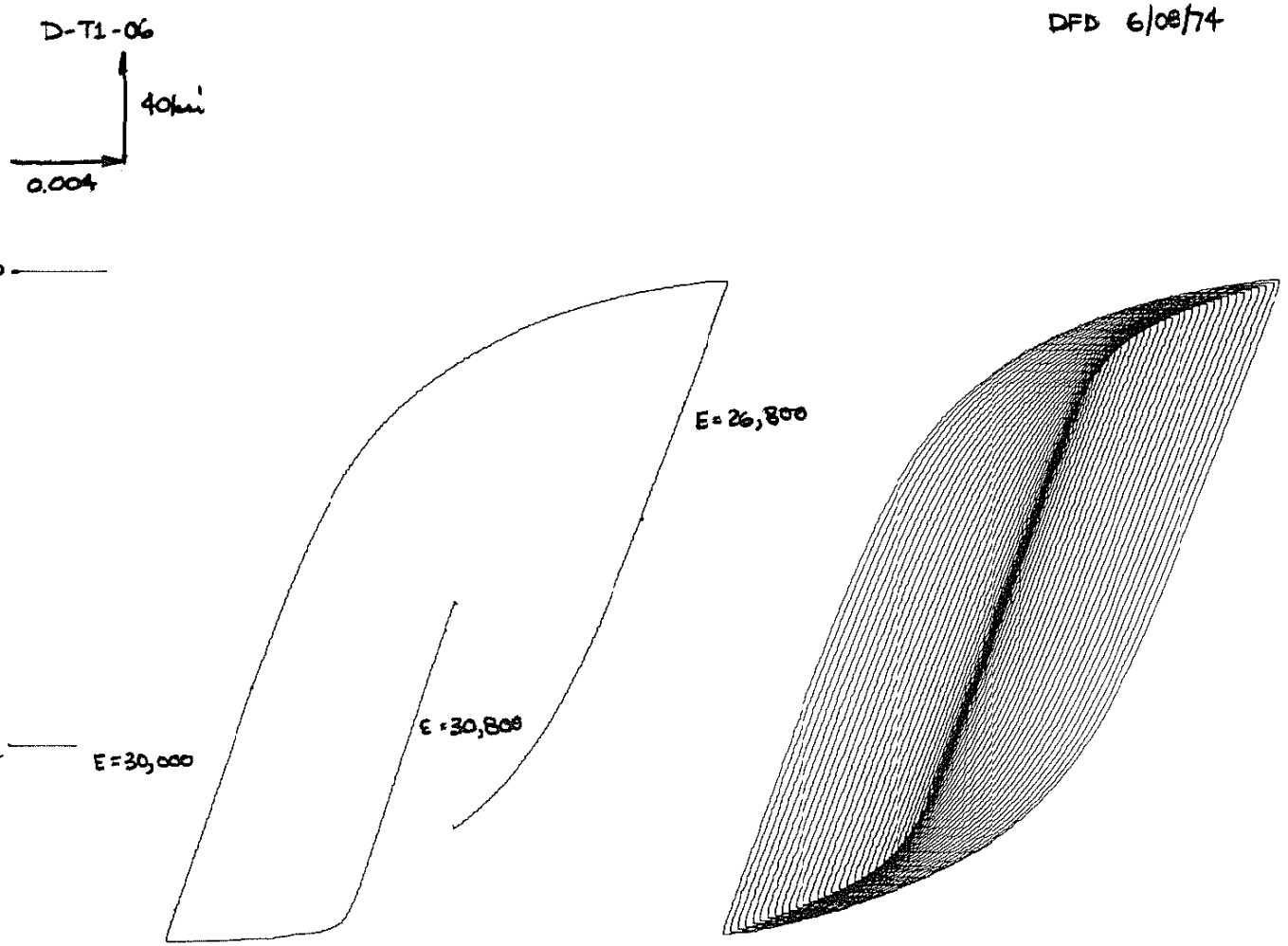

1
1/2
5
10
20
50



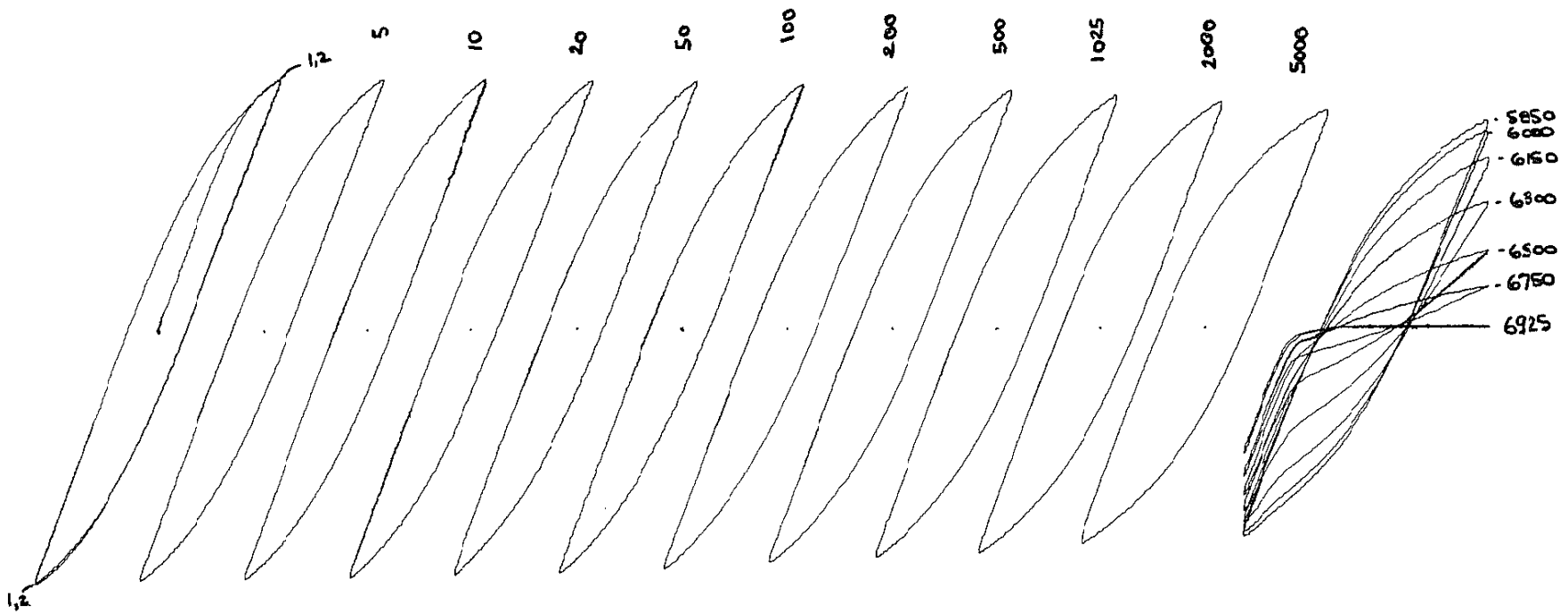
N_f = 1990

D-T1-06

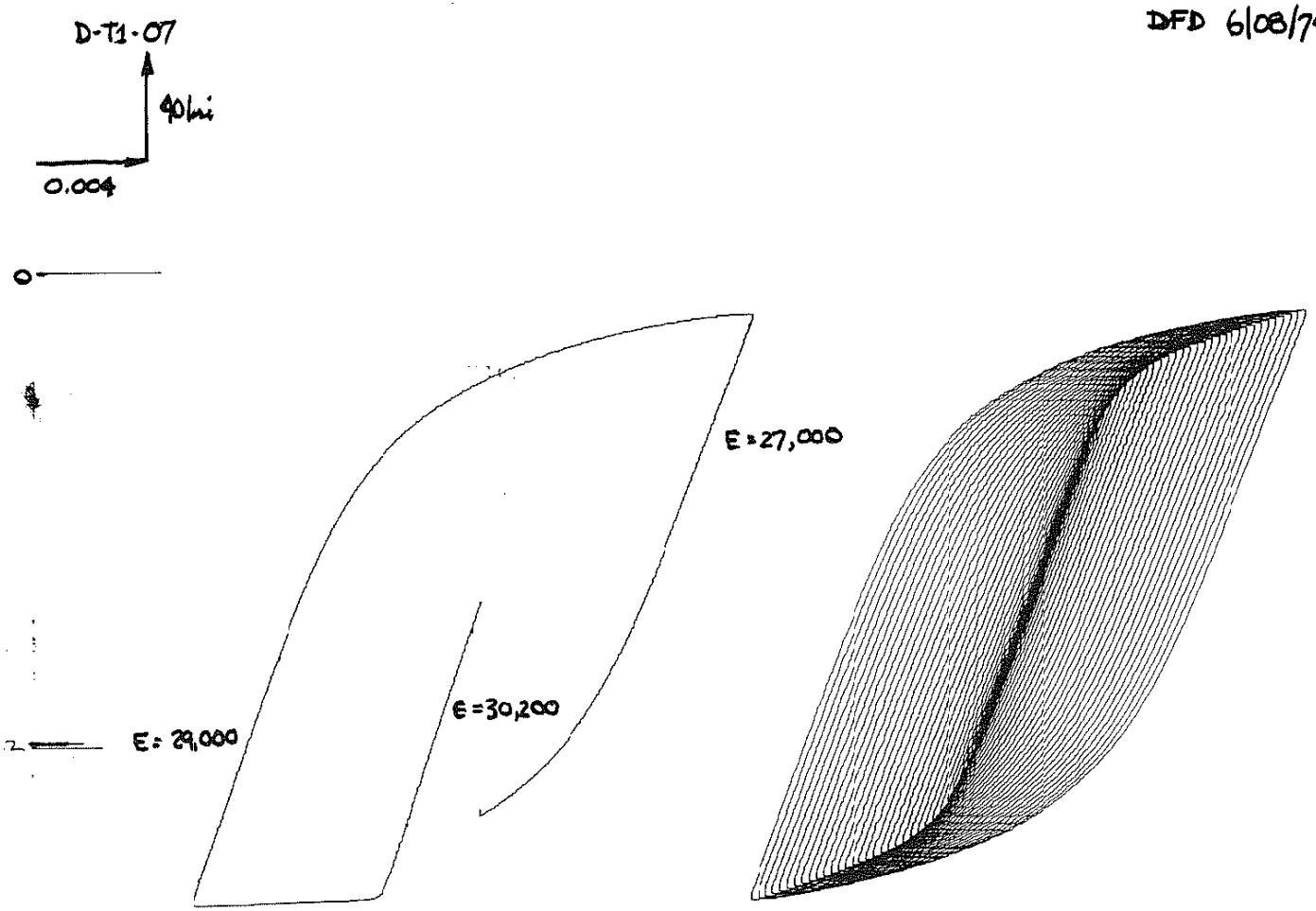
DFD 6/08/74

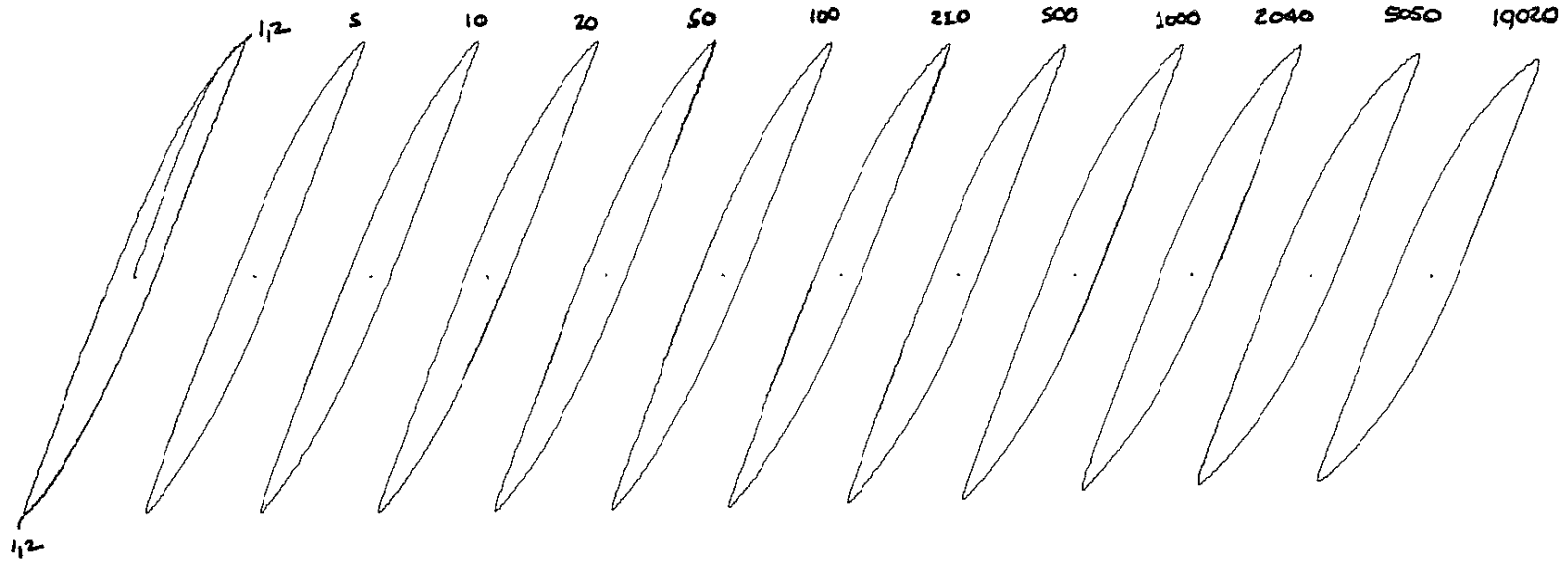


D-T1-06

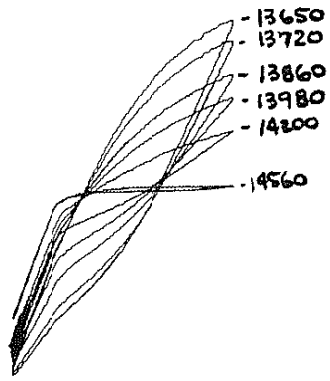


N_f = 6150/6925


D-T1-07
40ksi
0.004
0
E=27,000
E=30,200
E=29,000
-1702


1/2
5
10
20
50
100
210
500
1000
2040
5050
19020
1/2

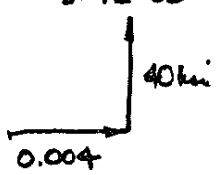
D-T1-07

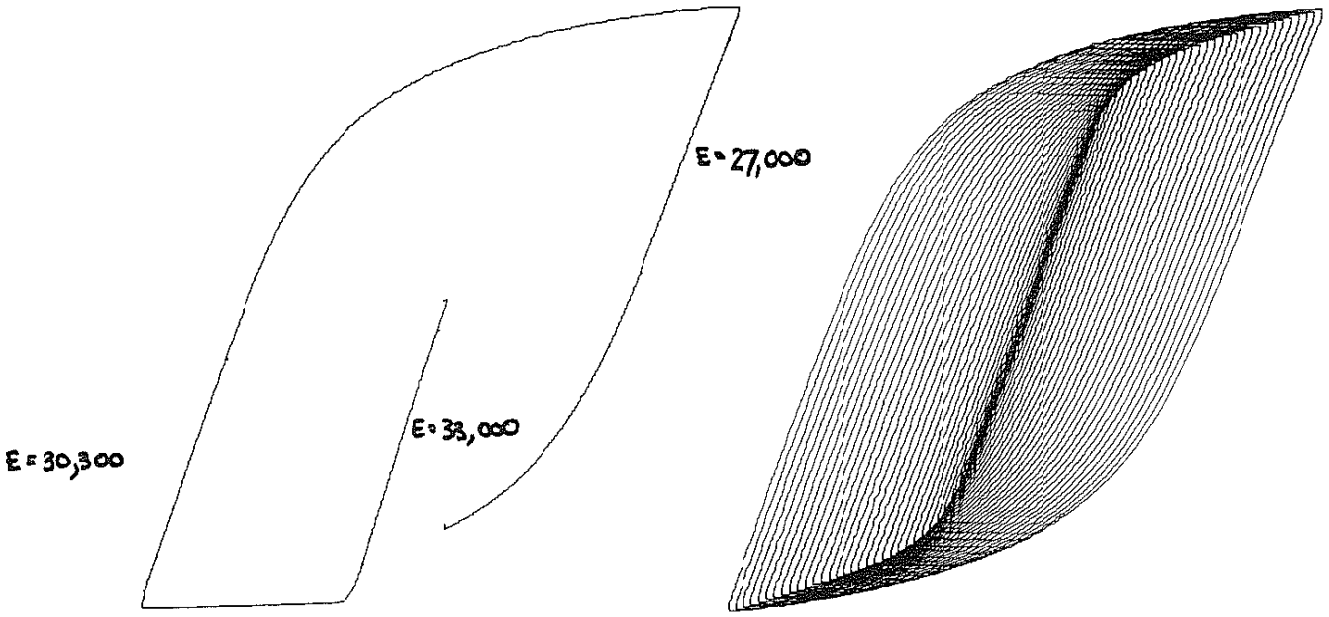


N_f = 13,600/14560

D-T1-08

