Technical Report

FIBER AND YARN PROPERTIES AS RELATED TO ROPE DEPLOYMENT IN DEEP SEA MOORINGS

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This program is narrowly focused to provide constitutive relations for fibrous materials for inclusion in overall modeling of mechanical behavior of very long mooring lines. The quantitative data developed should be of direct value in the design and deployment of marine ropes. It is of corresponding value in characterizing the behavior of two major classes of fibers (PET and ARAMID) for application to industrial products.

The materials studied included ENKA PET both with and without marine finish, designated as 855T and 855TN. The ARAMID specimens were DuPont KEVLAR 960 (with marine finish) and 961 (without).

A wide range of physical tests were conducted on the fiber and yarn samples furnished by the Naval Civil Engineering Department at Port Hueneme. These are included in the following listing of properties and behavior studies.

Properties and Behavior Studies

Tensile Stress/Strain Behavior (Dry)

a. In original state

b. After tensile cycling to 30% of original breaking stress

c. After cycling to 60% of original breaking stress

Determination of Tangent Modulus Curves

a. In original state

b. After 30% cycling

c. After 60% cycling

Creep Under Various Constant Loads (Dry)

Creep Recovery Under Zero Load (Dry)

Creep Under Various Constant Loads (Wet)

Creep Recovery Under Zero Load (Wet)

Friction Coefficient Under Various Loads

a. At 10°, 21°, 25°, and 29° (Dry)

b. At 10°, 21°, 25°, and 29° (Wet)

Abrasion Resistance Under Various Loads

Lateral Deformation: Pressure Volume Relations

I. TENSILE STRESS STRAIN BEHAVIOR

KEVLAR ARAMID

Tensile tests were undertaken on 10 inch gage specimens at a strain rate of 0.1 per minute and a special tabbing system was used to suppress jaw breaks. The Instron data was recorded with a NICOLET digital oscilloscope and subsequently analyzed via an IBM PC computer so as to provide direct printout of the stress strain behavior.

The tensile stress strain behavior is presented in form of summary tables and individual stress strain curves. A separate set of data is presented for tests of dry yarn and for tests of wet yarn. In each case 5 specimens of yarn, both dry and wet were subjected to a single stress strain test to failure at the indicated strain rate of 0.1 per minute. Breaking stress (in gm/denier) and breaking strain were recorded in each table.

An additional five specimens were then loaded to 30% of their breaking stress then unloaded and reloaded for 10 cycles. After the 10^{th} cycle the yarn was stressed monotonically to failure and breaking stress and elongation to rupture were recorded.

A third set of 5 specimens was then loaded to 60% of breaking stress, unloaded and reloaded 10 times before conducting the final full stress strain test. Again, breaking stress and strains were recorded in the tables.

The KEVLAR yarns were prepared with and without marine finish. KEVLAR T960 was a 1500 denier yarn with marine finish and KEVLAR T961 was 1500 denier without finish.

The KEVLAR data are presented in the following order of tables and accompanying graphs.

SINGLE LOAD STRESS STRAIN BEHAVIOR

KEVLAR T960 (1500 Denier) WITH Marine Finish

Dry and Wet Tests

SINGLE LOAD STRESS -STRAIN BEHAVIOR

KEVLAR T960 YARN(1500 DENIER WITH MARINE FINISH)

DRY YARN

	ORIGINAL		AFTER 30% B.S. 10 CYCLES		AFTER 60% B.S. 10 CYCLES	
	BREAKING STRESS GM/DENIER	BREAKING STRAIN	BREAKING STRESS GM/DENIER	BREAKING STRAIN	BREAKING STRESS GM/DENIER	BREAKING STRAIN
1	15.0	.036	14.7	.033	14.0	.026
2	14.9	.034	14.6	.032	14.8	.027
3	15.6	.038	14.4	.032	14.0	.027
4	15.2	.036	14.5	.032	12.9	.026
5	14.4	.034	15.5	.033	14.9	.029
MEAN	15.02	.036	14.74	.032	14.12	.027

SINGLE LOAD STRESS -STRAIN BEHAVIOR

KEVLAR T960 YARN (1500 DENIER WITH MARINE FINISH)

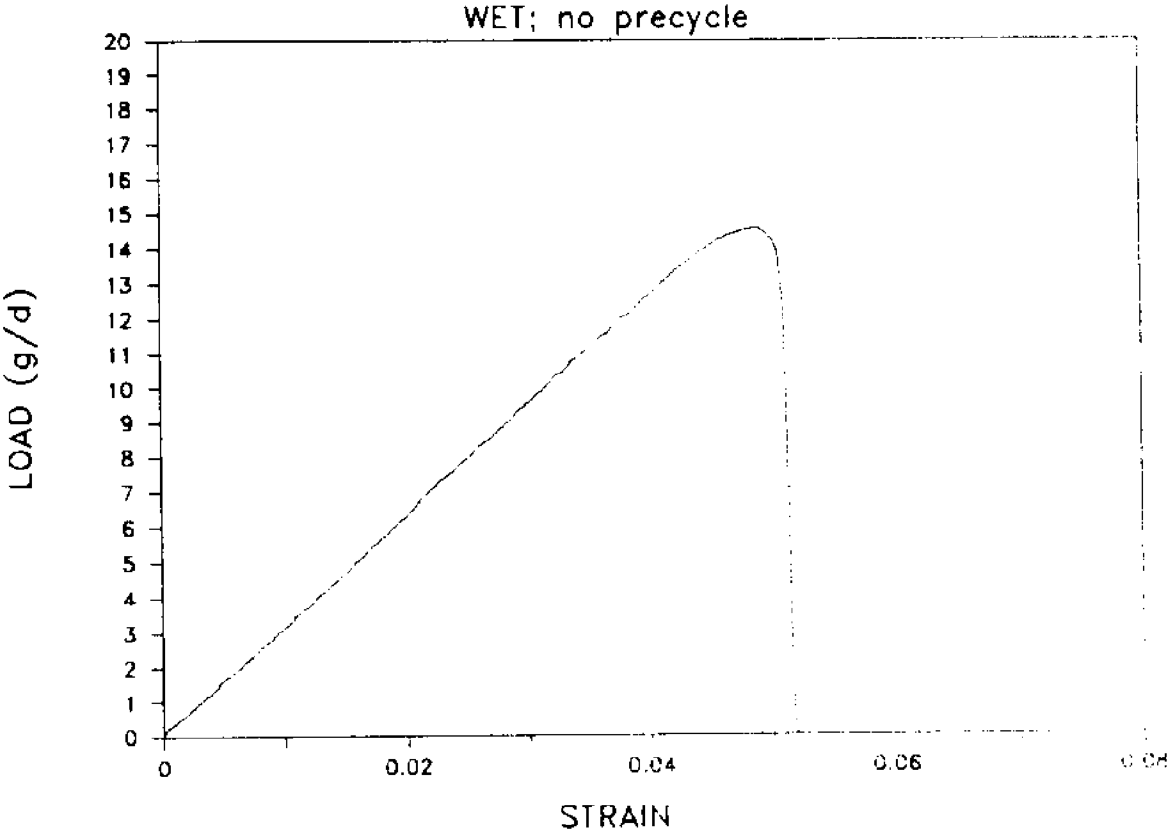
WET YARN

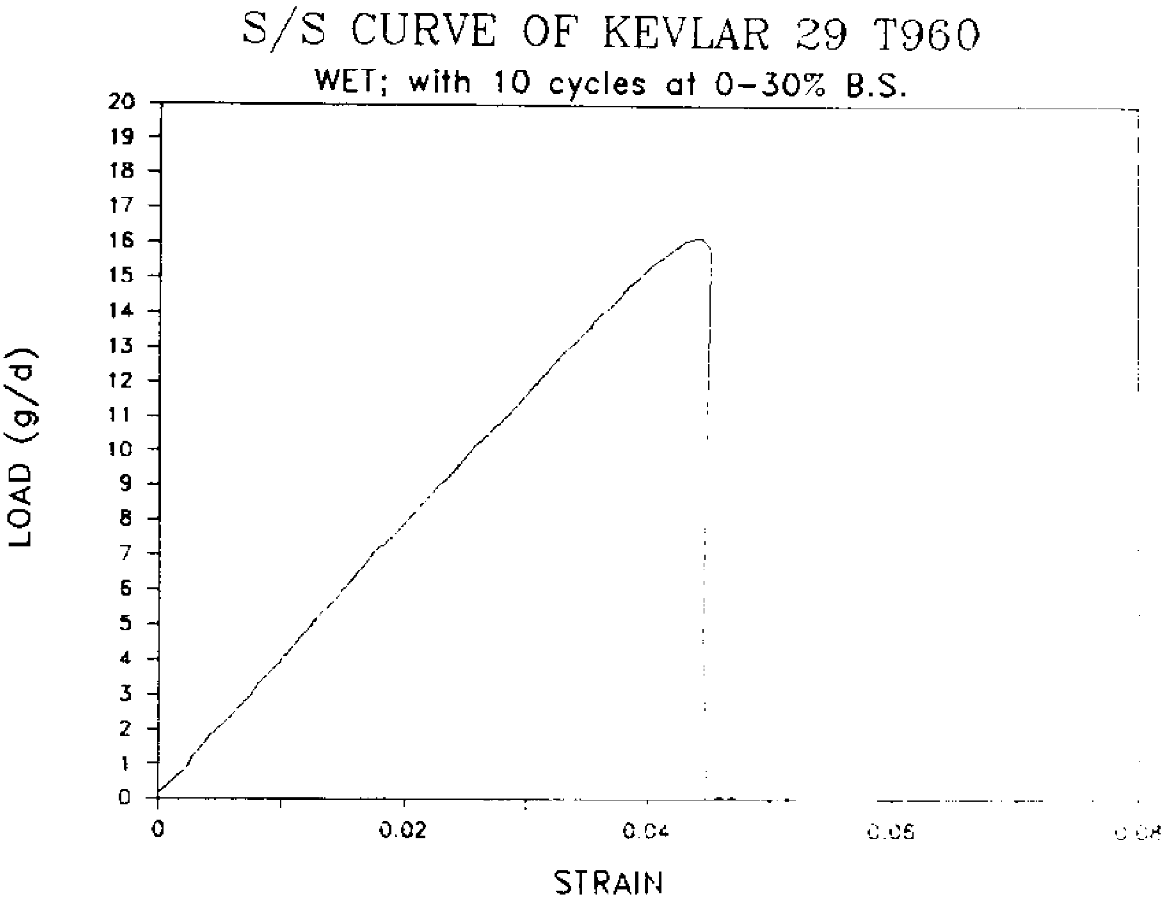
	ORIGINAL		AFTER 30% B.S. 10 CYCLES		AFTER 60% B.S. 10 CYCLES	
	BREAKING STRESS GM/DENIER	BREAKING STRAIN	BREAKING STRESS GM/DENIER	BREAKING STRAIN	BREAKING STRESS GM/DENIER	BREAKING STRAIN
1	16.6	XXX	13.8	XXX	16.0	0.042 *
2	16.0	XXX	14.8	XXX	14.2	XXX
3	16.0	XXX	16.4	0.045 *	13.6	XXX
4	14.8	0.052 *	17.4	XXX	16.6	XXX
5	13.5	XXX	17.2	XXX	16.1	XXX
MEAN	15.4	XXX	15.9	XXX	15.3	XXX

* representative value

S/S CURVE OF KEVLAR 29 T960

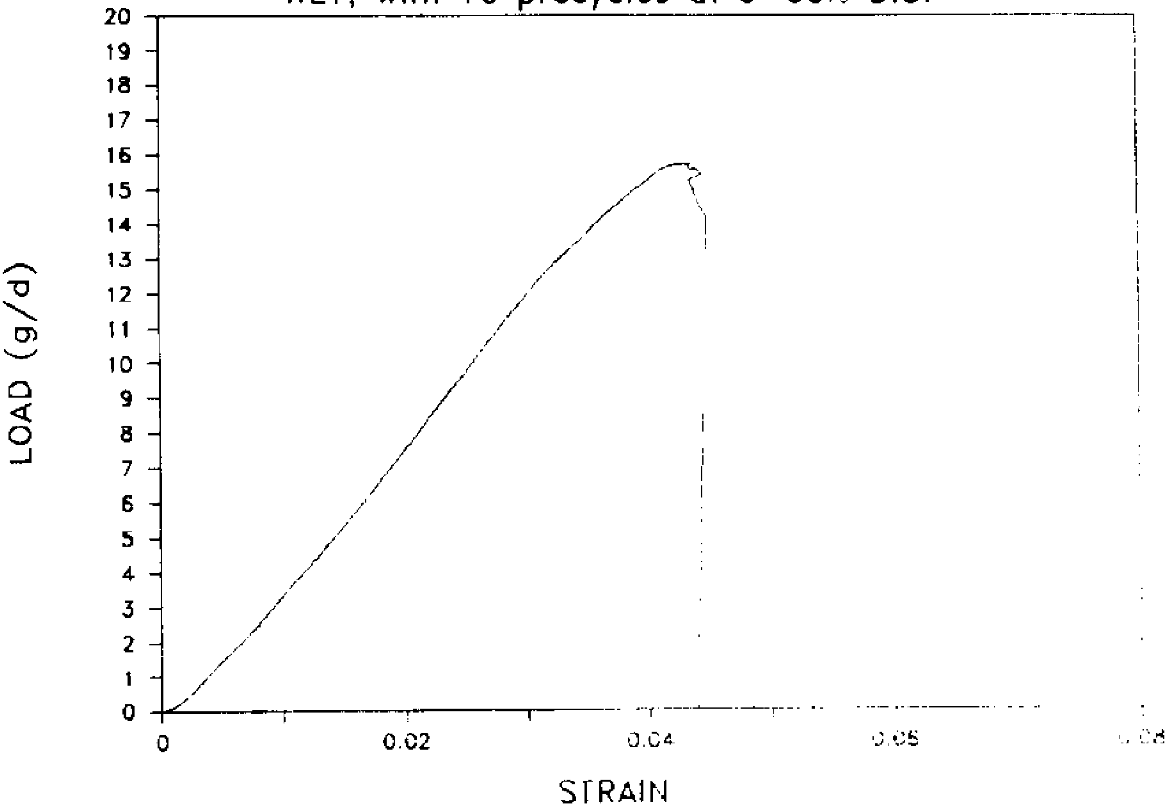
WET; no precycle



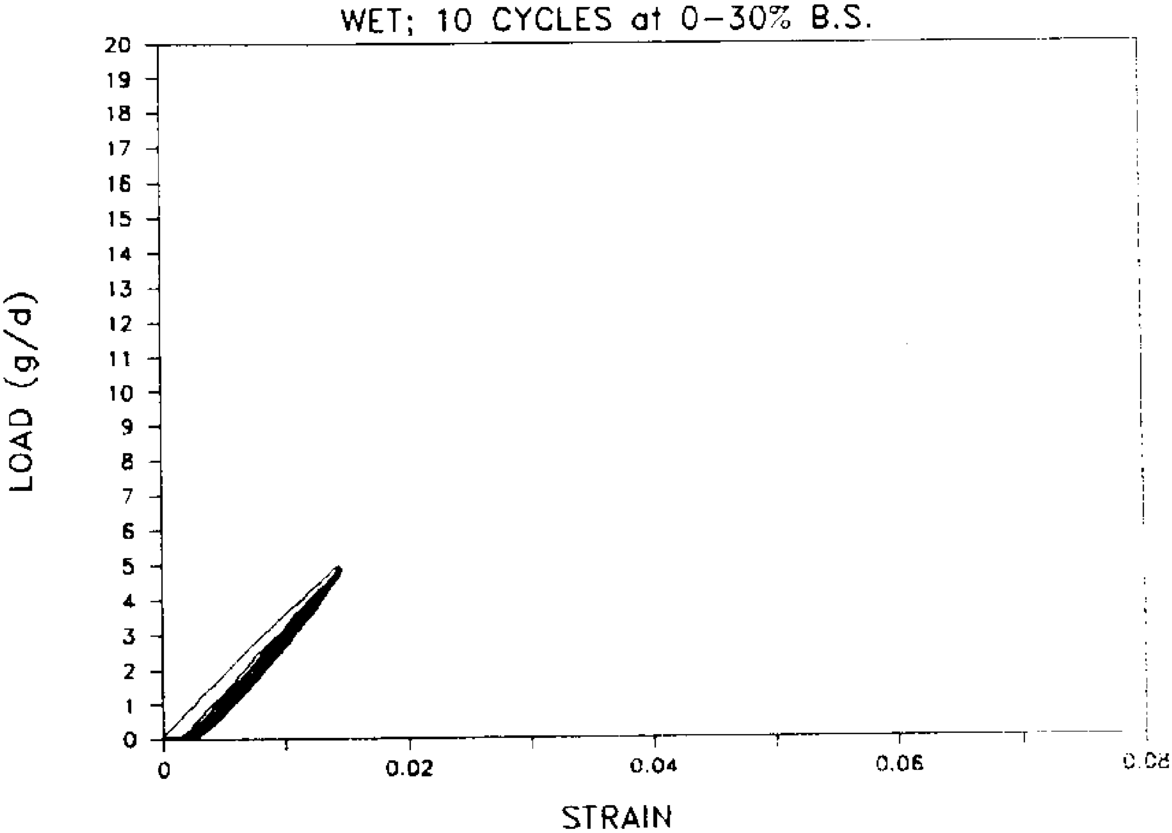

S/S CURVE OF KEVLAR 29 T960
WET; with 10 cycles at 0-30% B.S.
LOAD (g/d)
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
0
0.02
0.04
STRAIN

S/S CURVE OF KEVLAR 29 T960

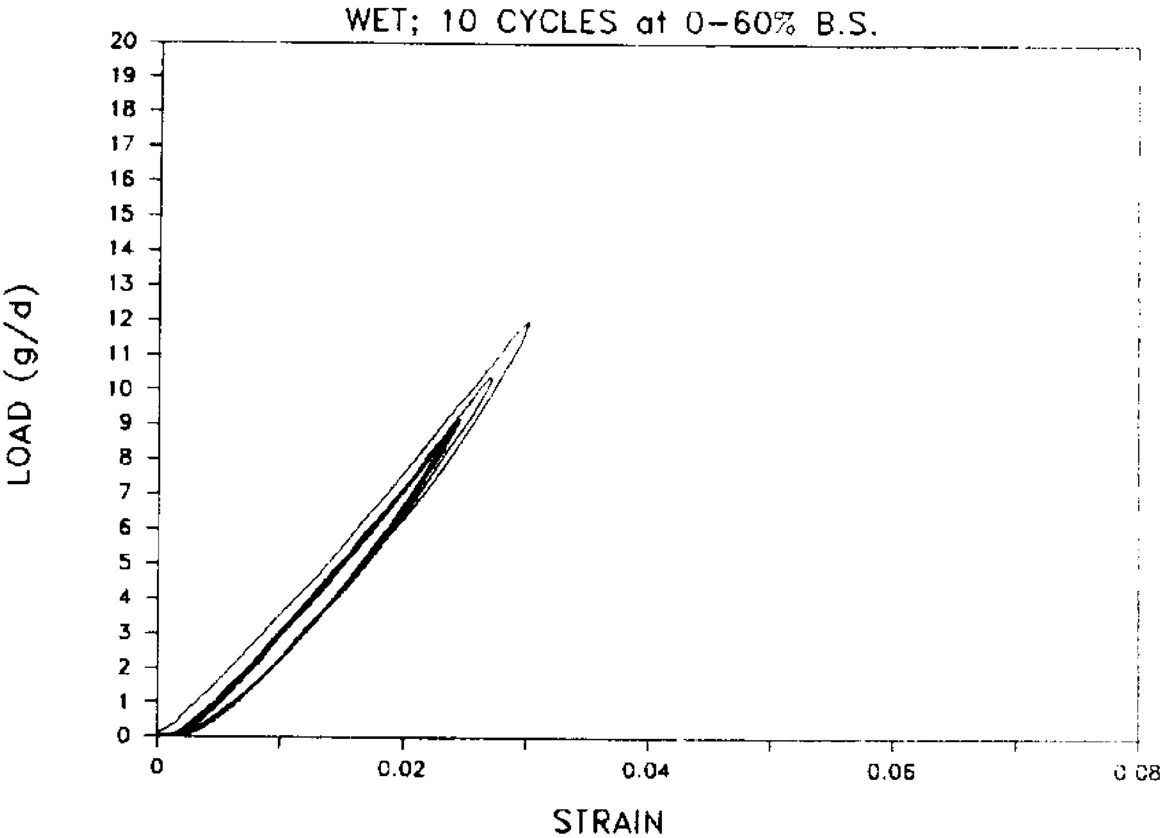
WET; with 10 precycles at 0–60% B.S.



PRECYCLE S/S CURVE OF KEVLAR 29 T960

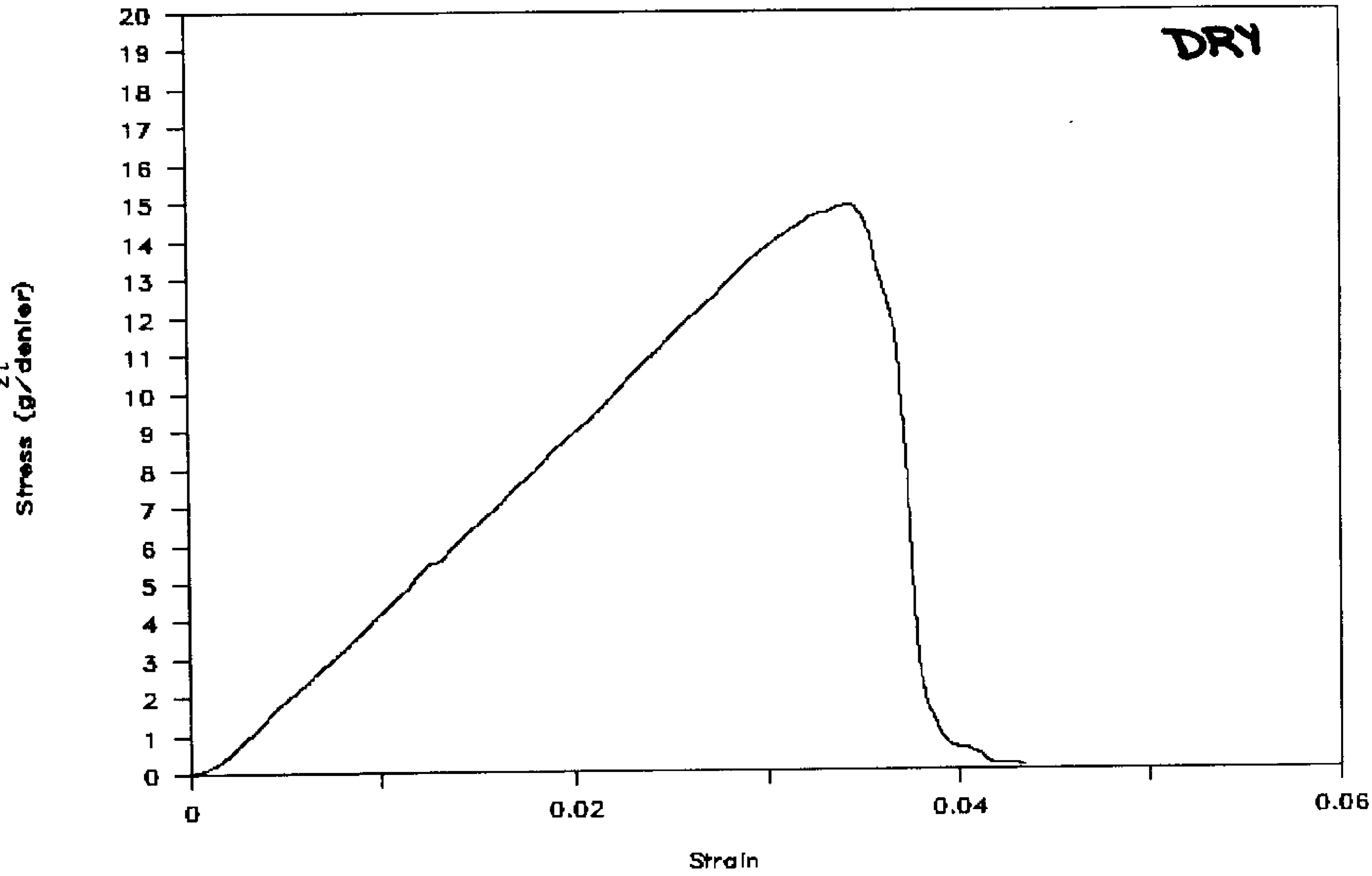


PRECYCLE S/S CURVE OF KEVLAR 29 T960



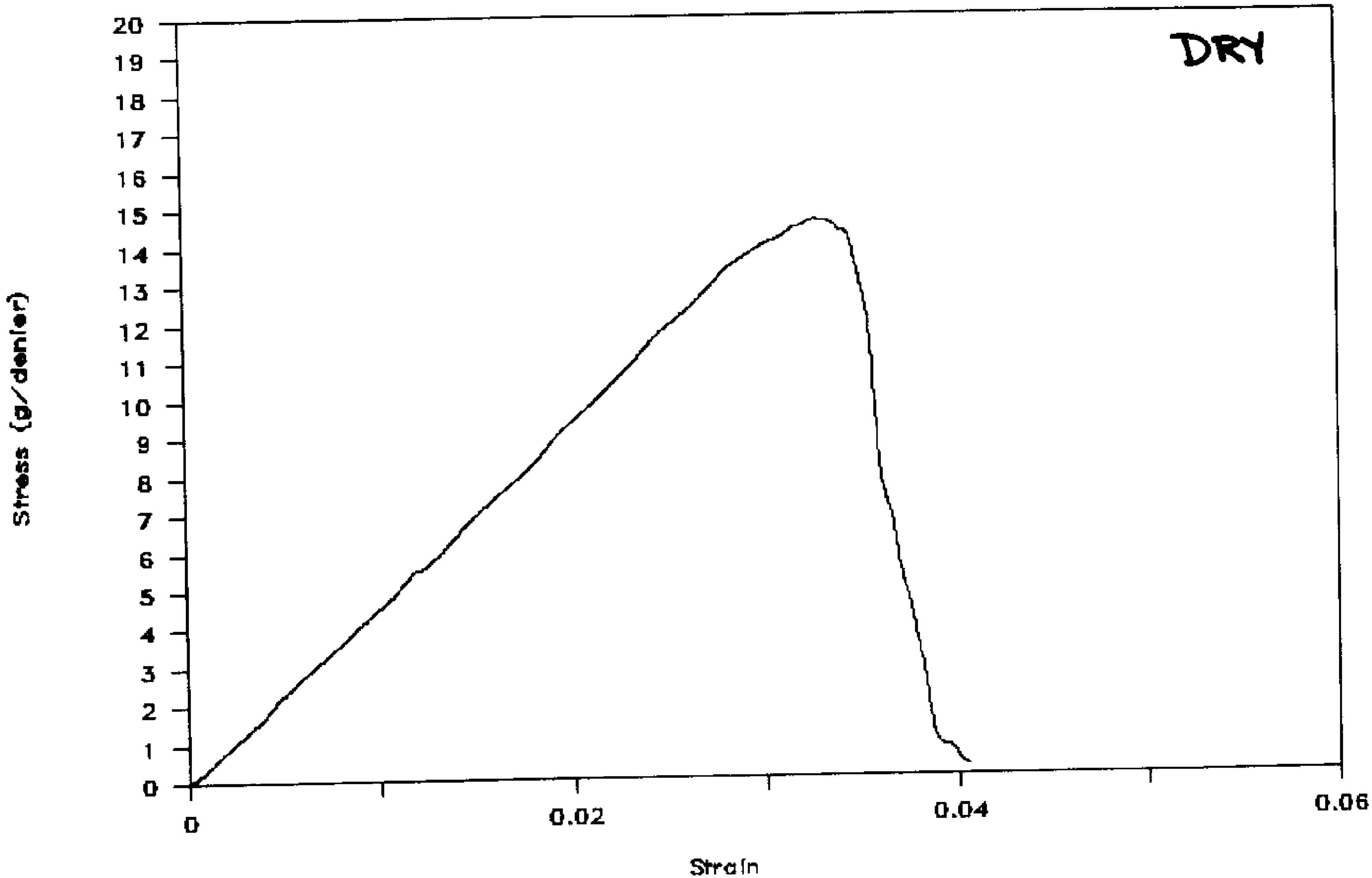
KEVLAR 960 Single Pull

Test 1



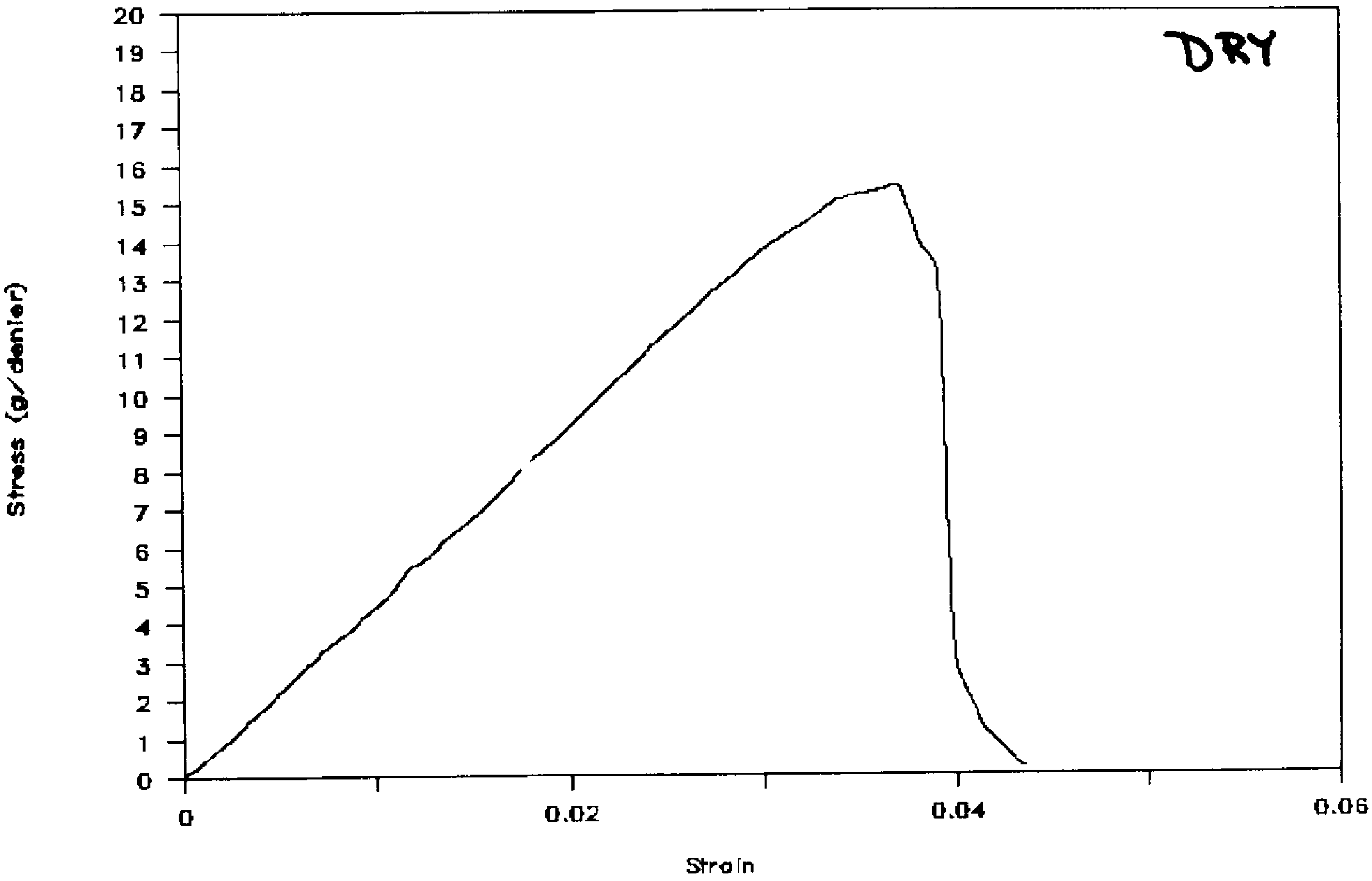
KEVLAR 960 Single Pull

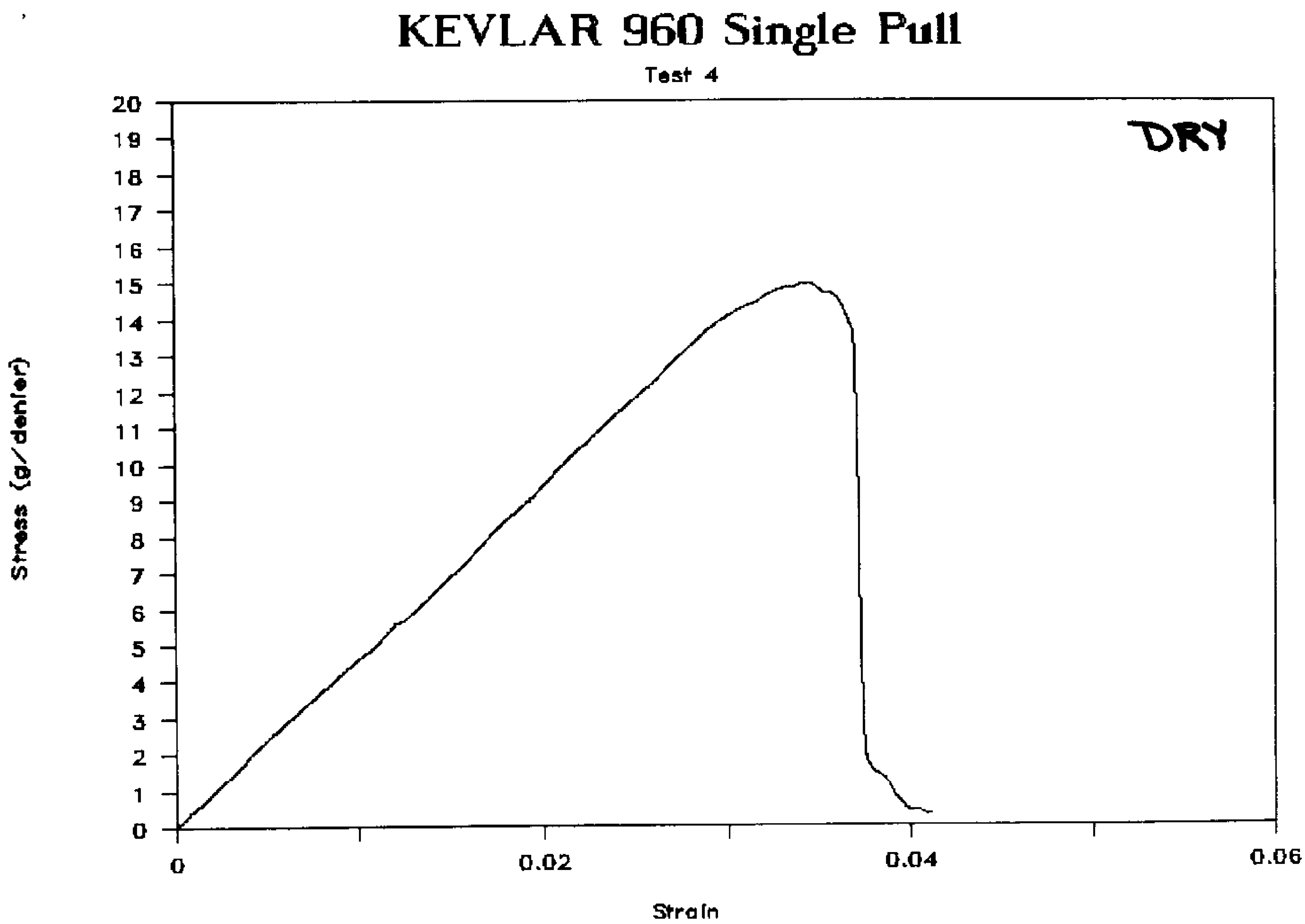
Test 2



KEVLAR 960 Single Pull

Test 3

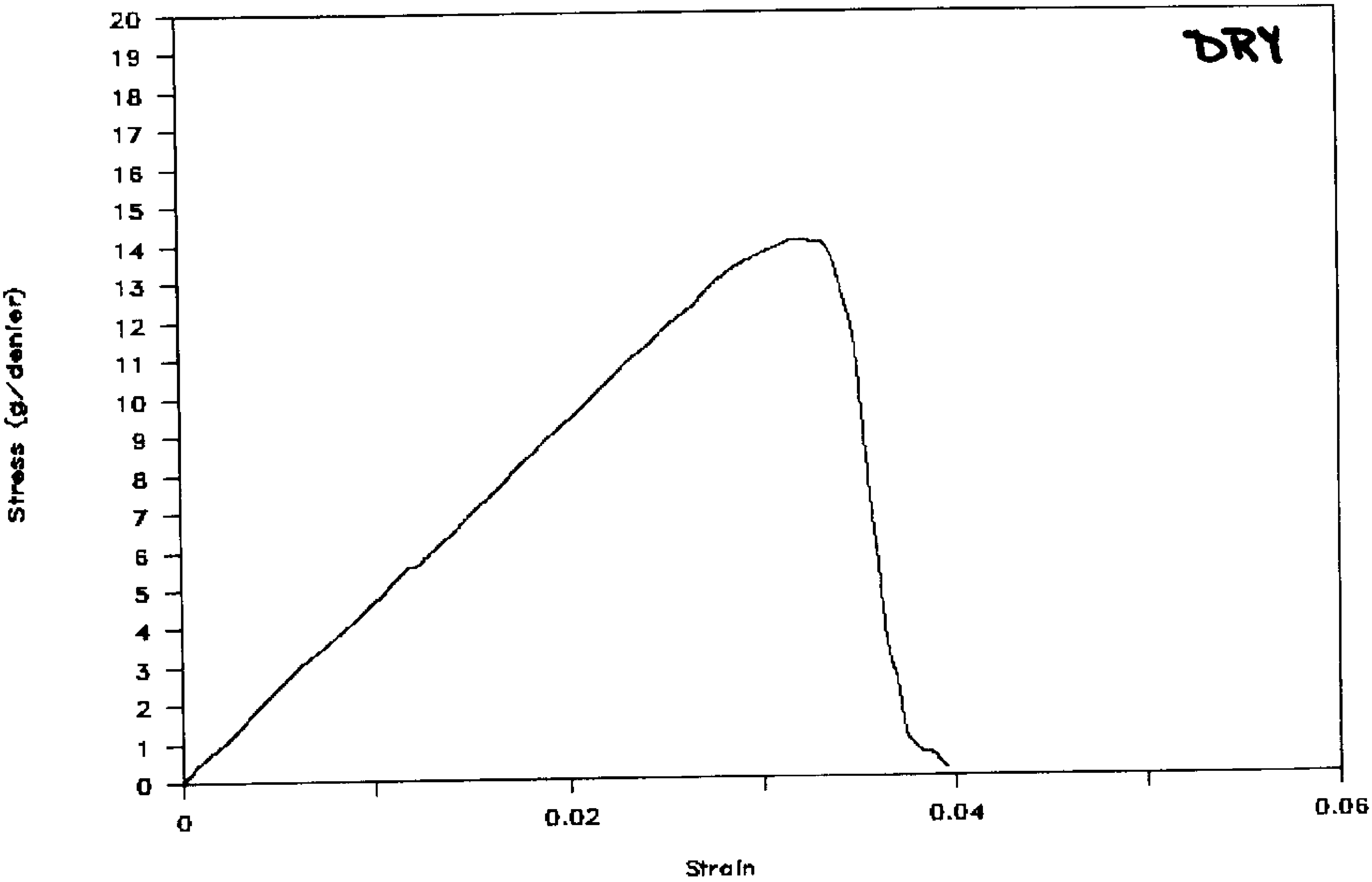




KEVLAR 960 Single Pull
Test 4
DRY
Stress (g/denier)
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
0
0.02
0.04
0.06
Strain

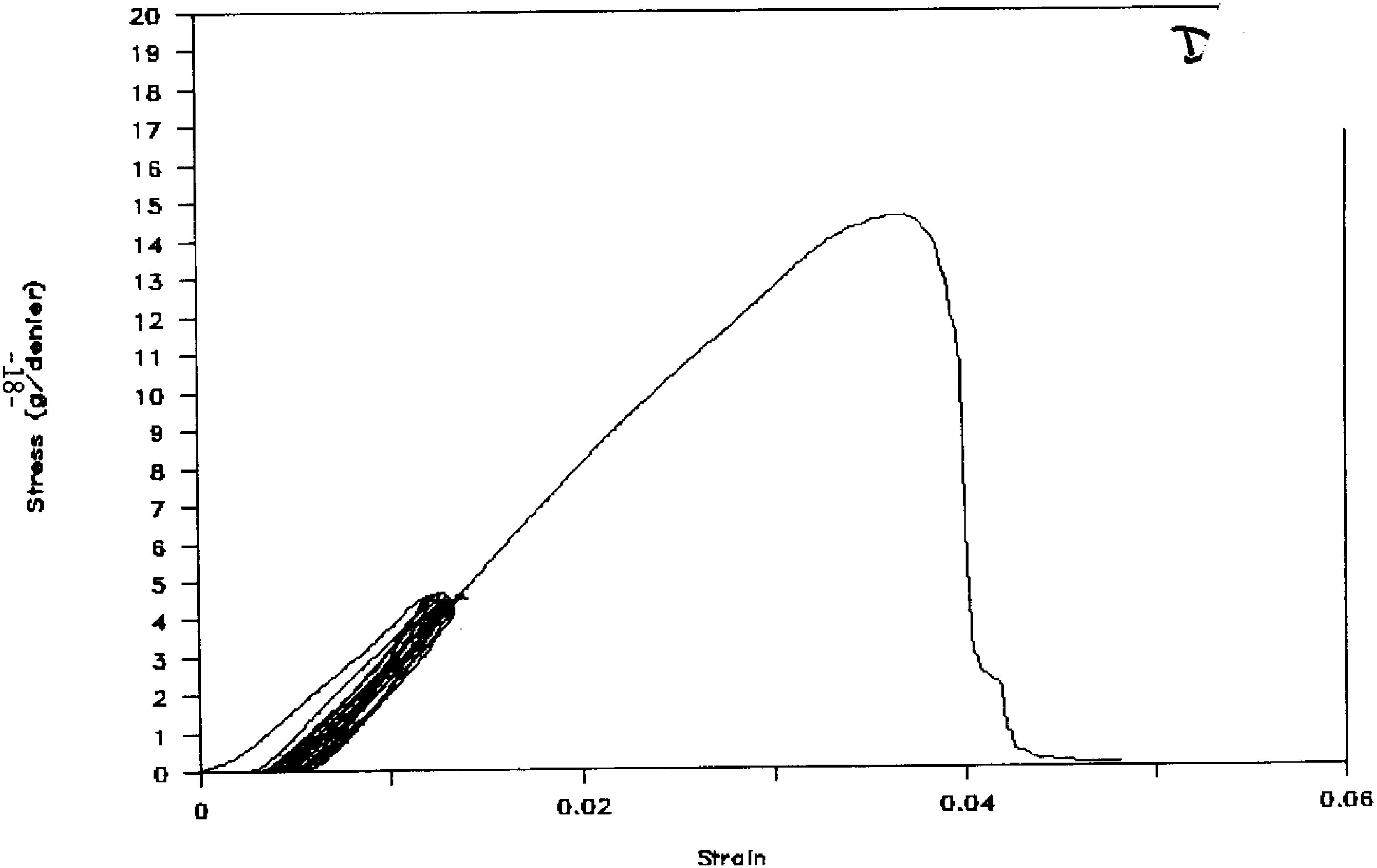
KEVLAR 960 Single Pull

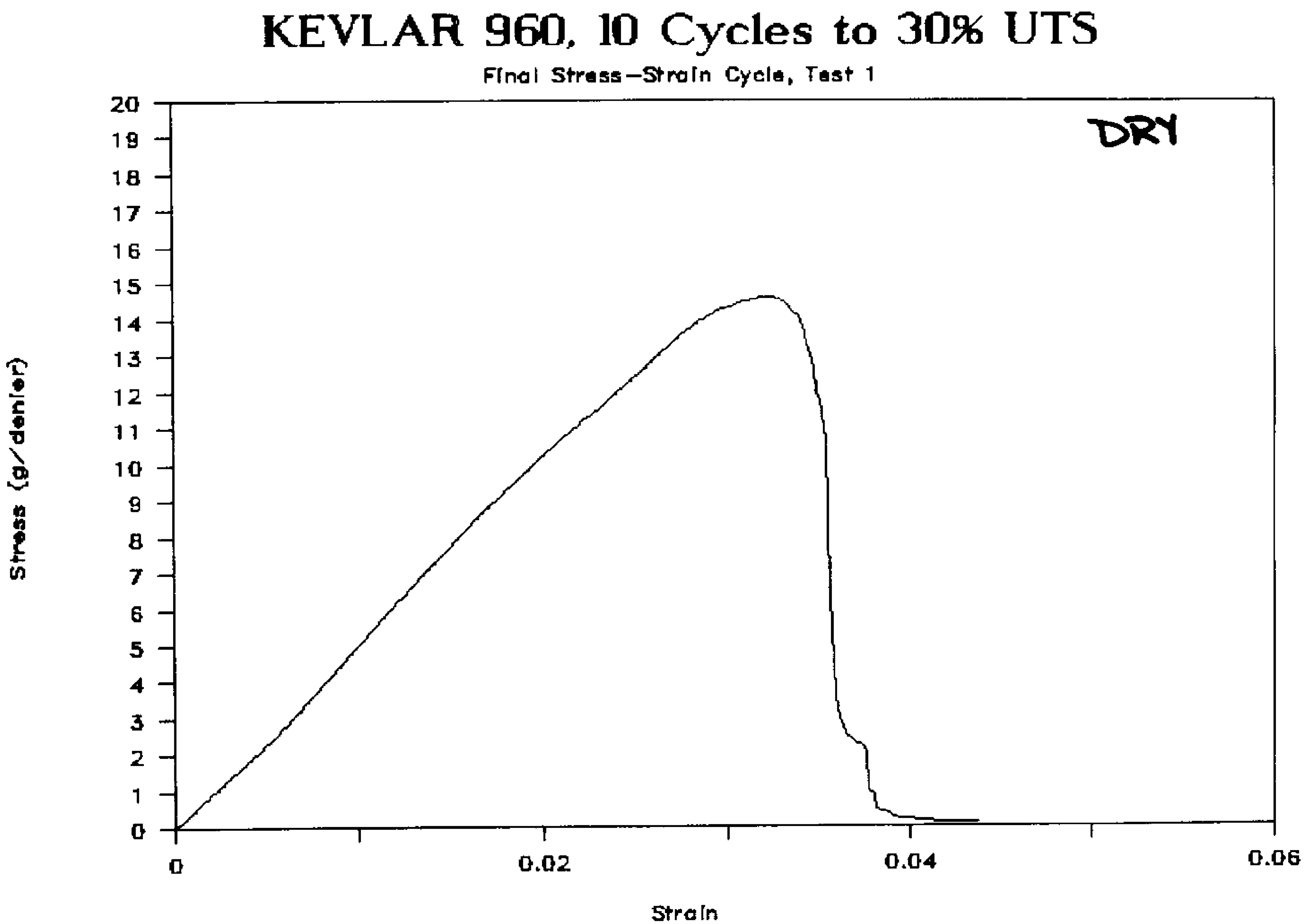
Test 5

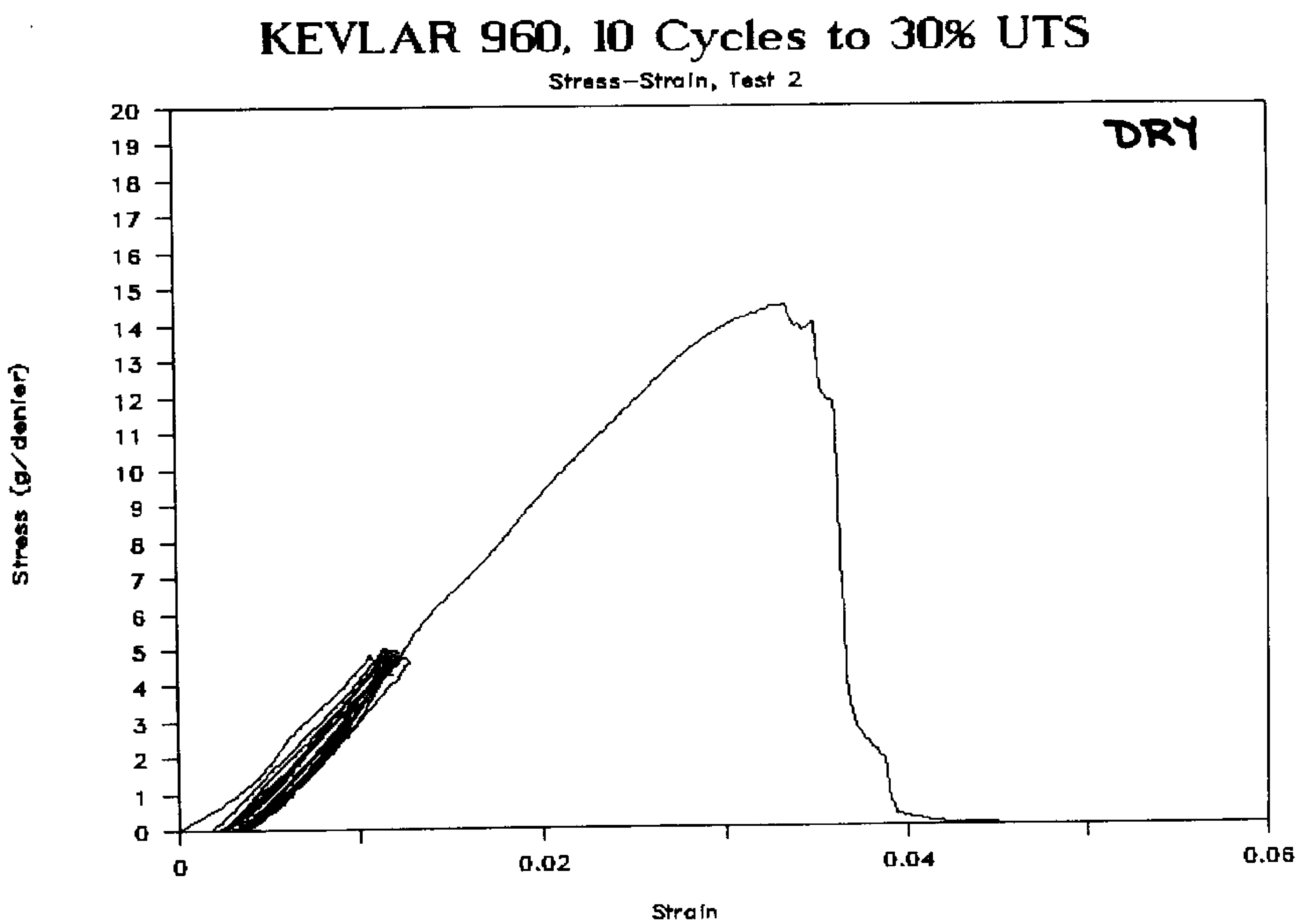


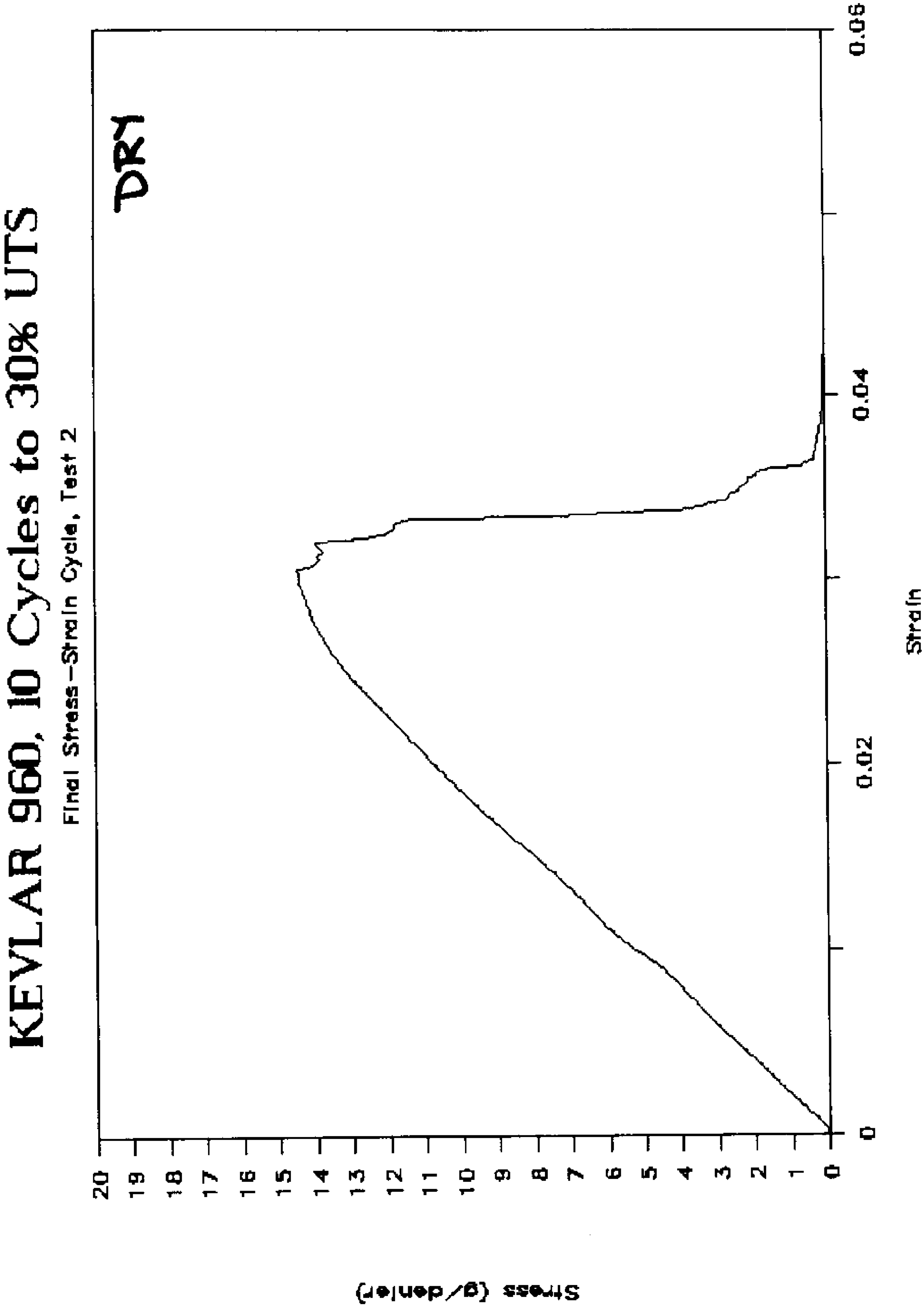
KEVLAR 960, 10 Cycles to 30% UTS

Stress–Strain, Test 1

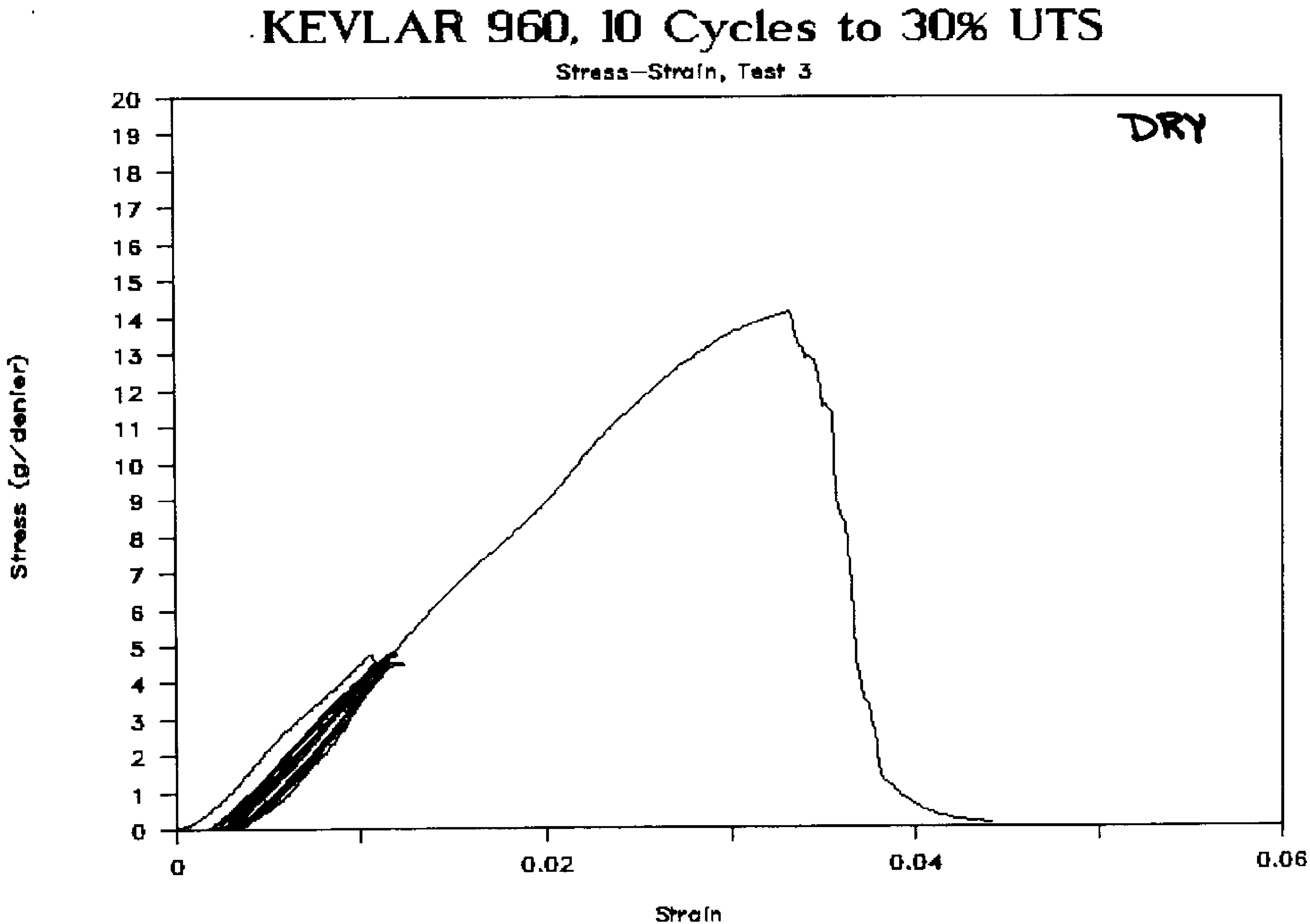



KEVLAR 960, 10 Cycles to 30% UTS
Final Stress–Strain Cycle, Test 1
DRY
Stress (g/denier)
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
0
0.02
0.04
0.06
Strain


KEVLAR 960, 10 Cycles to 30% UTS
Stress—Strain, Test 2
DRY
Stress (g/denier)
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
0
0.02
0.04
0.06
Strain

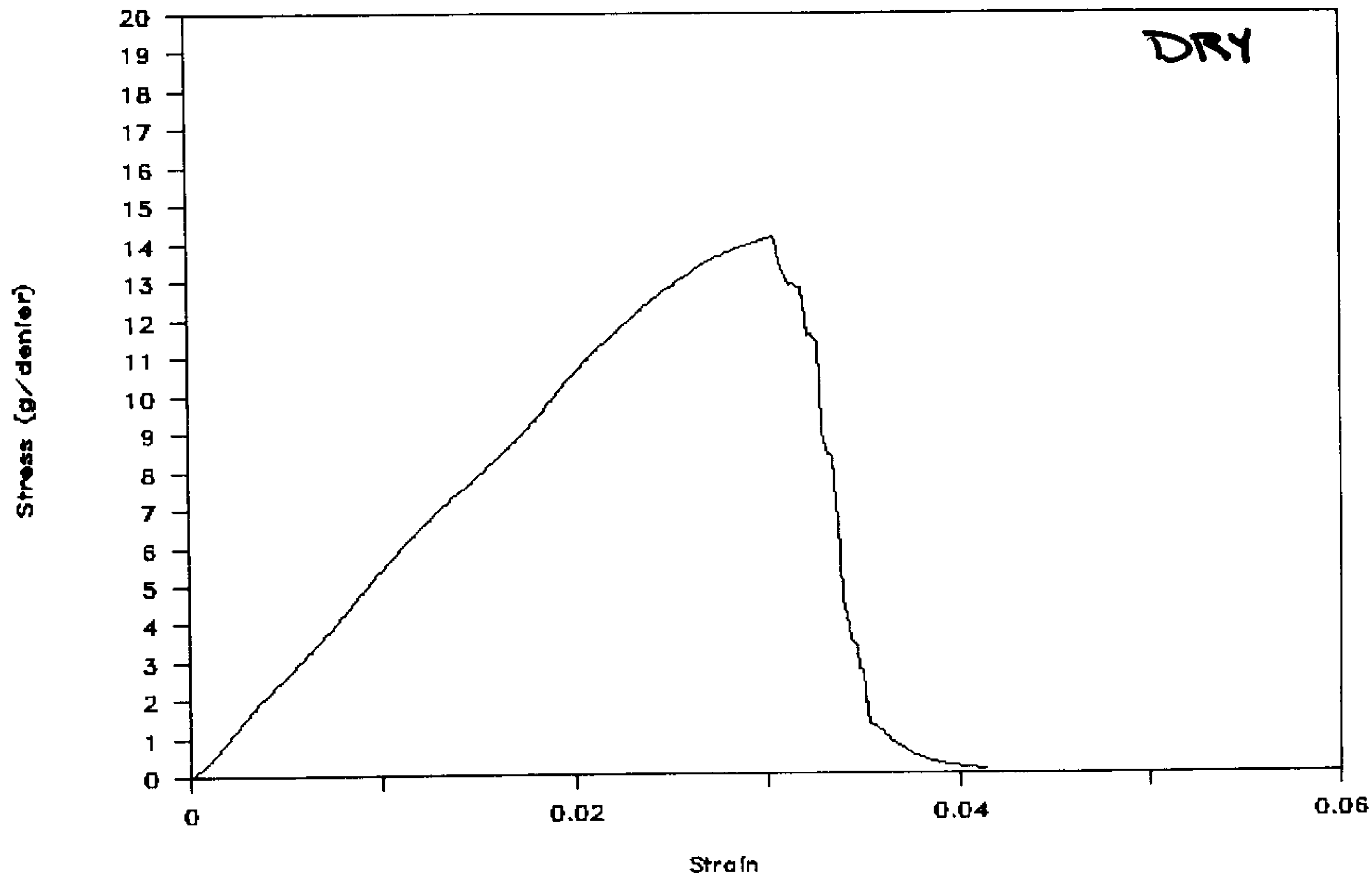


KEVLAR 960, 10 Cycles to 30% UTS
Final Stress—Strain Cycle, Test 2
DRY
Stress (g/denier)
Strain
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
0
0.02
0.04
0.06


KEVLAR 960, 10 Cycles to 30% UTS
Stress—Strain, Test 3
DRY
Stress (g/denier)
Strain
0
0.02
0.04
0.06
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20