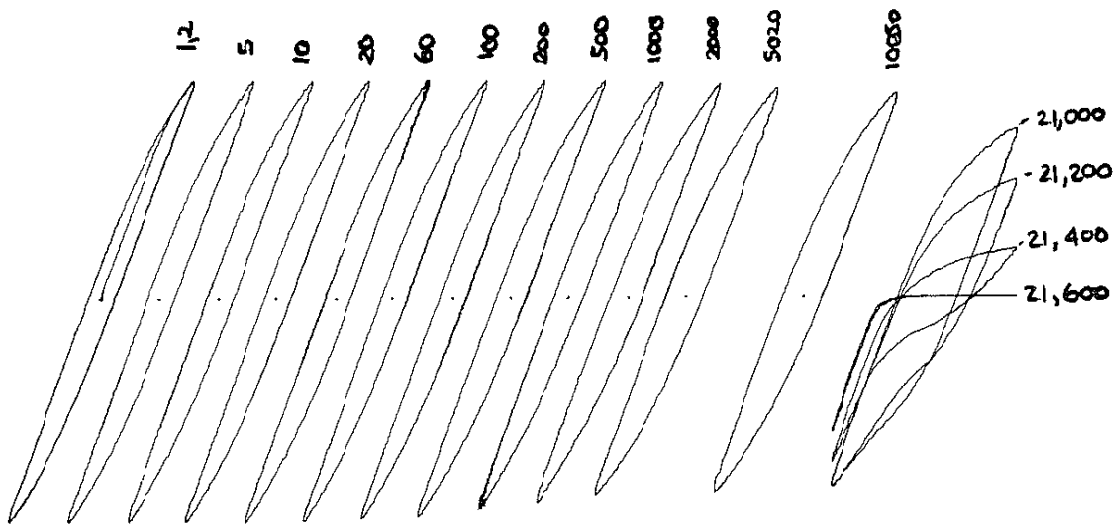
DFD 6/08/74





D-T1-08

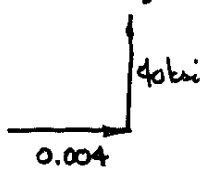
2 OF 2

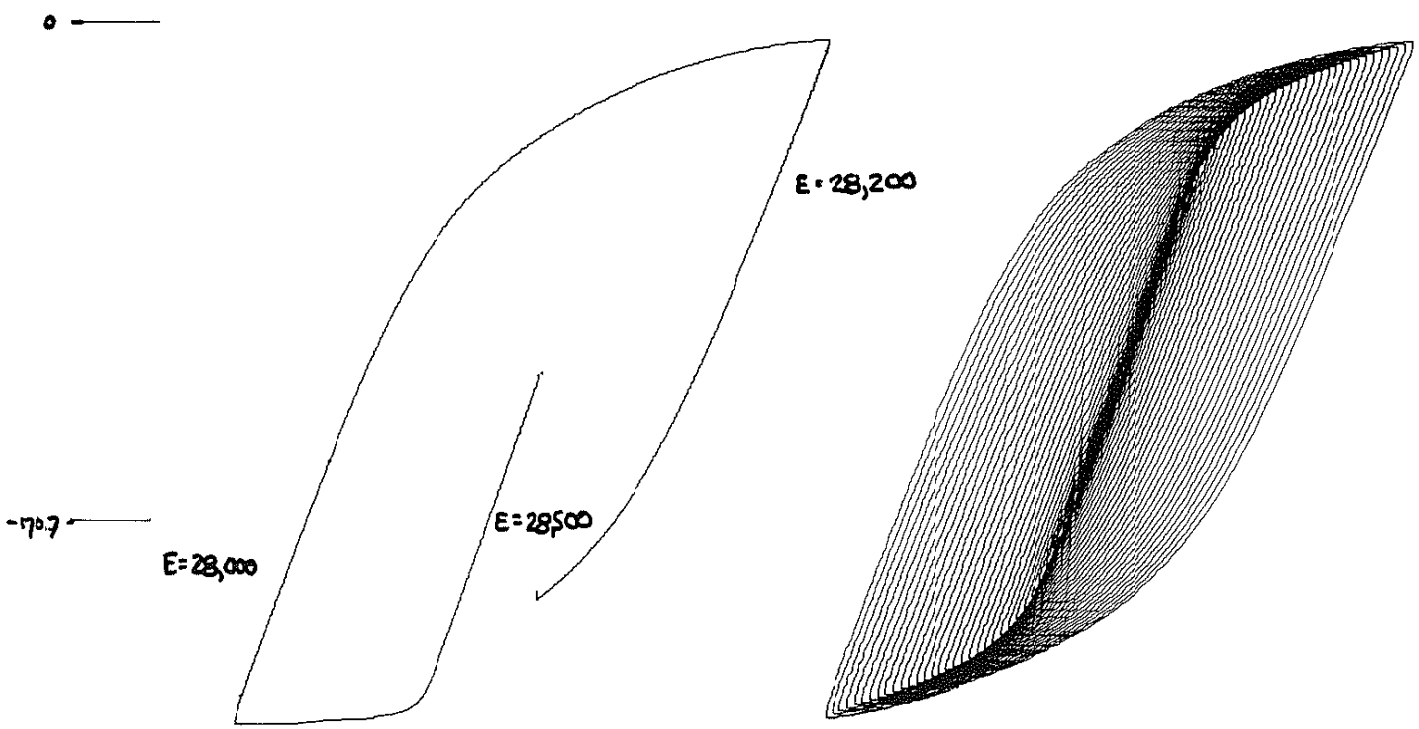


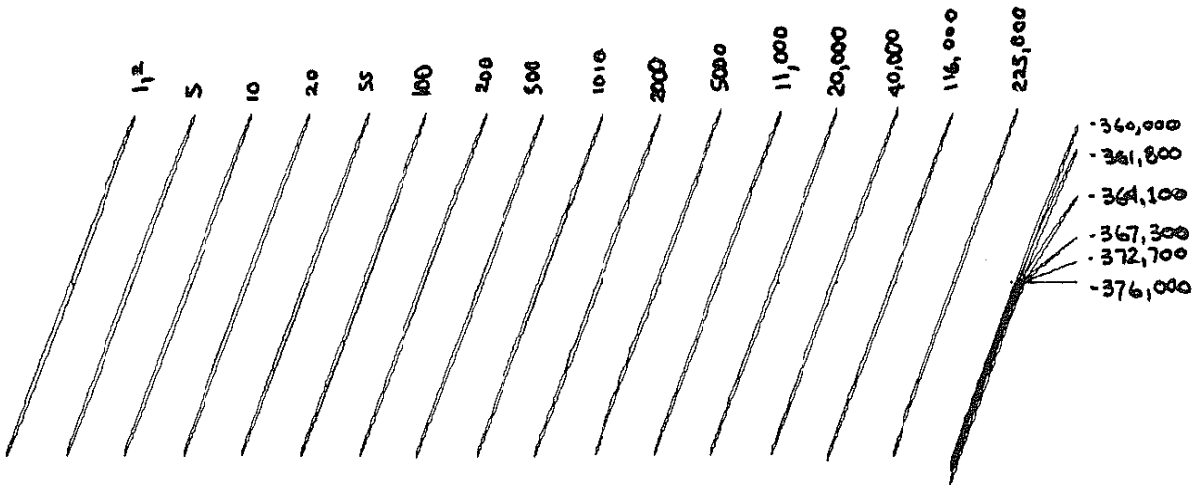
$N_f = 21{,}000$

D-T2-09

DFD 6/09/74






1,2
5
10
20
55
100
200
500
1010
2000
5000
11,000
20,000
40,000
116,000
235,000
-360,000
-361,800
-364,100
-367,300
-372,700
-376,000

$N_4 = 362{,}000/$

D-T1-10

40ksi

0.004

0

-17ksi

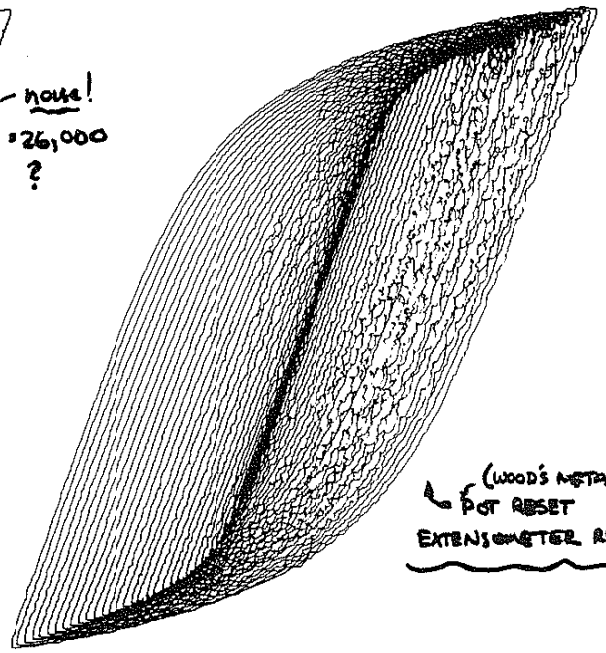
E = 30,300

E = 31,700

- none!

E = 26,000

?