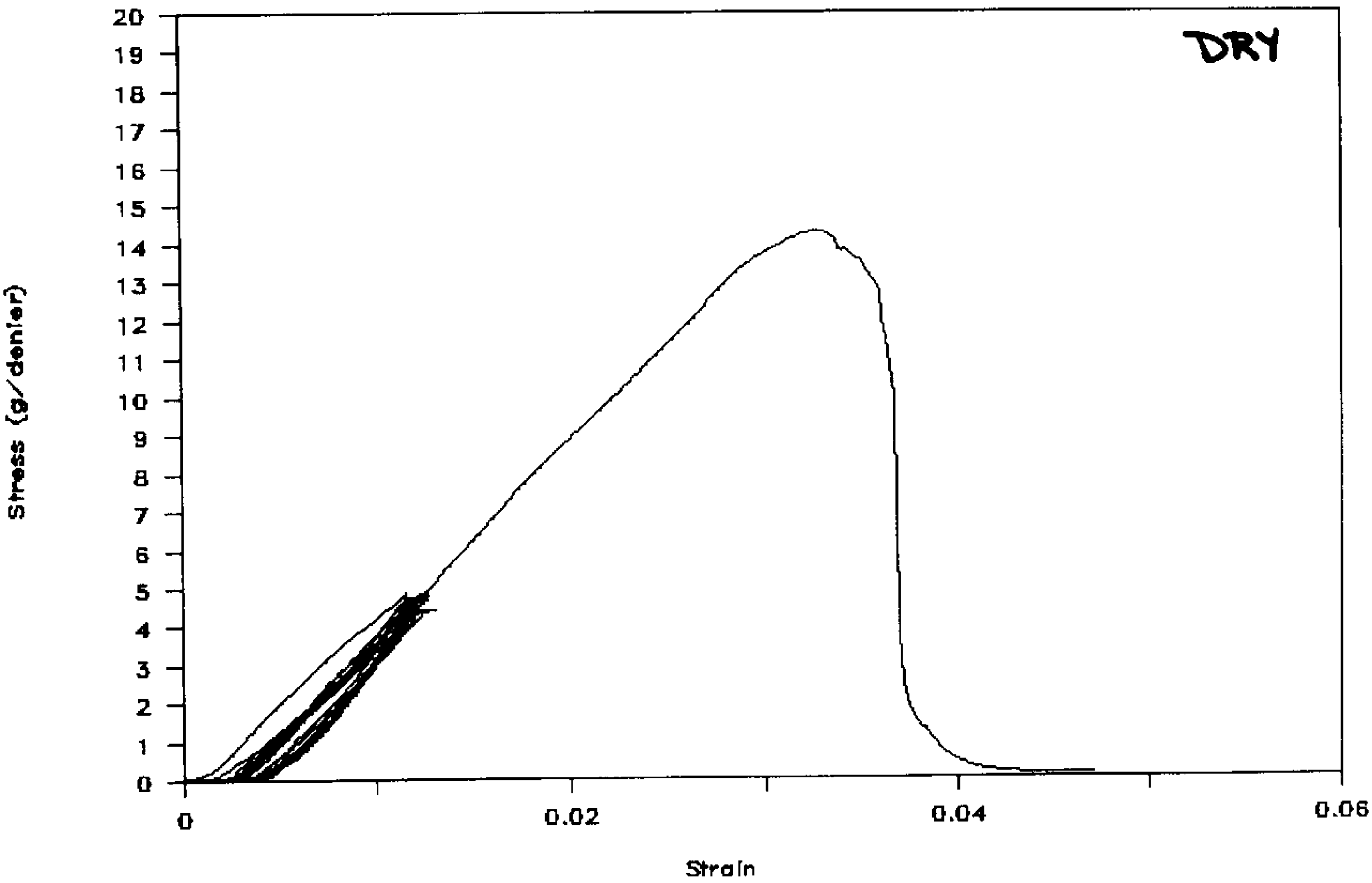
KEVLAR 960, 10 Cycles to 30% UTS

Final Stress–Strain Cycle, Test 3



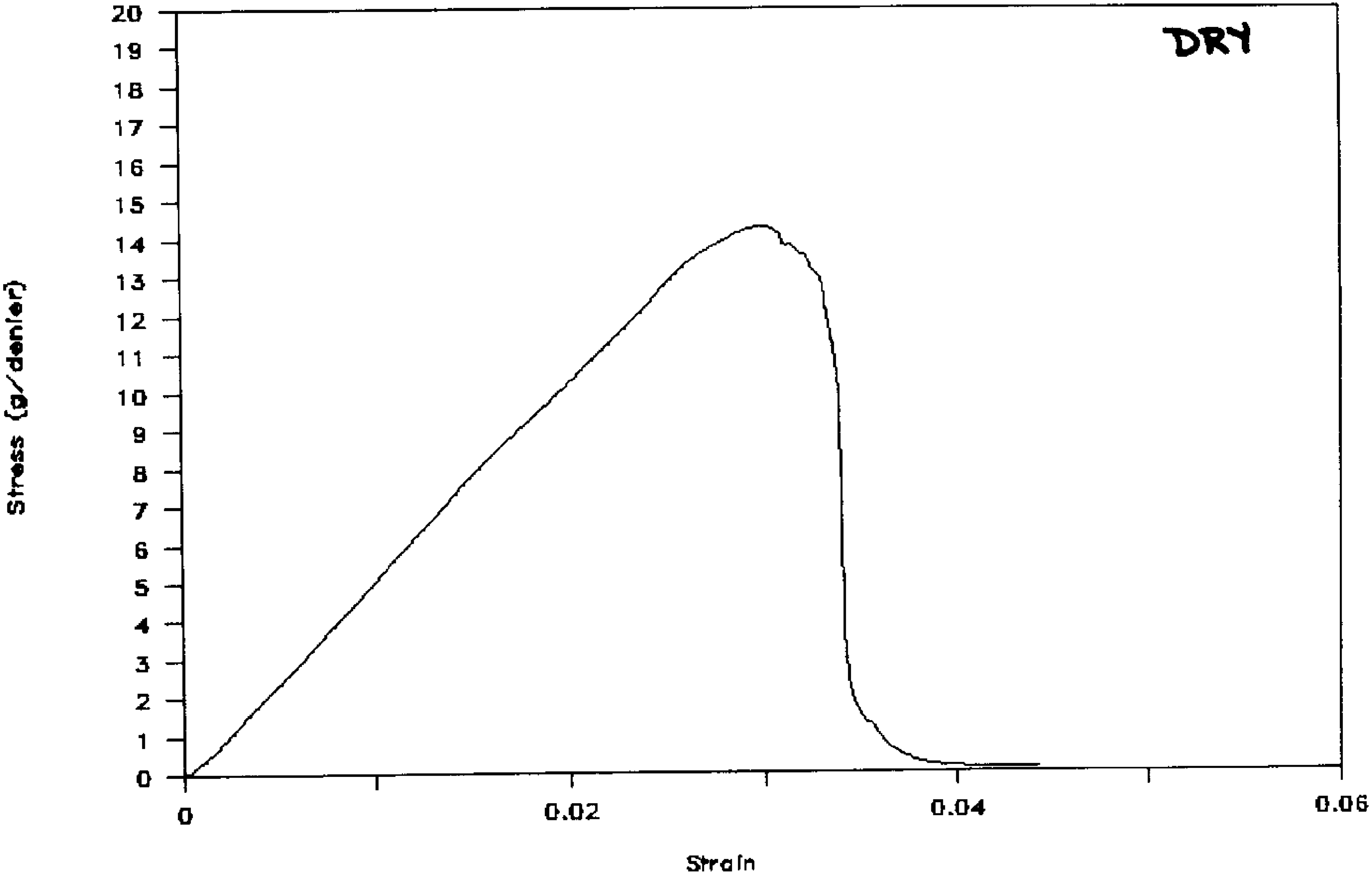
KEVLAR 960, 10 Cycles to 30% UTS

Stress—Strain, Test 4

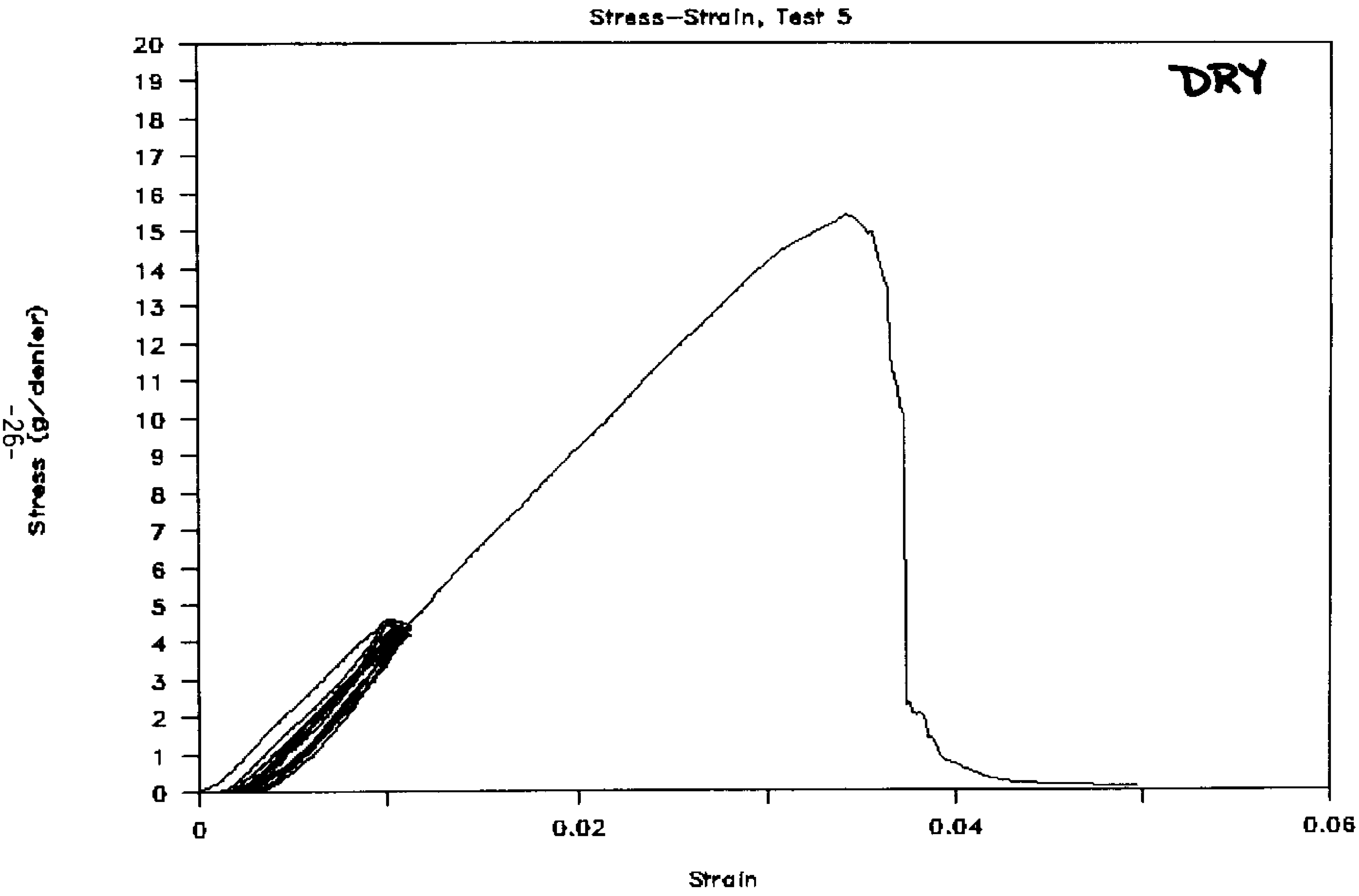


KEVLAR 960, 10 Cycles to 30% UTS

Final Stress—Strain Cycle, Test 4

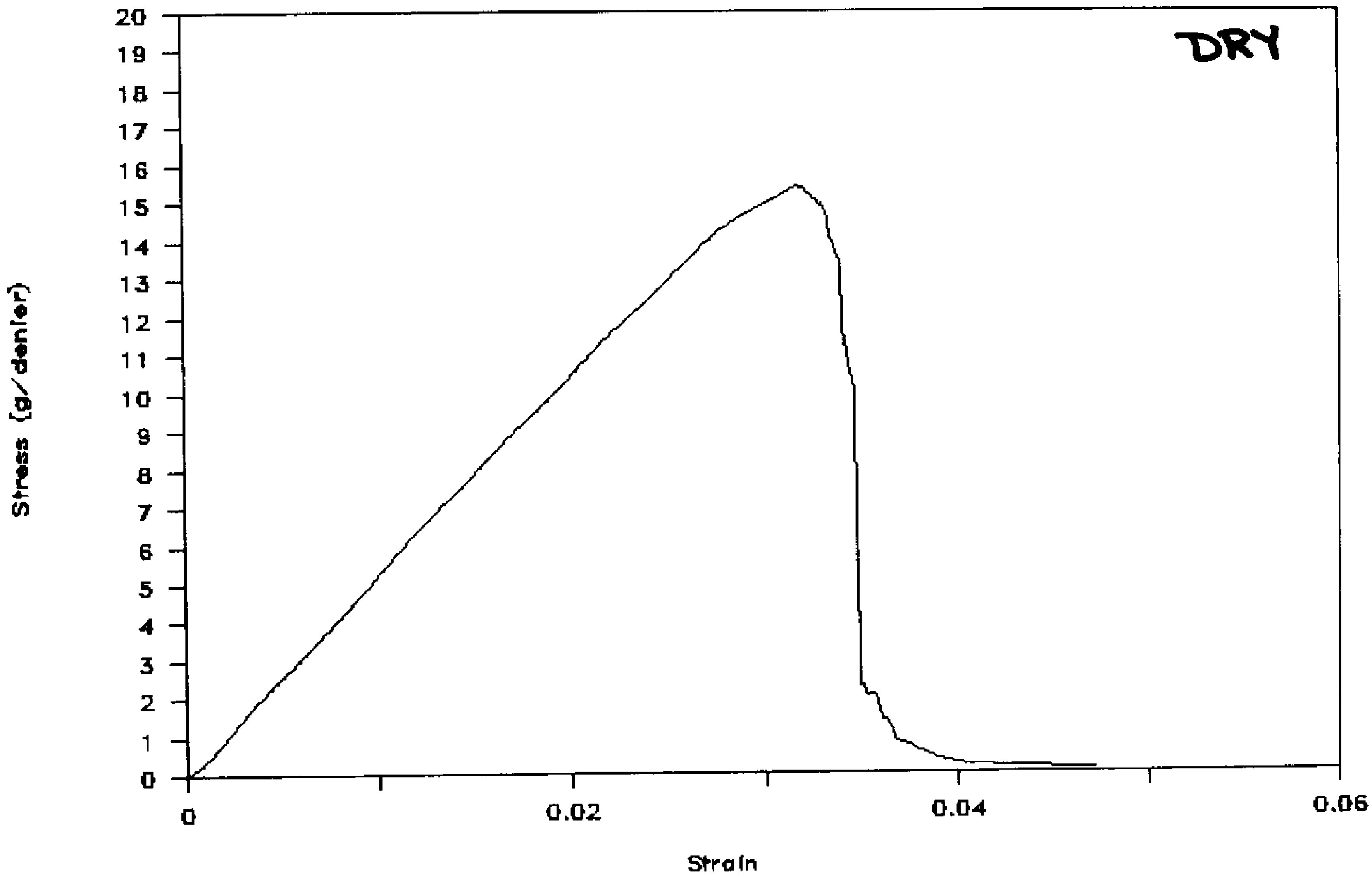


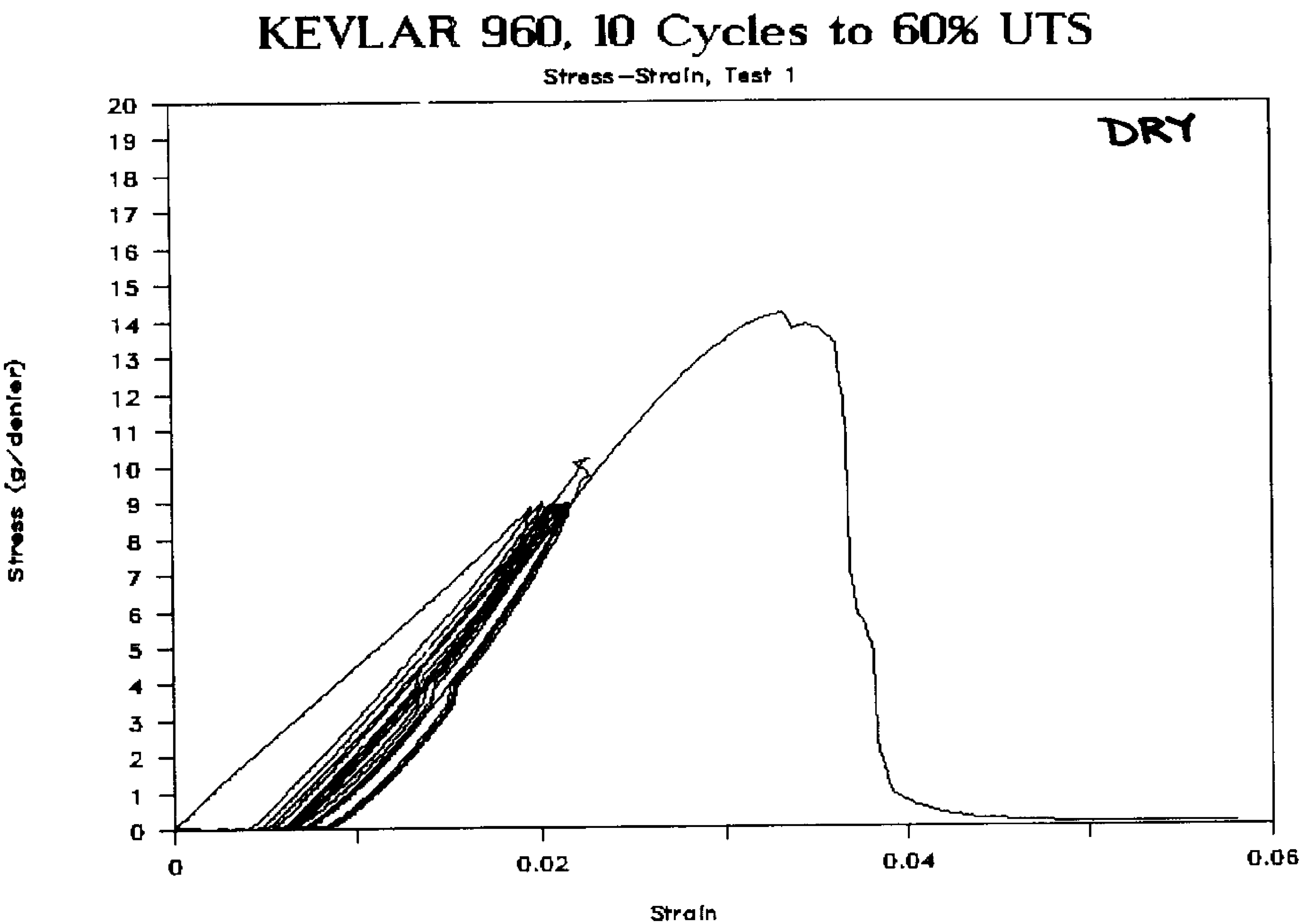
KEVLAR 960, 10 Cycles to 30% UTS



KEVLAR 960, 10 Cycles to 30% UTS

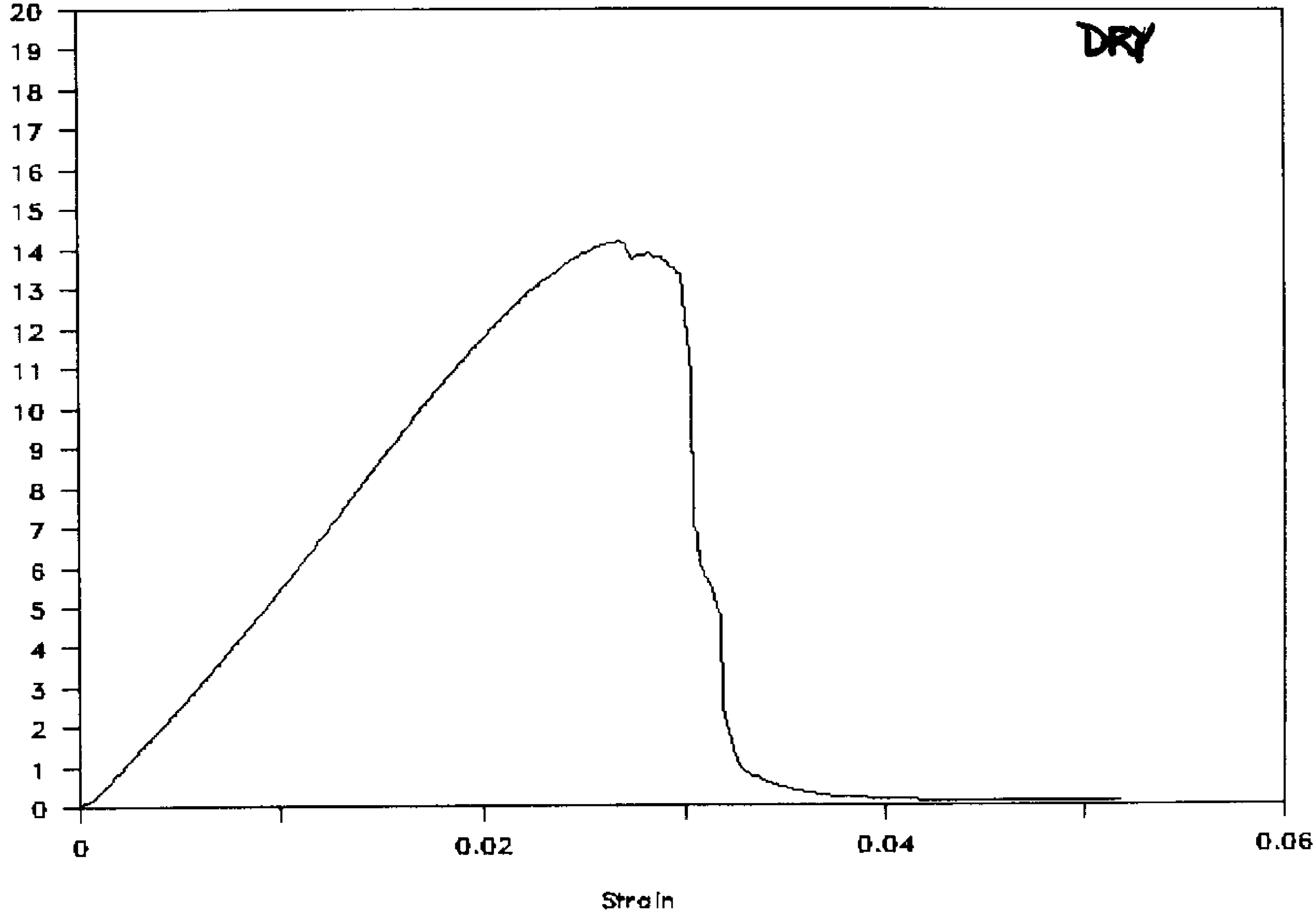
Final Stress—Strain Cycle, Test 5



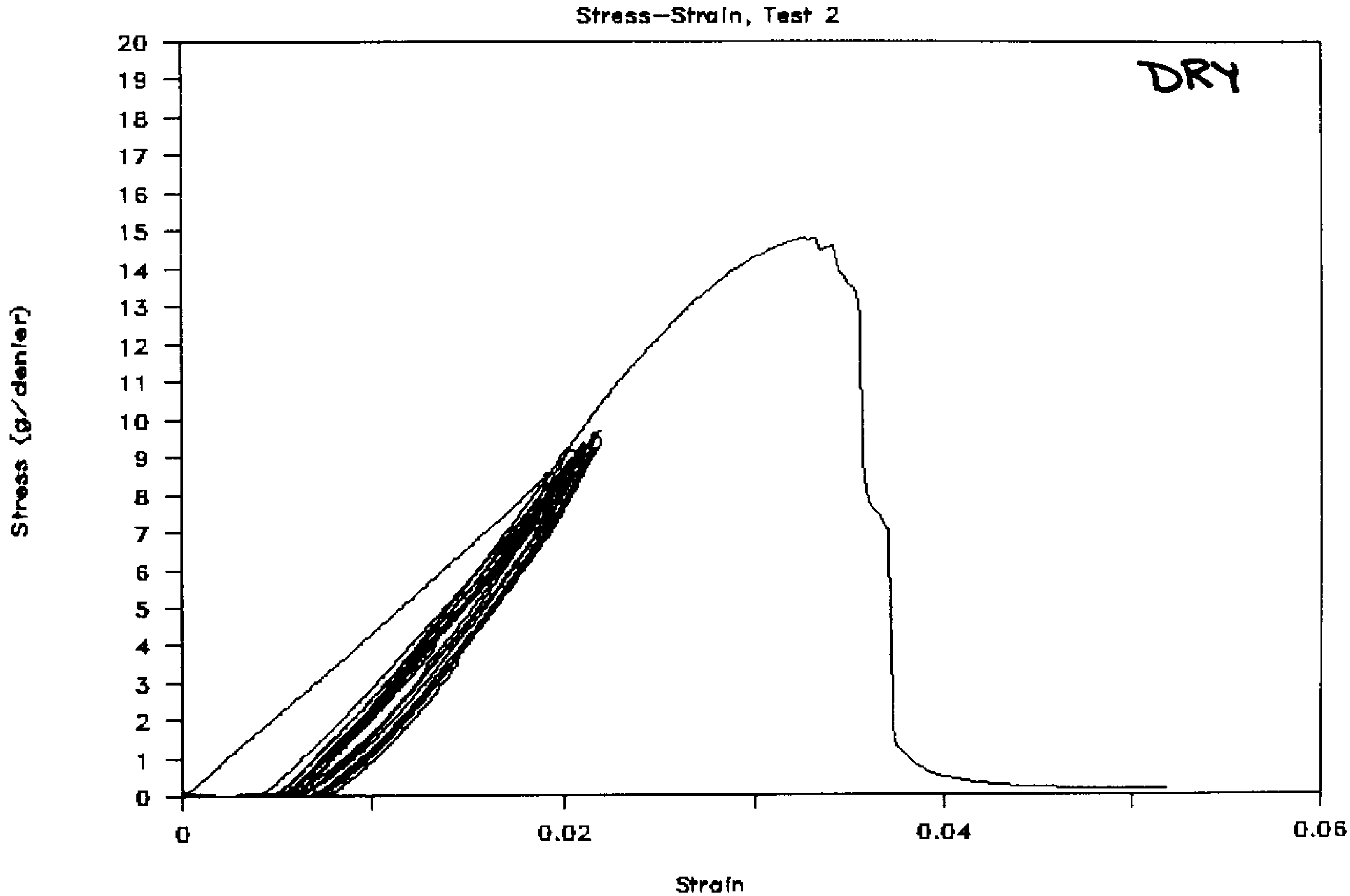

KEVLAR 960, 10 Cycles to 60% UTS
Stress—Strain, Test 1
DRY
Stress (g/denier)
Strain
0
0.02
0.04
0.06
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20

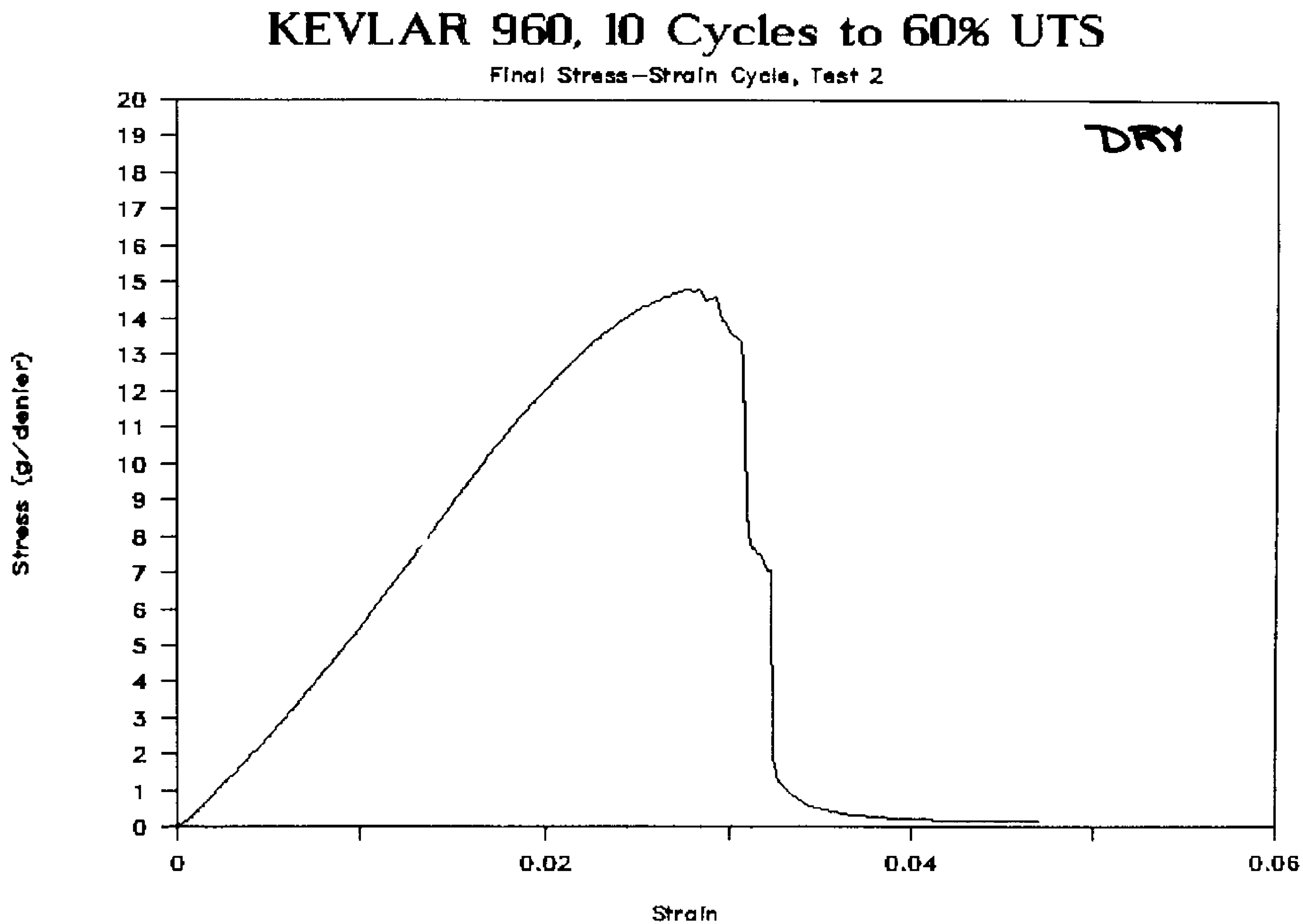
KEVLAR 960, 10 Cycles to 60% UTS

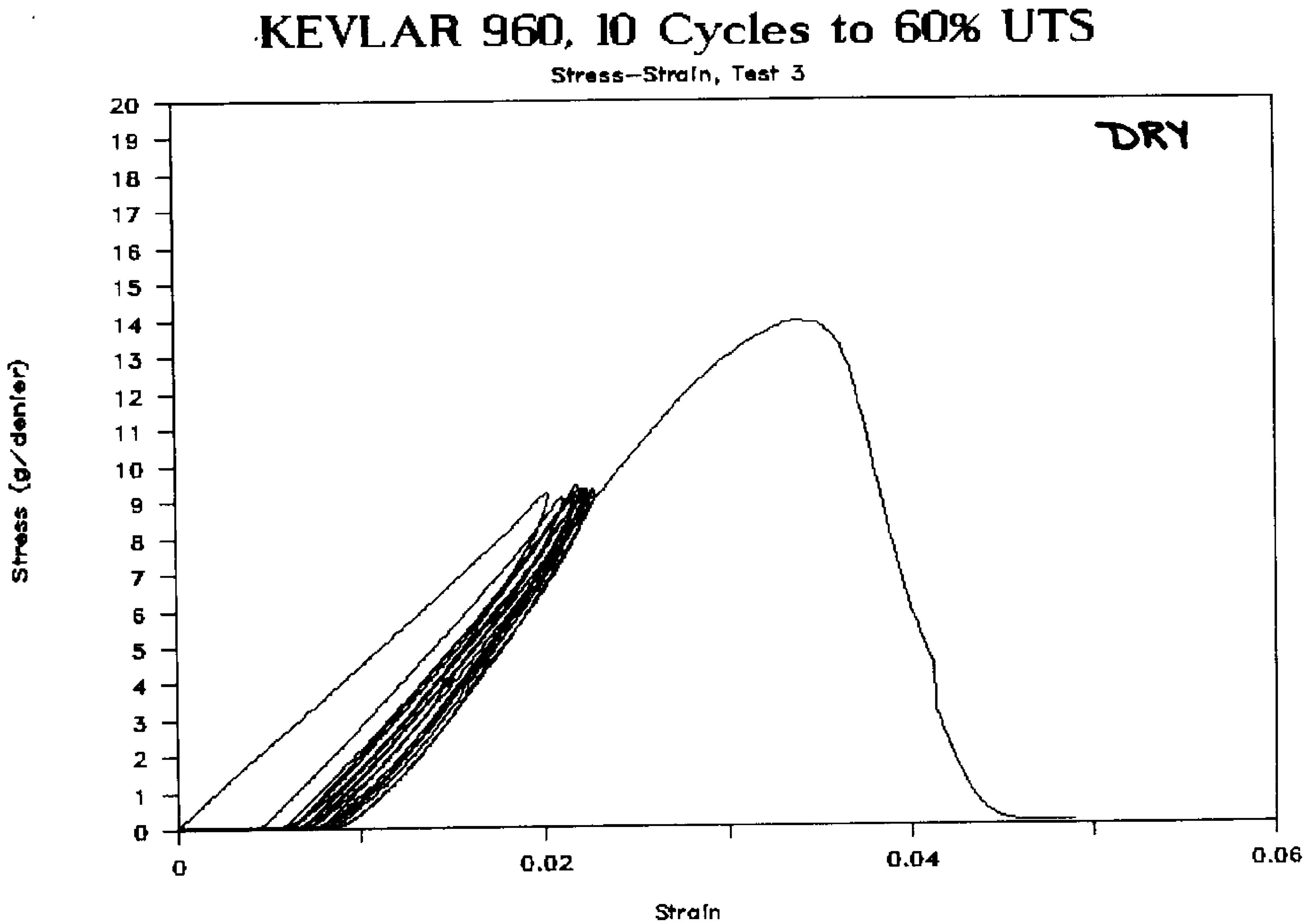
Final Stress—Strain Cycle, Test 1



KEVLAR 960, 10 Cycles to 60% UTS

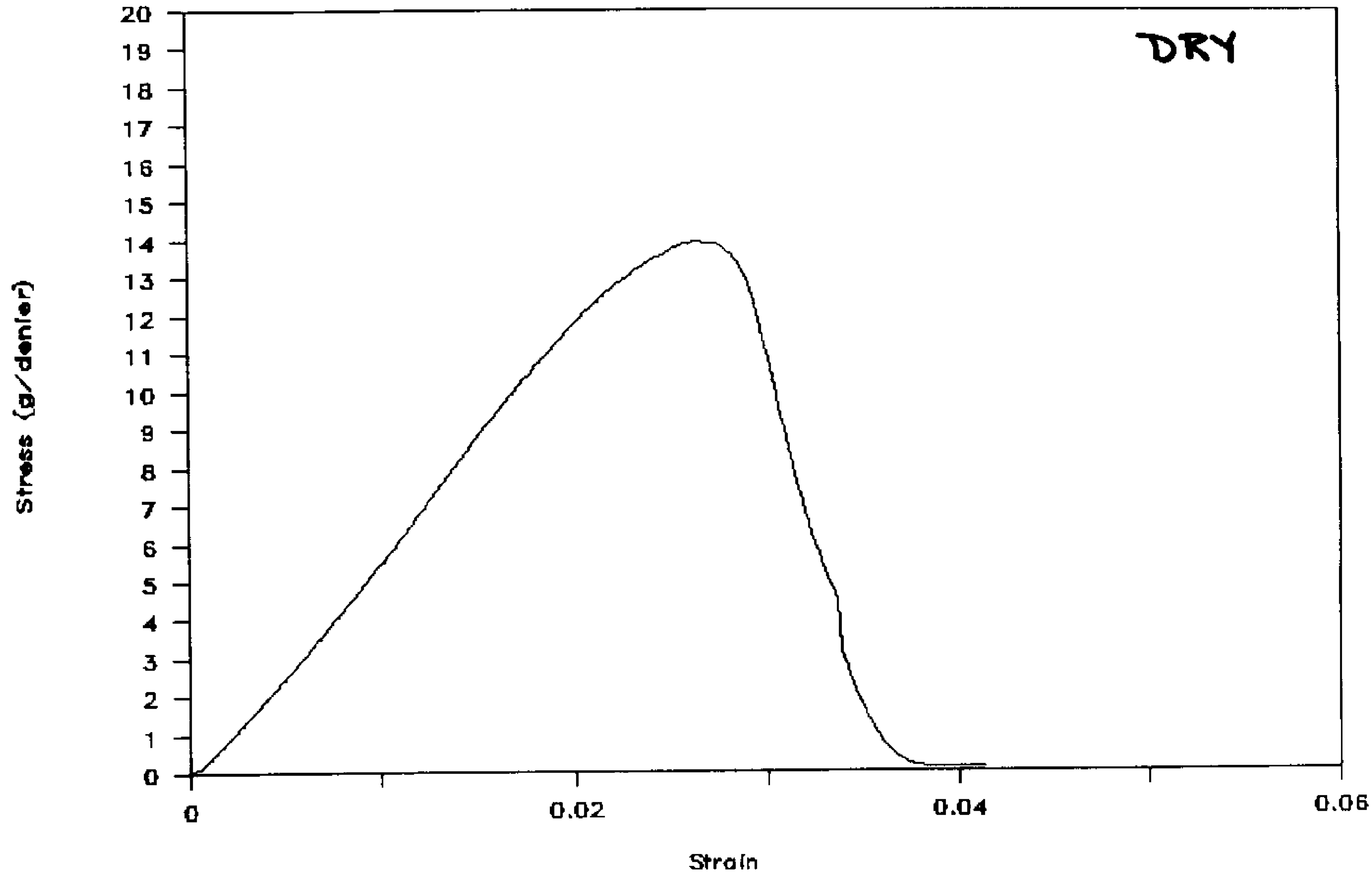



KEVLAR 960, 10 Cycles to 60% UTS
Final Stress-Strain Cycle, Test 2
DRY
Stress (g/denier)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
0
0.02
0.04
0.06
Strain


KEVLAR 960, 10 Cycles to 60% UTS
Stress-Strain, Test 3
DRY
Stress (g/denier)
Strain
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
0
0.02
0.04
0.06

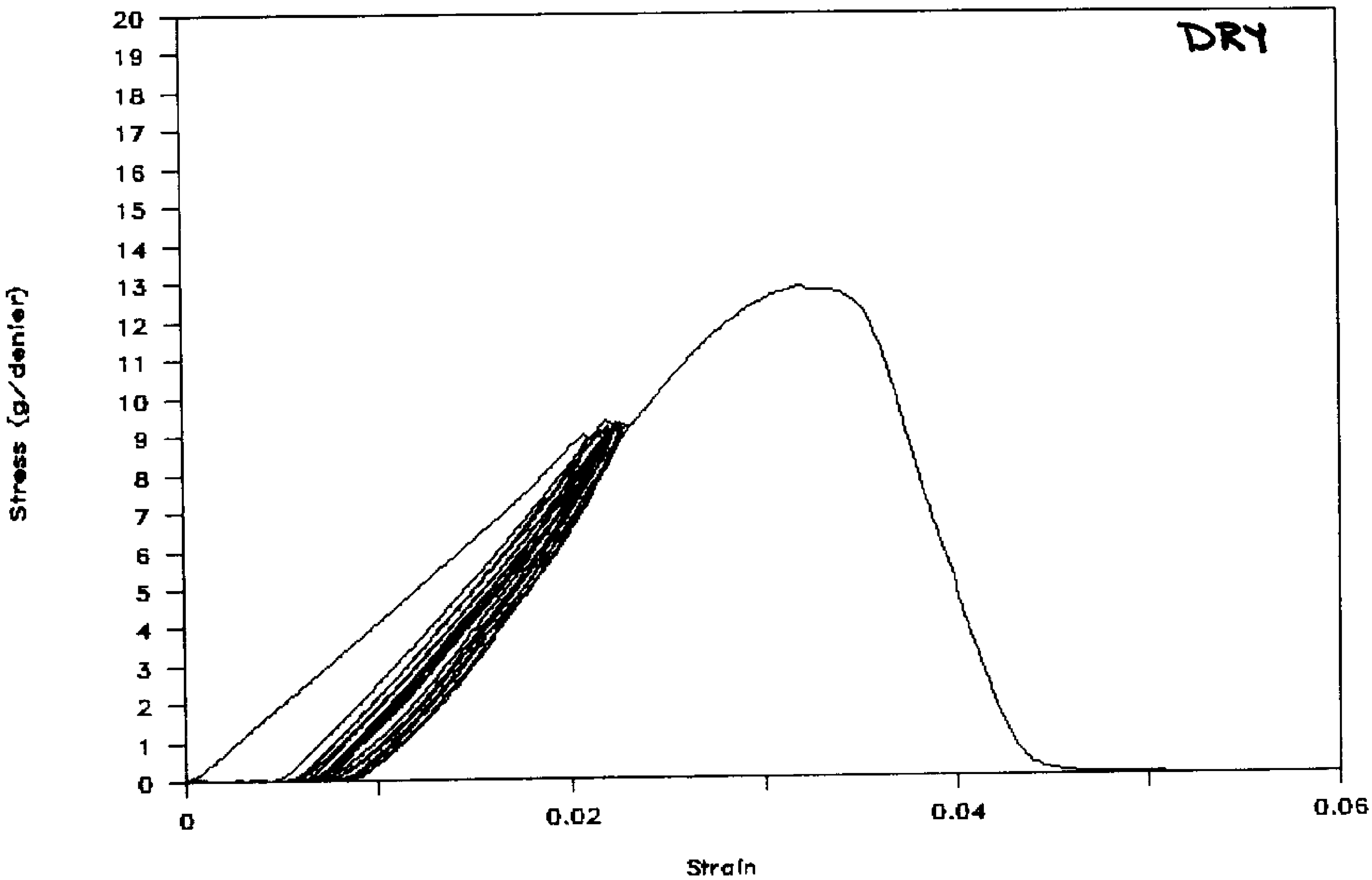
KEVLAR 960, 10 Cycles to 60% UTS

Final Stress—Strain Cycle, Test 3



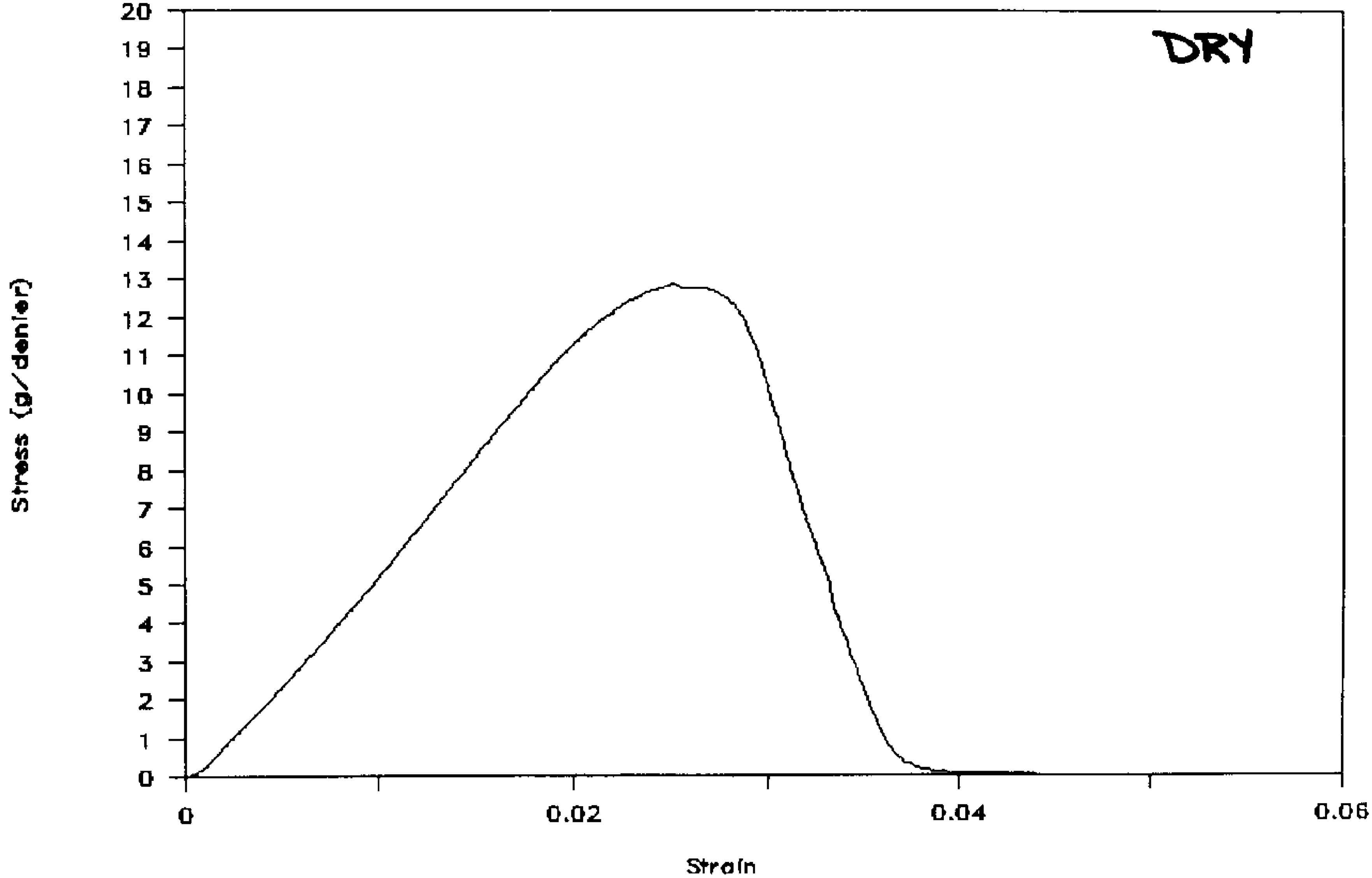
KEVLAR 960, 10 Cycles to 60% UTS

Stress—Strain, Test 4



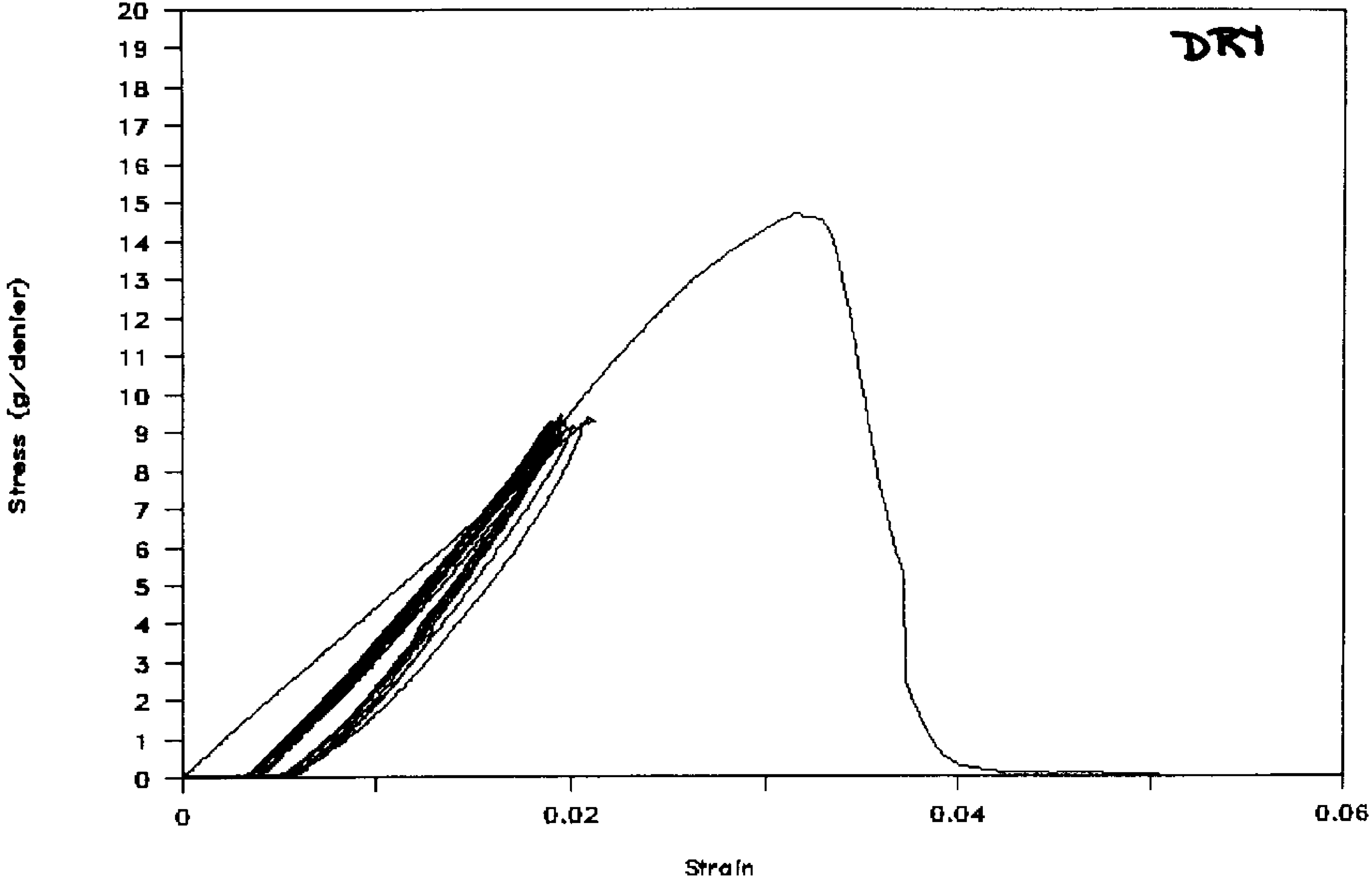
KEVLAR 960, 10 Cycles to 60% UTS

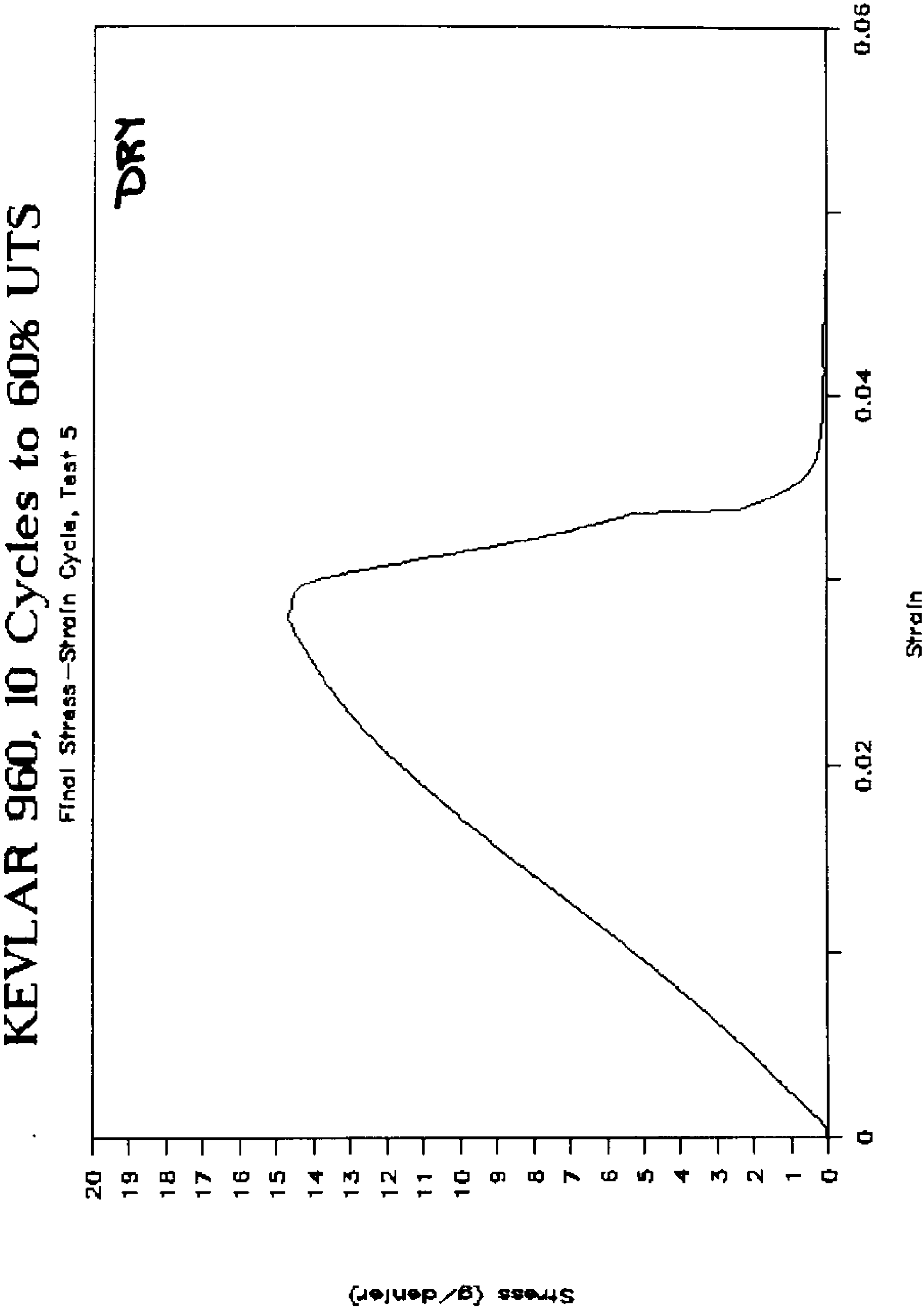
Final Stress—Strain Cycle, Test 4



KEVLAR 960, 10 Cycles to 60% UTS

Stress–Strain, Test 5




KEVLAR 960, 10 Cycles to 60% UTS
Final Stress—Strain Cycle, Test 5
DRY
Stress (g/denier)
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
Strain
0 0.02 0.04 0.06

SINGLE LOAD STRESS STRAIN BEHAVIOR

KEVLAR T961 (1500 denier) WITHOUT Marine Finish

Dry and Wet Tests

SINGLE LOAD STRESS -STRAIN BEHAVIOR

KEVLAR T961 YARN(1500 DENIER WITHOUT FINISH)

DRY YARN

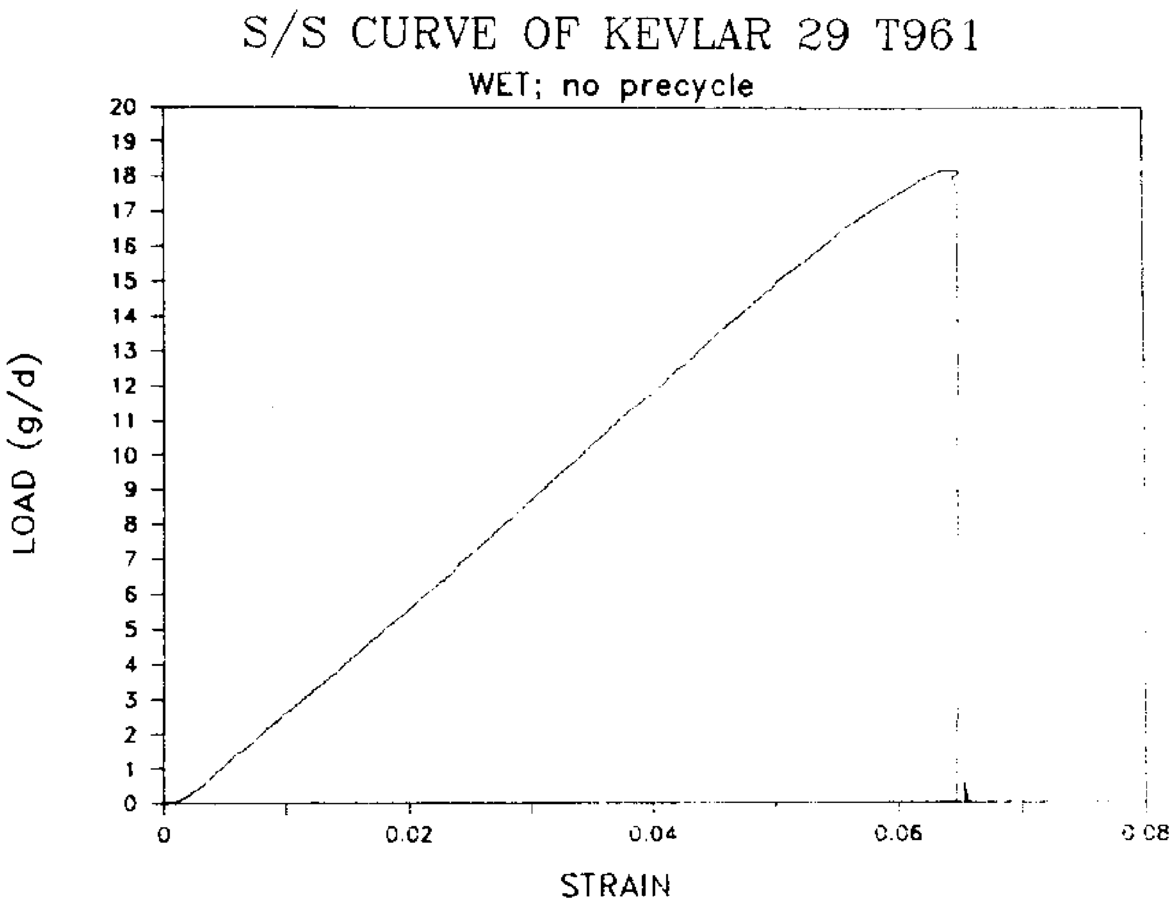
	ORIGINAL		AFTER 30% B.S. 10 CYCLES		AFTER 60% B.S. 10 CYCLES	
	BREAKING STRESS GM/DENIER	BREAKING STRAIN	BREAKING STRESS GM/DENIER	BREAKING STRAIN	BREAKING STRESS GM/DENIER	BREAKING STRAIN
1	15.8	.037	16.8	.034	17.8	.031
2	16.5	.035	16.0	.033	16.2	.028
3	16.5	.036	18.2	.036	16.5	.031
4	x	x	17.8	.037	16.3	.032
5	x	x	x	x	x	x
MEAN	16.26	.036	17.2	.035	16.7	.03