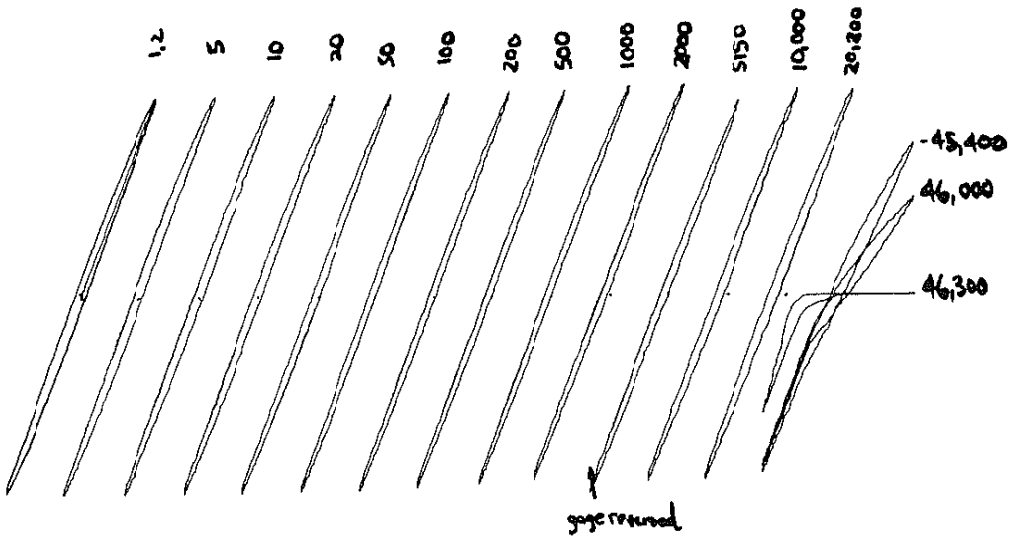


(WOOD'S METAL)

POT RESET

EXTENSOMETER RESET !