SINGLE LOAD STRESS -STRAIN BEHAVIOR

KEVLAR T961 YARN (1500 DENIER WITHOUT FINISH)
WET YARN

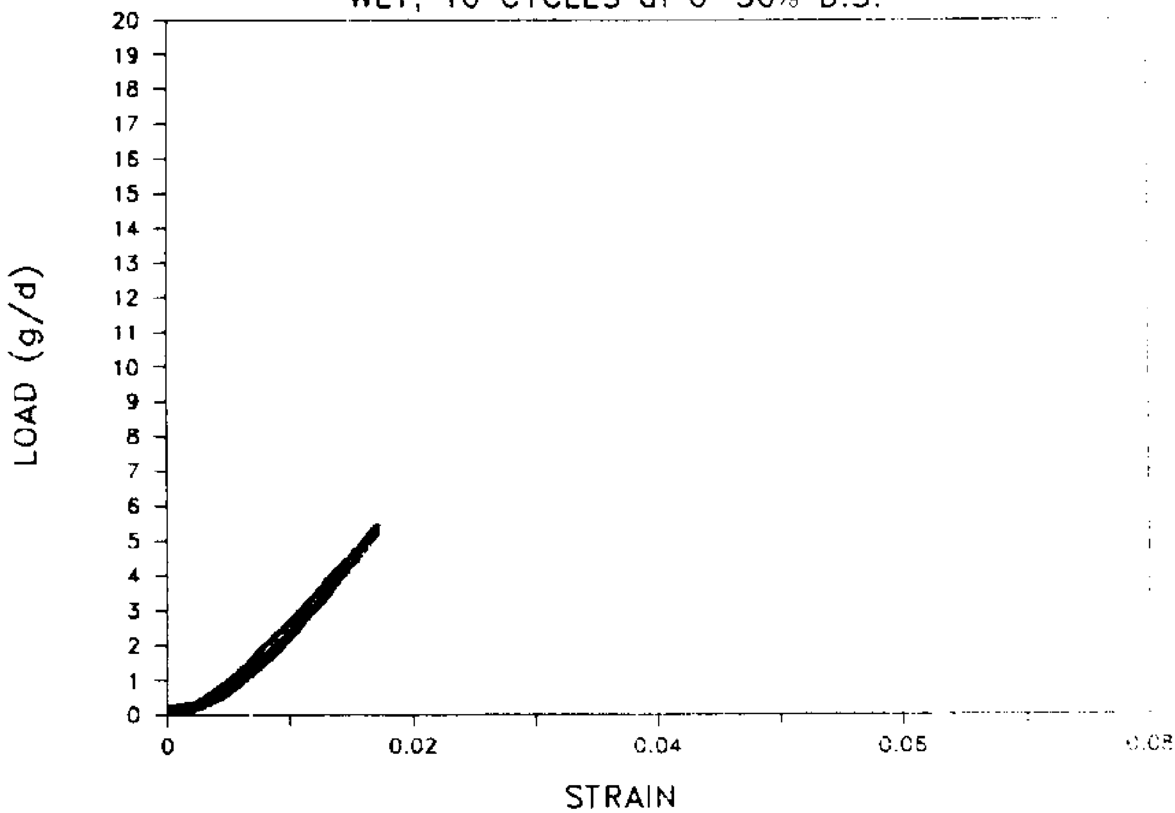
	ORIGINAL		AFTER 30% B.S. 10 CYCLES		AFTER 60% B.S. 10 CYCLES	
	BREAKING STRESS GM/DENIER	BREAKING STRAIN	BREAKING STRESS GM/DENIER	BREAKING STRAIN	BREAKING STRESS GM/DENIER	BREAKING STRAIN
1	17.0	XXX	16.1	0.053 *	16.4	XXX
2	17.2	XXX	15.7	XXX	16.3	XXX
3	18.4	0.064 *	17.8	XXX	18.0	XXX
4	17.4	XXX	14.5	XXX	17.2	0.053 *
5	16.7	XXX	XXX	XXX	18.9	XXX
MEAN	17.3	XXX	16.0	XXX	17.4	XXX

* representative value


S/S CURVE OF KEVLAR 29 T961
WET; no precycle
LOAD (g/d)
STRAIN
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
0
0.02
0.04
0.06
0.08

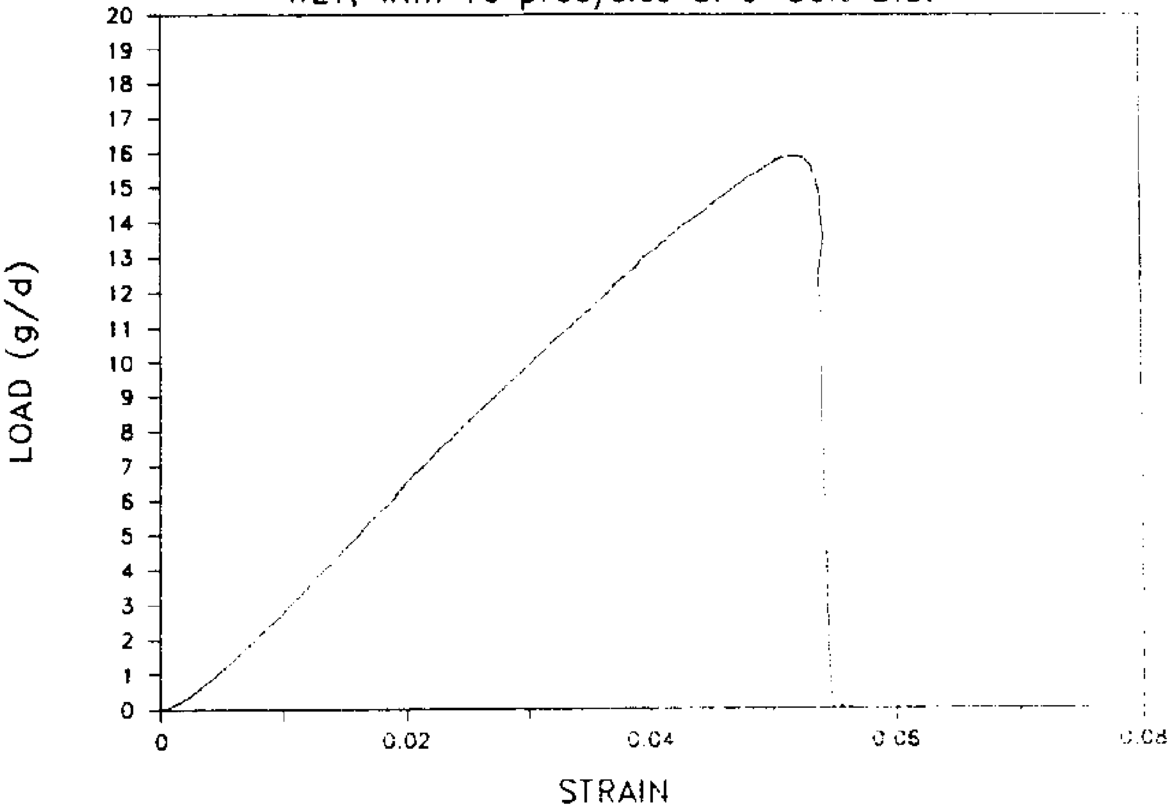
PRECYCLE S/S CURVE OF KEVLAR 29 T961

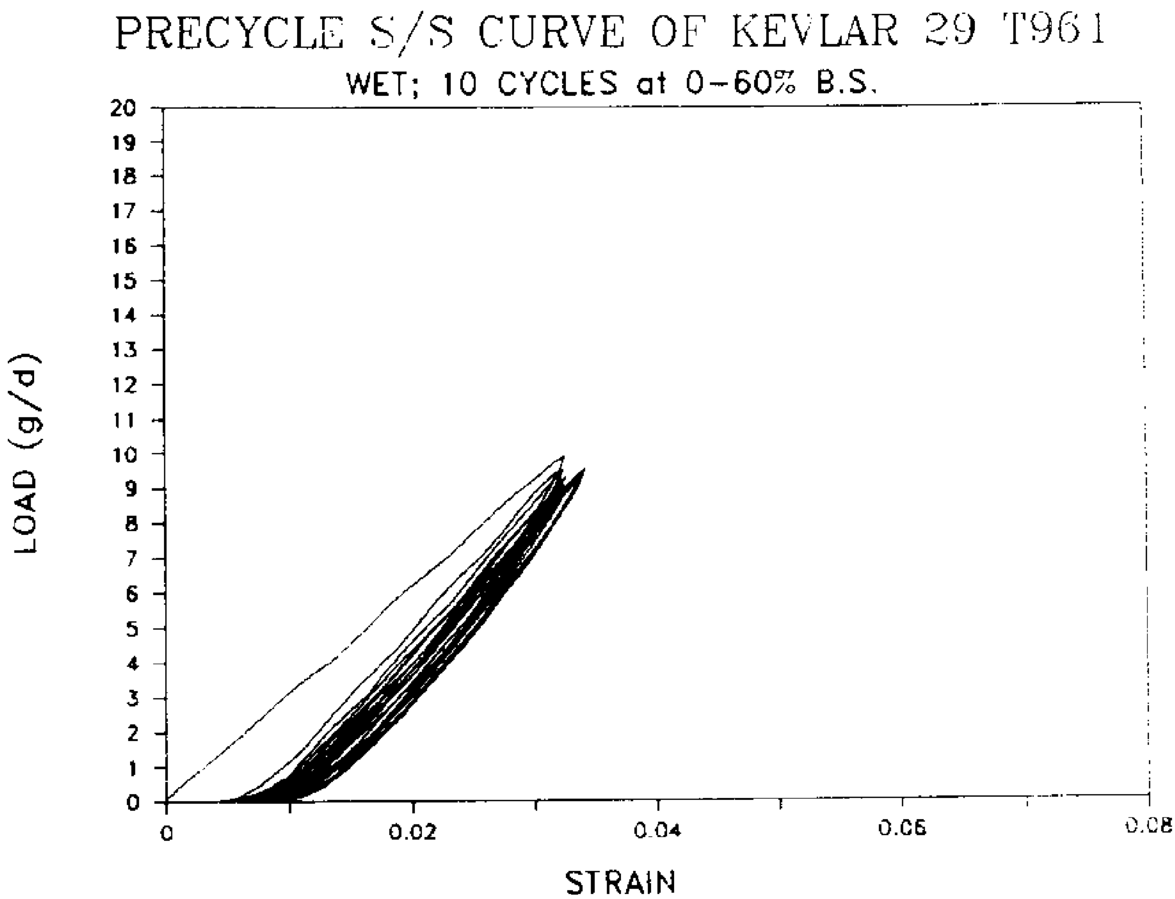
WET; 10 CYCLES at 0-30% B.S.

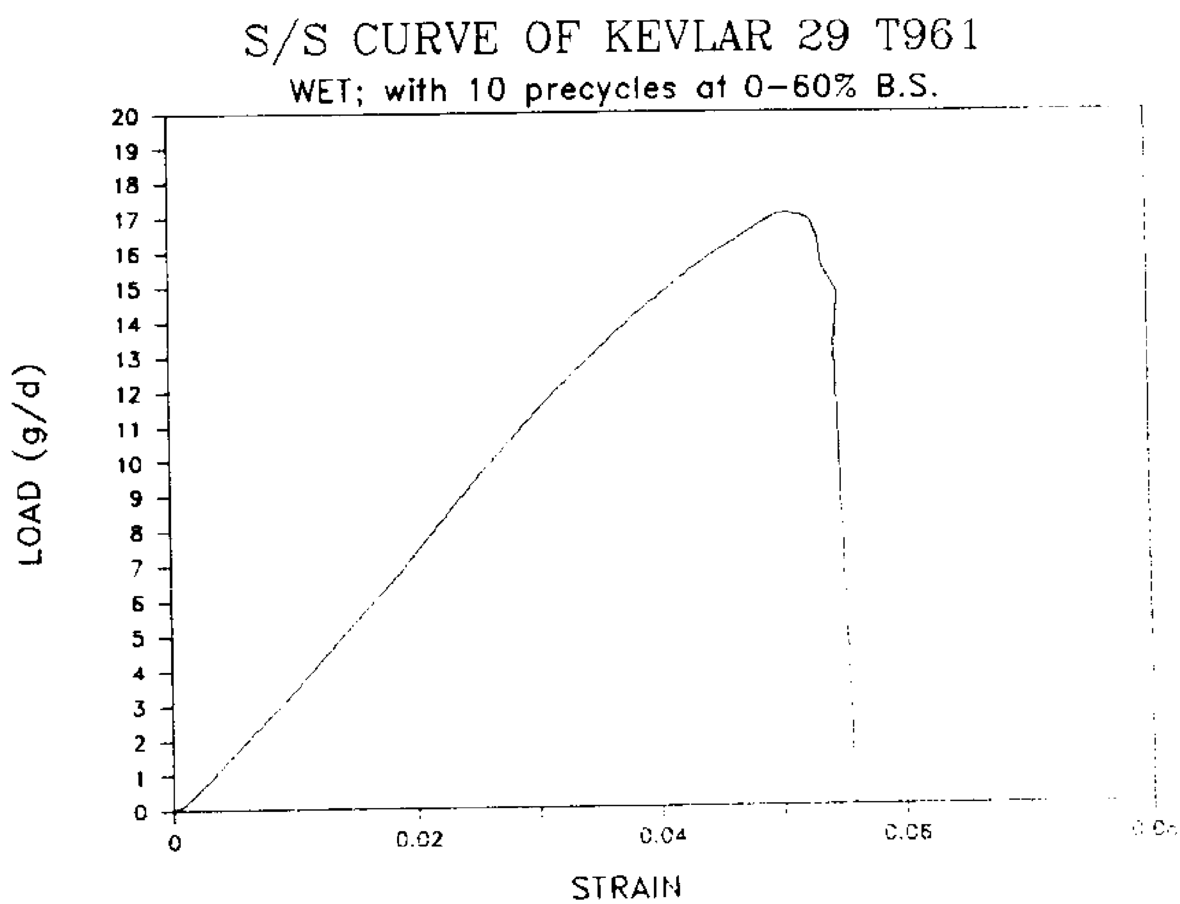


S/S CURVE OF KEVLAR 29 T961

WET; with 10 precycles at 0–30% B.S.




PRECYCLE S/S CURVE OF KEVLAR 29 T961
WET; 10 CYCLES at 0-60% B.S.
LOAD (g/d)
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
0
0.02
0.04
0.06
0.08
STRAIN


S/S CURVE OF KEVLAR 29 T961
WET; with 10 precycles at 0-60% B.S.
LOAD (g/d)
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
0
0.02
0.04
0.06
STRAIN

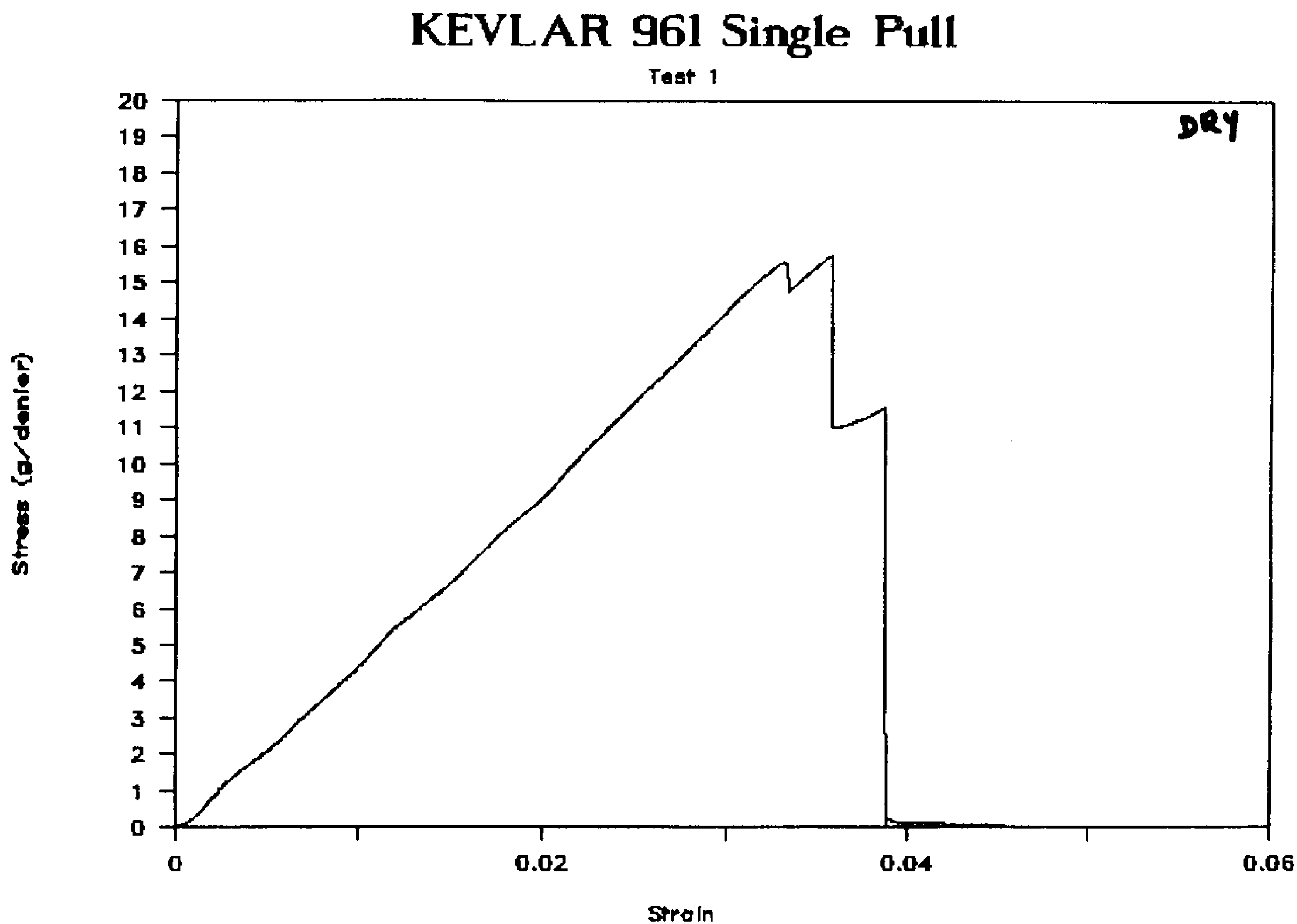


FIG. A-9A STRESS/STRAIN BEHAVIOR OF KEVLAR 961, INITIAL CYCLES (DRY)

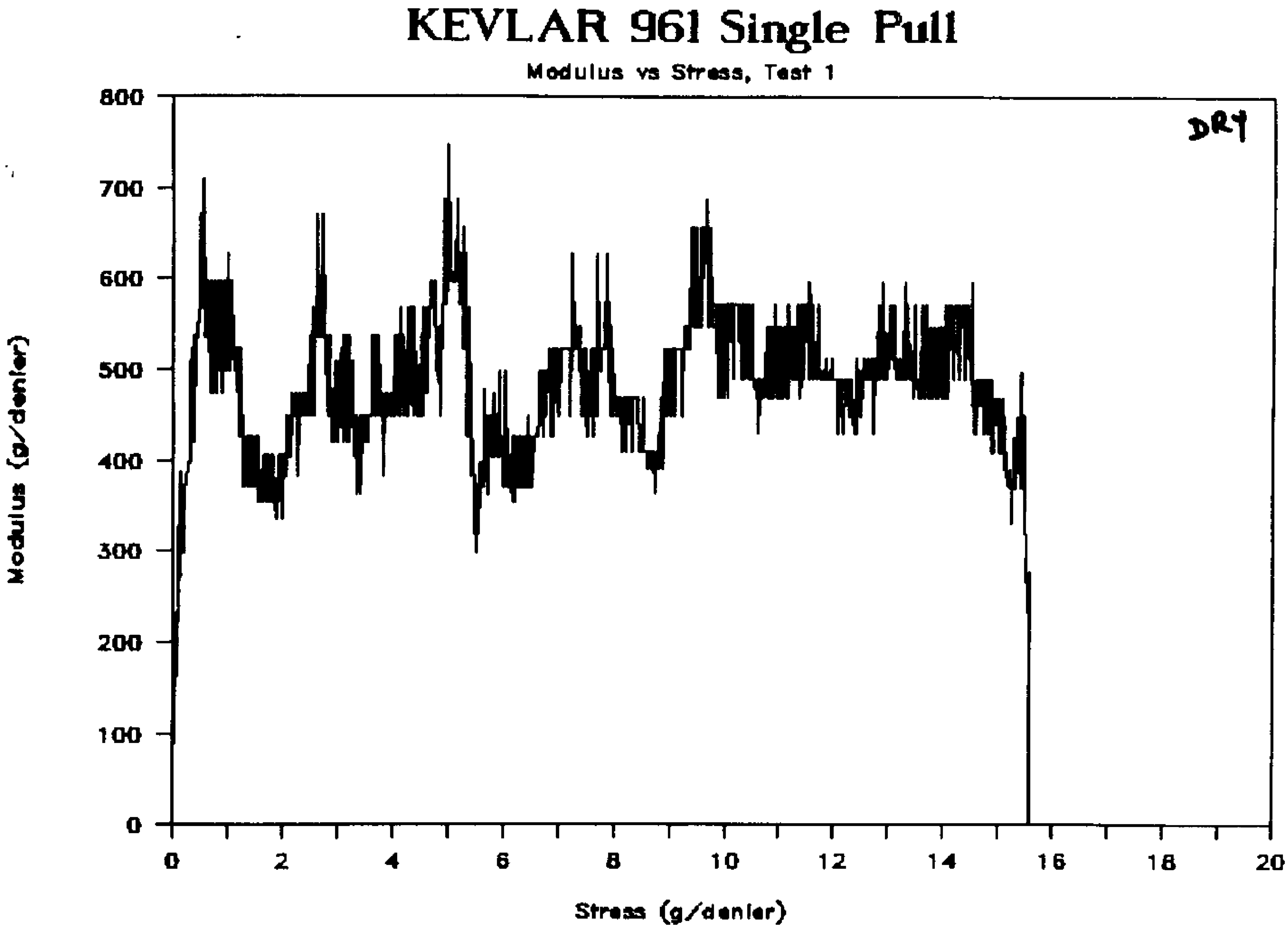
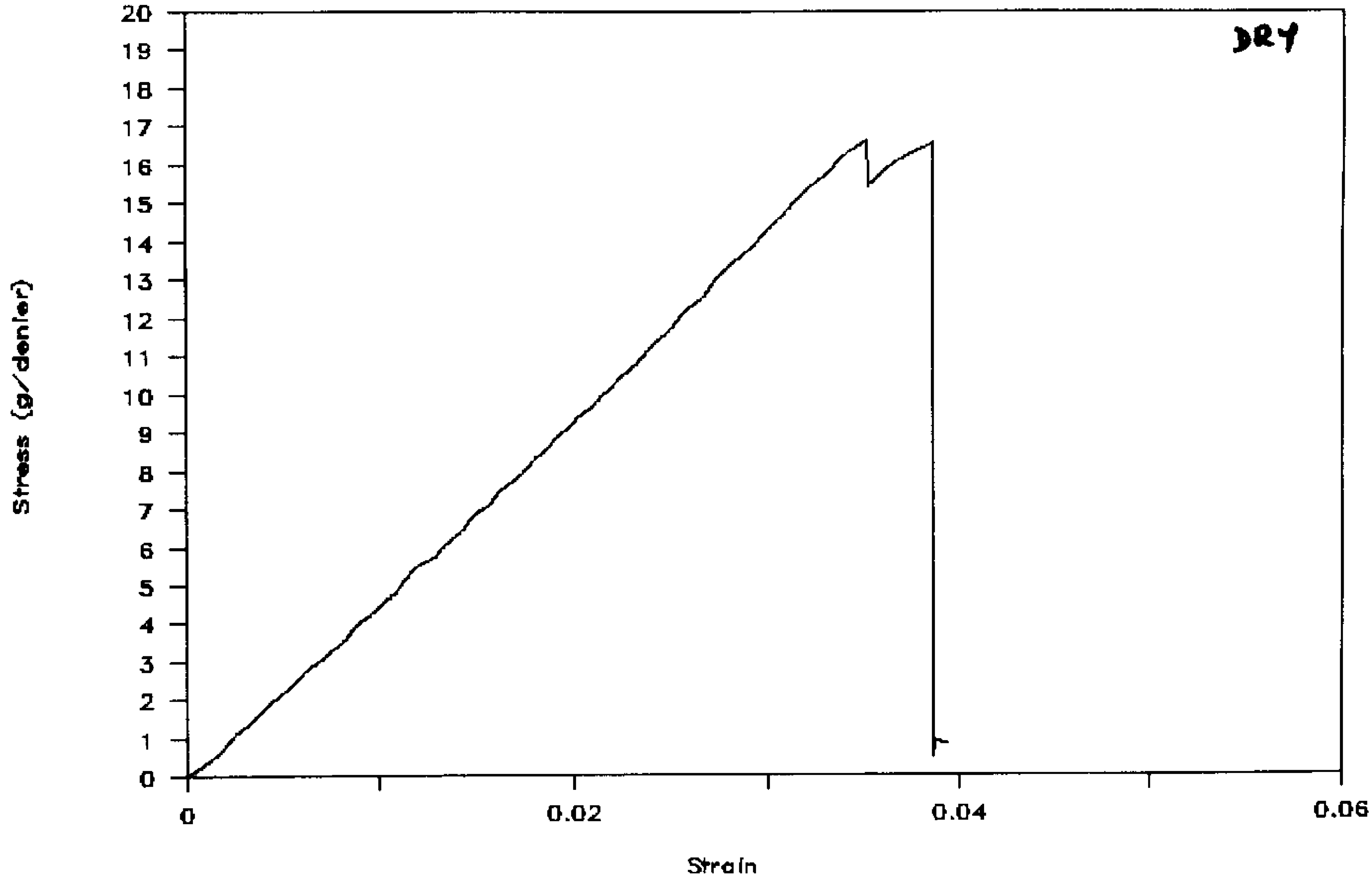


FIG. A-9B TANGENT MODULUS VS STRESS OF KEVLAR 961, INITIAL CYCLE (DRY)

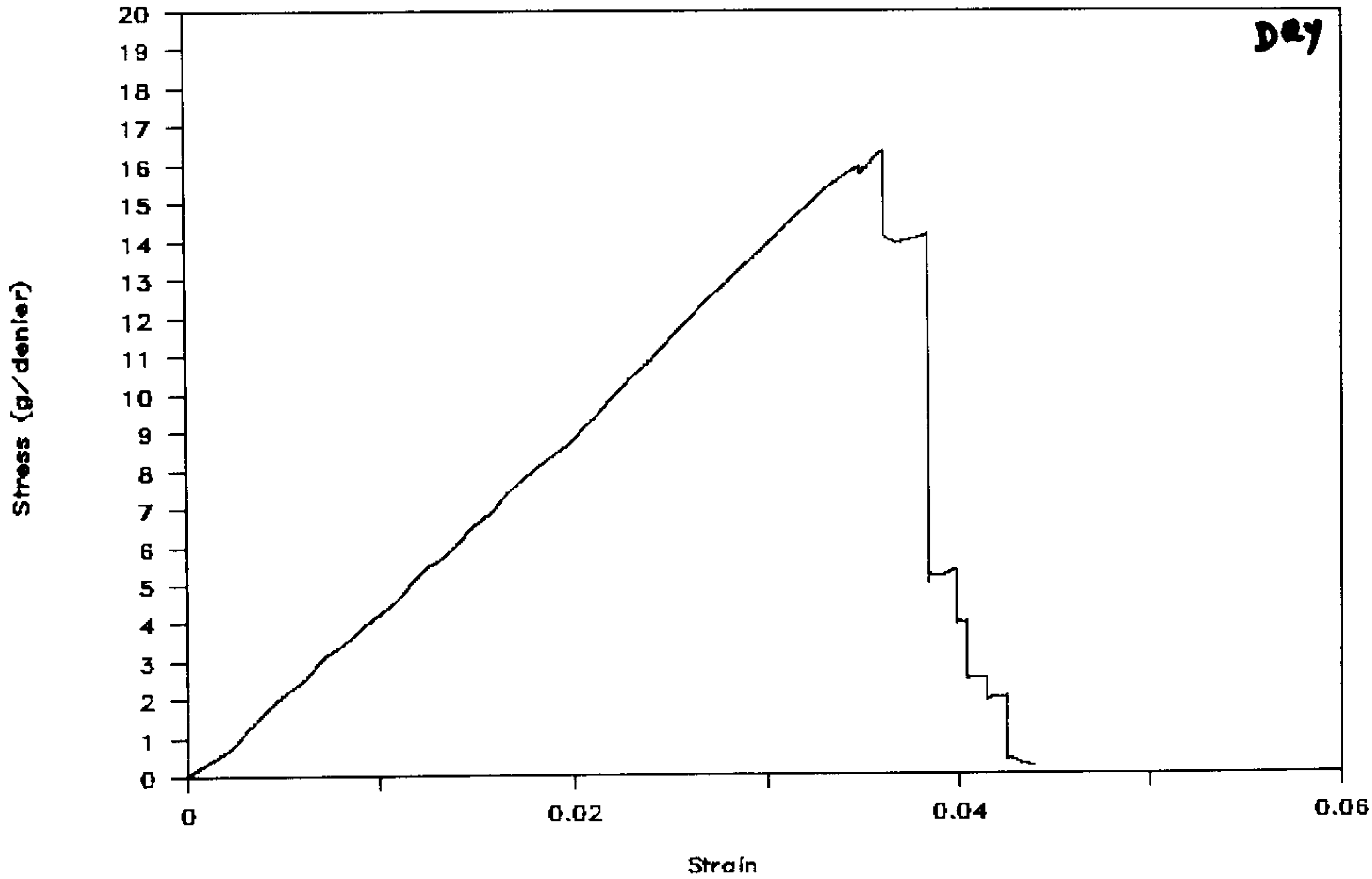
KEVLAR 961 Single Pull

Test 2

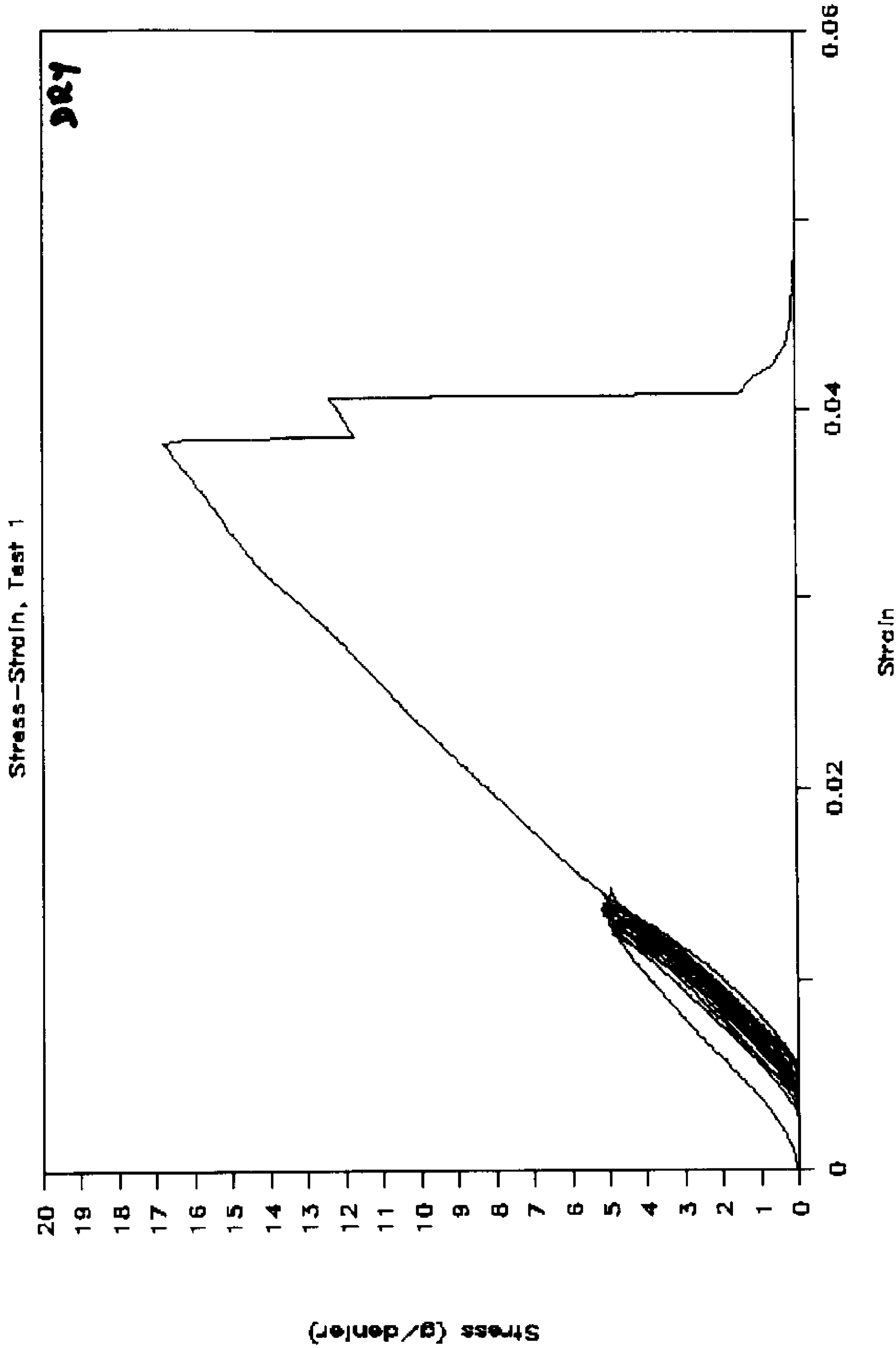


KEVLAR 961 Single Pull

Test 3

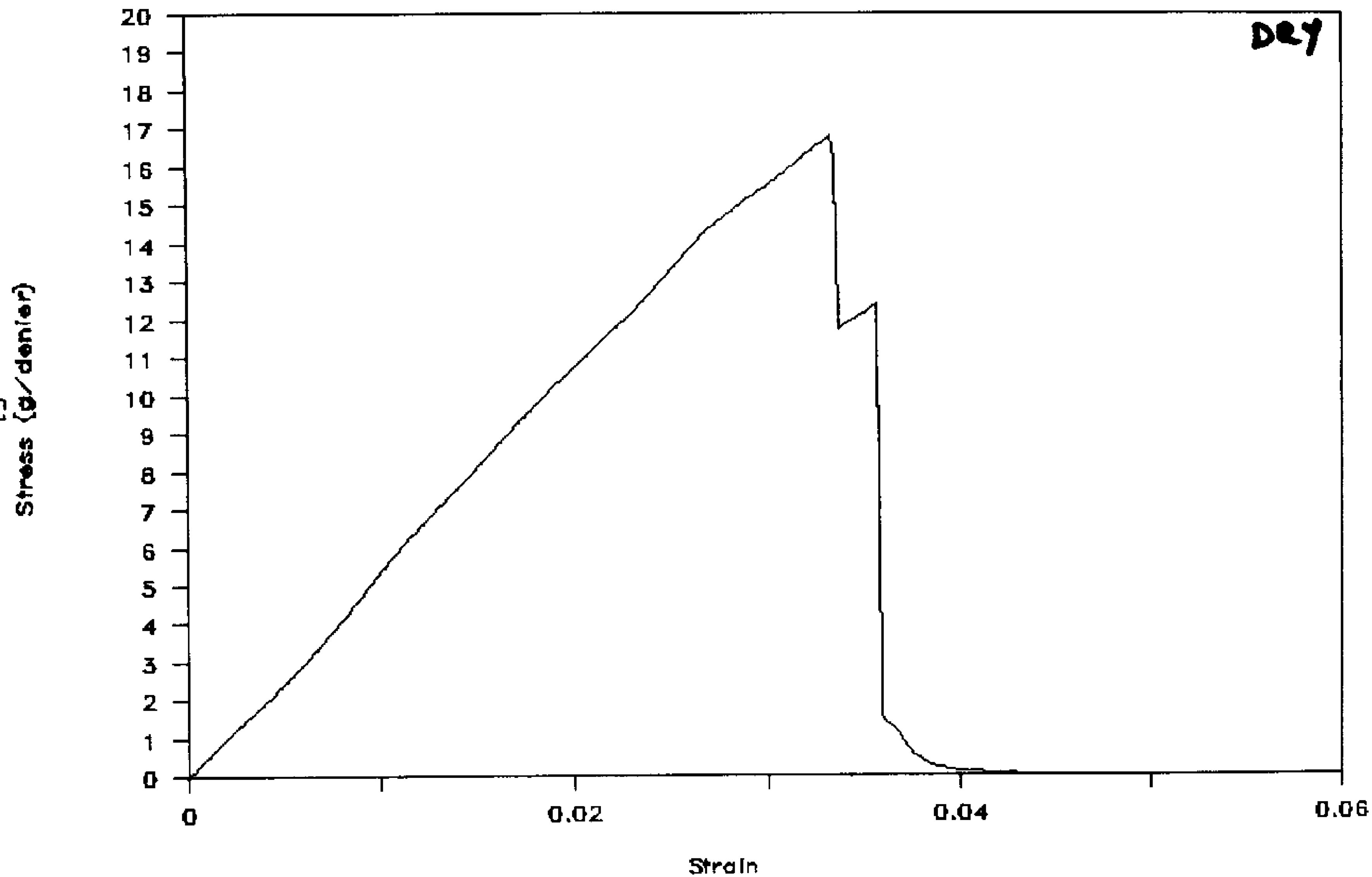


KEVLAR 961, 10 Cycles to 30% UTS



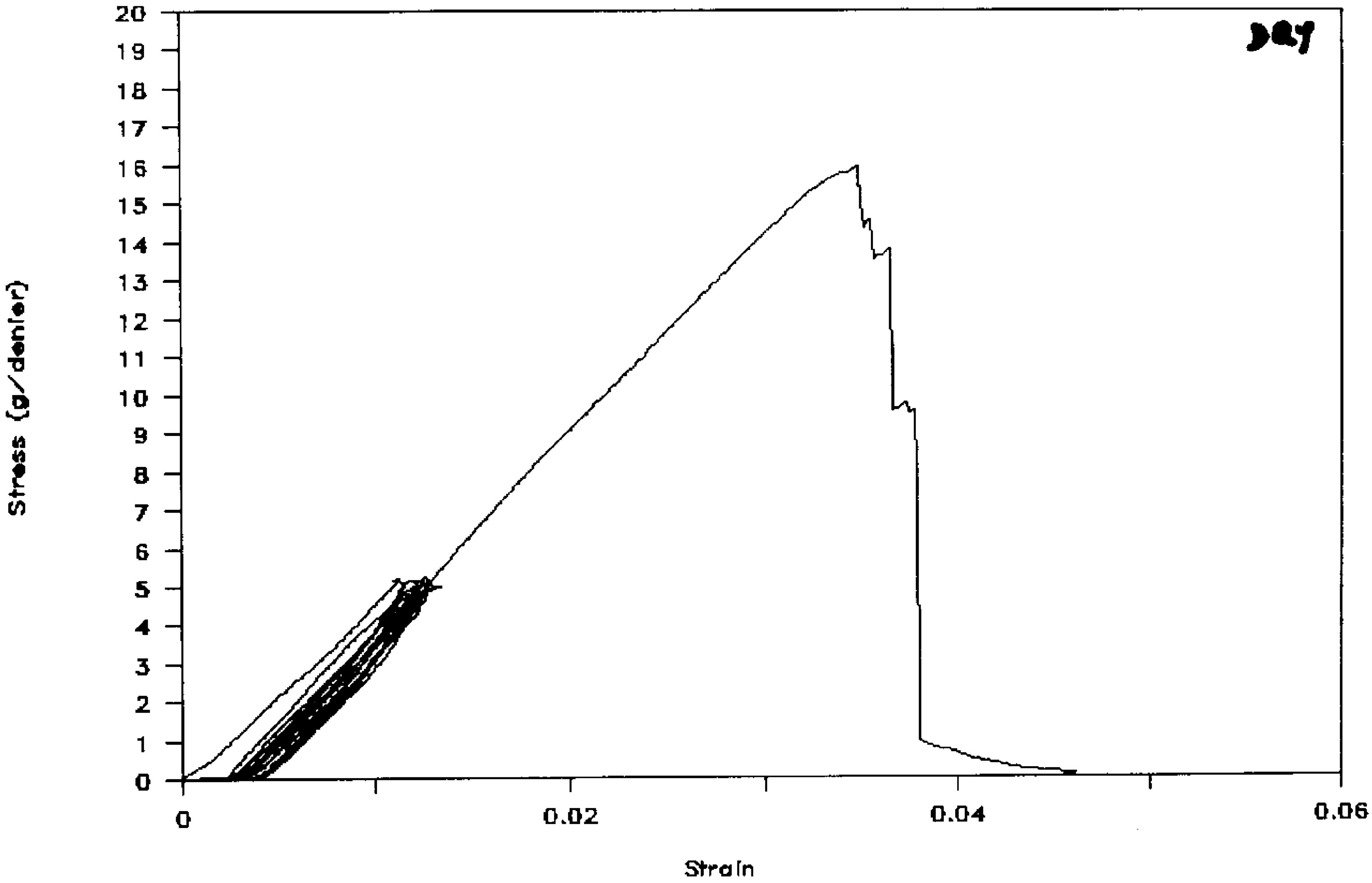
KEVLAR 961, 10 Cycles to 30% UTS

Final Stress—Strain Cycle, Test 1



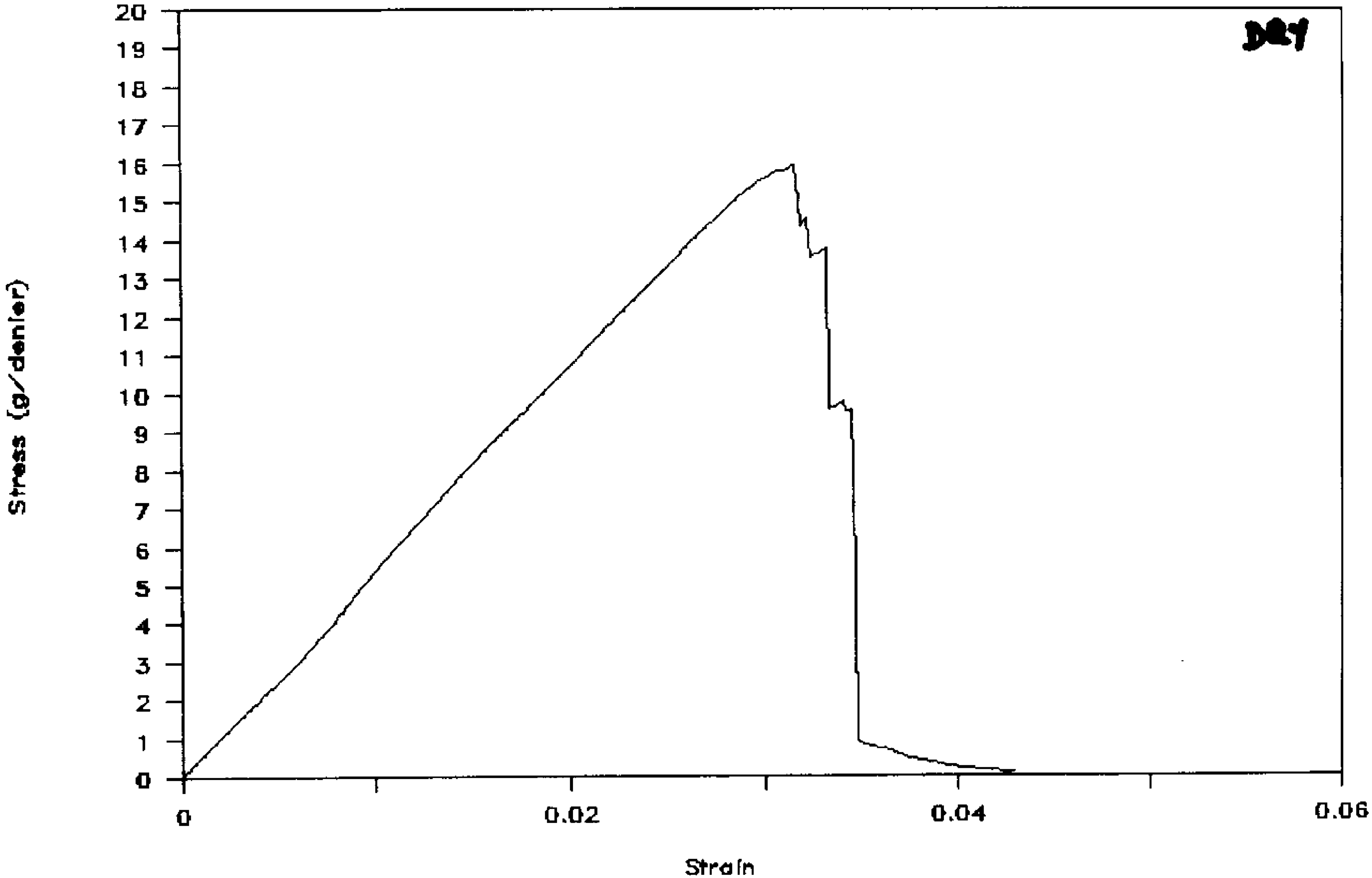
KEVLAR 961, 10 Cycles to 30% UTS

Stress–Strain, Test 2



KEVLAR 961, 10 Cycles to 30% UTS

Final Stress—Strain Cycle, Test 2



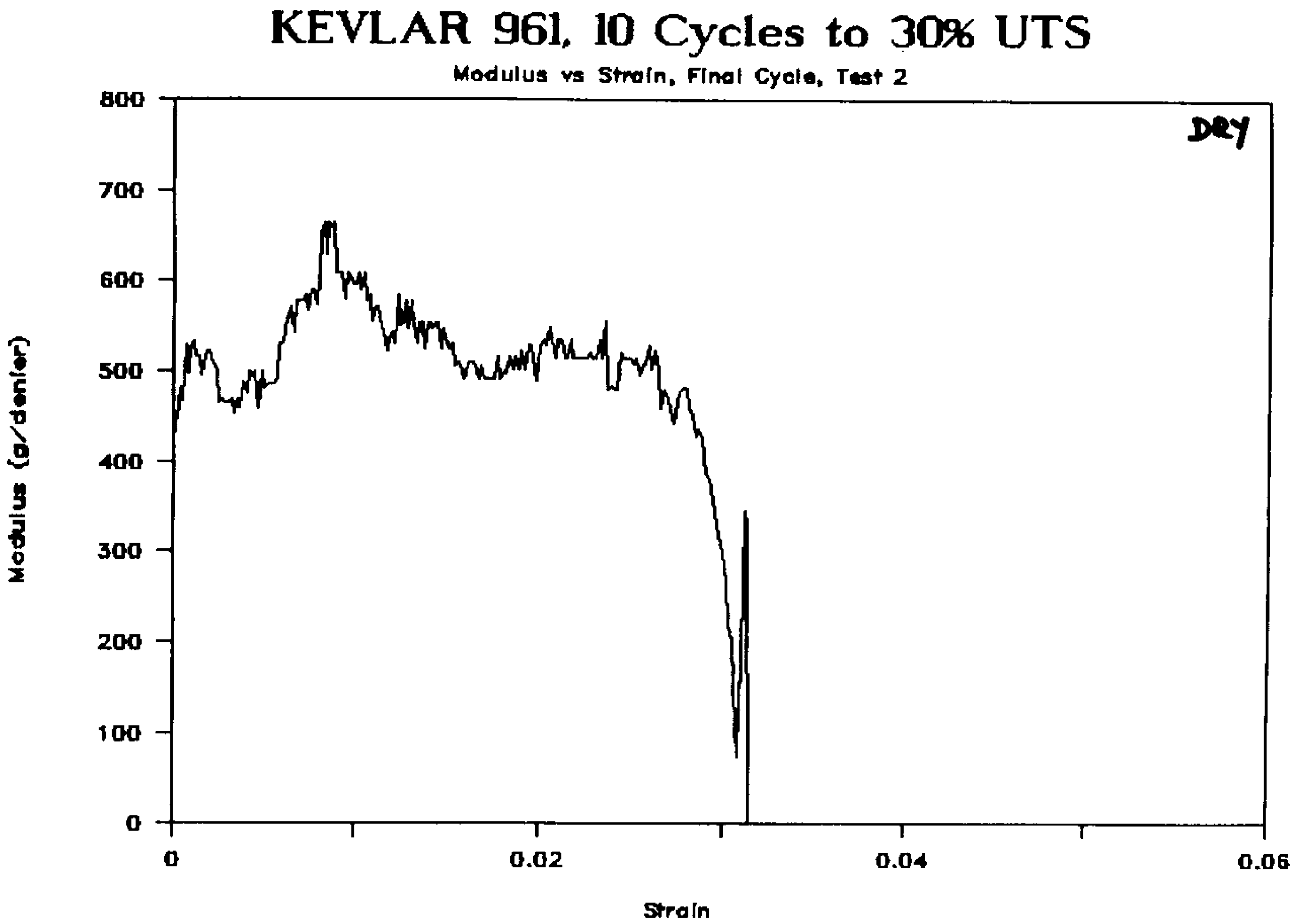


FIG. A-10c TANGENT MODULUS VS STRAIN FOR KEVLAR 961 AFTER 10 CYCLES TO 30% OF UTS (DRY)

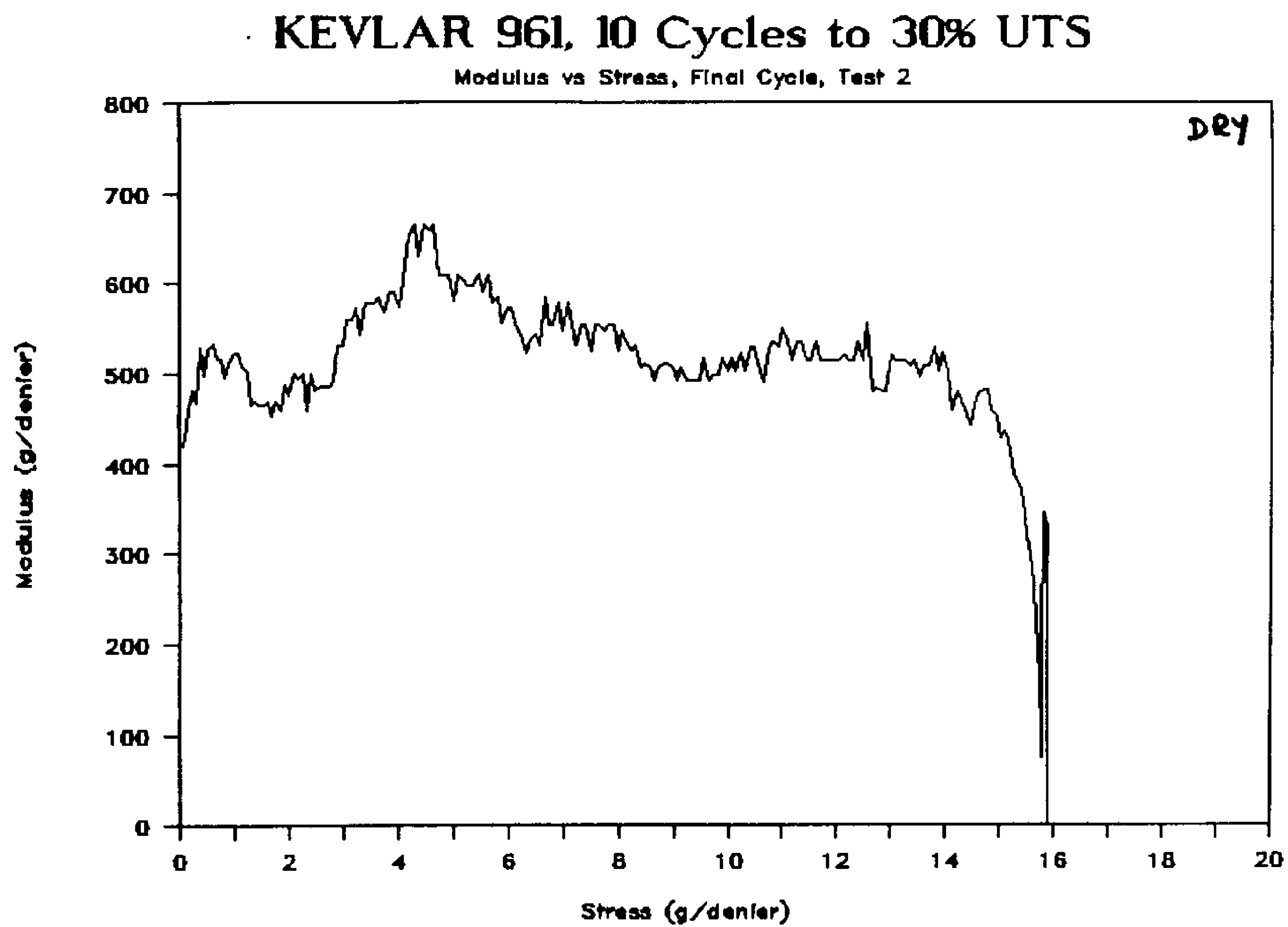
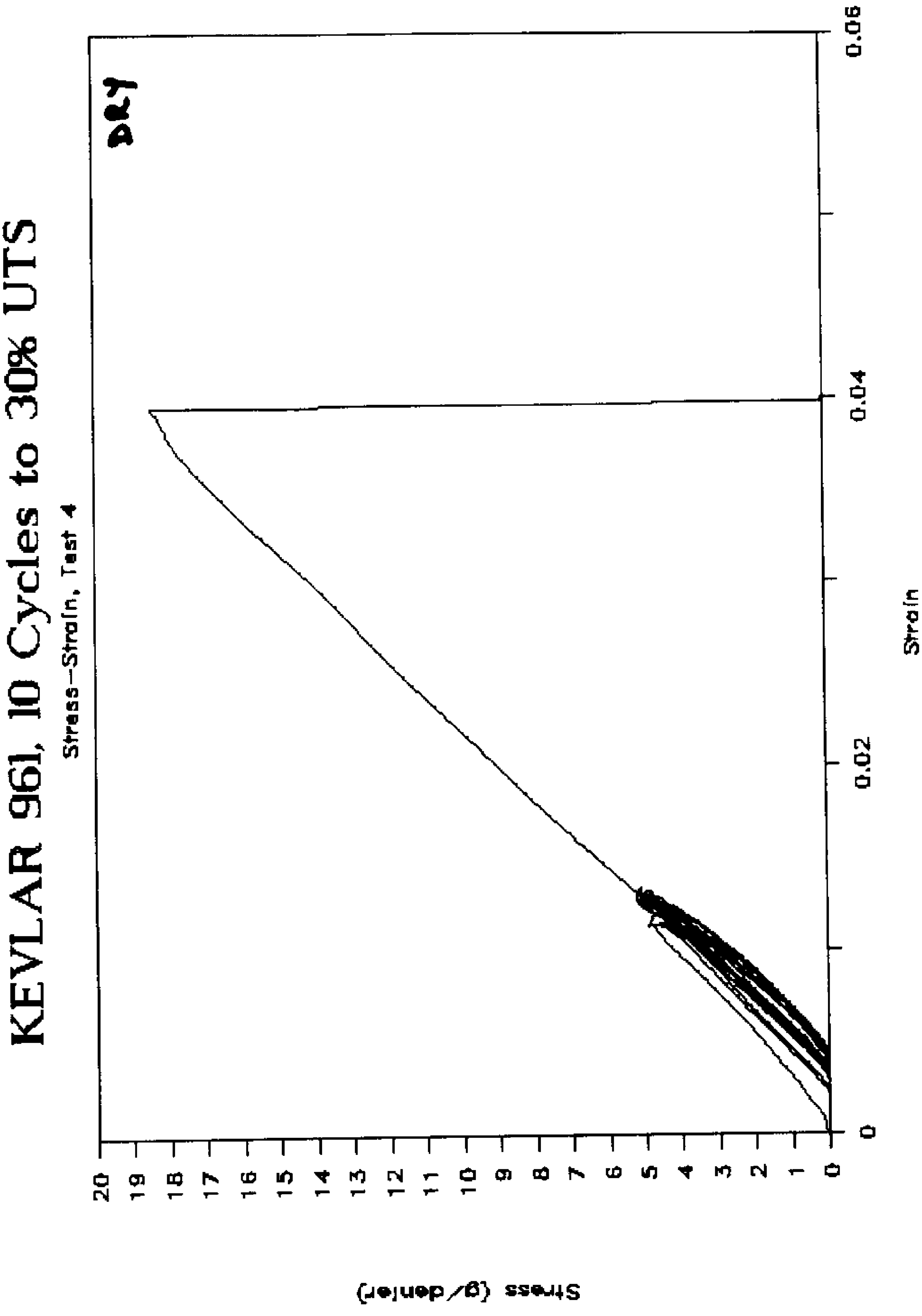
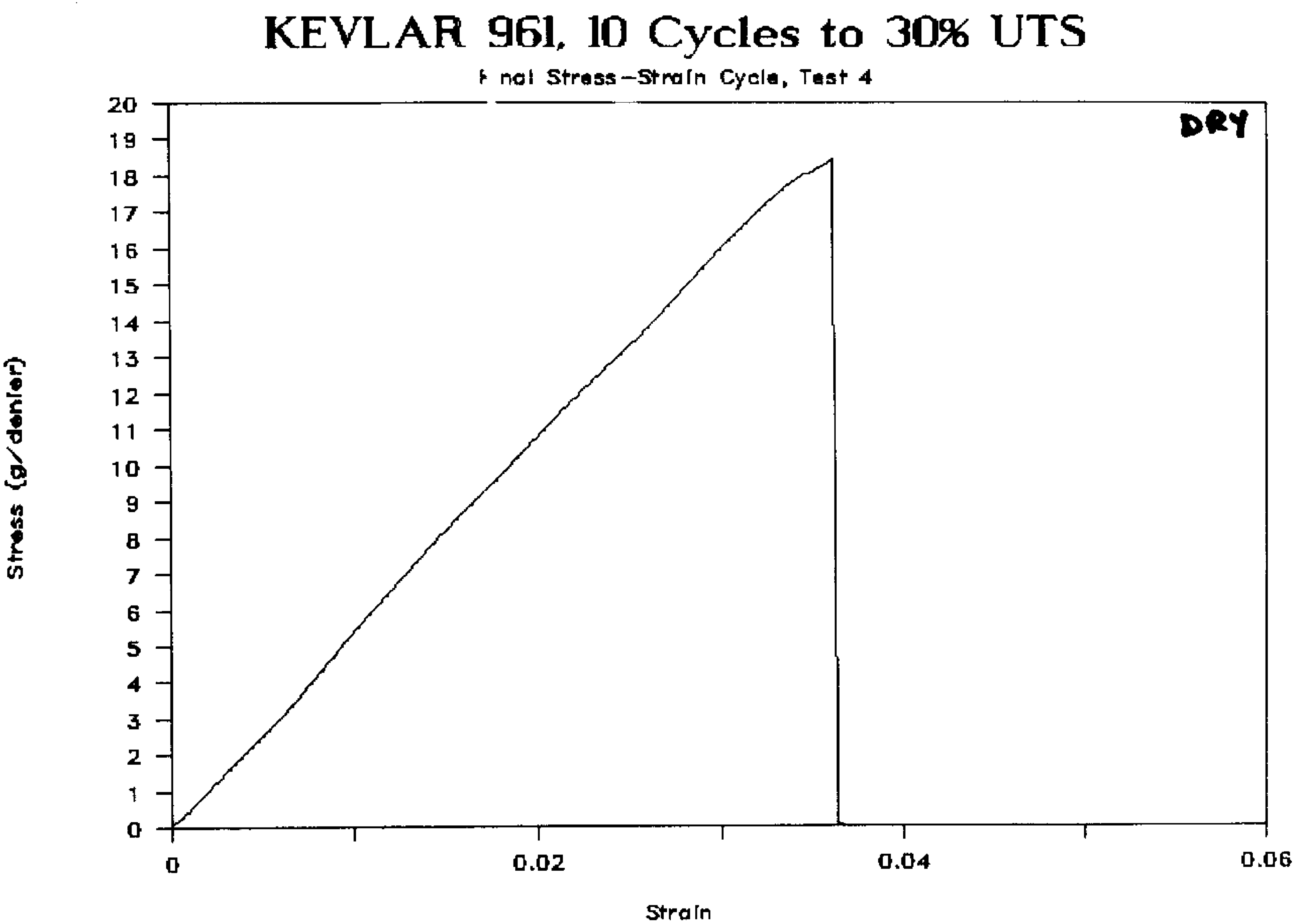


FIG. A-10D TANGENT MODULUS VS STRESS FOR KEVLAR 961 AFTER 10 CYCLES TO 30% OF UTS (DRY)



KEVLAR 961, 10 Cycles to 30% UTS
Stress—Strain, Test 4
DRY
Stress (g/denier)
Strain
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
0.02
0.04
0.06



KEVLAR 961, 10 Cycles to 30% UTS
F nal Stress-Strain Cycle, Test 4
DRY
Stress (g/denier)
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
0
0.02
0.04
0.06
Strain

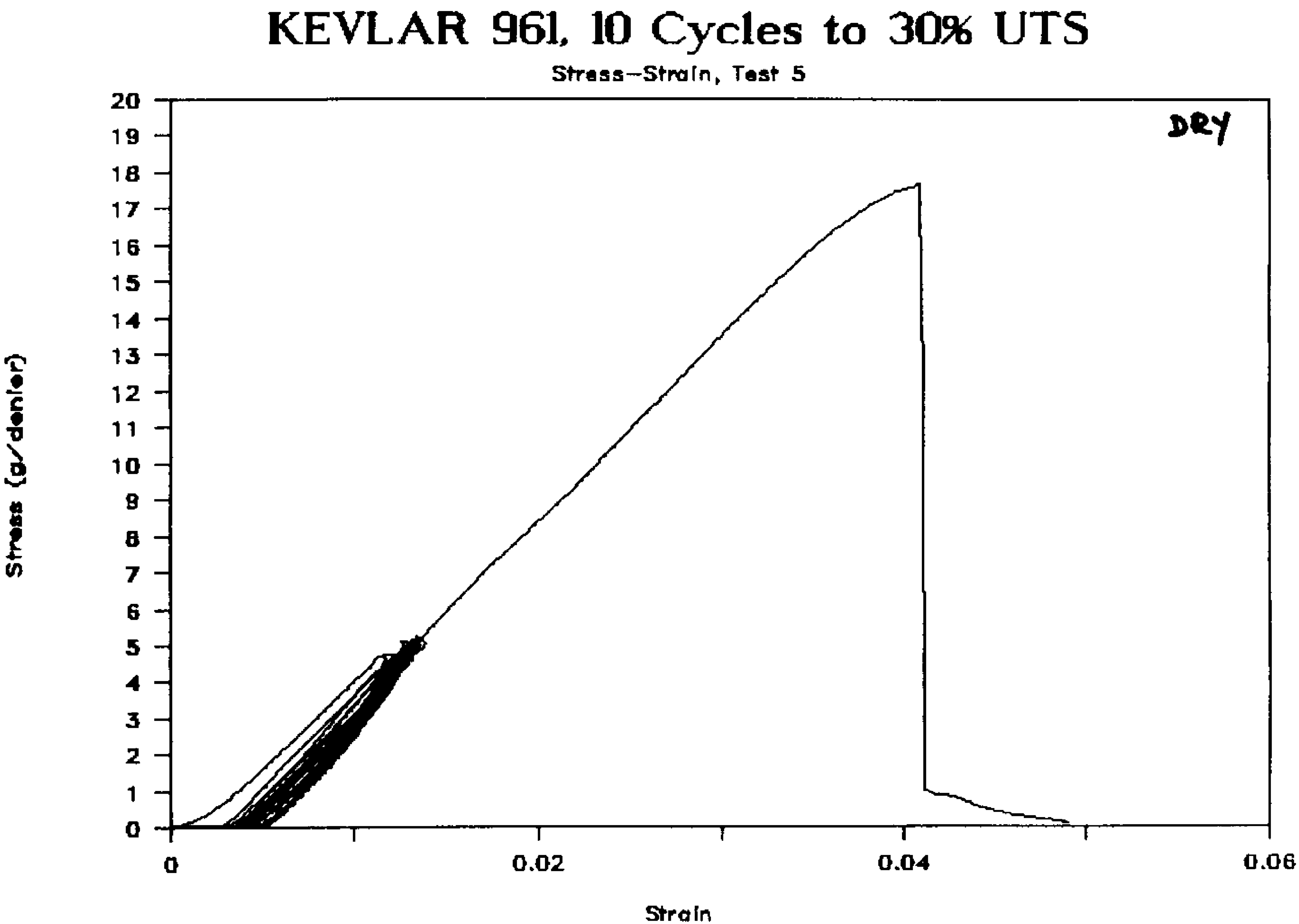


FIG. A-10A STRESS/STRAIN BEHAVIOR OF KEVLAR 961 DURING 10 CYCLES TO 30% UTS (DRY)

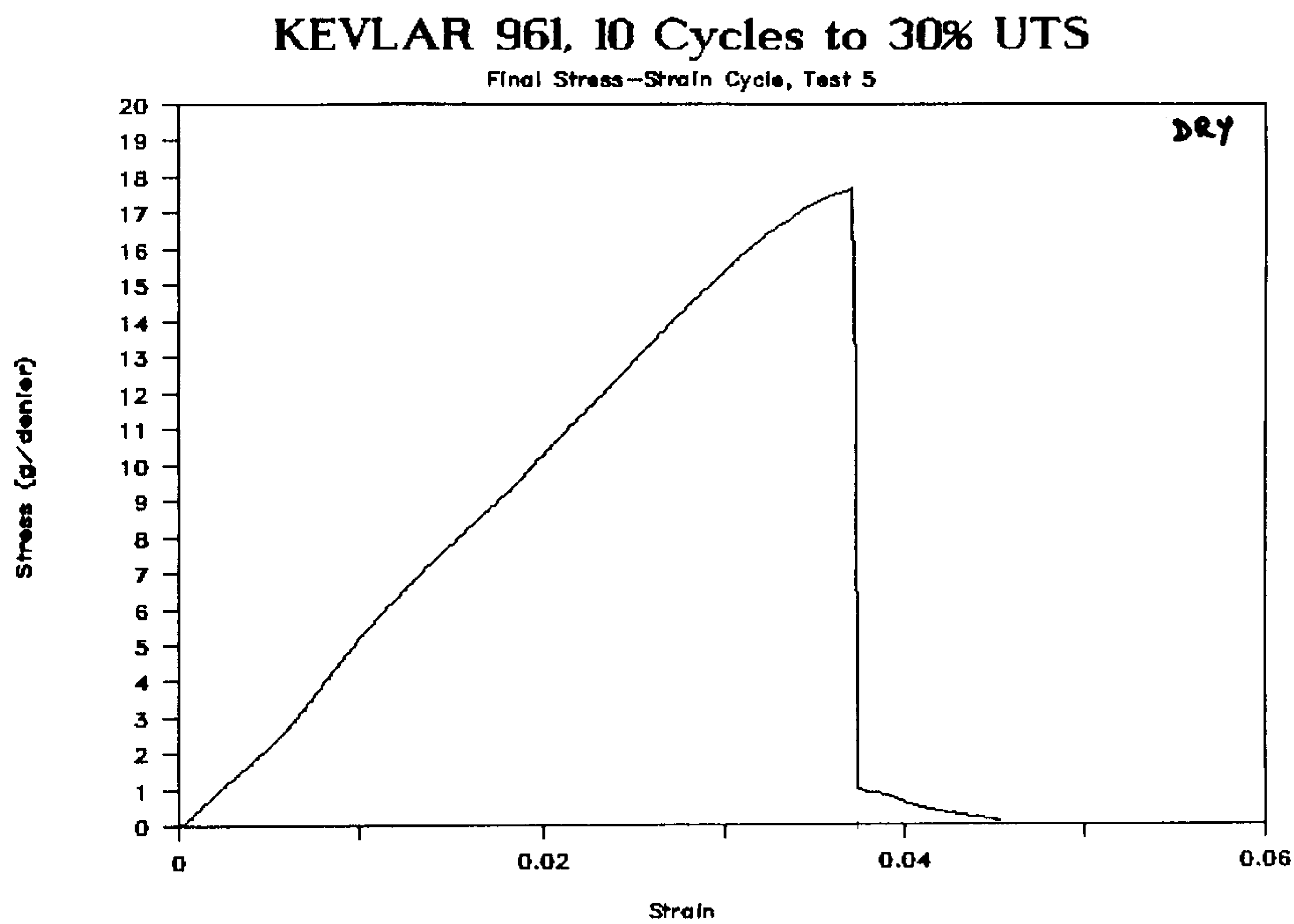
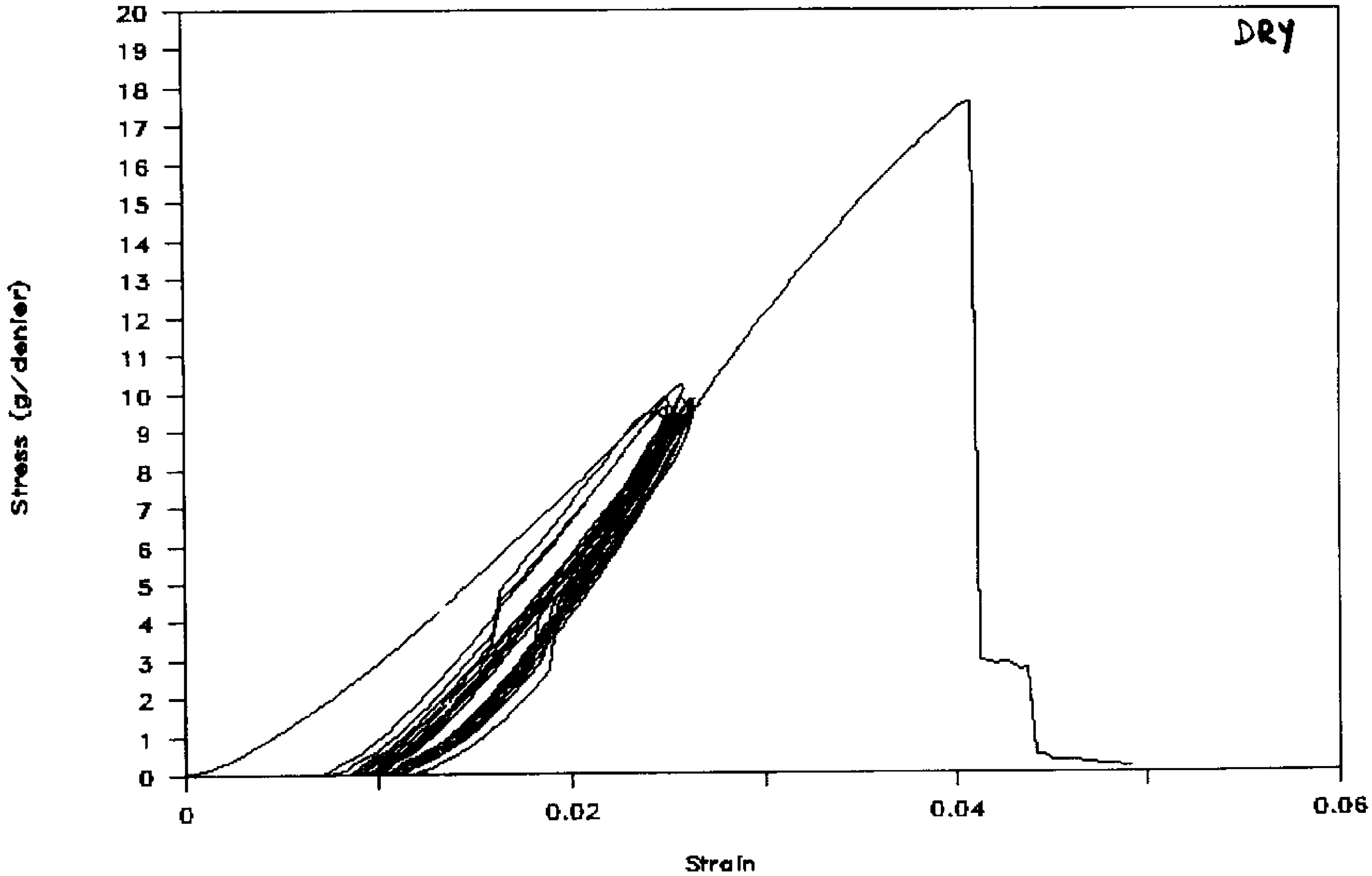


FIG. A-10B STRESS/STRAIN BEHAVIOR OF KEVLAR 961 AFTER 10 CYCLES TO 30% OF UTS (DRY)

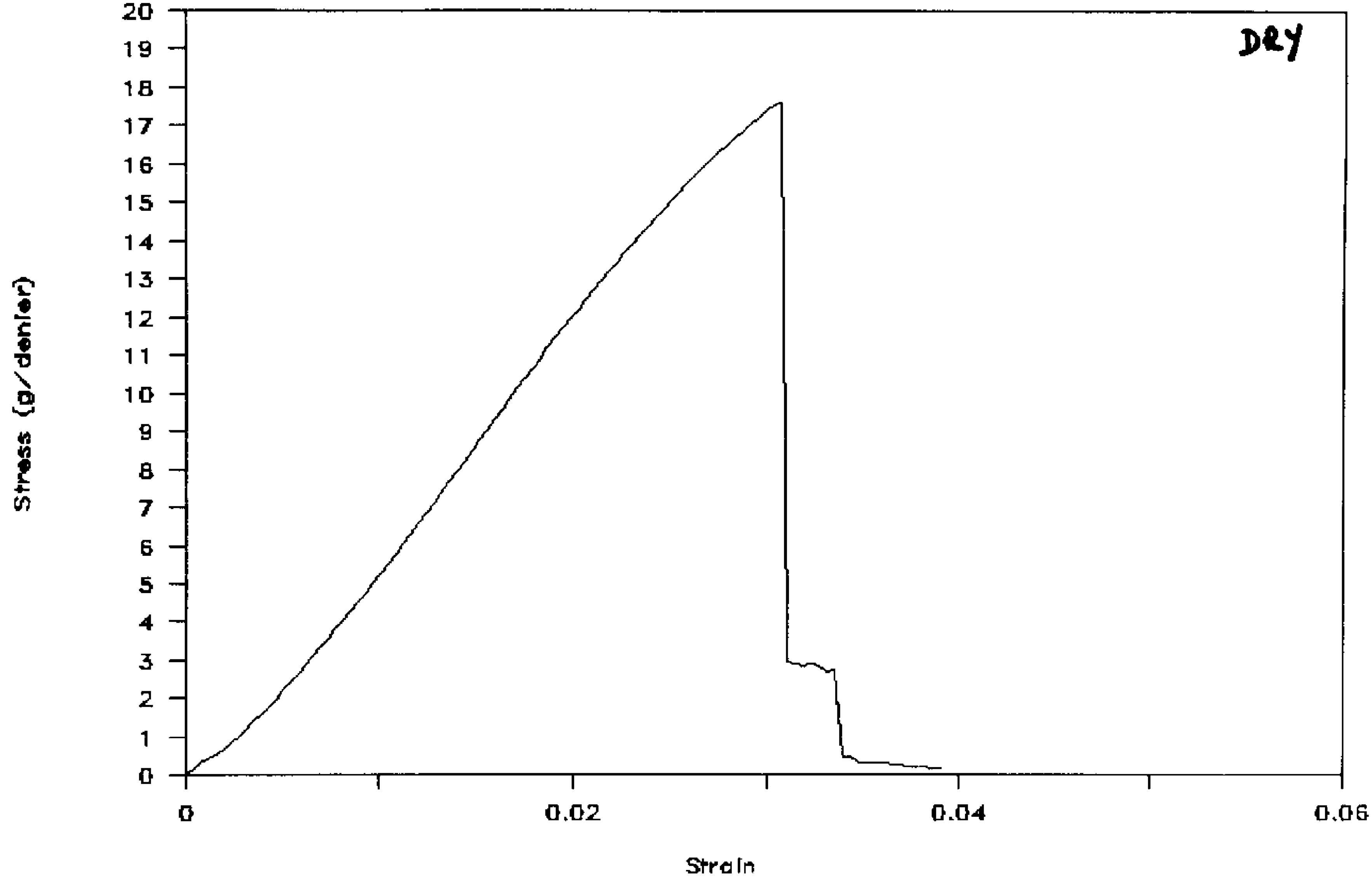
KEVLAR 961, 10 Cycles to 60% UTS

Stress—Strain, Test 1



KEVLAR 961, 10 Cycles to 60% UTS

Final Stress—Strain Cycle, Test 1



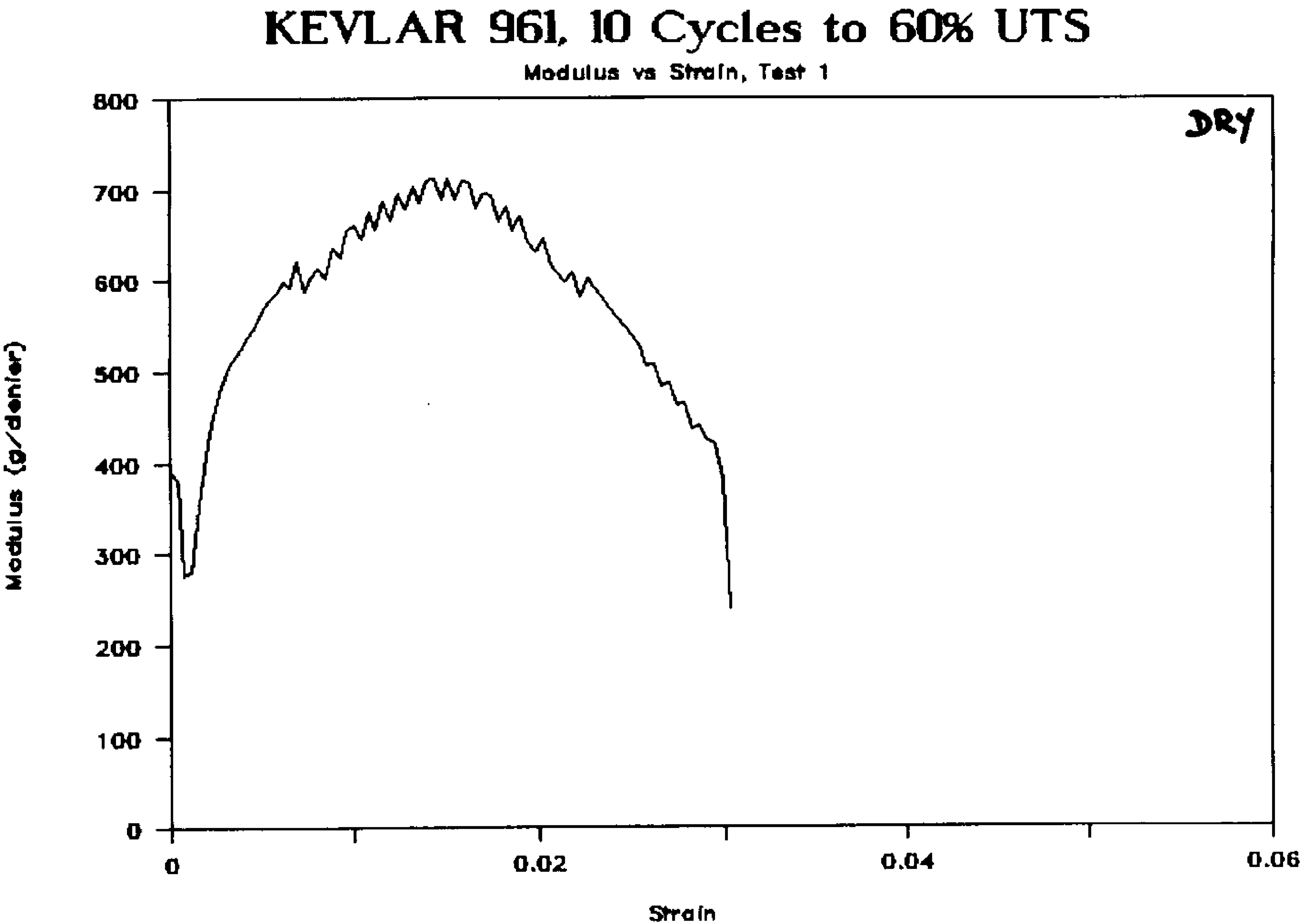


FIG. A-11c TANGENT MODULUS VS STRAIN FOR KEVLAR 961 AFTER 10 CYCLES TO 30% OF UTS (DRY)