D-T1-10

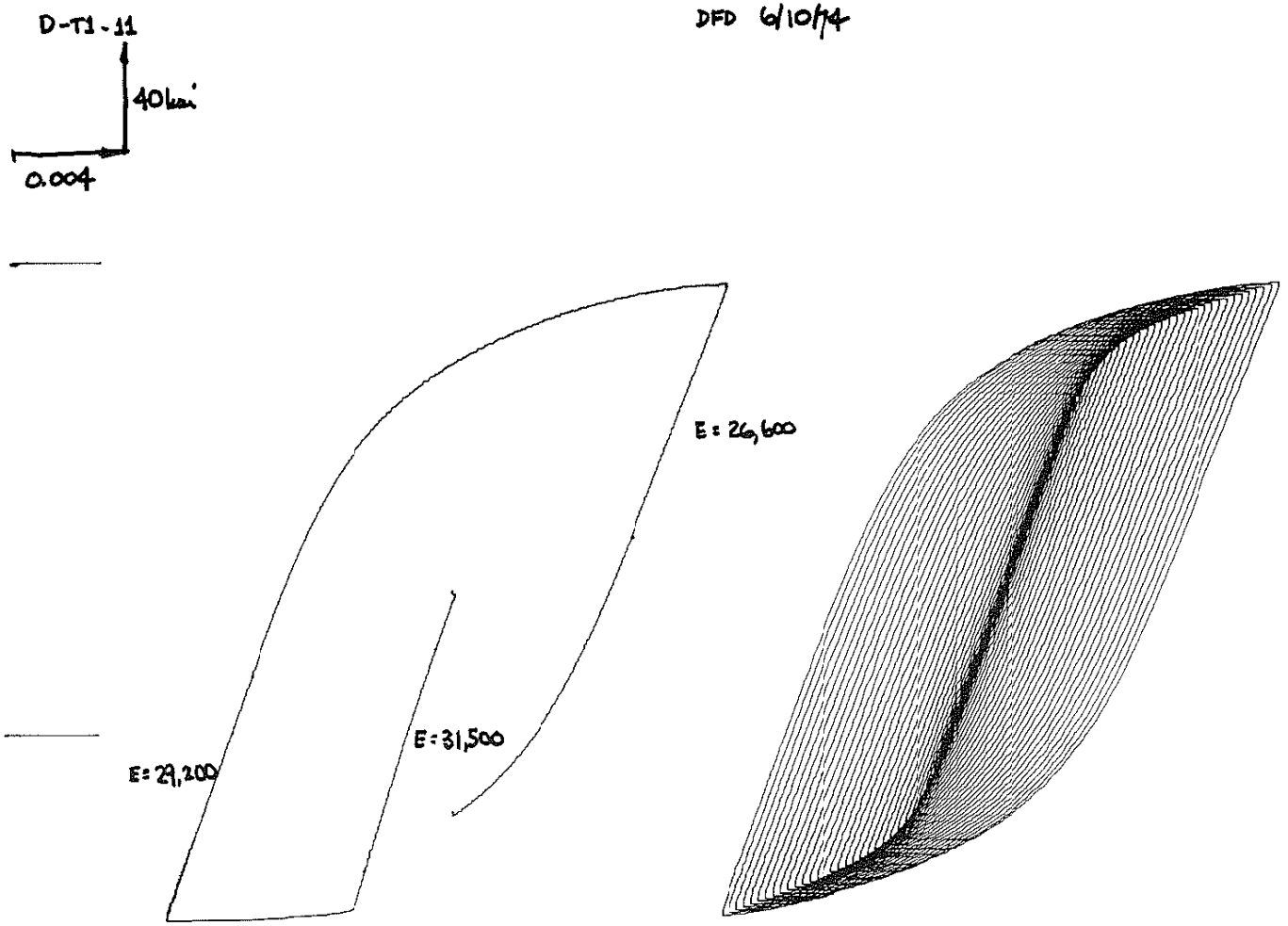


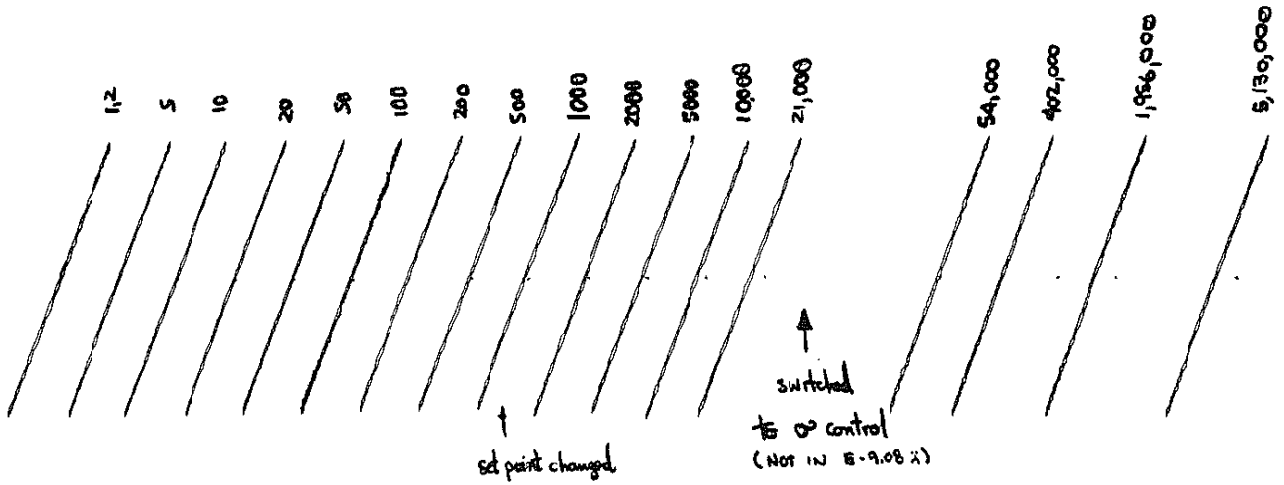
N_f = 45,500

D-T1-11

DFD 6/10/14

1 OF 2

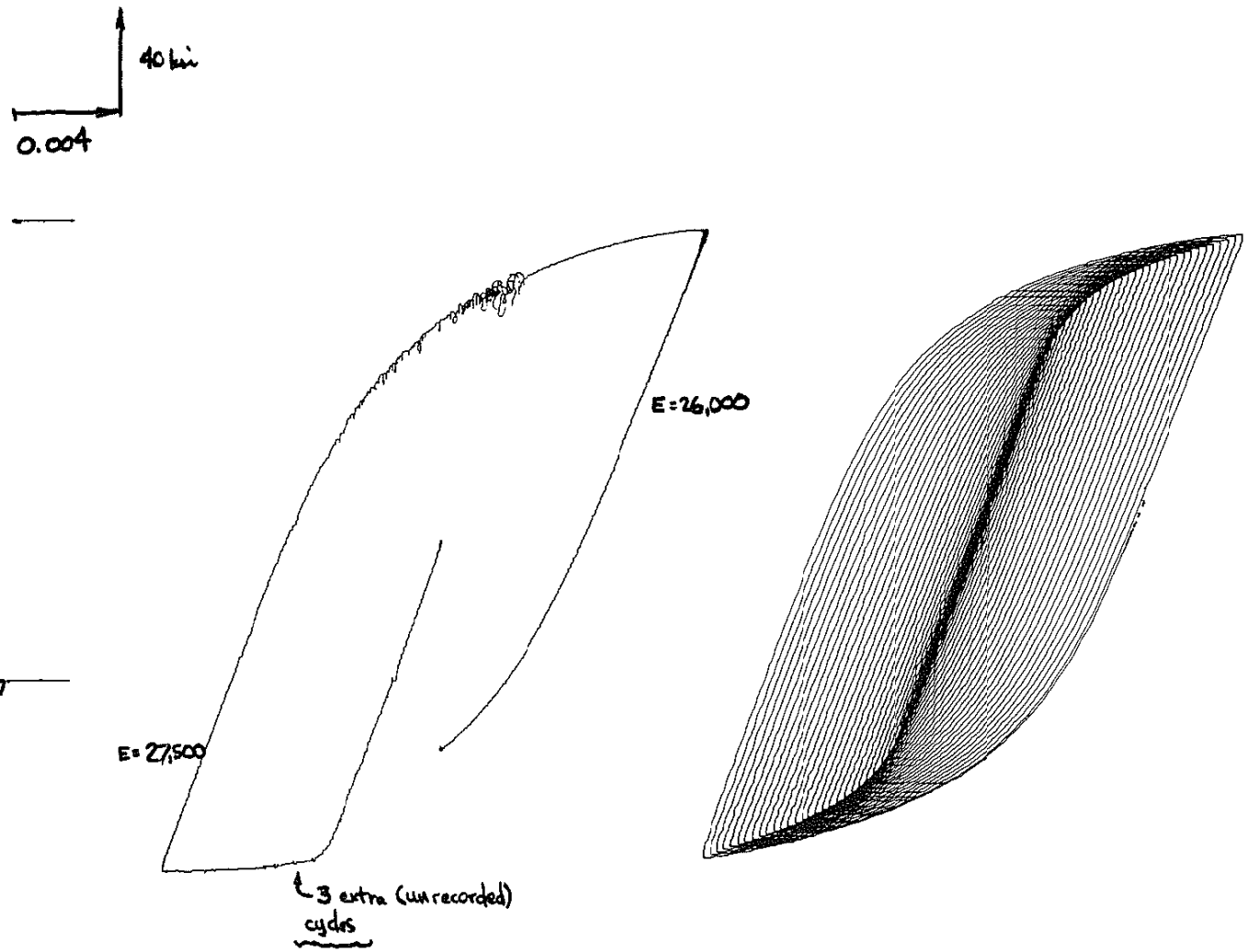


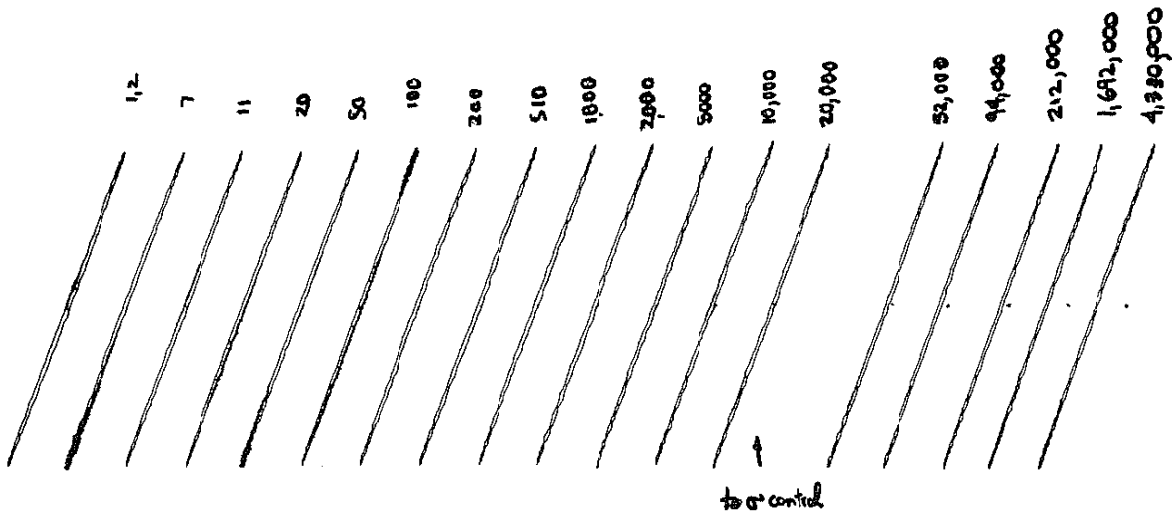


TEST STOPPED @ N = 5,400,000

D-T1-12

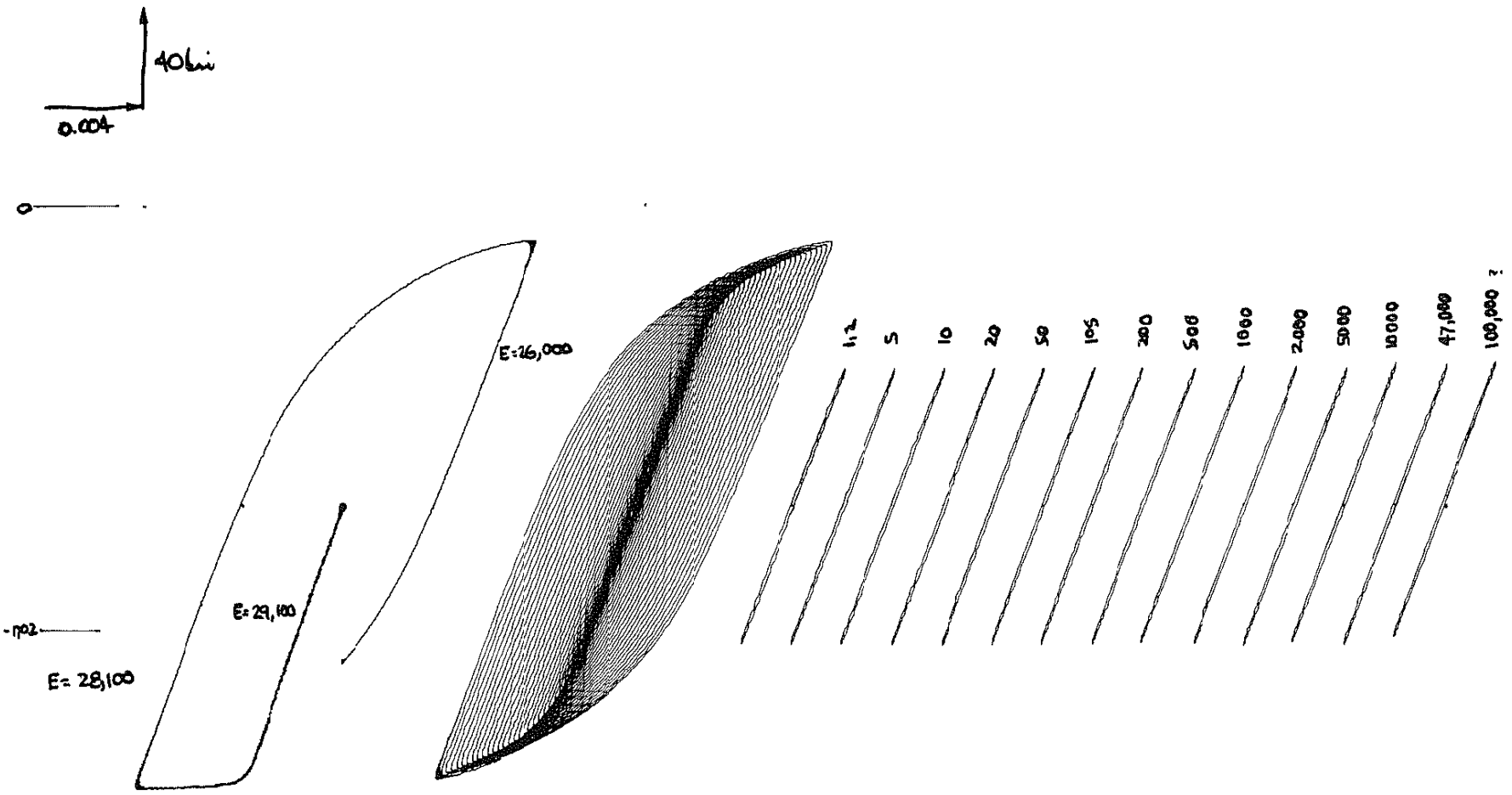
DFD 6/12/74

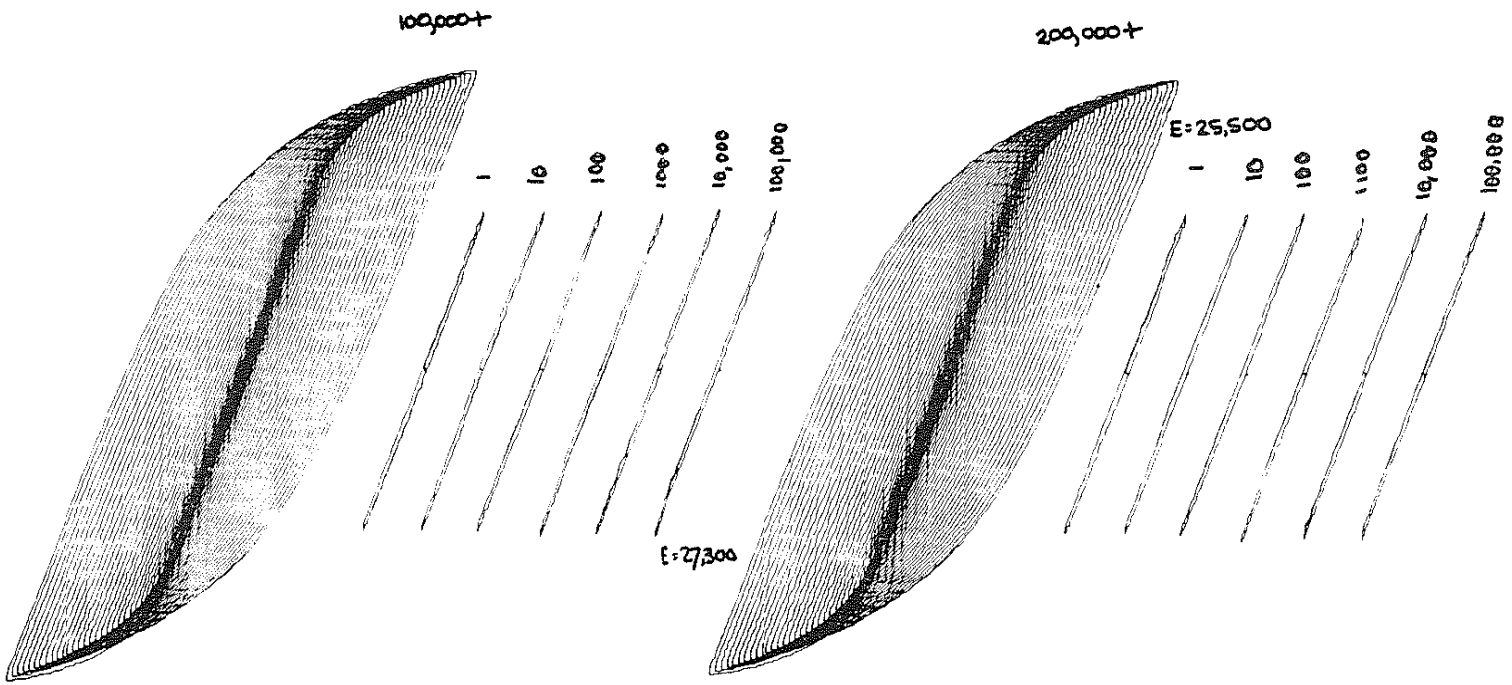


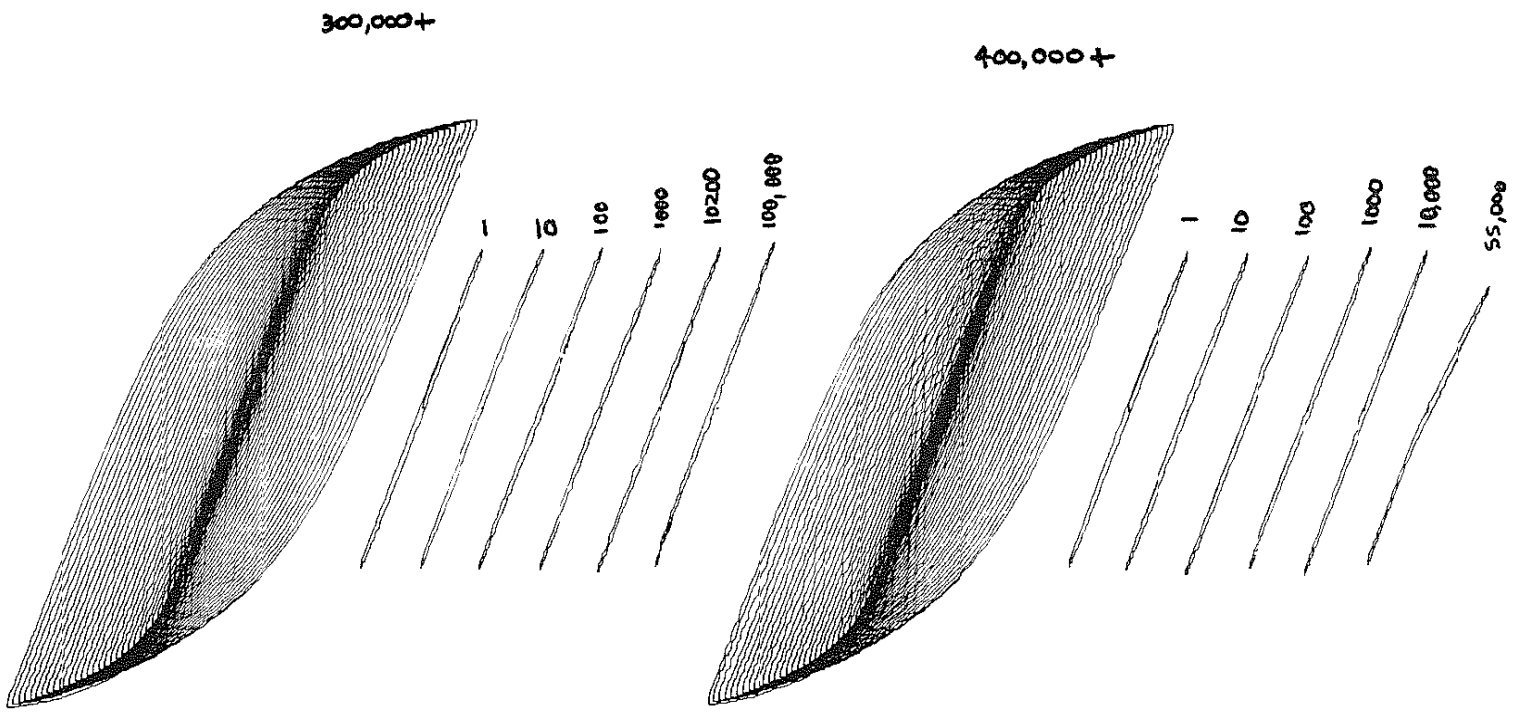

1,2
7
11
20
50
100
200
510
1000
2000
5000
10,000
20,000
53,000
94,000
212,000
1,692,000
4,330,000
to 0° control