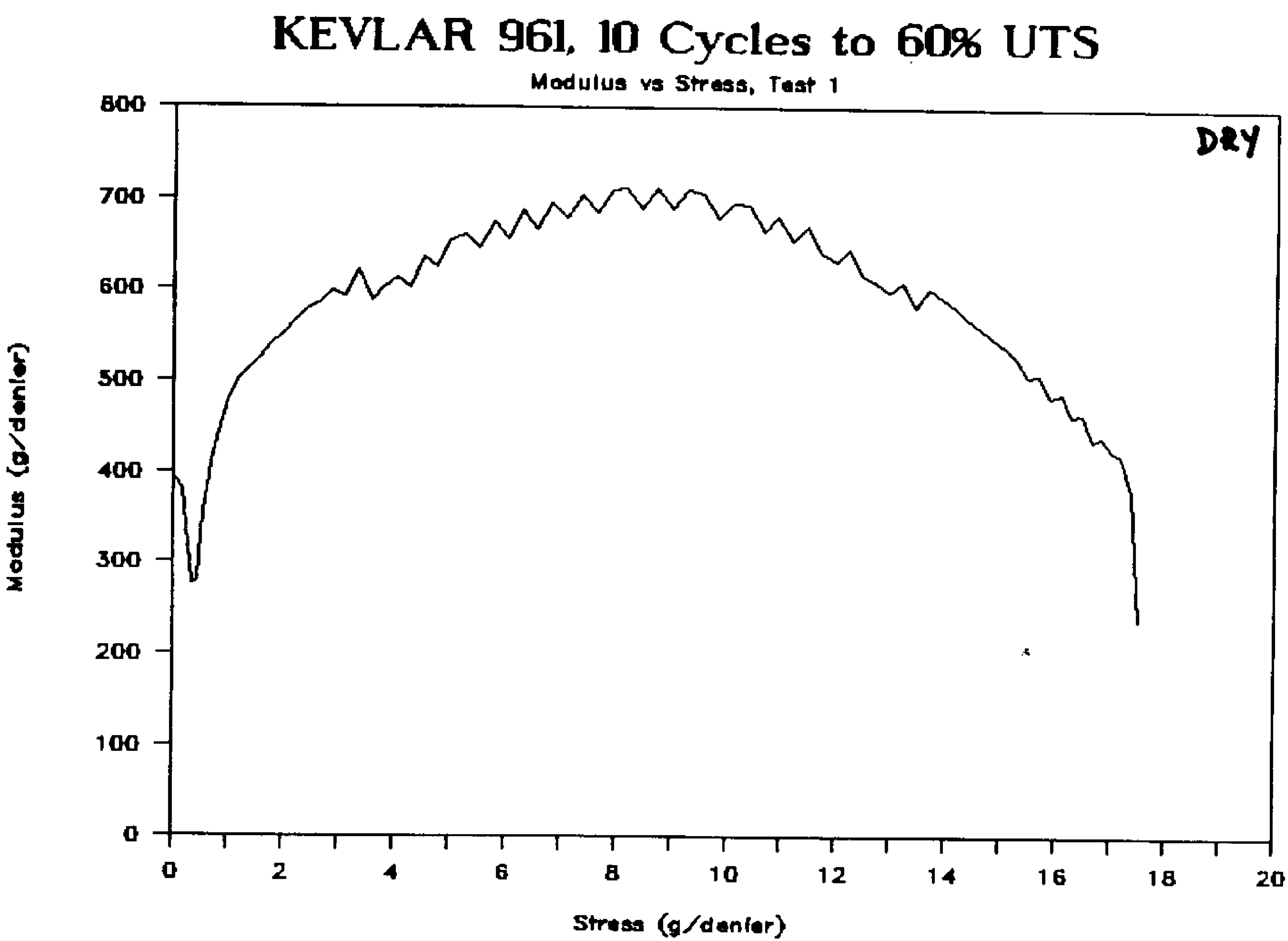
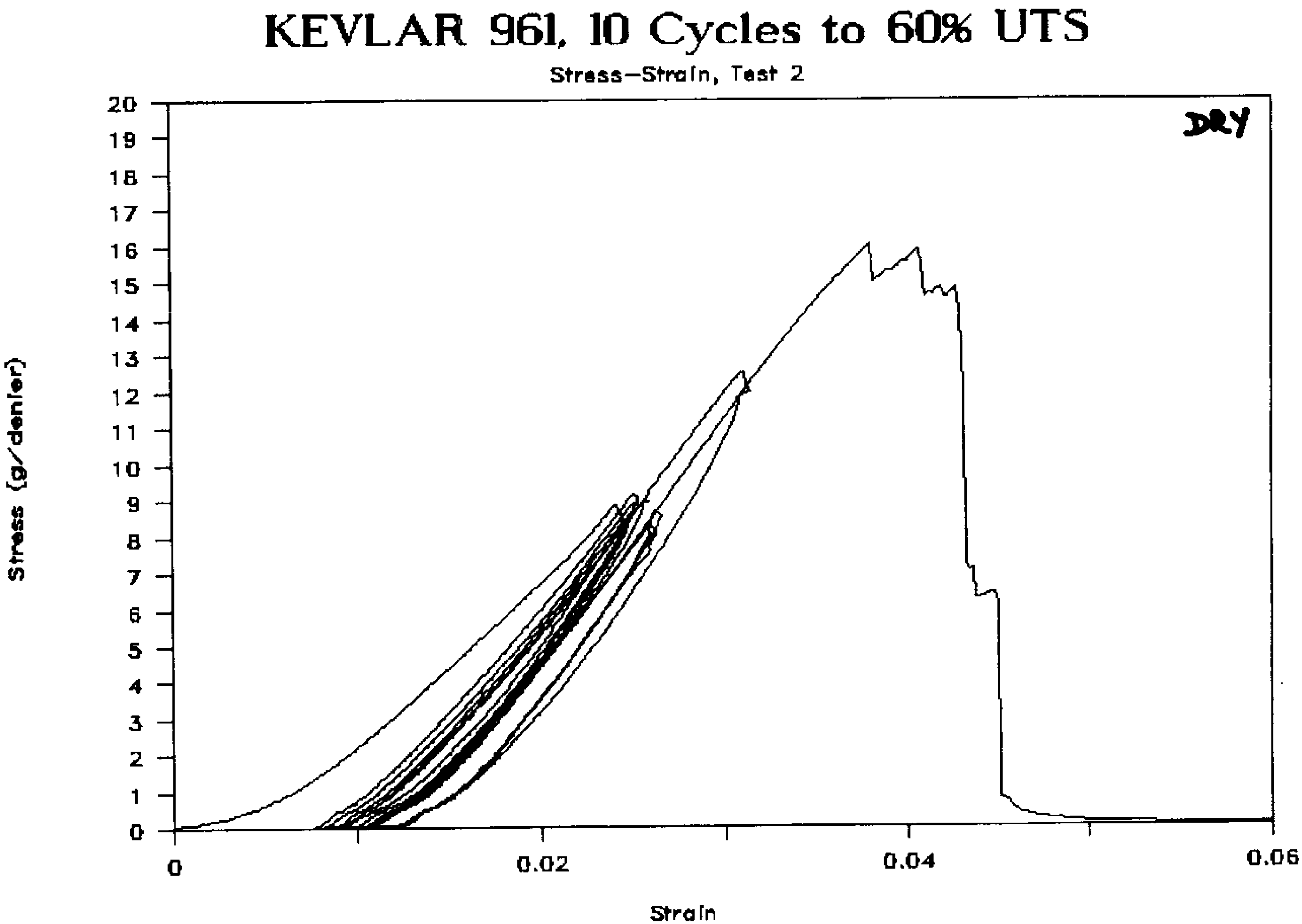
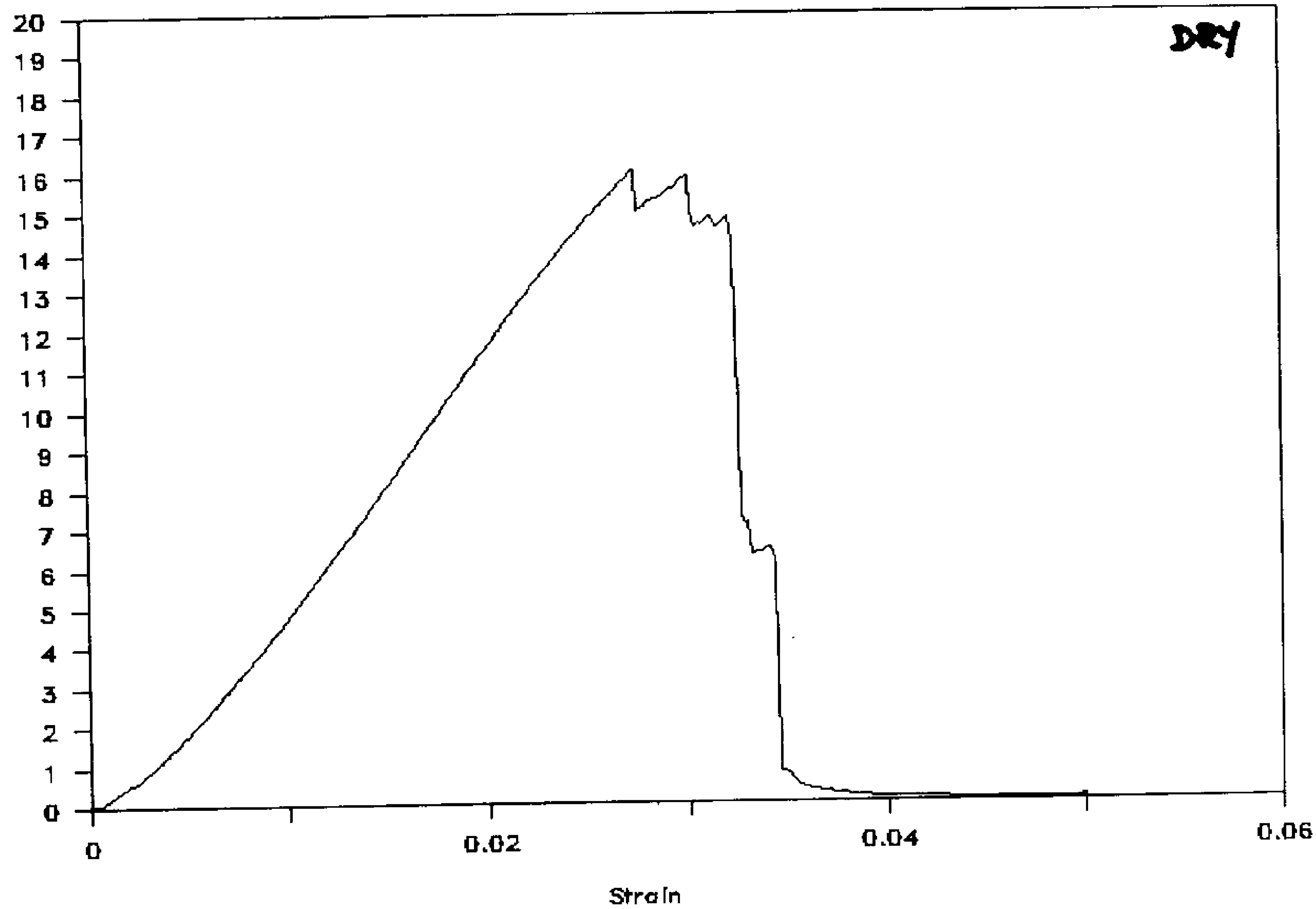


FIG. A-11D TANGENT MODULUS VS STRESS FOR KEVLAR 961 AFTER 10 CYCLES TO 30% OF UTS (DRY)


KEVLAR 961, 10 Cycles to 60% UTS
Stress–Strain, Test 2
DRY
Stress (g/denier)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
0
0.02
0.04
0.06
Strain

KEVLAR 961, 10 Cycles to 60% UTS

Final Stress—Strain Cycle, Test 2



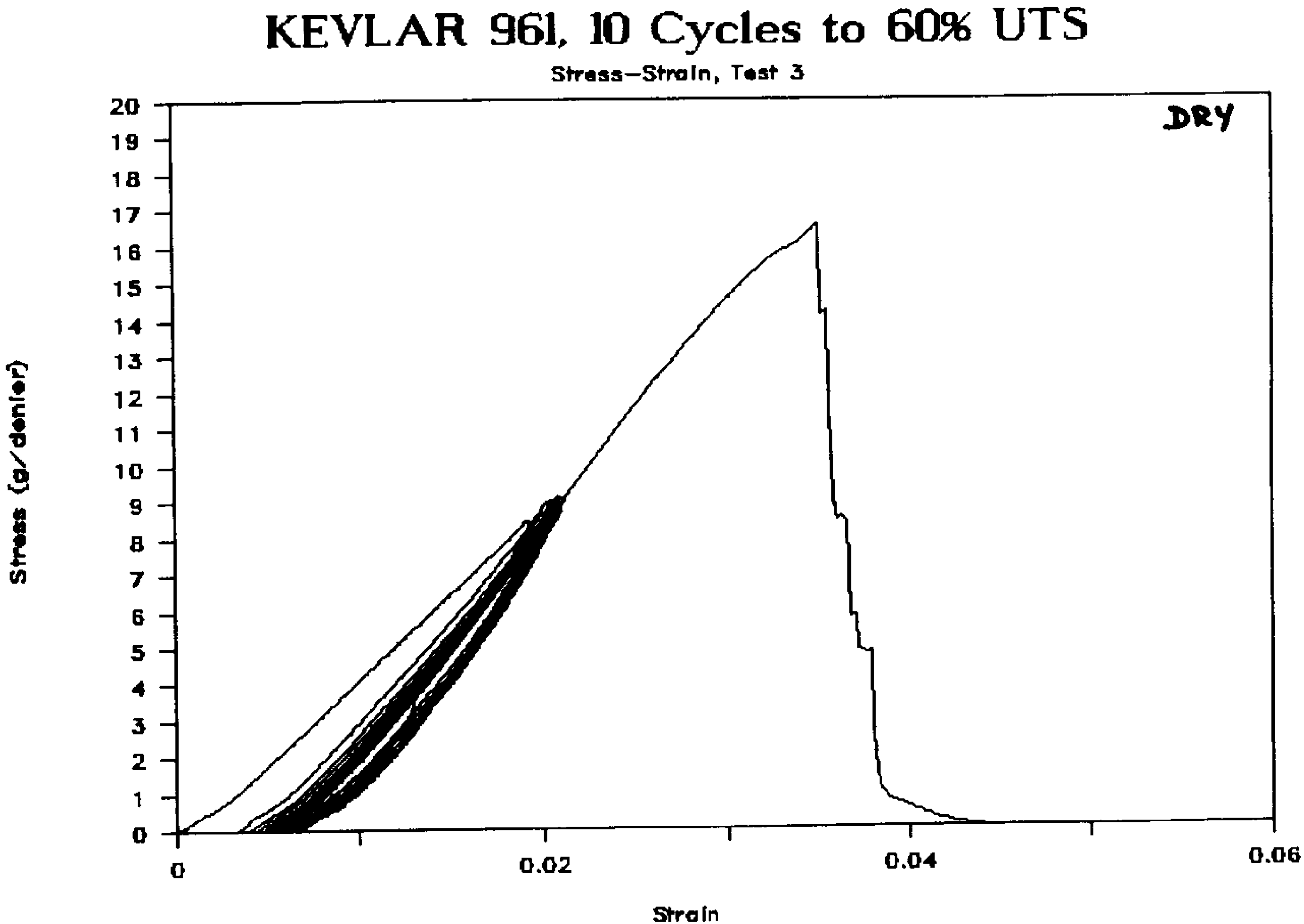


FIG. A-11A STRESS/STRAIN BEHAVIOR OF KEVLAR 961 DURING 10 CYCLES TO 30% UTS (DRY)

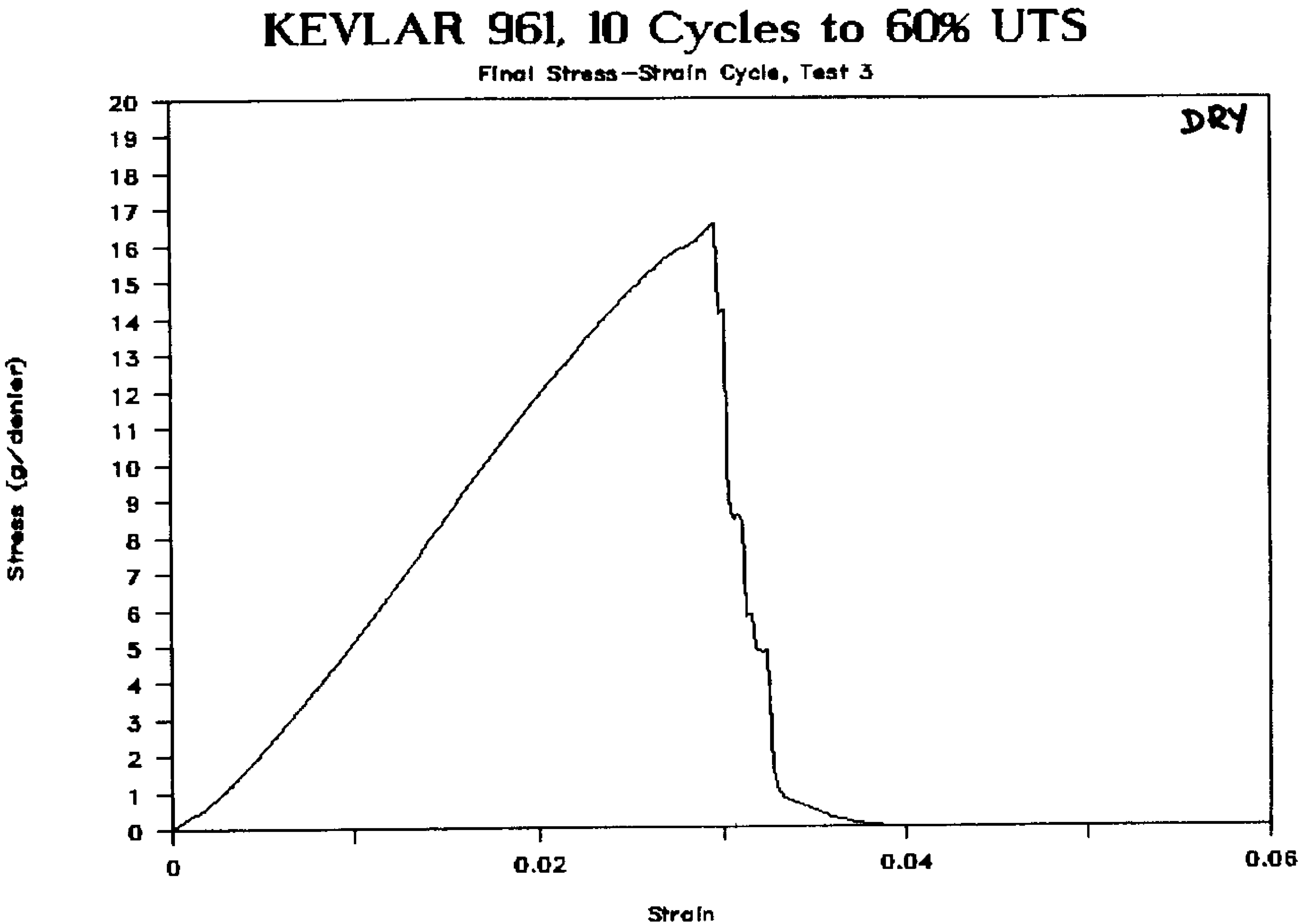
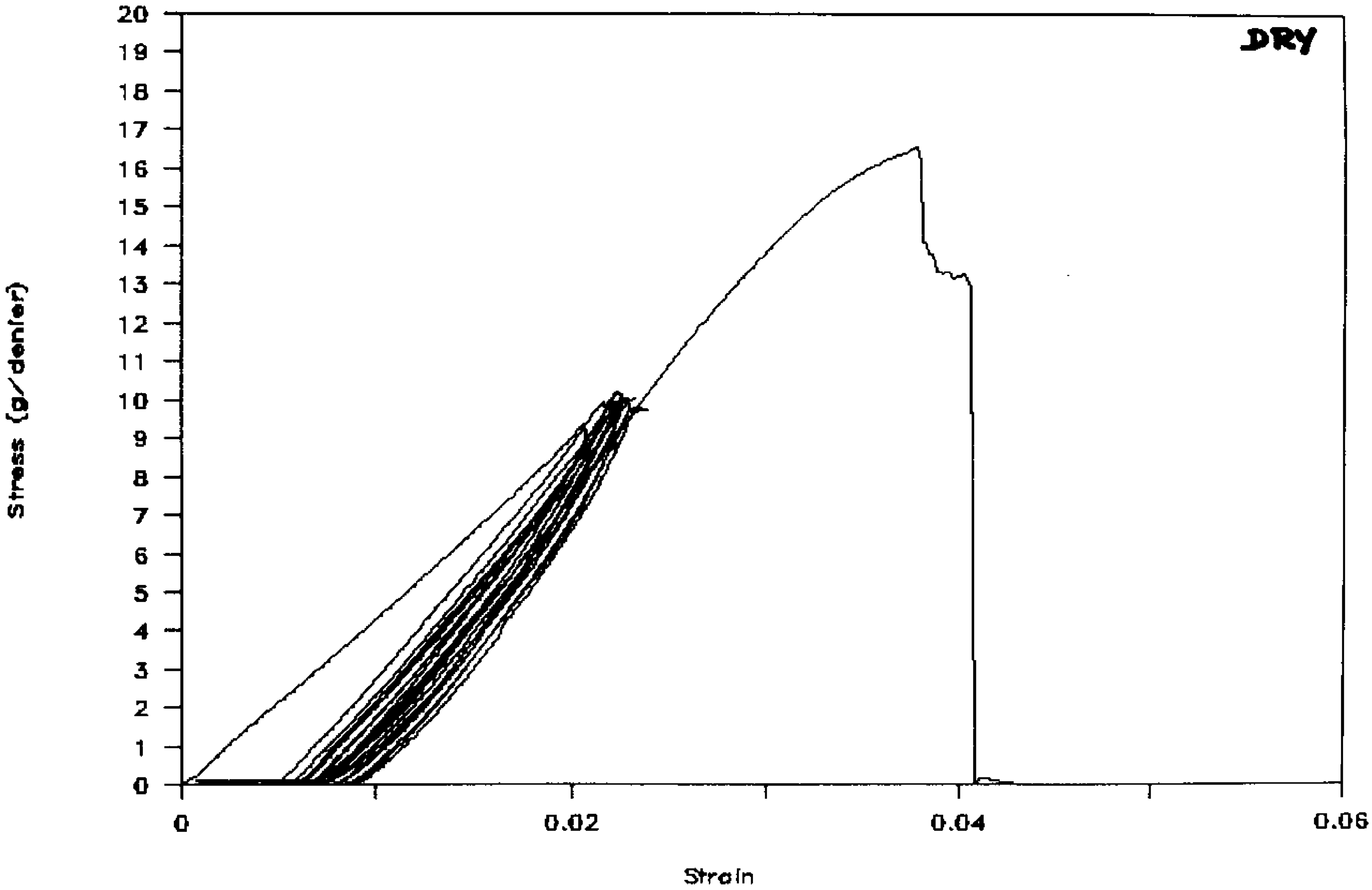


FIG. A-11B STRESS/STRAIN BEHAVIOR OF KEVLAR 961 AFTER 10 CYCLES TO 30% UTS (DRY)

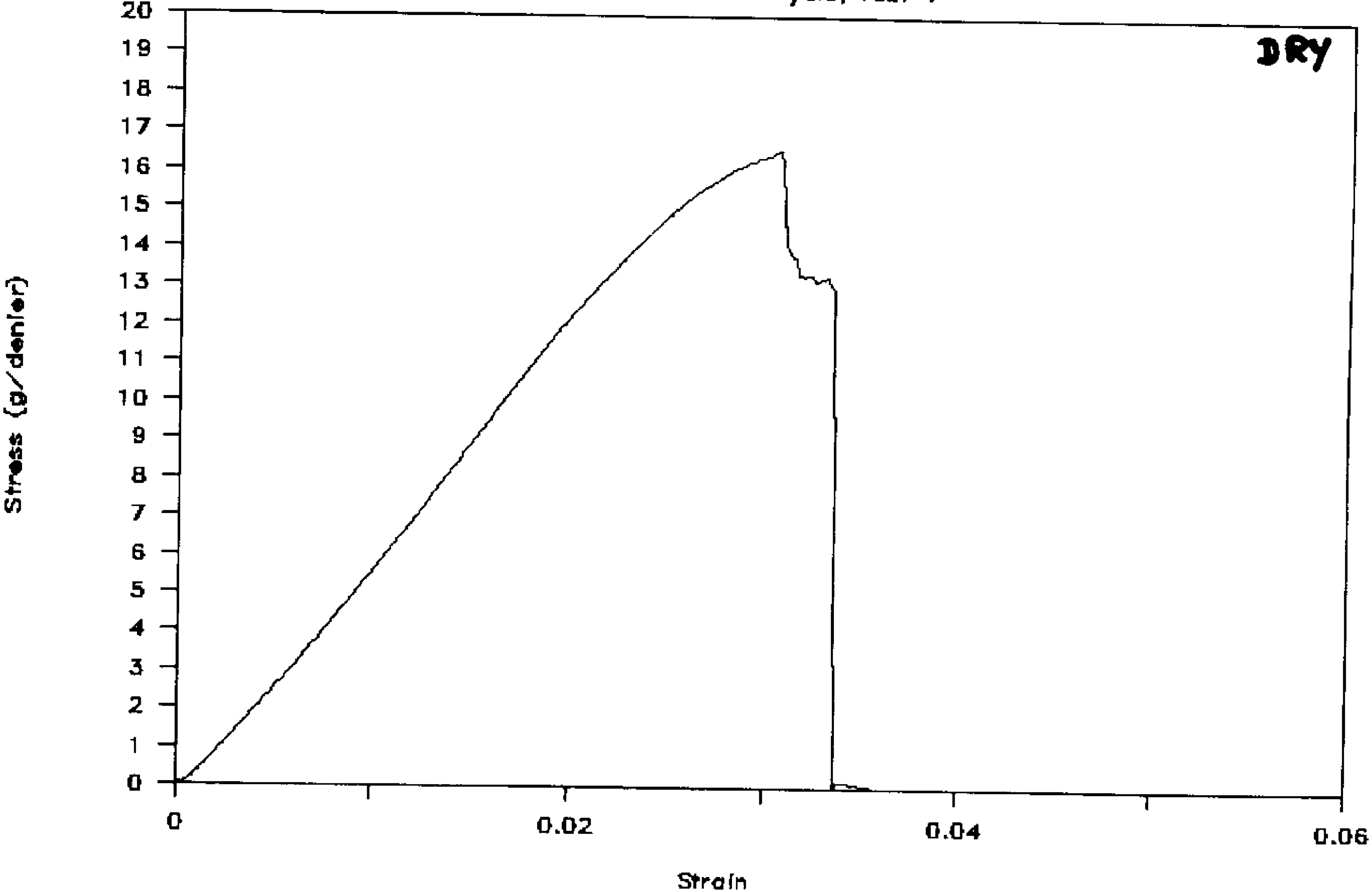
KEVLAR 961, 10 Cycle to 60% UTS

Stress—Strain, Test 4



KEVLAR 961, 10 Cycle to 60% UTS

Final Stress-Strain Cycle, Test 4



II. TENSILE STRESS STRAIN BEHAVIOR

ENKA POLYESTER

The identical tensile tests conducted on the KEVLAR yarns (with and without marine finish) were also run on the polyester yarns produced by ENKA (with and without finish). Single monotonic stress strain tests were run on 1000 denier ENKA polyester yarns and breaking load and extensions were recorded for 5 specimens of each ENKA type. Cyclic tests were then run to 30% of the previously recorded breaking stress and after the 10th cycle the full stress strain curve was recorded. The procedure was then repeated for a third set of 5 yarn specimens, this time after cycling to 60% of breaking load. Each set of tables listed below was followed by individual stress strain curves of the various yarn groups.

Finally a special set of 1000 denier ENKA polyester yarns formed into 20 ply yarn with marine finish was tensile tested both singly and after cycling to 30% and 60% of their breaking strength. Final breaking loads and extension were recorded.

SINGLE LOAD STRESS STRAIN BEHAVIOR

ENKA Polyester (1000 Denier) WITH Marine Finish

Dry and Wet Tests

SINGLE LOAD STRESS -STRAIN BEHAVIOR

ENKA 855TN YARN (1000 DENIER POLYESTER WITH MARINE FINISH)

DRY YARN

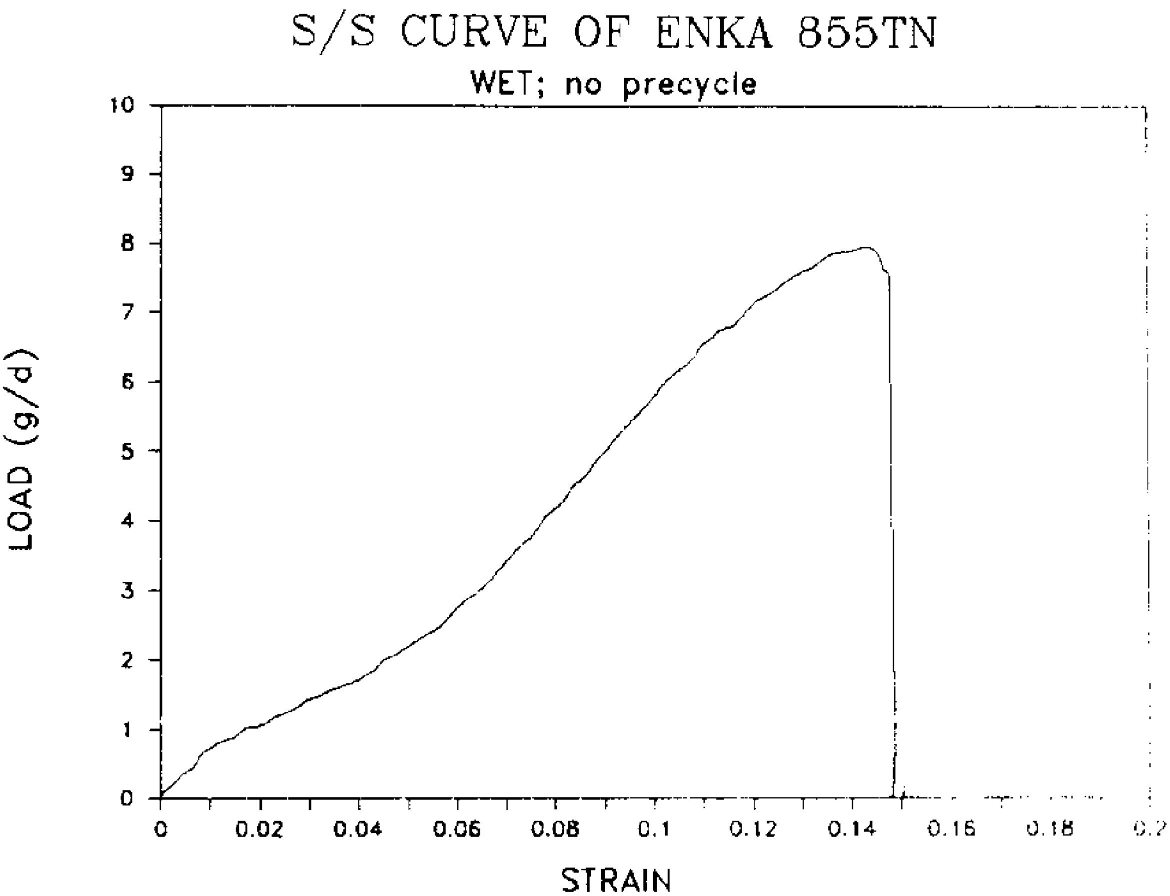
	ORIGINAL		AFTER 30% B.S. 10 CYCLES		AFTER 60% B.S. 10 CYCLES	
	BREAKING STRESS GM/DENIER	BREAKING STRAIN	BREAKING STRESS GM/DENIER	BREAKING STRAIN	BREAKING STRESS GM/DENIER	BREAKING STRAIN
1	8.6	.135	8.5	.118	8.4	.108
2	8.6	.135	8.25	.102	8.6	.108
3	8.3	.12	8	.1	8.35	.1
4	8.15	.125	8.25	.103	7.9	.098
5	8.78	.135	8.2	.108	8.1	.092
MEAN	8.48	.13	8.24	.106	8.27	.101

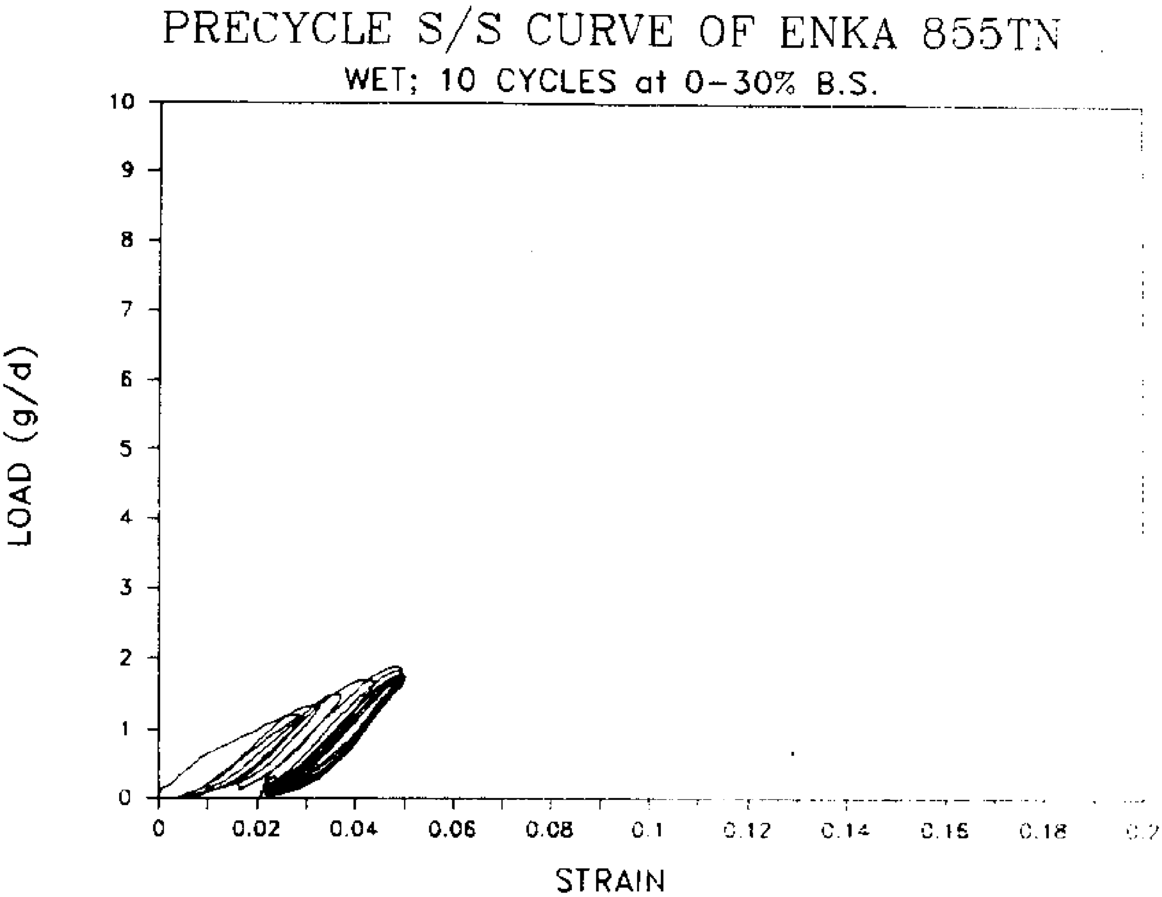
SINGLE LOAD STRESS -STRAIN BEHAVIOR

ENKA 855TN YARN (1000 DENIER POLYESTER WITH FINISH)
WET YARN

	ORIGINAL		AFTER 30% B.S. 10 CYCLES		AFTER 60% B.S. 10 CYCLES	
	BREAKING STRESS GM/DENIER	BREAKING STRAIN	BREAKING STRESS GM/DENIER	BREAKING STRAIN	BREAKING STRESS GM/DENIER	BREAKING STRAIN
1	7.3	XXX	8.4	XXX	7.8	XXX
2	8.5	XXX	7.8	0.140 *	7.8	0.110 *
3	8.1	0.143 *	8.2	XXX	7.8	XXX
4	8.1	XXX	8.0	XXX	8.3	XXX
5	8.1	XXX	7.9	XXX	8.0	XXX
MEAN	8.0	XXX	8.1	XXX	7.9	XXX

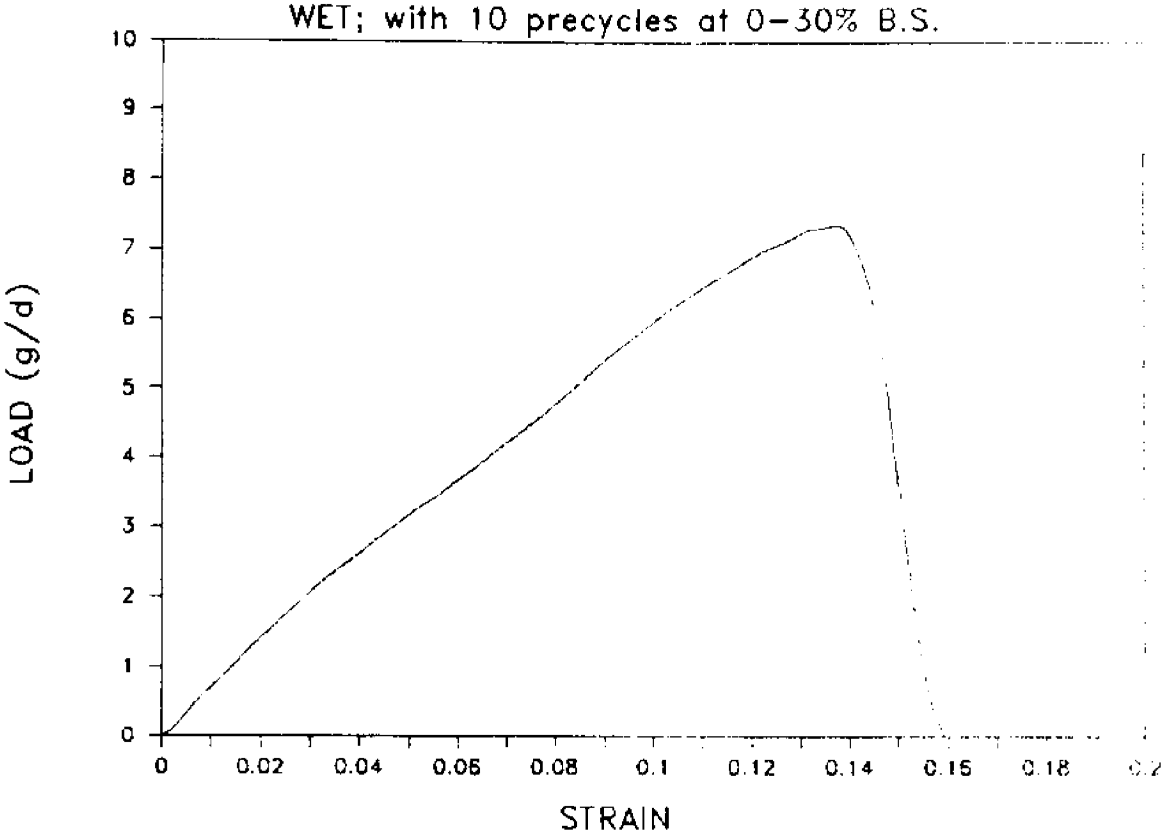
* representative value

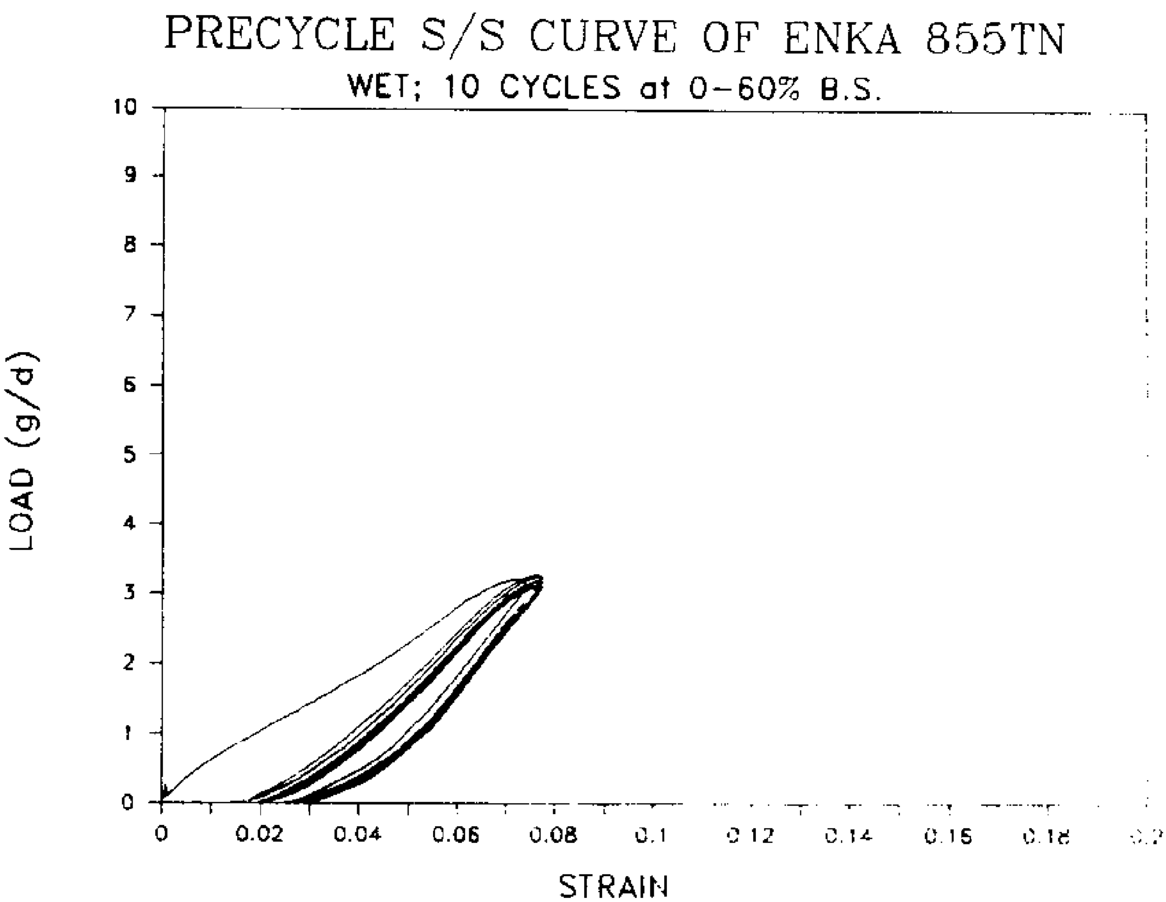

S/S CURVE OF ENKA 855TN
WET; no precycle
LOAD (g/d)
STRAIN
0
1
2
3
4
5
6
7
8
9
10
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2