No failure @ N=

D-T1-13 DFD 6/17/74 1 of 3



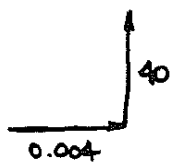

100,000+
1
10
100
1000
10,000
100,000
E=27,300
200,000+
E=25,500
1
10
100
1,000
10,000
100,000

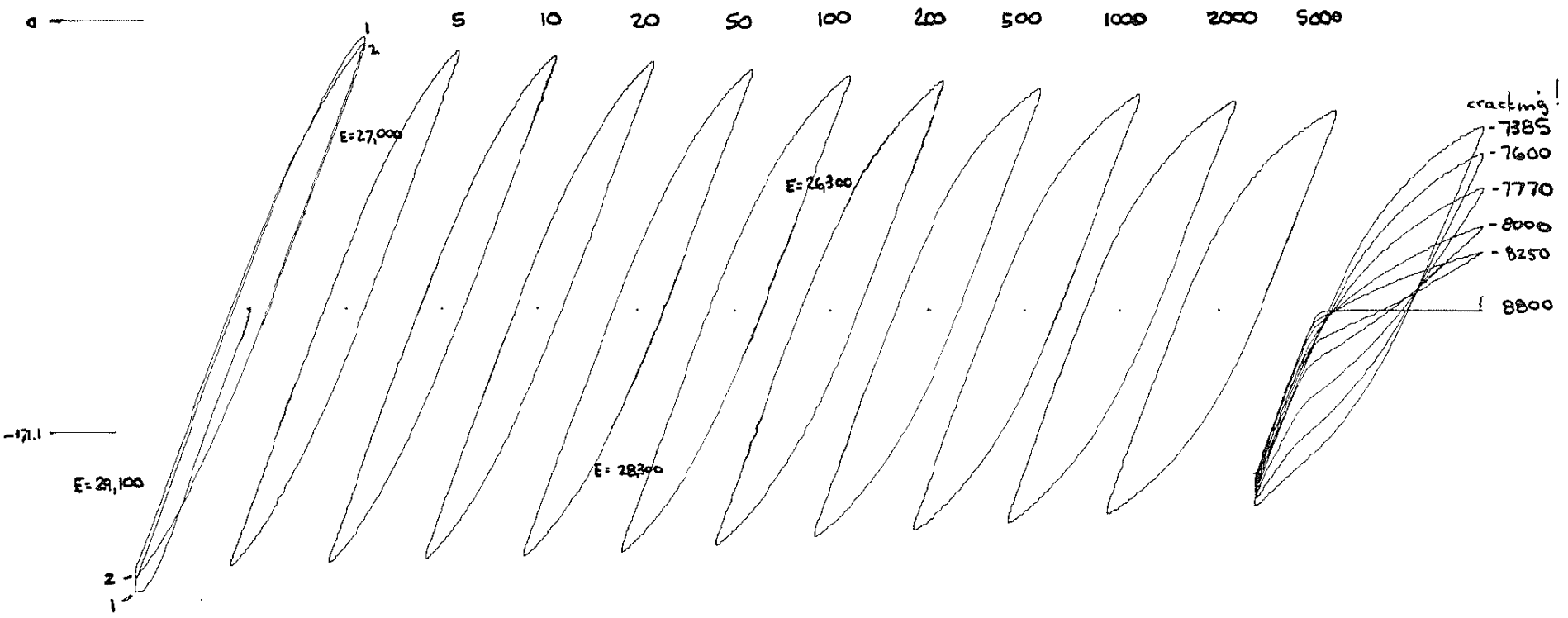

300,000+
1
10
100
1000
10200
100,000
400,000+
1
10
100
1000
10,000
55,000

N_f = 450,000

D-T1-14

DFD 6/19/74

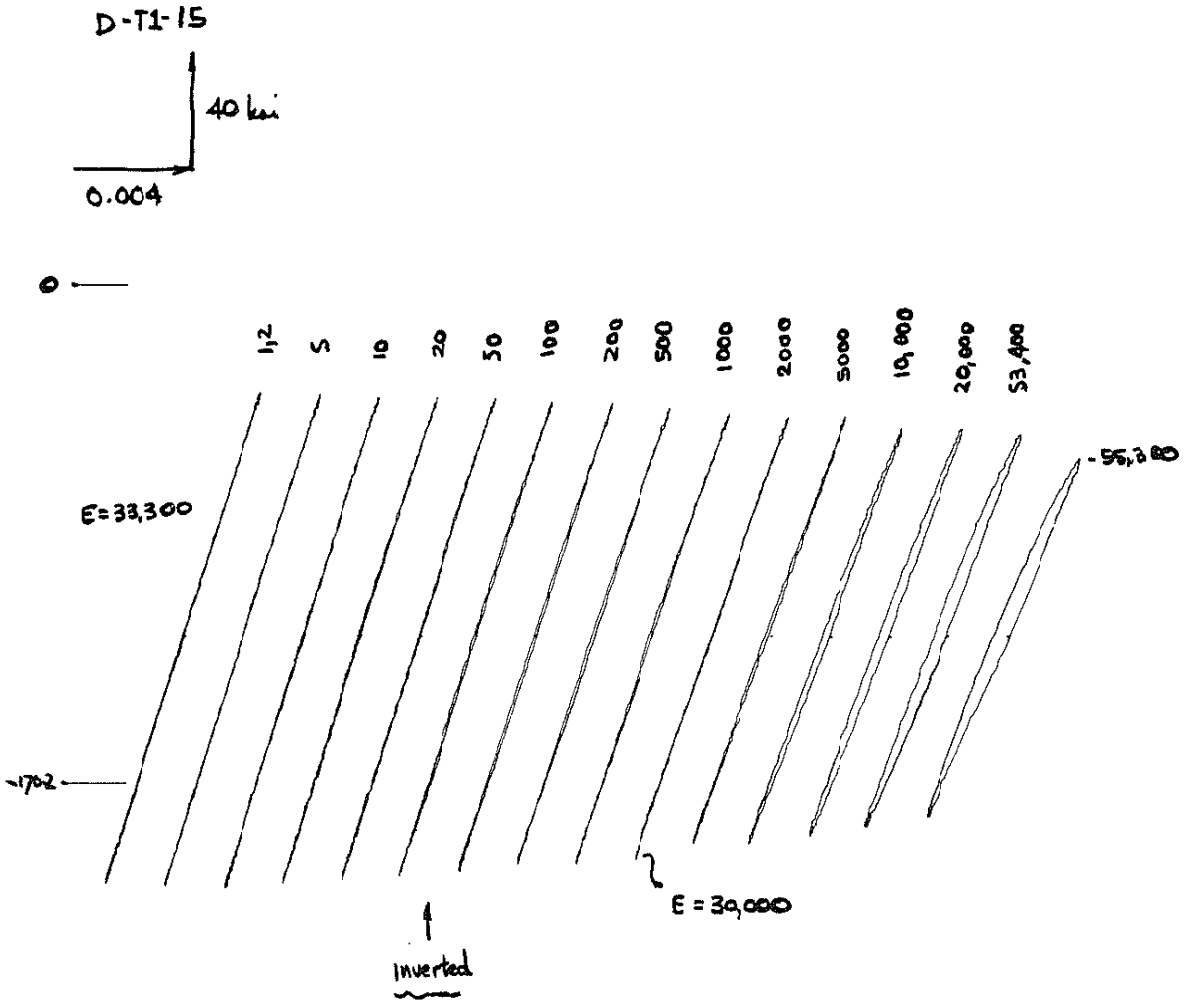




$N_f = 7600$

D-T1-15

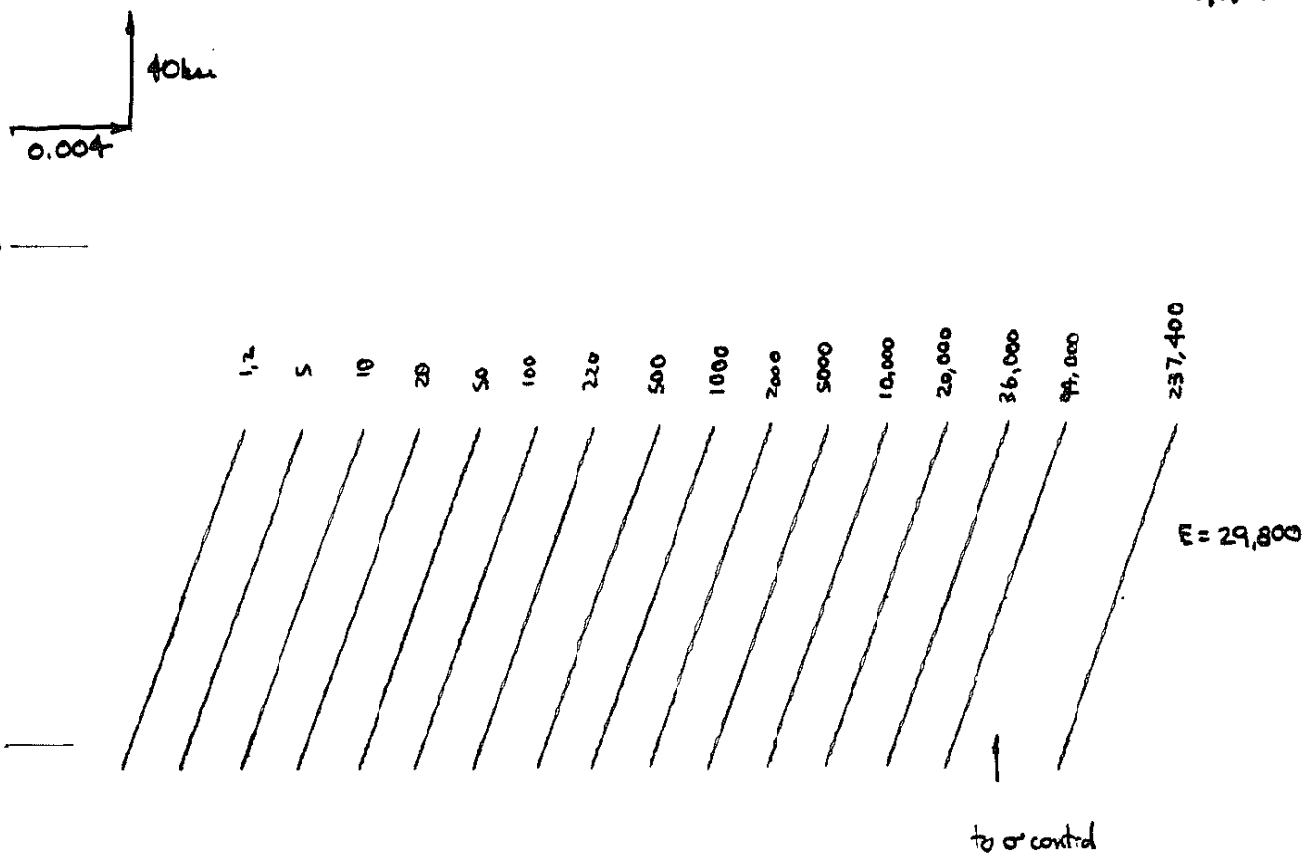
DFD 6/19/74



$N_f = 55,500$

D-T1-K6

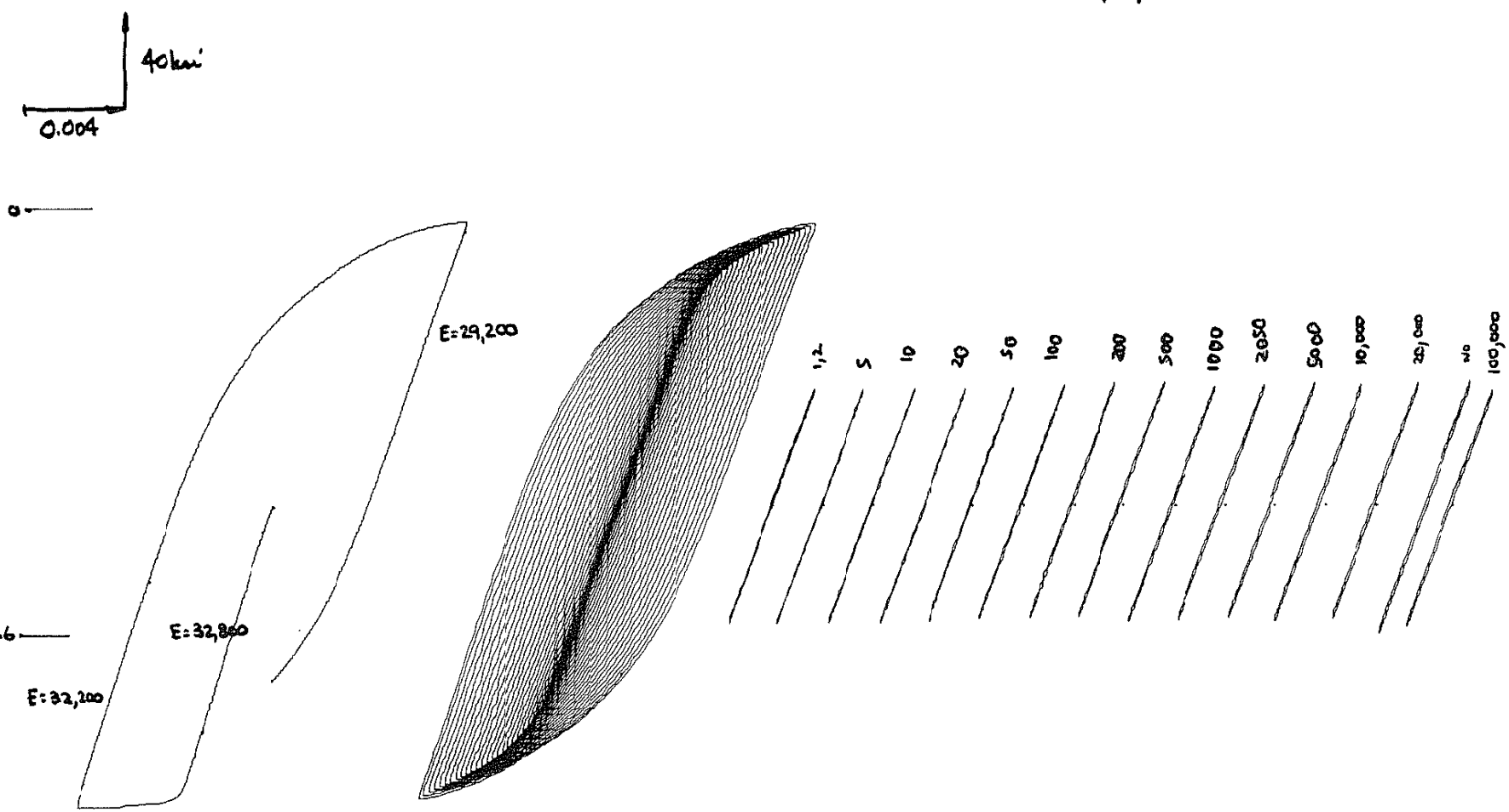
DFD 6/9/74

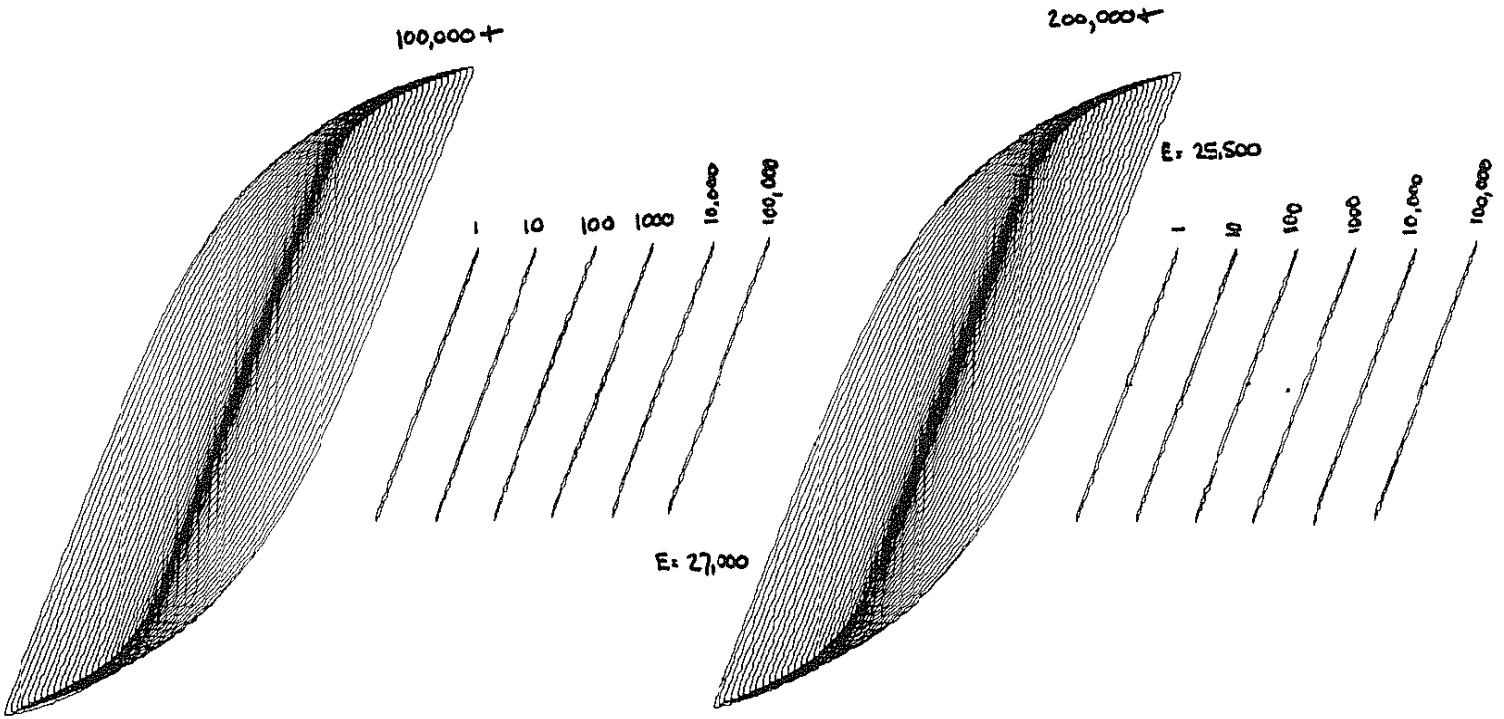


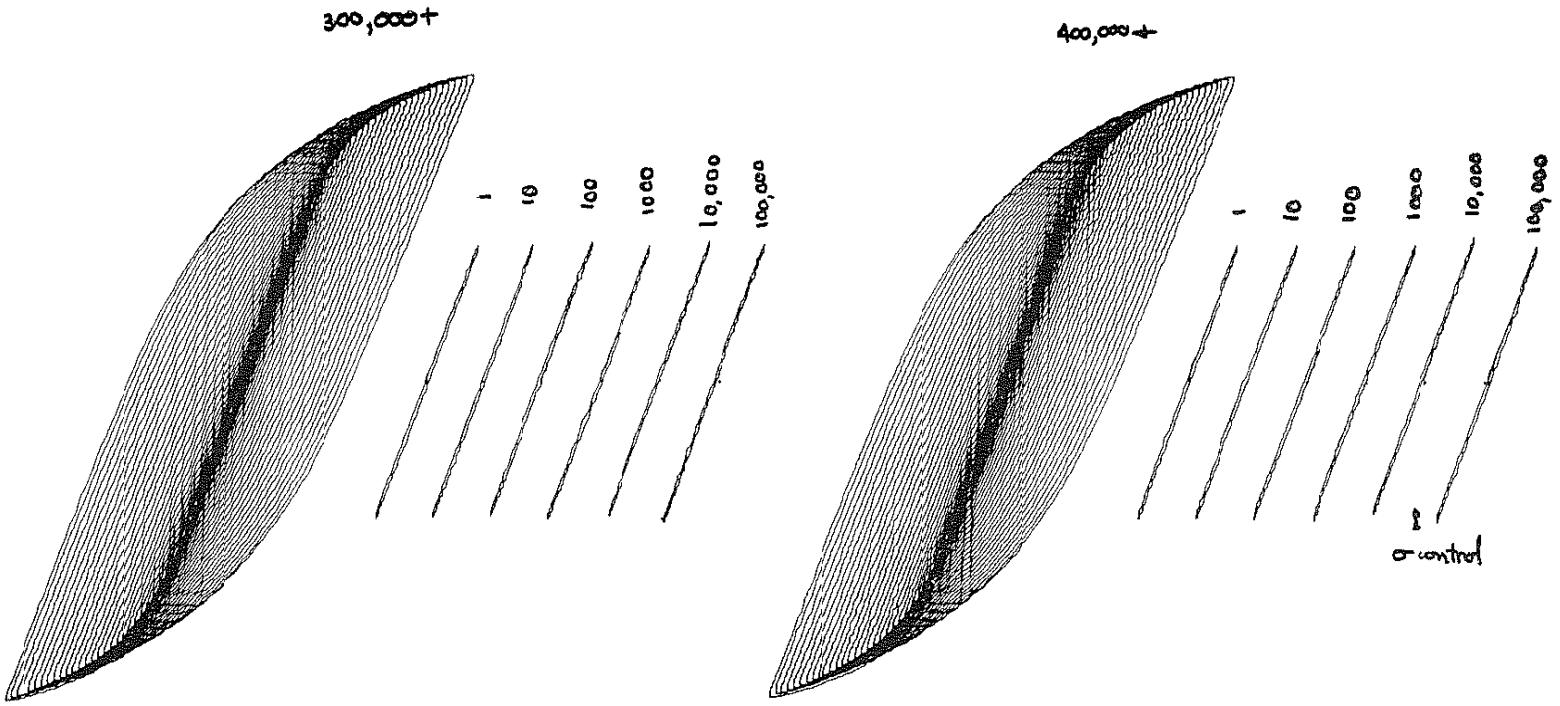
$N_f = 420,000$

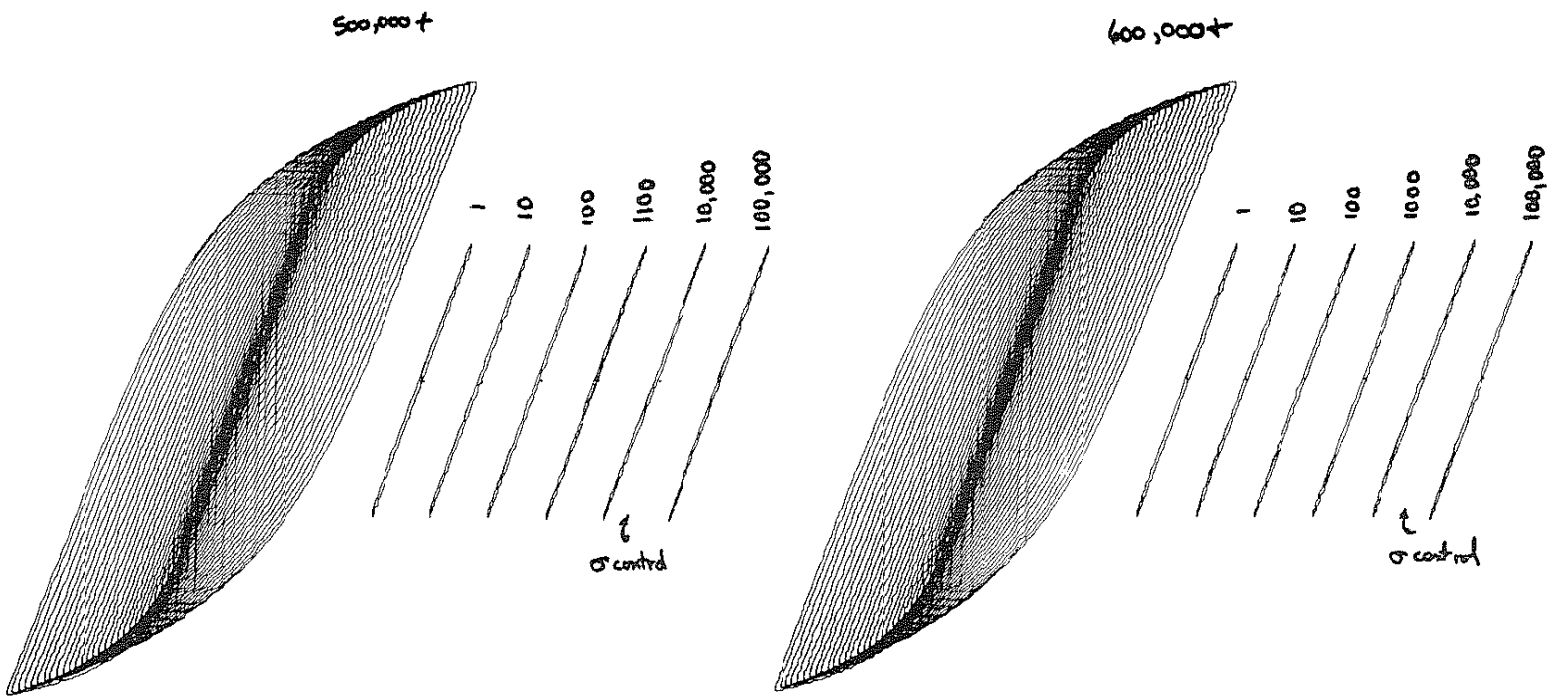
D-T1-17

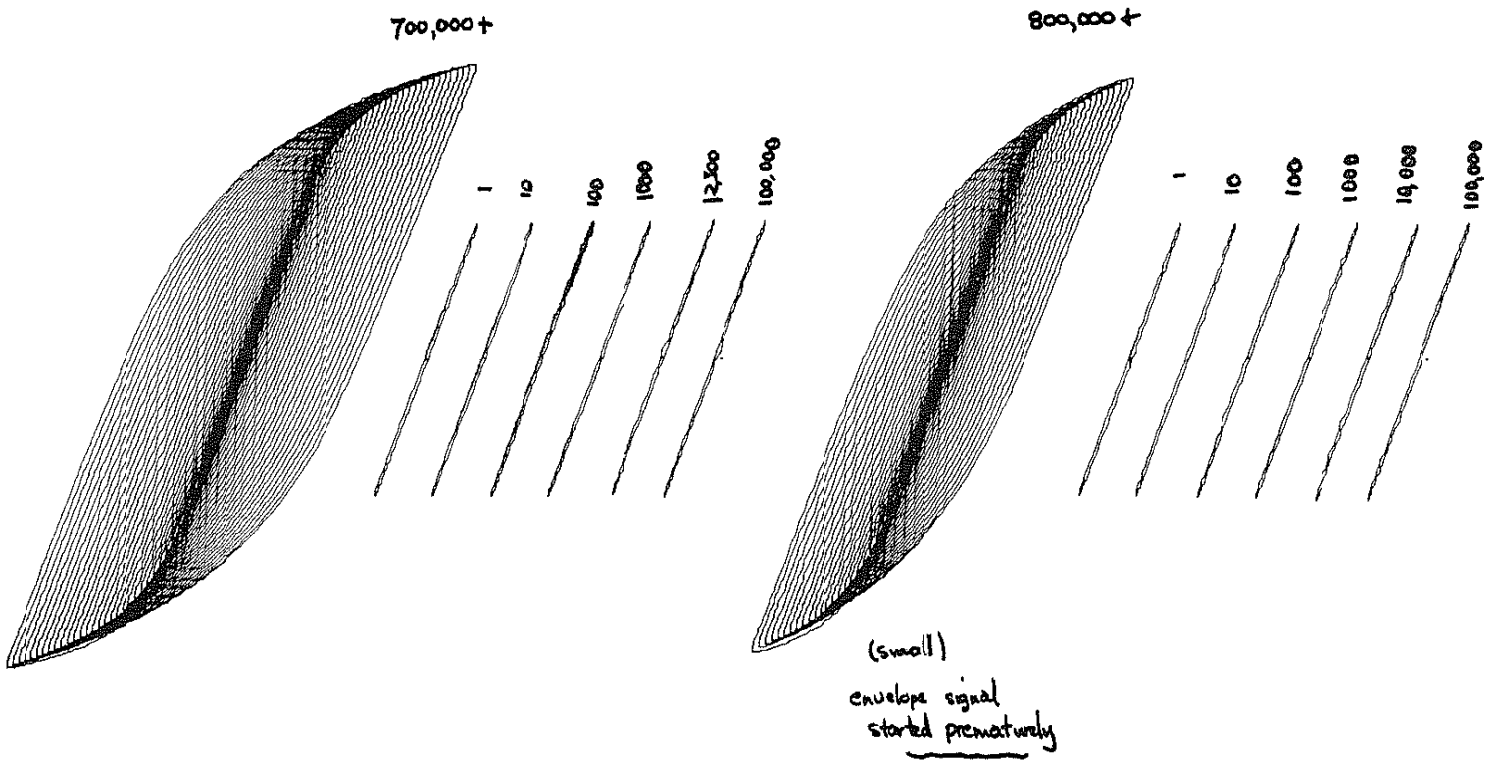
DFD 6/20/74