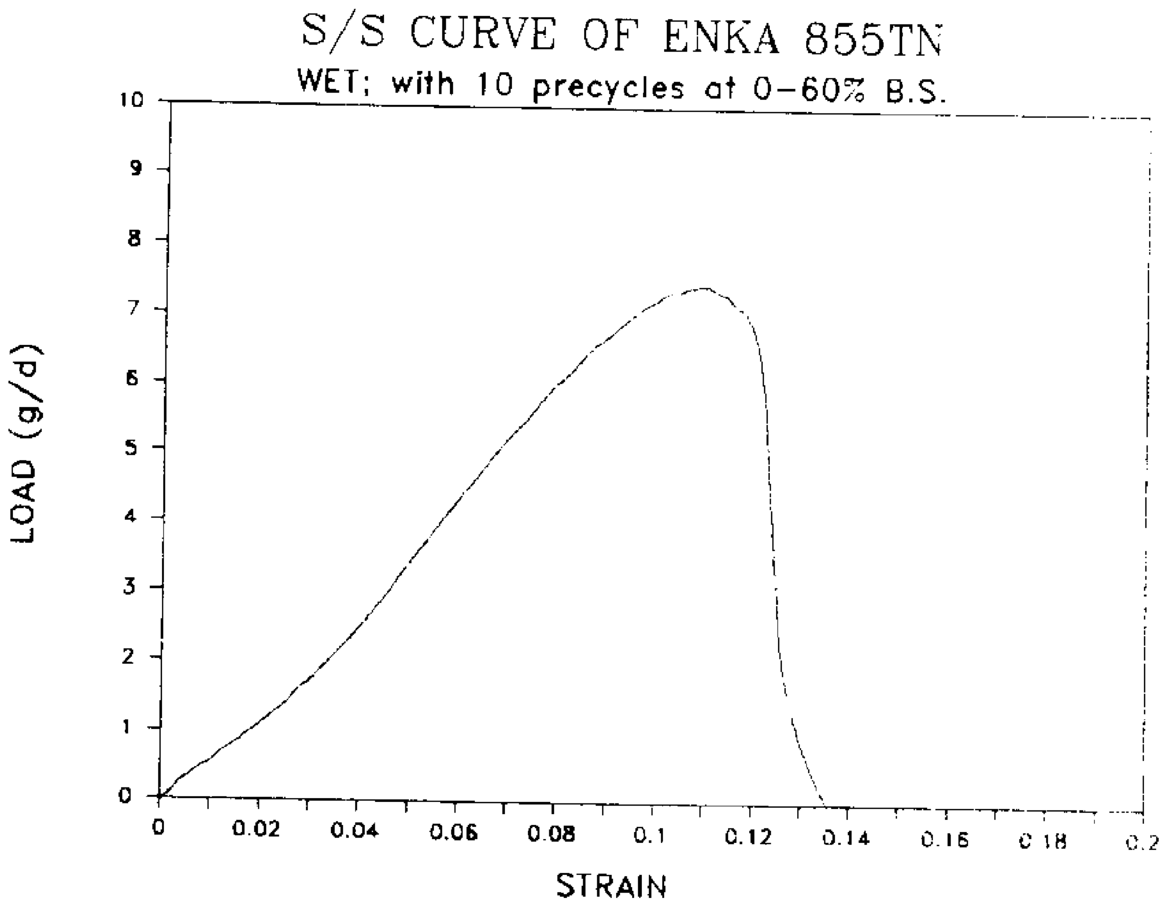

PRECYCLE S/S CURVE OF ENKA 855TN
WET; 10 CYCLES at 0-30% B.S.
LOAD (g/d)
STRAIN
0
1
2
3
4
5
6
7
8
9
10
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18

S/S CURVE OF ENKA 855TN

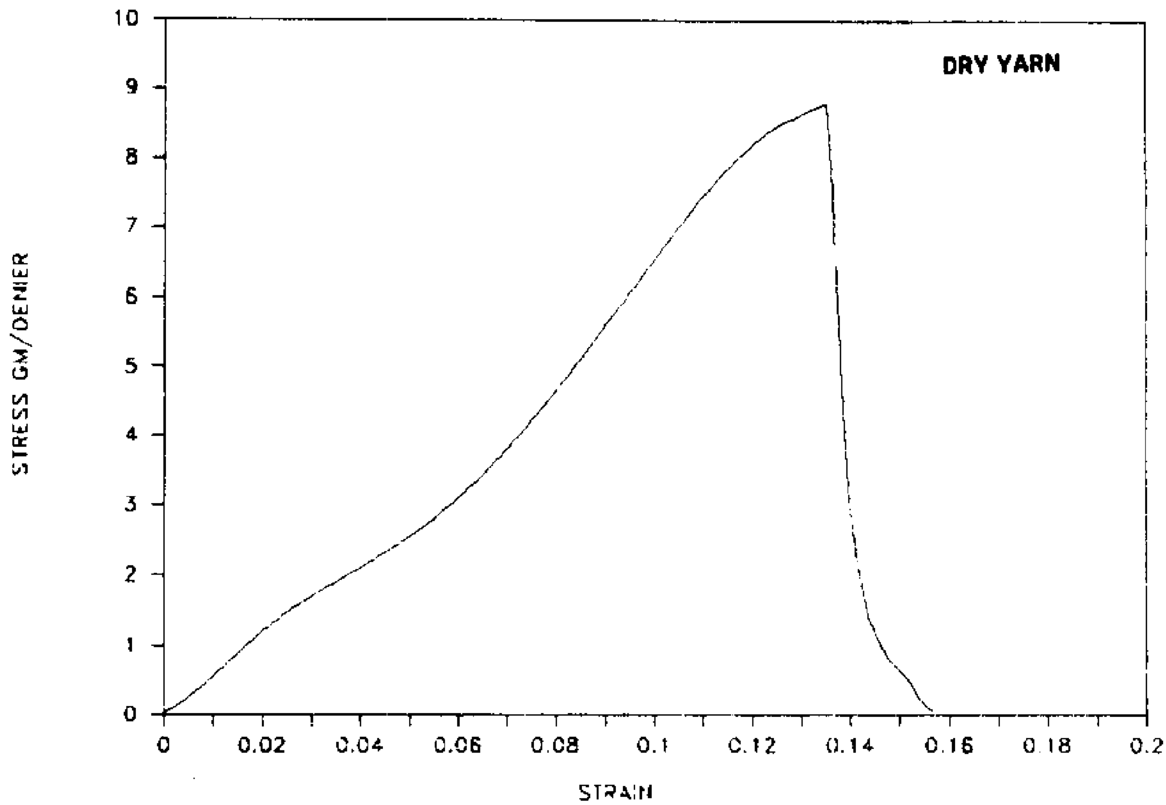
WET; with 10 precycles at 0–30% B.S.



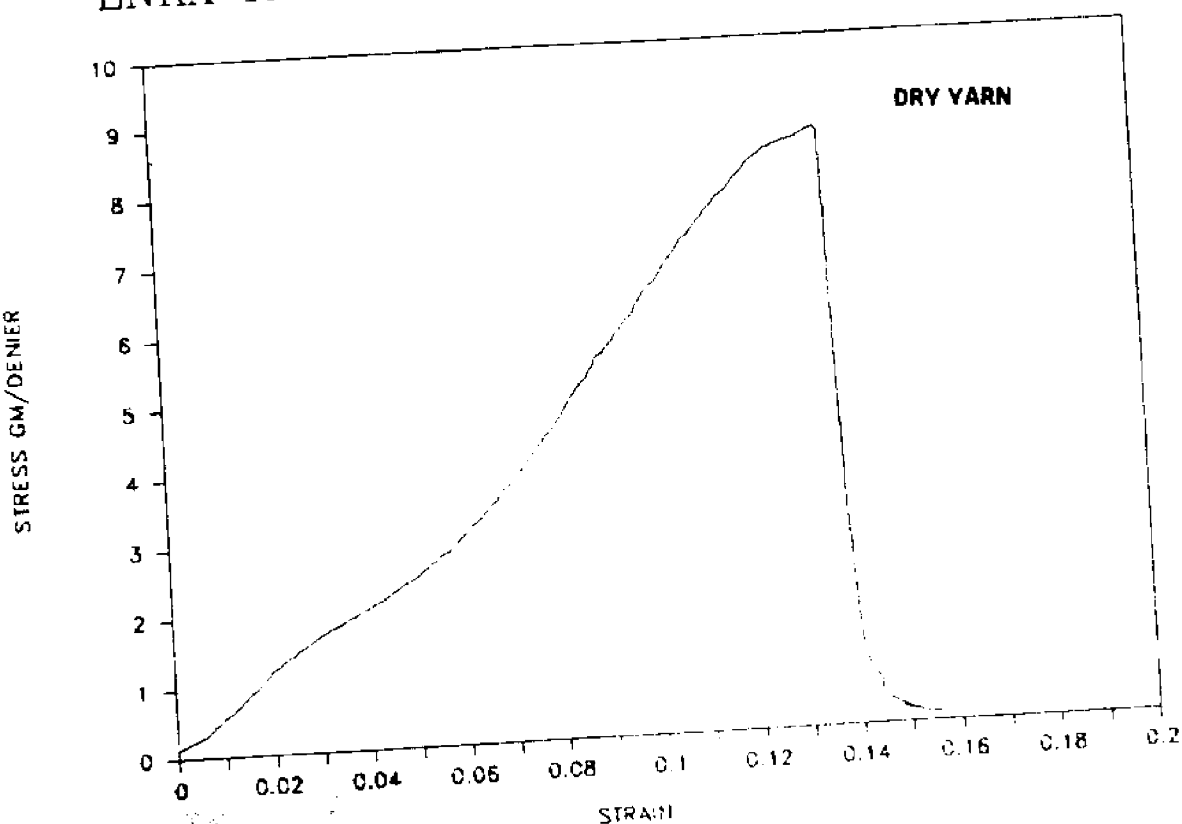

PRECYCLE S/S CURVE OF ENKA 855TN
WET; 10 CYCLES at 0-60% B.S.
LOAD (g/d)
STRAIN
0
1
2
3
4
5
6
7
8
9
10
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18


S/S CURVE OF ENKA 855TN
WET; with 10 precycles at 0-60% B.S.
LOAD (g/d)
10
9
8
7
6
5
4
3
2
1
0
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
STRAIN