100,000+
1
10
100
1000
10,000
100,000
E= 27,000
200,000+
E= 25,500
1
10
100
1000
10,000
100,000

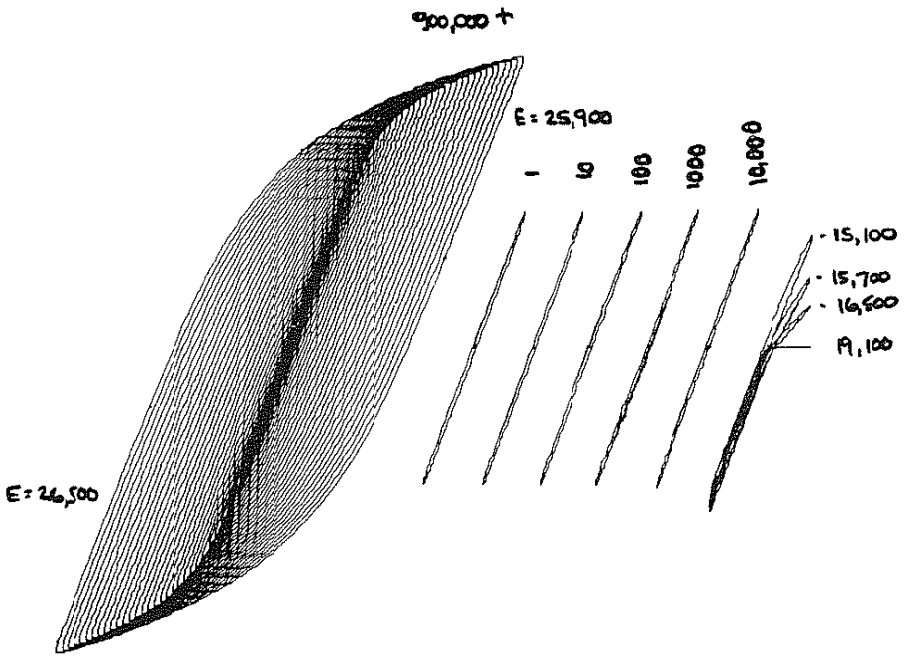

300,000+
1
10
100
1000
10,000
100,000
400,000+
1
10
100
1000
10,000
100,000
1
0 control


500,000 +
1
10
100
1100
10,000
100,000
τ
σ control
600,000+
1
10
100
1000
10,000
100,000
τ
σ control



(small)

envelope signal
started prematurely



$N_f = 915,000$

FINIS!

STRAIN-LIFE RESULTS

STRAIN - LIFE RESULTS

	Spec. No.	Strain Amplitude $\Delta\epsilon/2 \times 10^{-5}$	Revs. to Failure $2N_f$	Elastic Strain Amplitude $\Delta\epsilon_e/2 \times 10^{-5}$	Plastic Strain Amplitude $\Delta\epsilon_p/2 \times 10^{-5}$	Saturation * Stress Amplitude $\Delta\sigma/2$, ksi
Group I	DT1 - 04	1,032	1,058	294	738	88.1
	DT1 - 05	653	3,880	331	322	88.6
	DT1 - 06	463	12,300	303	160	82.2
	DT1 - 07	368	27,200	265	103	70.7
	DT1 - 08	308	42,000	241	67	67.8
	DT1 - 10	250	91,000	232	18	66.1
	DT1 - 09	210	724,000**	209	> 1	59.3
	DT1 - 12	194	9.2×10^6**	194	---	55.1
	DT1 - 11	169	10.8×10^6**	169	---	47.1
Group II	DT1 - 14	461	15,200	301	160	82.8
	DT1 - 15	251	111,000	223	23	66.5
	DT1 - 16	200	840,000	200	---	58.9
Group III	DT1 - 13	200	900,000	200	---	55.1
	DT1 - 17	169	1.83×10^6	169	---	46.7

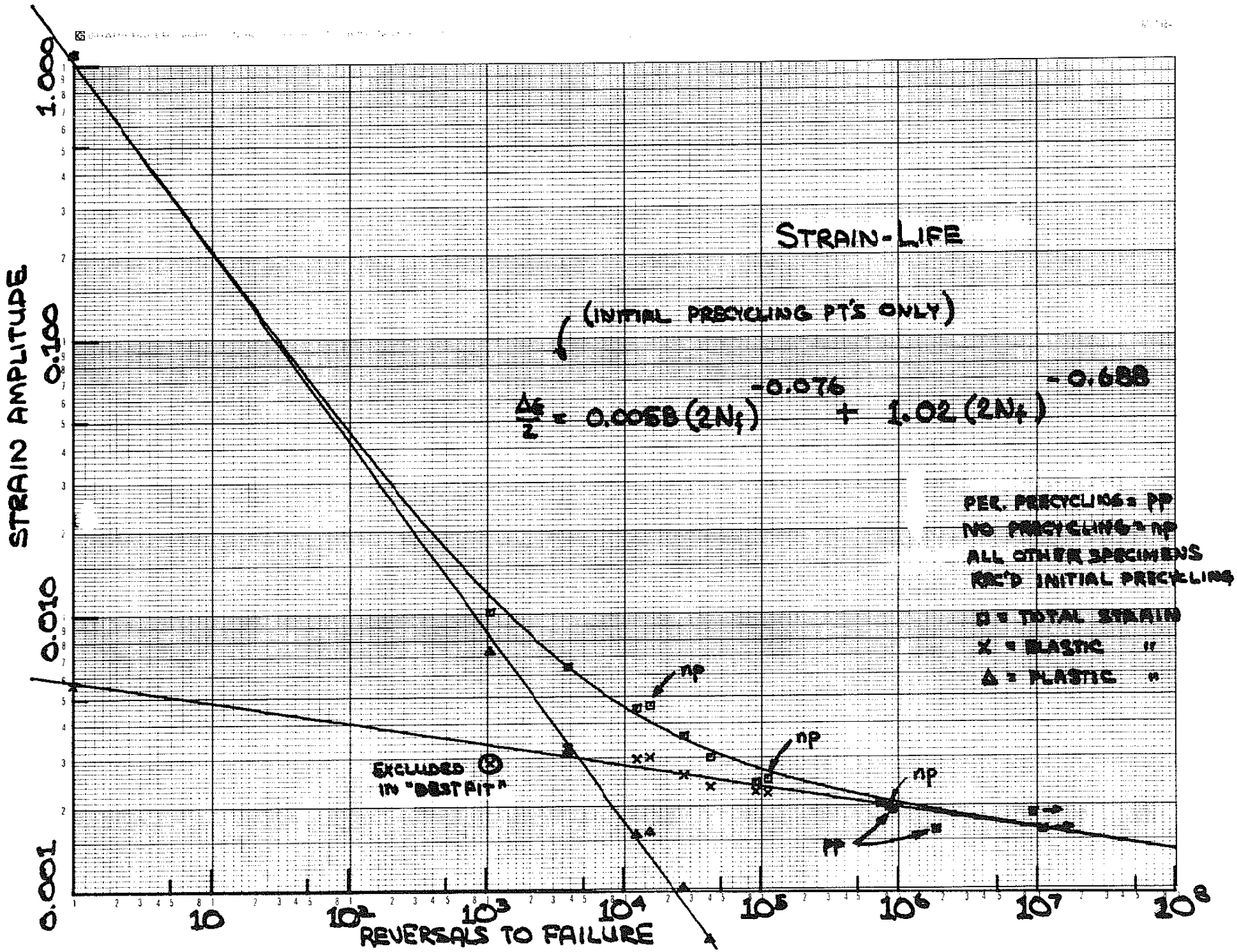
GROUP I = Received an initial precycle

GROUP II = Tested at constant amplitude without precycling

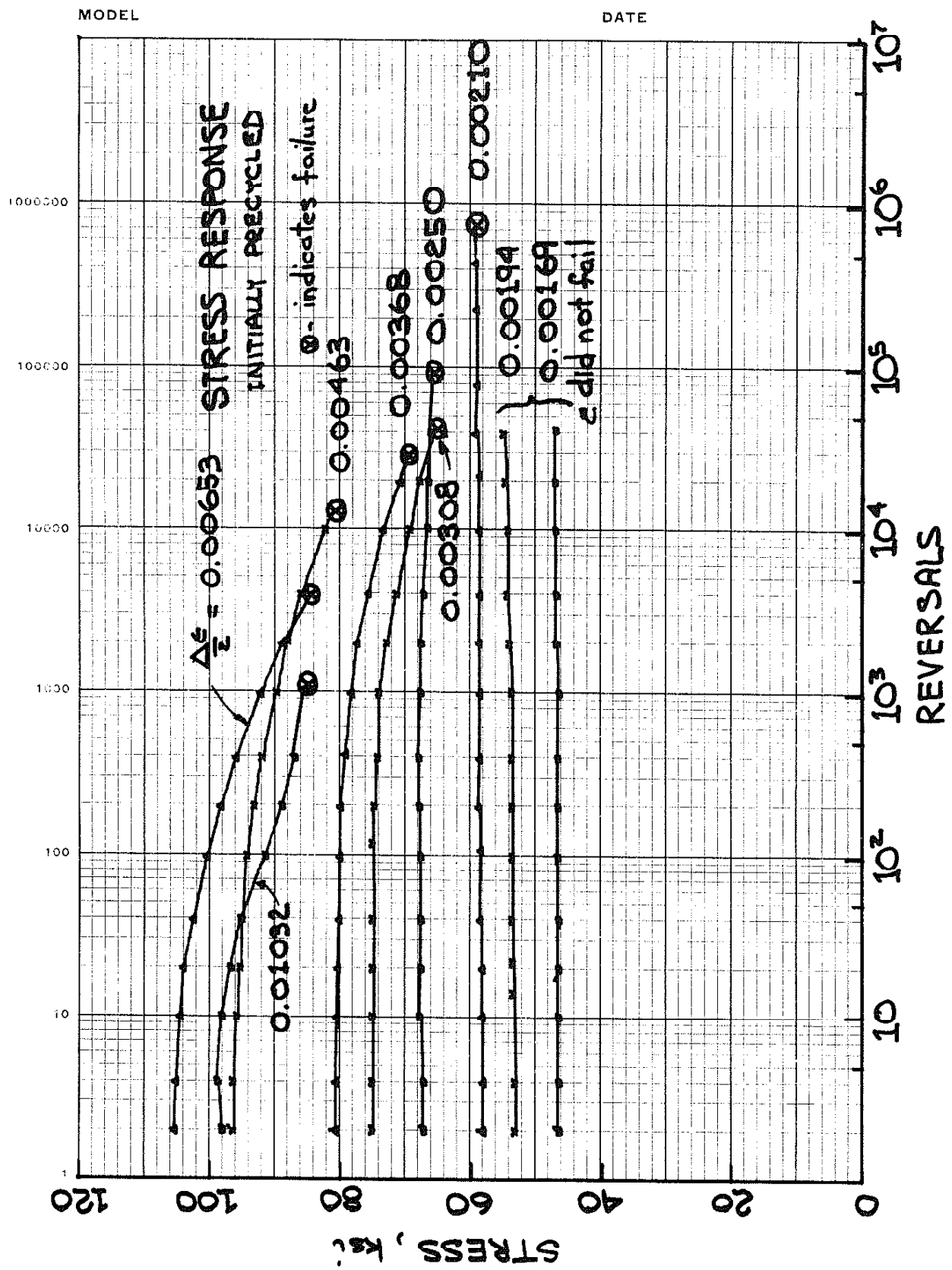
GROUP III = Received an initial precycle plus periodic precycling (overstrain).

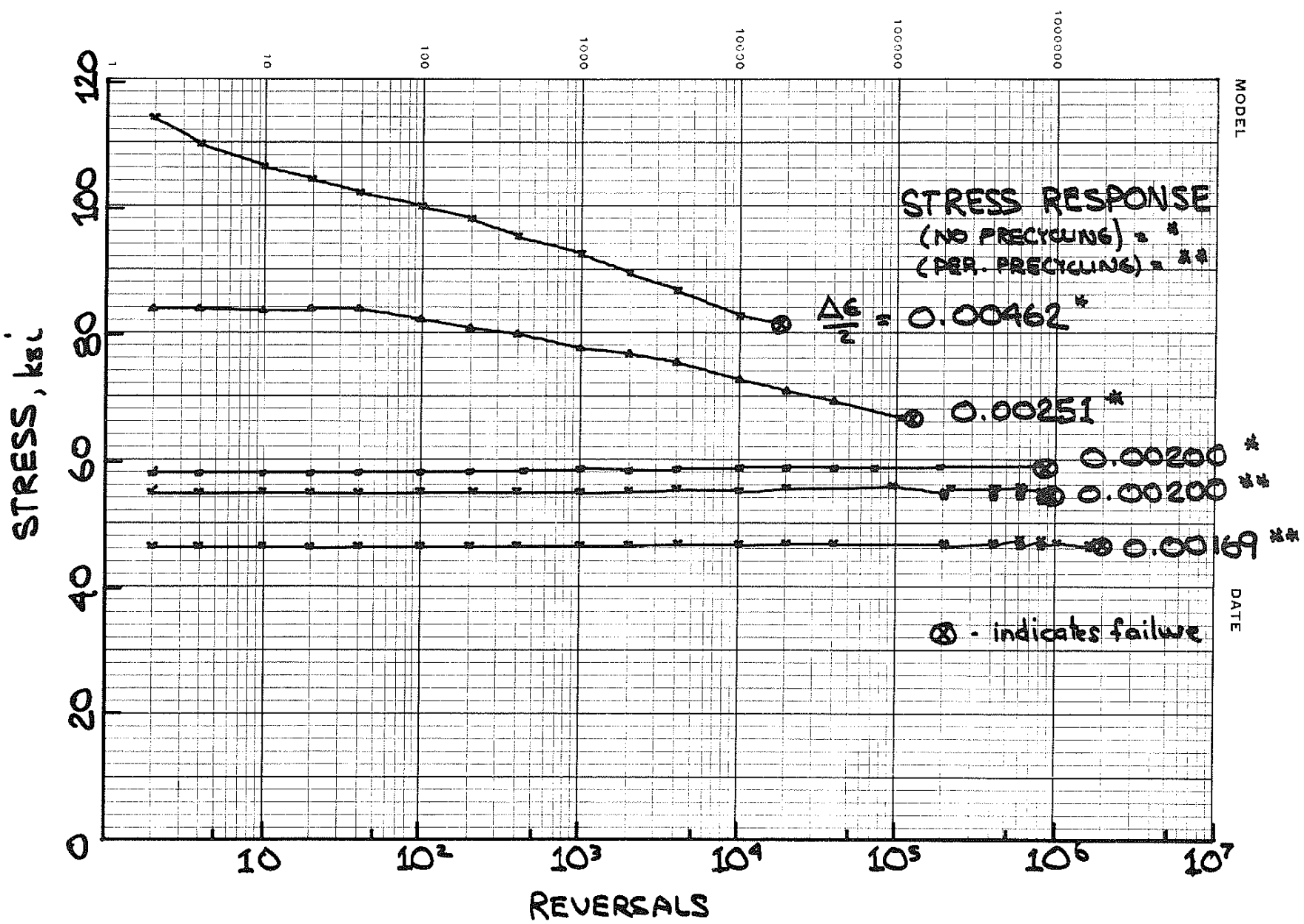
* Measured at 50% of life to failure

** Runout, specimen did not fail


STRAIN-LIFE
(INITIAL PRECYCLING PT'S ONLY)
$\frac{\Delta\varepsilon}{2} = 0.0058(2N_f)^{-0.076} + 1.02(2N_f)^{-0.688}$
PER. PRECYCLING = PP
NO PRECYCLING = nP
ALL OTHER SPECIMENS
REC'D INITIAL PRECYCLING
□ = TOTAL STRAIN
X = ELASTIC "
Δ = PLASTIC "
EXCLUDED IN "BEST FIT"
STRAIN AMPLITUDE
1.000
0.100
0.010
0.001
10
10^2
10^3
10^4
10^5
10^6
10^7
10^8
REVERSALS TO FAILURE

STRESS-TIME RESPONSE TO CONTROLLED STRAIN FATIGUE TESTS


MODEL
DATE
STRESS RESPONSE
INITIALLY PRECYCLED
⊗ - indicates failure
$\frac{\Delta\varepsilon}{2}$ = 0.00653
0.00463
0.00368
0.00308
0.00250
0.00210
0.00194
0.00169
did not fail
0.01032
STRESS, ksi
REVERSALS
1
10
100
1000
10000
100000
1000000
10^1
10^2
10^3
10^4
10^5
10^6
10^7
0
20
40
60
80
100
120


STRESS RESPONSE
(NO PRECYCLING) = *
(PER. PRECYCLING) = **
$\frac{\Delta\epsilon}{2}$ = 0.00462 *
0.00251 *
0.00200 *
0.00200 **
0.00169 **
⊗ - indicates failure
MODEL
DATE
STRESS, ksi
REVERSALS
0
20
40
60
80
100
120
1
10
100
1000
10000
100000
1000000
10
10^2
10^3
10^4
10^5
10^6
10^7

ADDITIONAL MATERIAL CHARACTERIZATION SHEETS

DATA SHEET FOR MATERIAL CHARACTERIZATION

Material: U.S.S. T-1 (Deere and Company)

Condition: as rec'd

Matrix Hardness: 256 BHN

Converted from: ----

Monotonic Properties:

Modulus of Elasticity, E	30.2	$\times 10^3$ ksi
Yield Strength, 0.2% S_y	105	ksi
Ultimate Strength, S_u	117	ksi
Red. in Area, % RA	66	
True Fracture Strength, σ_f	176	ksi
True Fracture Ductility, ϵ_f	1.08	
Strain Hardening Exponent, n	0.088	
Strength Coefficient, K	160	ksi
True Toughness, U_p	160,000	$in\text{-}lb/in^3$
Poisson's Ratio	-----	

Cyclic Properties:

Yield Strength, 0.2% S_y'	78	ksi
Strain Hardening Exponent, n'	0.136	
Strength Coefficient, K'	182	ksi
Fatigue Strength Coefficient, σ_f'	174	ksi
Fatigue Ductility Coefficient, ϵ_f'	1.02	
Fatigue Strength Exponent, b	-0.076	
Fatigue Ductility Exponent, c	-0.688	
Transition Fatigue Life, $2N_t$	5000	rev

Microstructure: Tempered Martensite

Magnification:

Comments:

1) Average compressive 0.002 offset = 110 ksi
2) Specimens removed from 5/8" plate parallel to rolling direction
3) Boron is not present in composition
4) Initial precycling had little effect on fatigue life as compared with non-precycled results
5) Periodic overstraining of a specimen run at a constant strain amplitude (0.0017) results in failure at 1.8×10^6 rev's. whereas runout occurs at a constant amplitude

Composition:

w/o C	= 0.228		w/o Mo	=	0.27
w/o Si	= 0.20		w/o Cu	=	----
w/o P	= 0.039		w/o Ni	=	0.98
w/o S	= 0.023		w/o Va	=	0.06
w/o Mn	= 0.73		w/o Al	=	----
w/o Cr	= 0.48		w/o B	=	*see comments

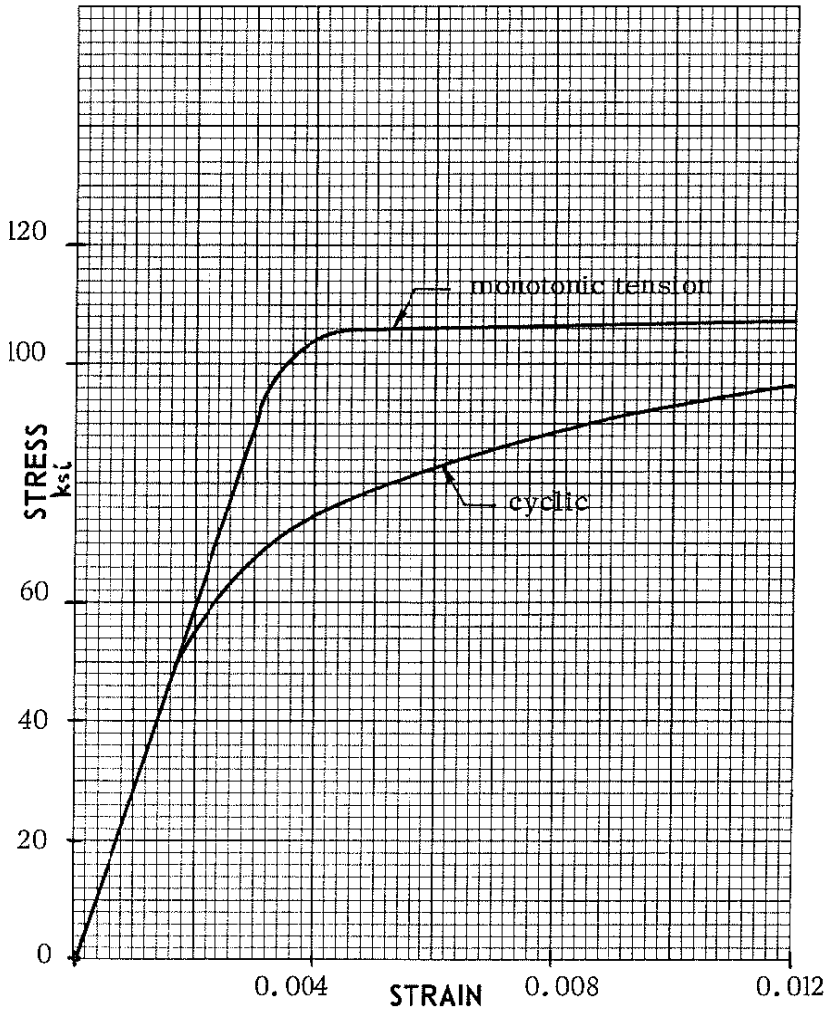
Grain Size: Grain Flow → 105mm 90 mm

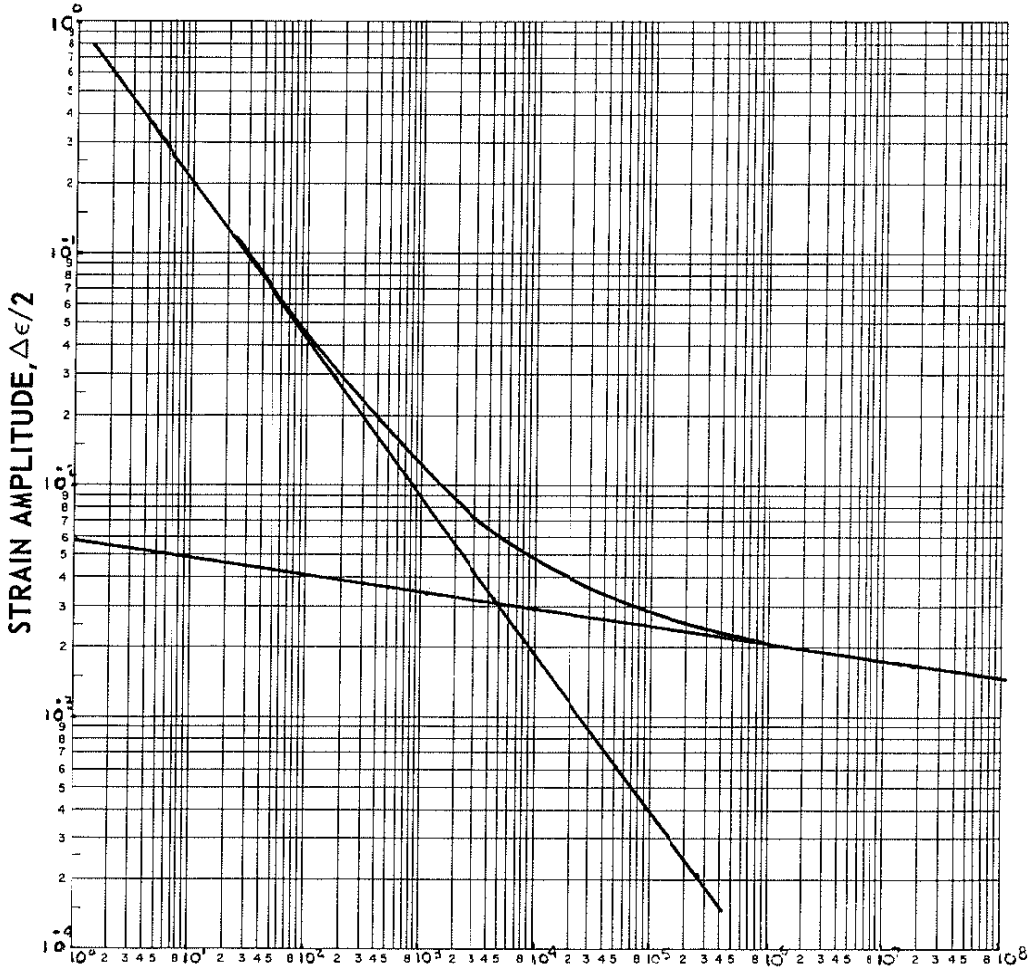
Eutectic Cell Size (Cast irons):

FRACTURE CONTROL PROGRAM
UNIVERSITY OF ILLINOIS
DFD 6/24/74

Material: U.S.S. T-1 (Deere and Company) **Hardness:** 256 BHN

Condition: as rec'd





DFD
6/24/74

FRACTURE CONTROL PROGRAM
UNIVERSITY OF ILLINOIS