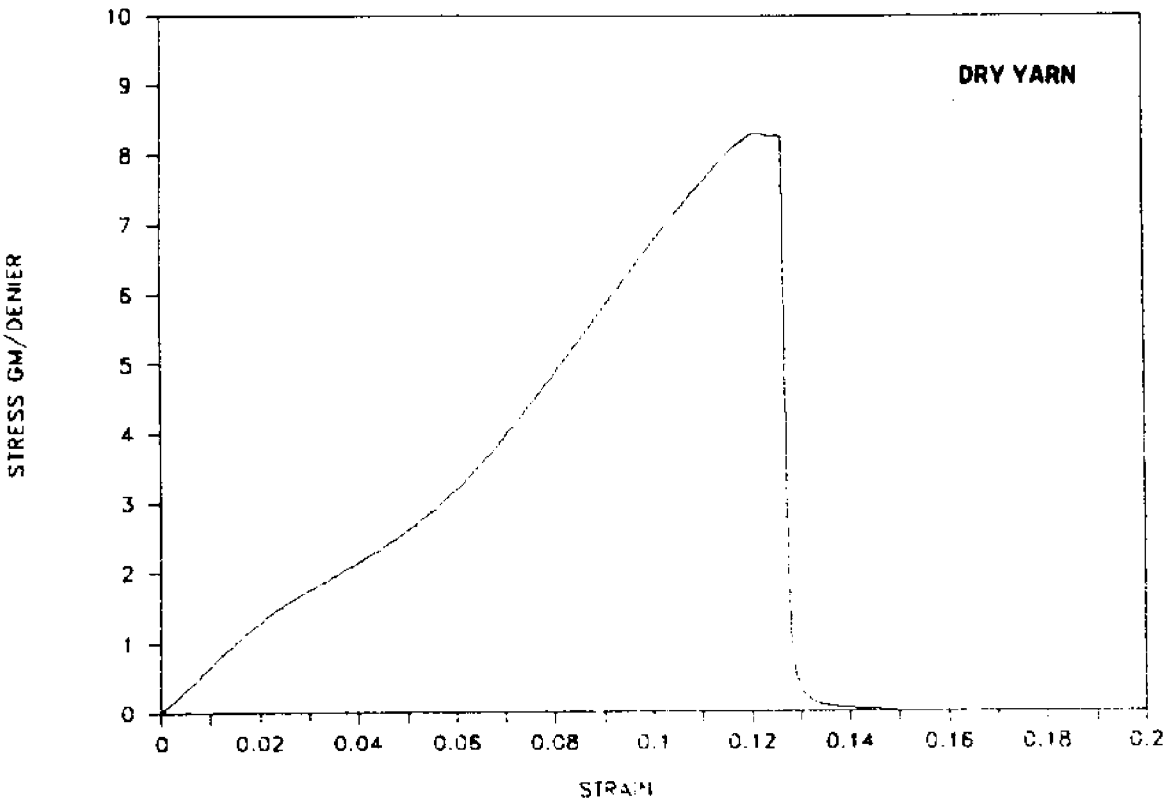
ENKA TN YARN STRESS-STRAIN GRAPH #1



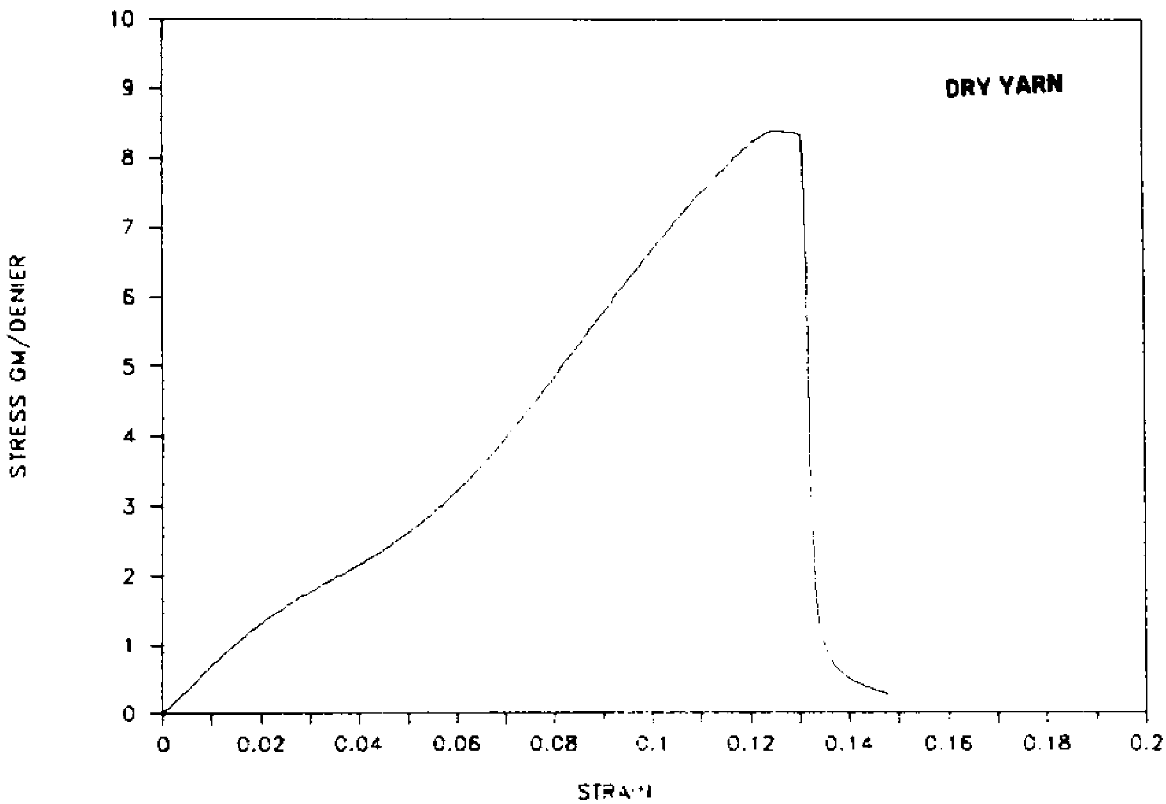
ENKA TN YARN STRESS–STRAIN GRAPH #2



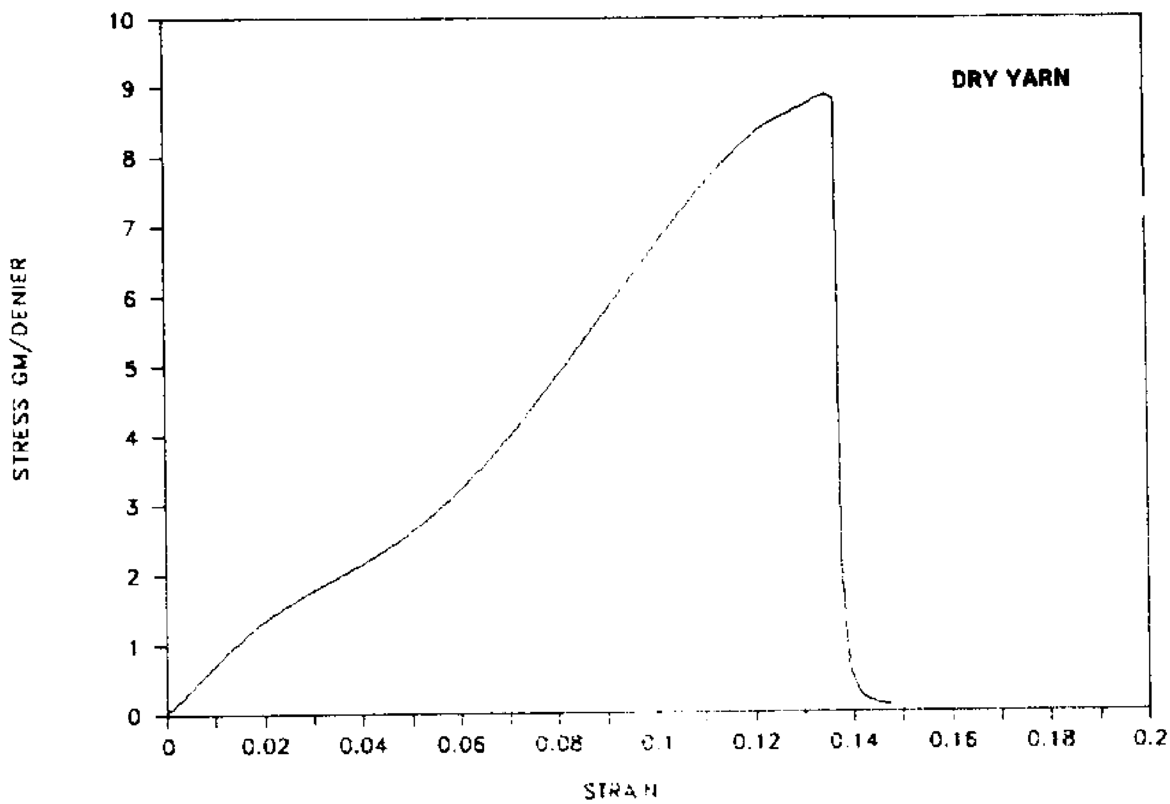
ENKA TN YARN STRESS–STRAIN GRAPH #3



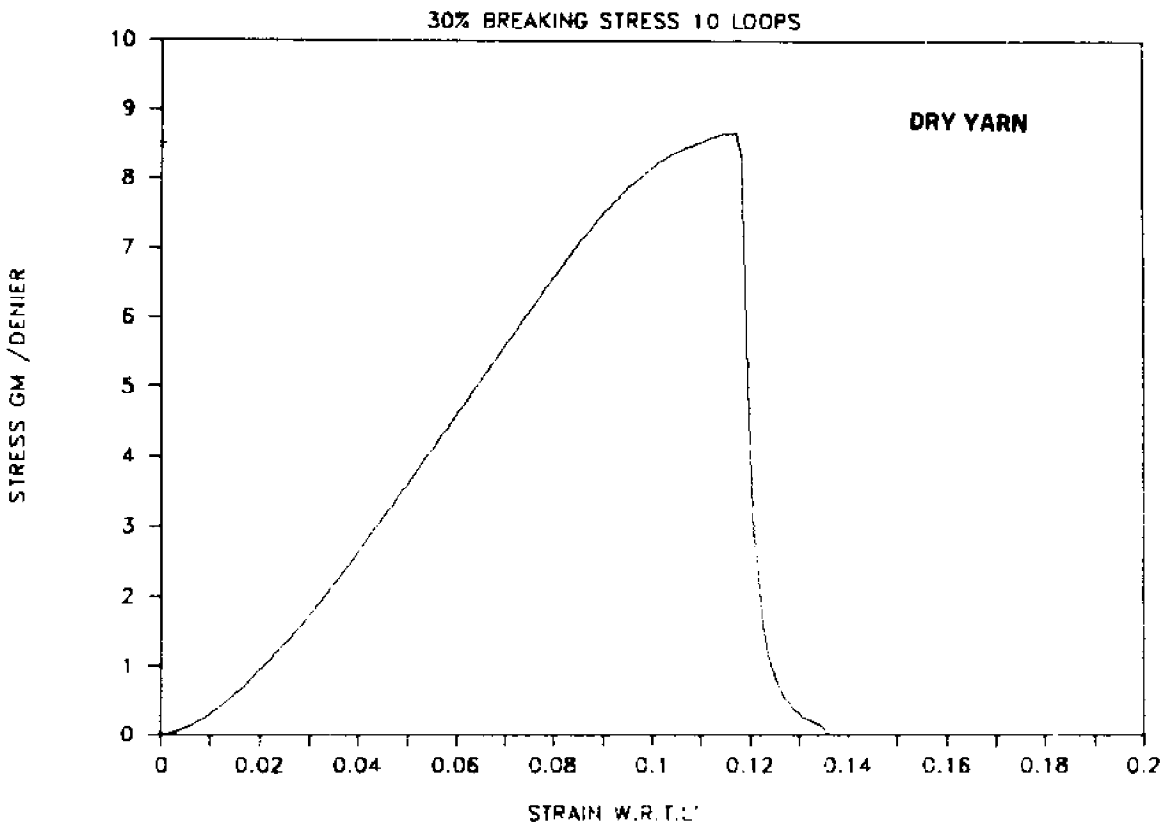
ENKA TN YARN STRESS-STRAIN GRAPH #4



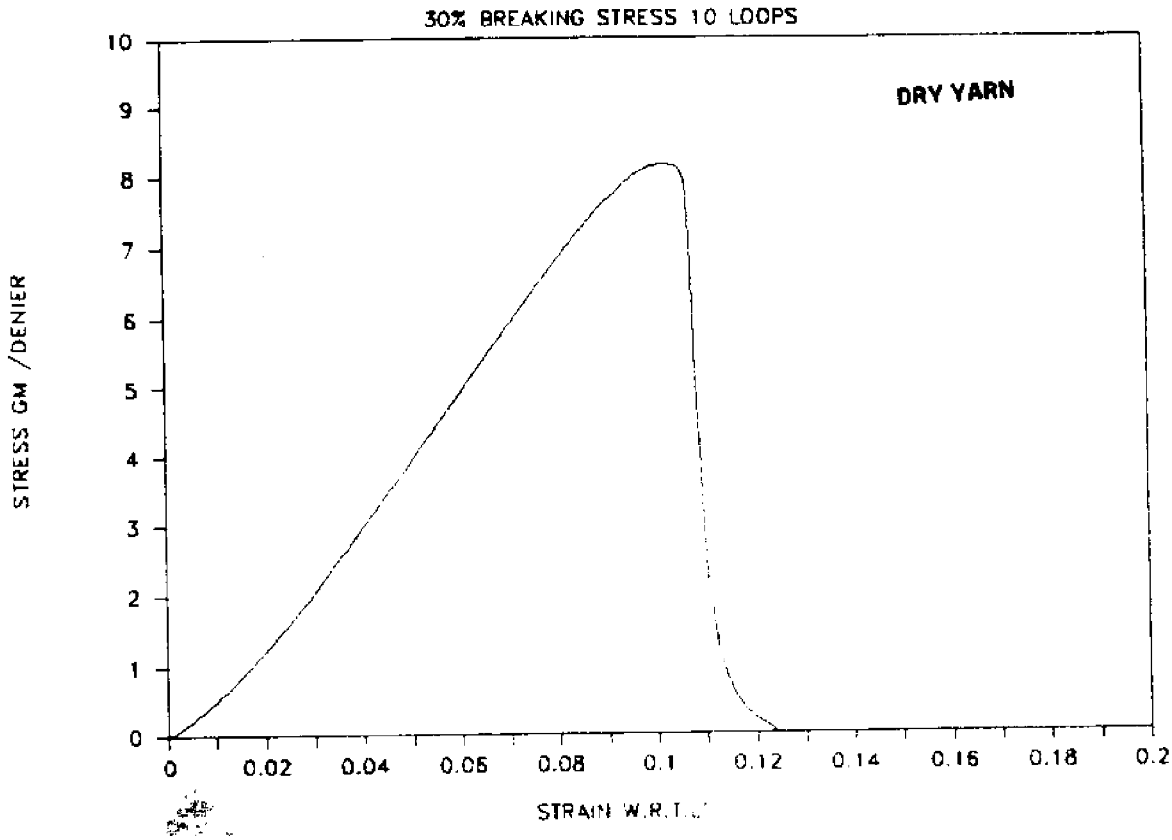
ENKA TN YARN STRESS–STRAIN GRAPH #5



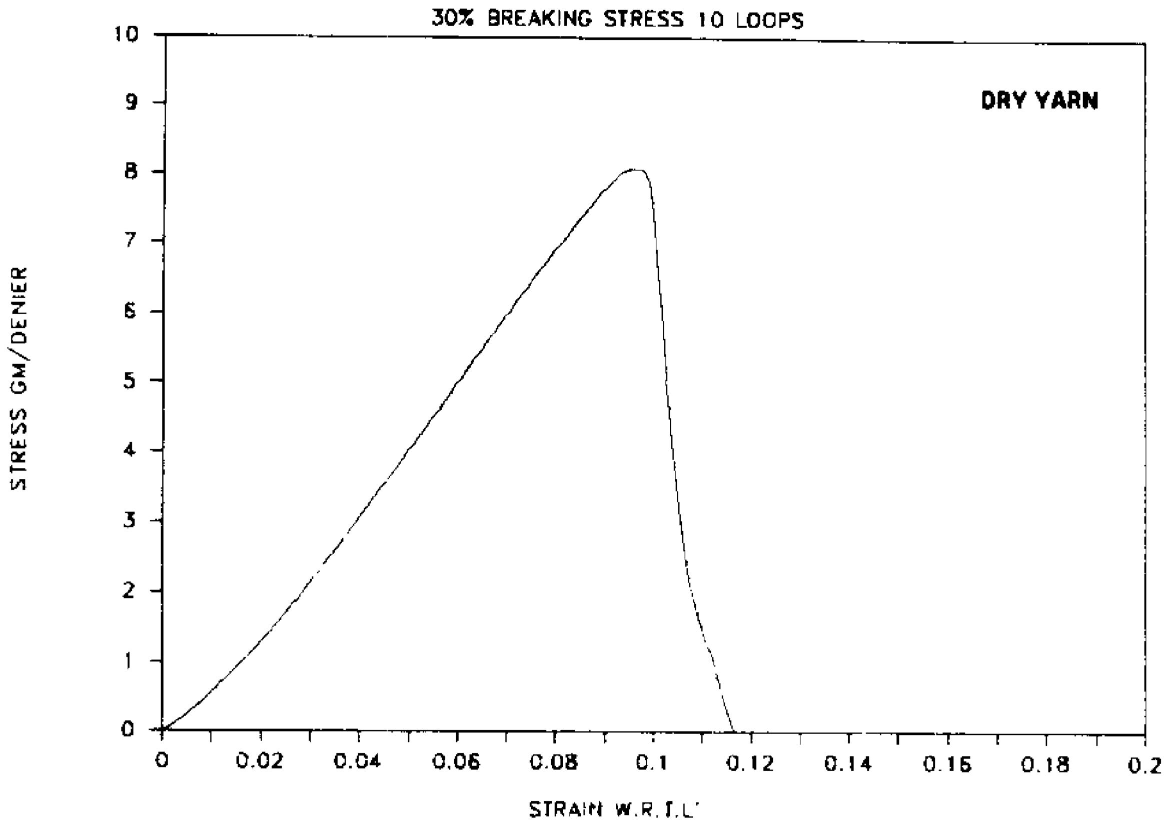
ENKA 855TN STRESS–STRAIN GRAPH #1



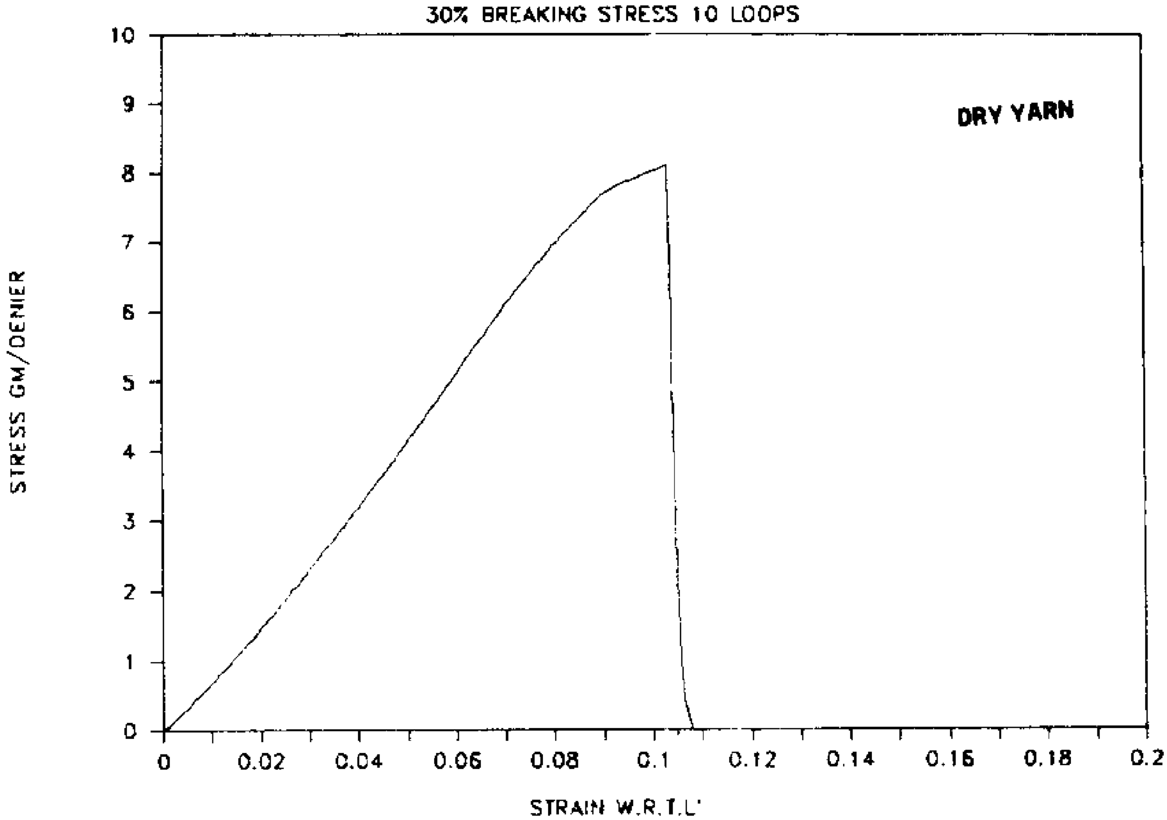
ENKA 855TN YARN STRESS-STRAIN GRAPH #2



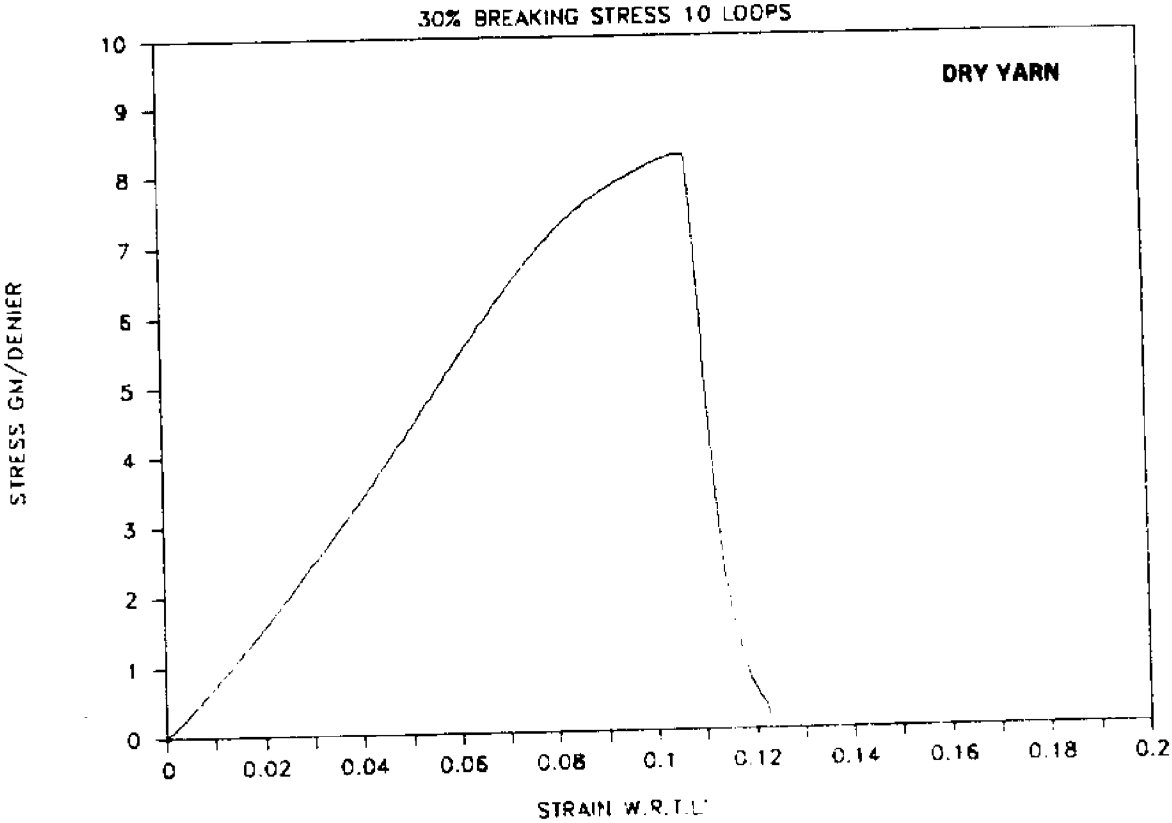
ENKA 855 TN YARN STRESS-STRAIN GRAPG #3



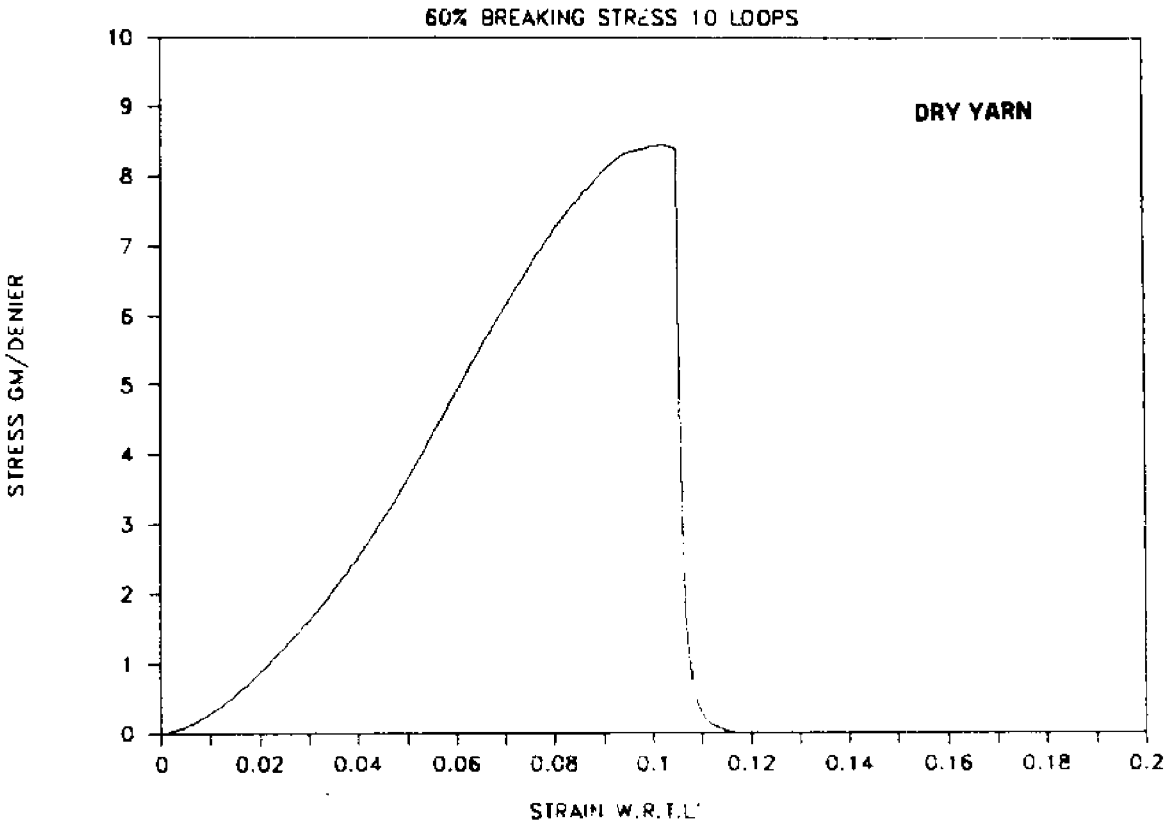
ENKA 855 TN YARN STRESS–STRAIN GRAPG #4



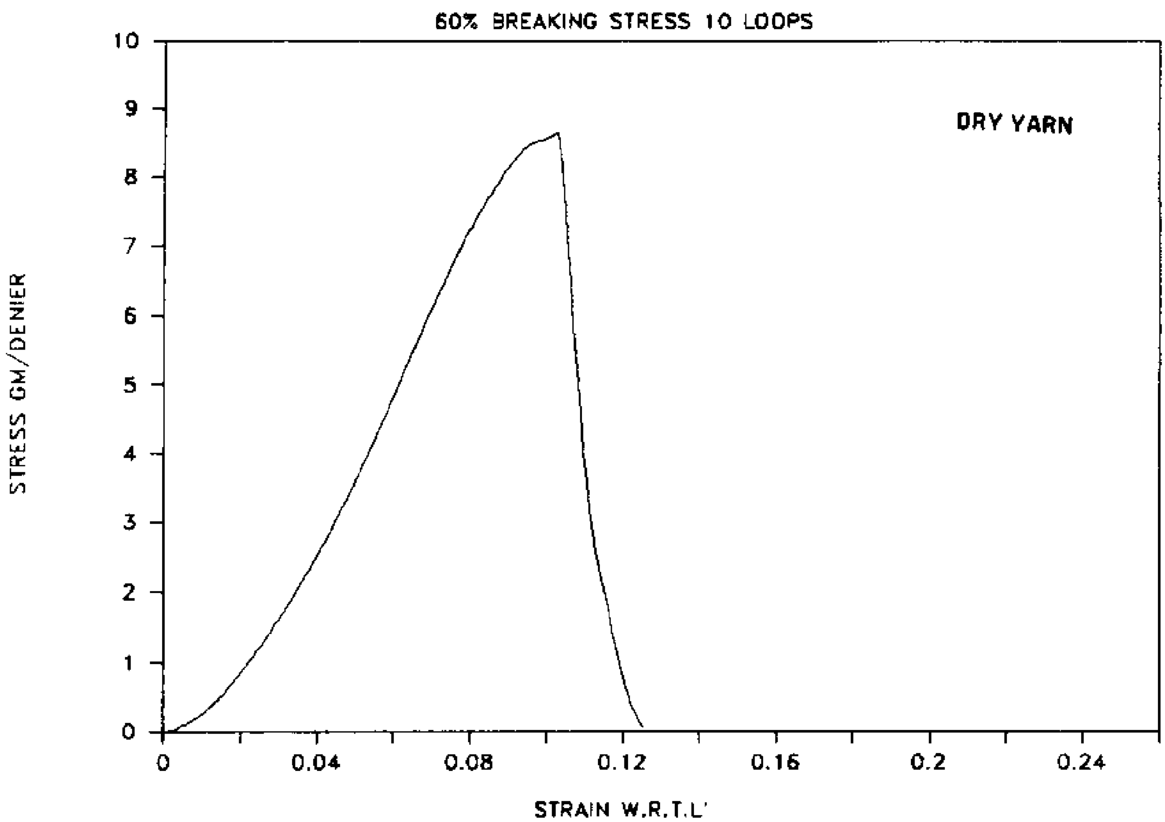
ENKA 855 TN YARN STRESS-STRAIN GRAPG #5



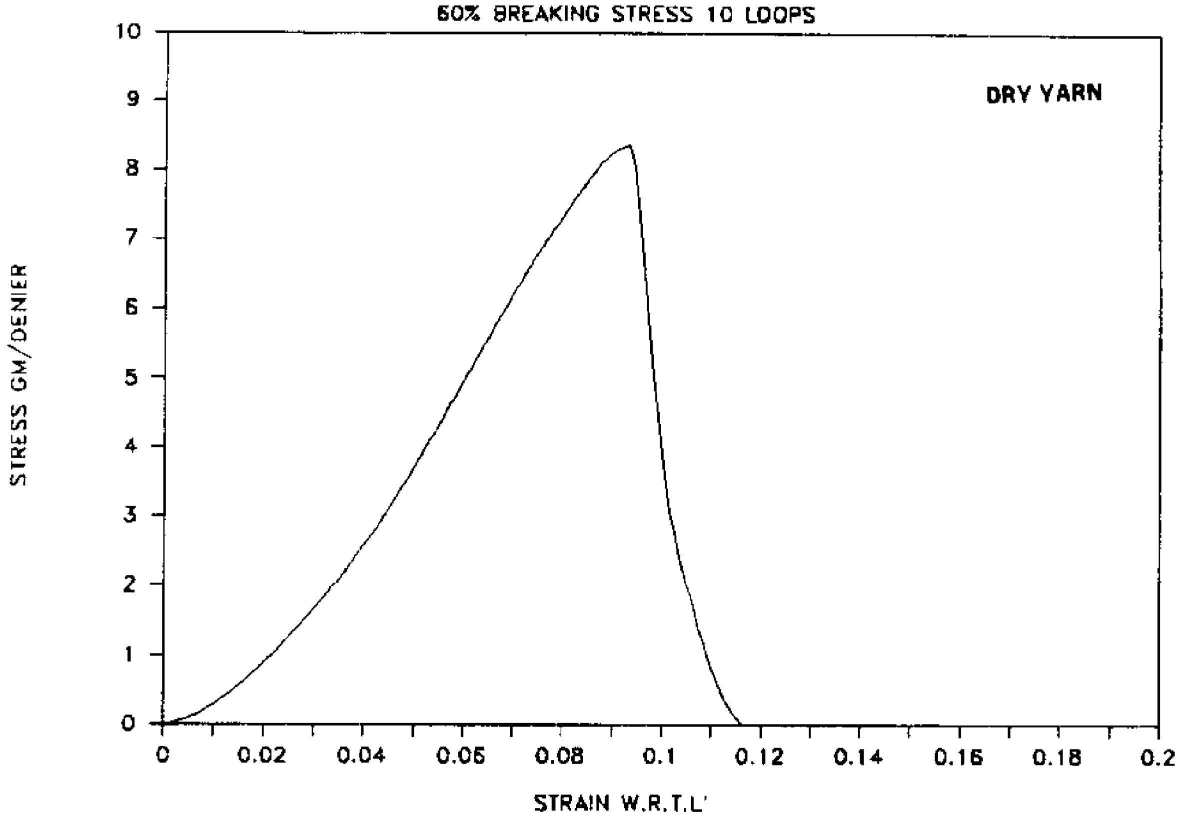
ENKA 855TN YARN STRESS–STRAIN GRAPH #1



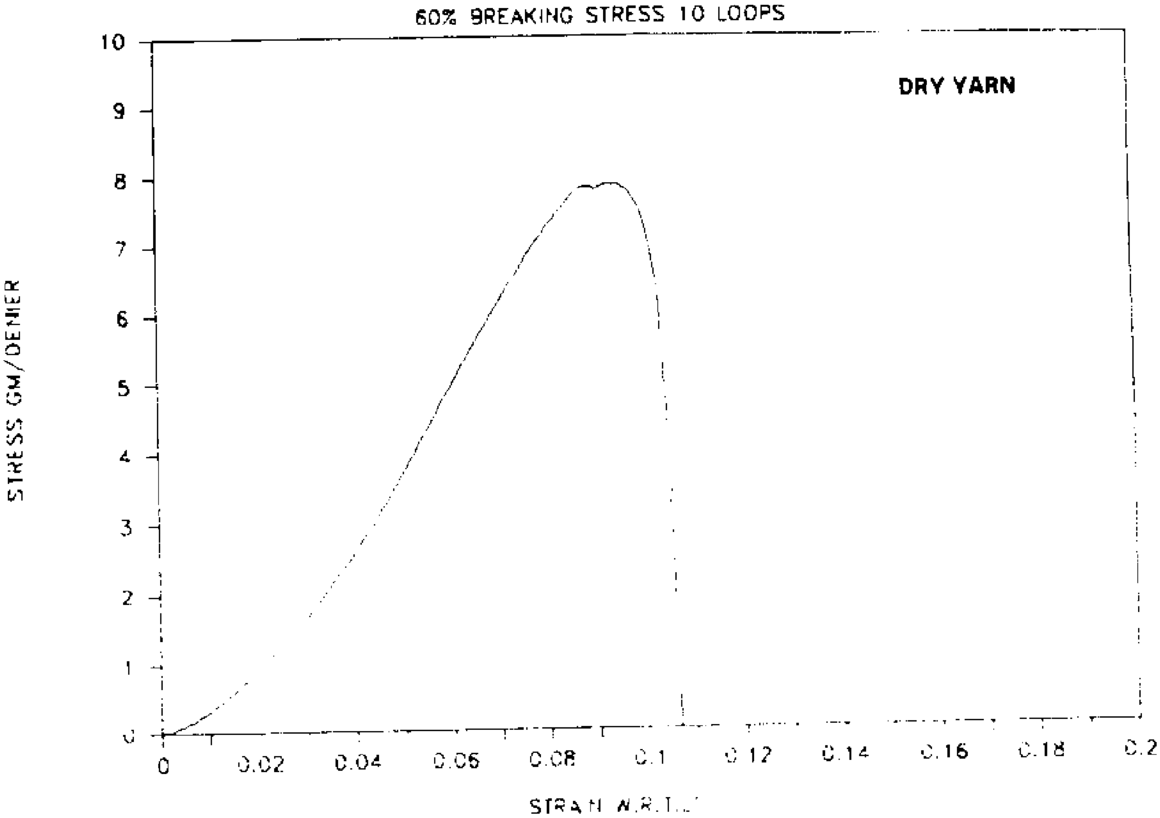
ENKA 855TN STRESS–STRAIN GRAPH #2



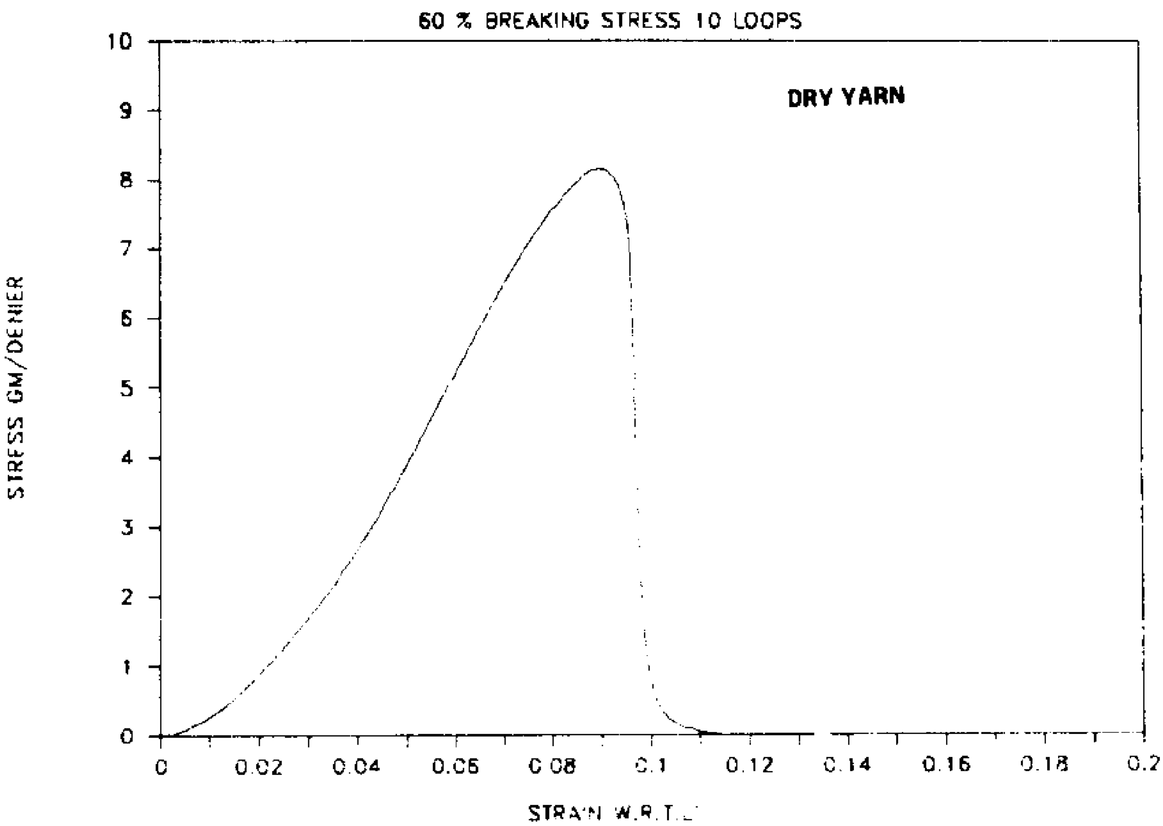
ENKA 855TN YARN STRESS–STRAIN GRAPH #3



ENKA 855TN STRESS-STRAIN GRAPH #4



ENKA 855TN STRESS-STRAIN GRAPH #5



SINGLE LOAD STRESS STRAIN BEHAVIOR

ENKA Polyester (1000 Denier) WITHOUT Marine Finish

Dry and Wet Tests

SINGLE LOAD STRESS -STRAIN BEHAVIOR

ENKA 855T YARN (1000 DENIER POLYESTER WITHOUT FINISH)

DRY YARN

	ORIGINAL		AFTER 30% B.S. 10 CYCLES		AFTER 60% B.S. 10 CYCLES	
	BREAKING STRESS GM/DENIER	BREAKING STRAIN	BREAKING STRESS GM/DENIER	BREAKING STRAIN	BREAKING STRESS GM/DENIER	BREAKING STRAIN
1	8.8	.133	8.3	.112	8.3	.107
2	8.8	.133	8.0	.105	8.25	.1
3	8.7	.135	8.8	.12	8.0	.085
4	8.6	.135	8.5	.104	x	x
5	x	x	x	x	x	x
MEAN	8.7	.134	8.5	.110	8.183	.097

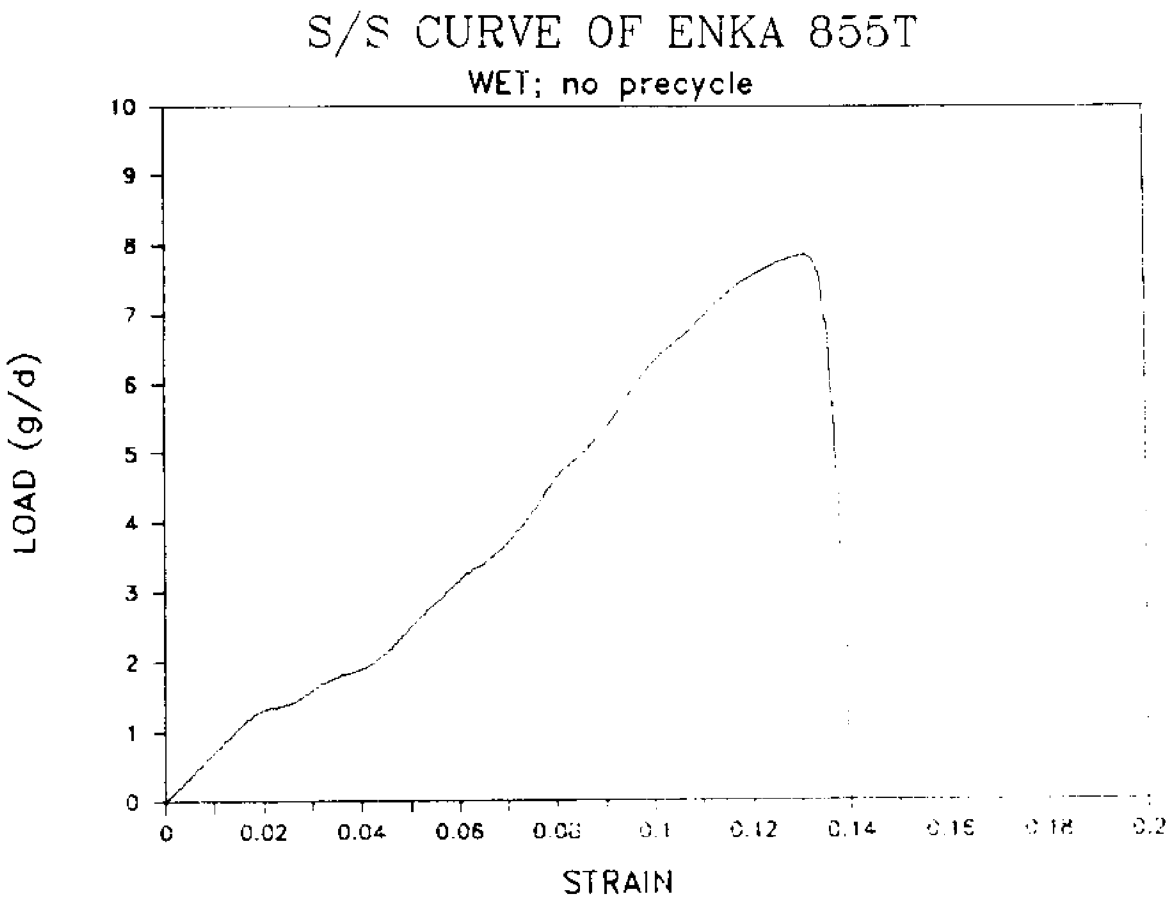
SINGLE LOAD STRESS -STRAIN BEHAVIOR

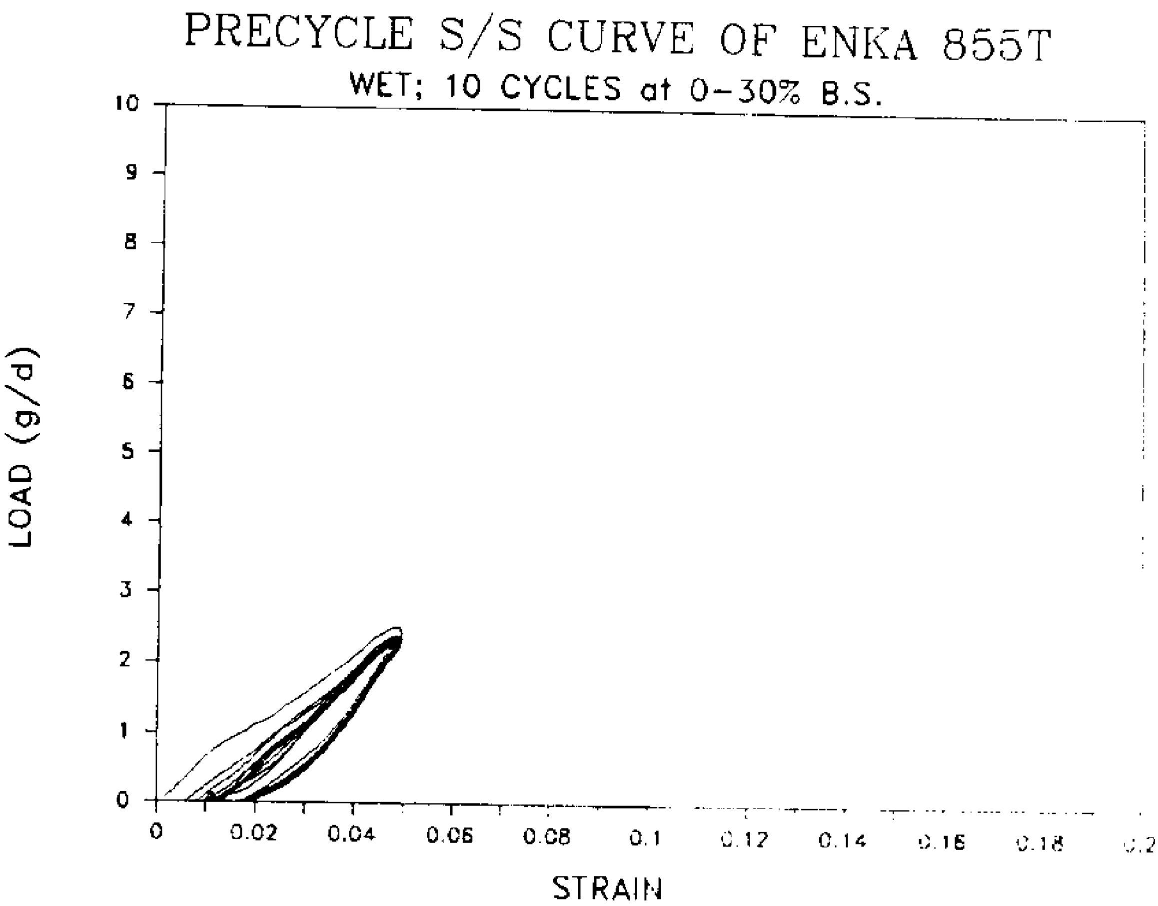
ENKA 855T YARN (1000 DENIER POLYESTER WITHOUT FINISH)

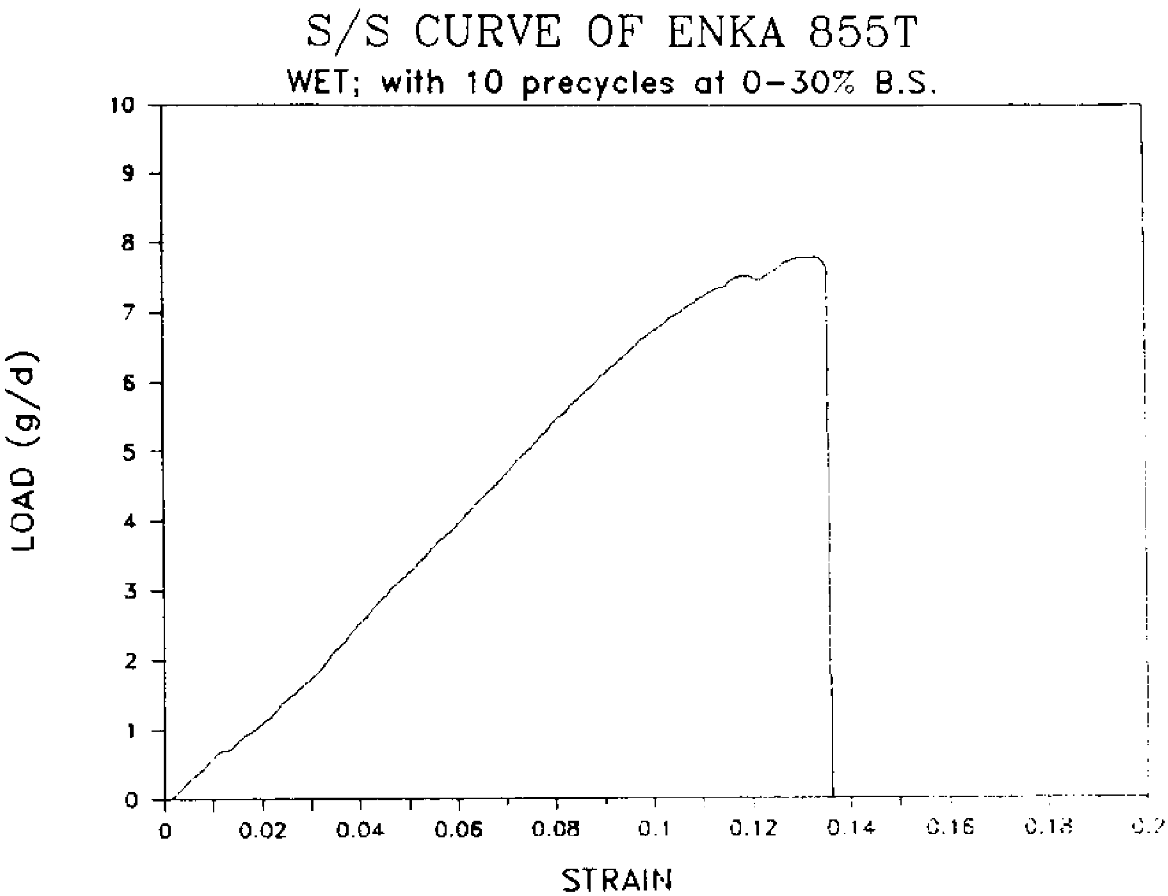
WET YARN

	ORIGINAL		AFTER 30% B.S. 10 CYCLES		AFTER 60% B.S. 10 CYCLES	
	BREAKING STRESS GM/DENIER	BREAKING STRAIN	BREAKING STRESS GM/DENIER	BREAKING STRAIN	BREAKING STRESS GM/DENIER	BREAKING STRAIN
1	7.8	XXX	8.0	XXX	9.2	XXX
2	8.7	XXX	8.3	XXX	8.2	XXX
3	8.1	0.132 *	8.0	0.130 *	7.8	0.113 *
4	7.7	XXX	8.0	XXX	8.4	XXX
5	8.4	XXX	8.4	XXX	8.3	XXX
MEAN	8.1	XXX	8.1	XXX	8.4	XXX

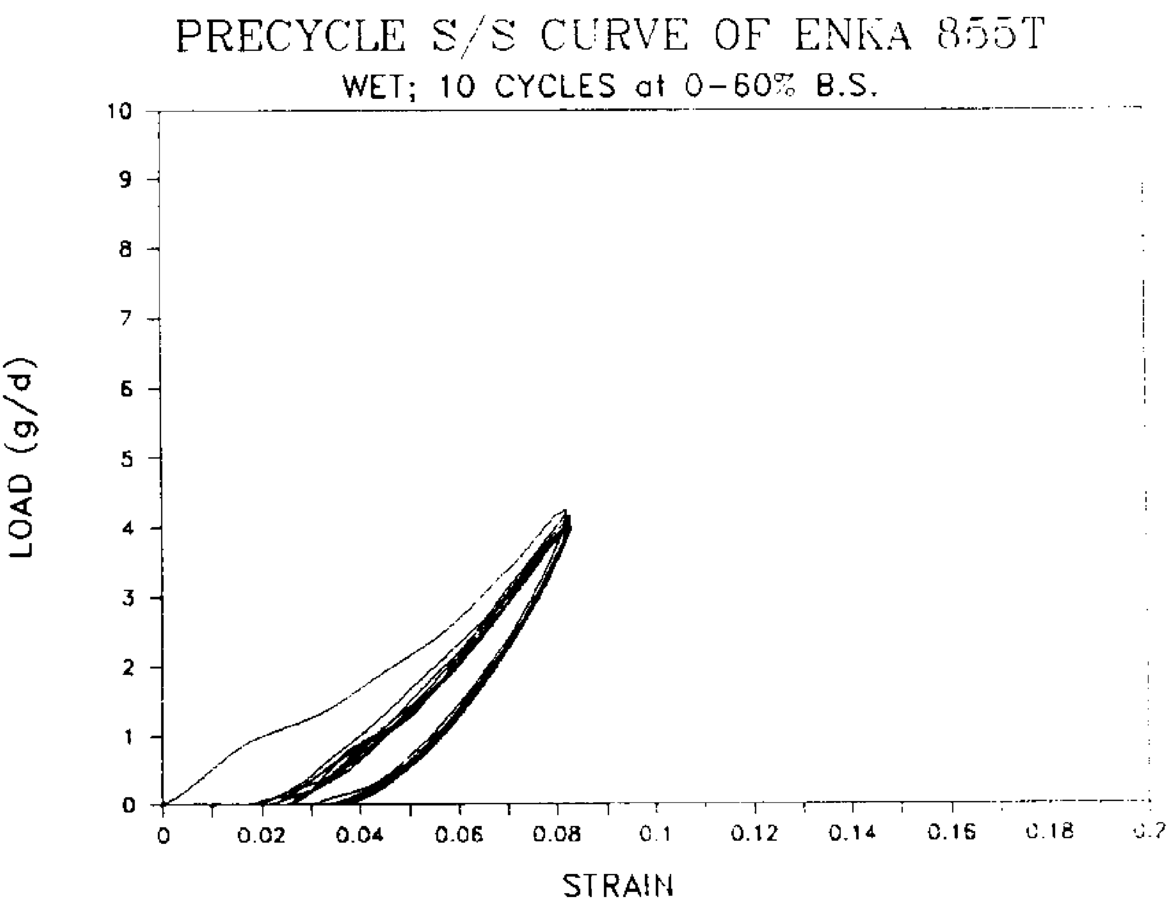
* representative value

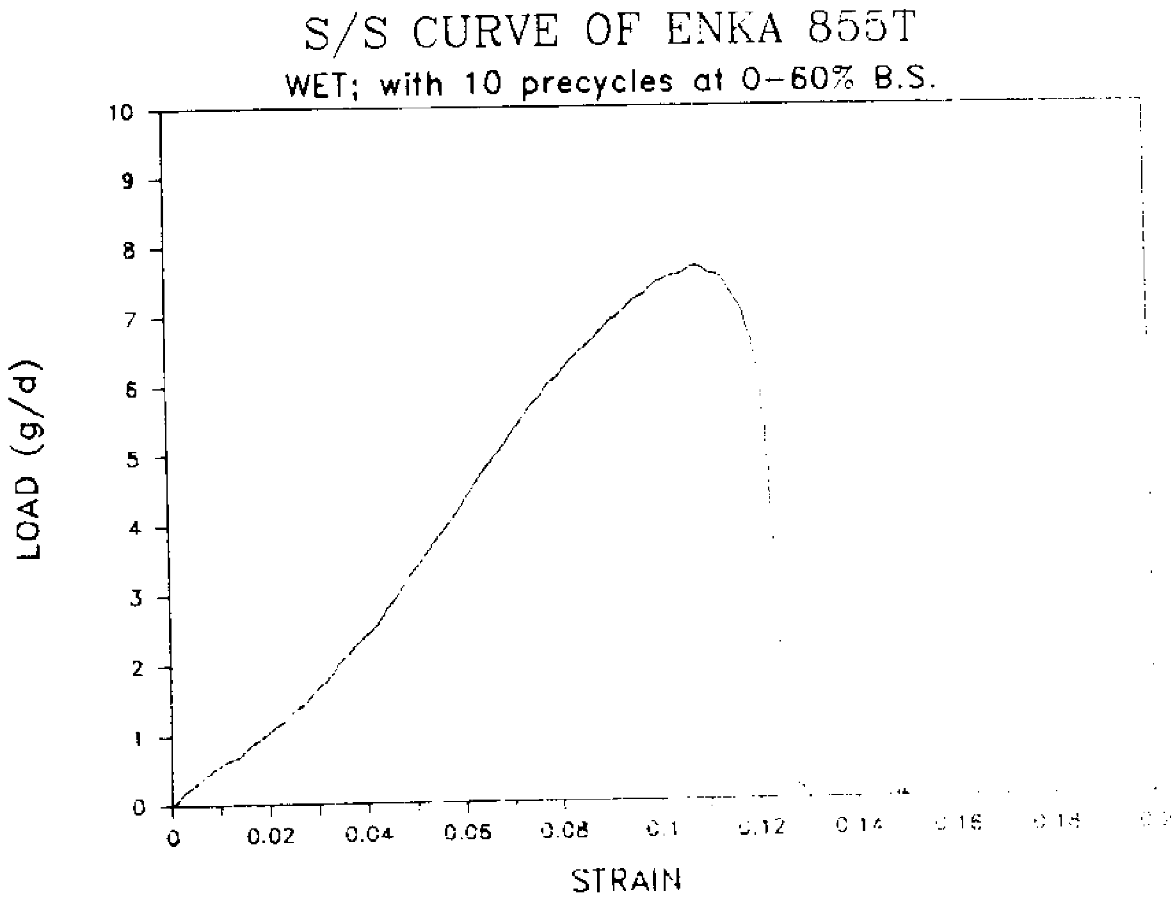

S/S CURVE OF ENKA 855T
WET; no precycle
LOAD (g/d)
STRAIN
0
1
2
3
4
5
6
7
8
9
10
0.02
0.04
0.06
0.12
0.14


PRECYCLE S/S CURVE OF ENKA 855T
WET; 10 CYCLES at 0-30% B.S.
LOAD (g/d)
STRAIN
0
1
2
3
4
5
6
7
8
9
10
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2



S/S CURVE OF ENKA 855T
WET; with 10 precycles at 0-30% B.S.
LOAD (g/d)
10
9
8
7
6
5
4
3
2
1
0
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
STRAIN

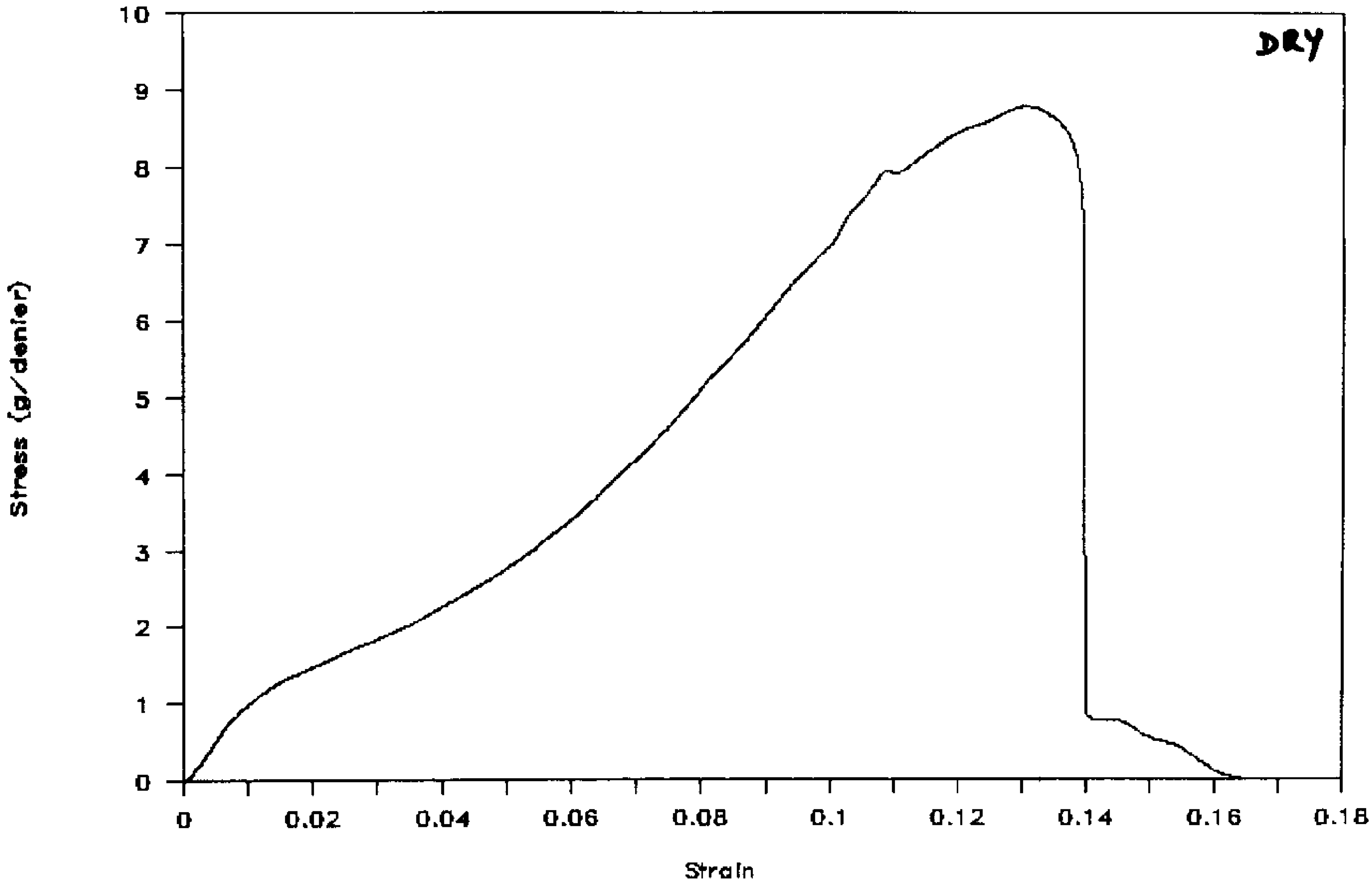

PRECYCLE S/S CURVE OF ENKA 855T
WET; 10 CYCLES at 0-60% B.S.
LOAD (g/d)
10
9
8
7
6
5
4
3
2
1
0
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
STRAIN

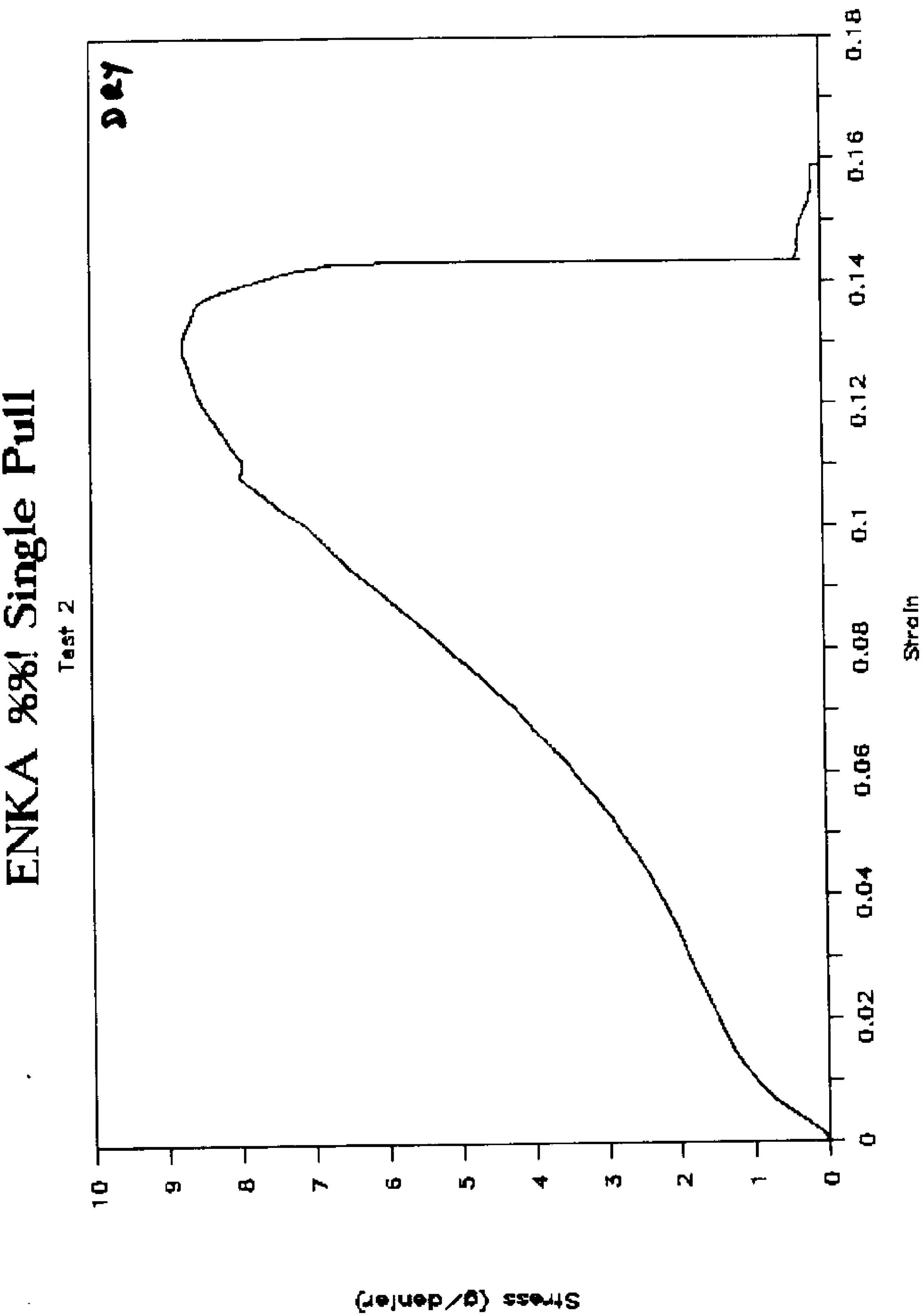


S/S CURVE OF ENKA 855T
WET; with 10 precycles at 0-60% B.S.
LOAD (g/d)
STRAIN
0
1
2
3
4
5
6
7
8
9
10
0.02
0.04
0.06
0.08

ENKA 551 Single Pull

Test 1

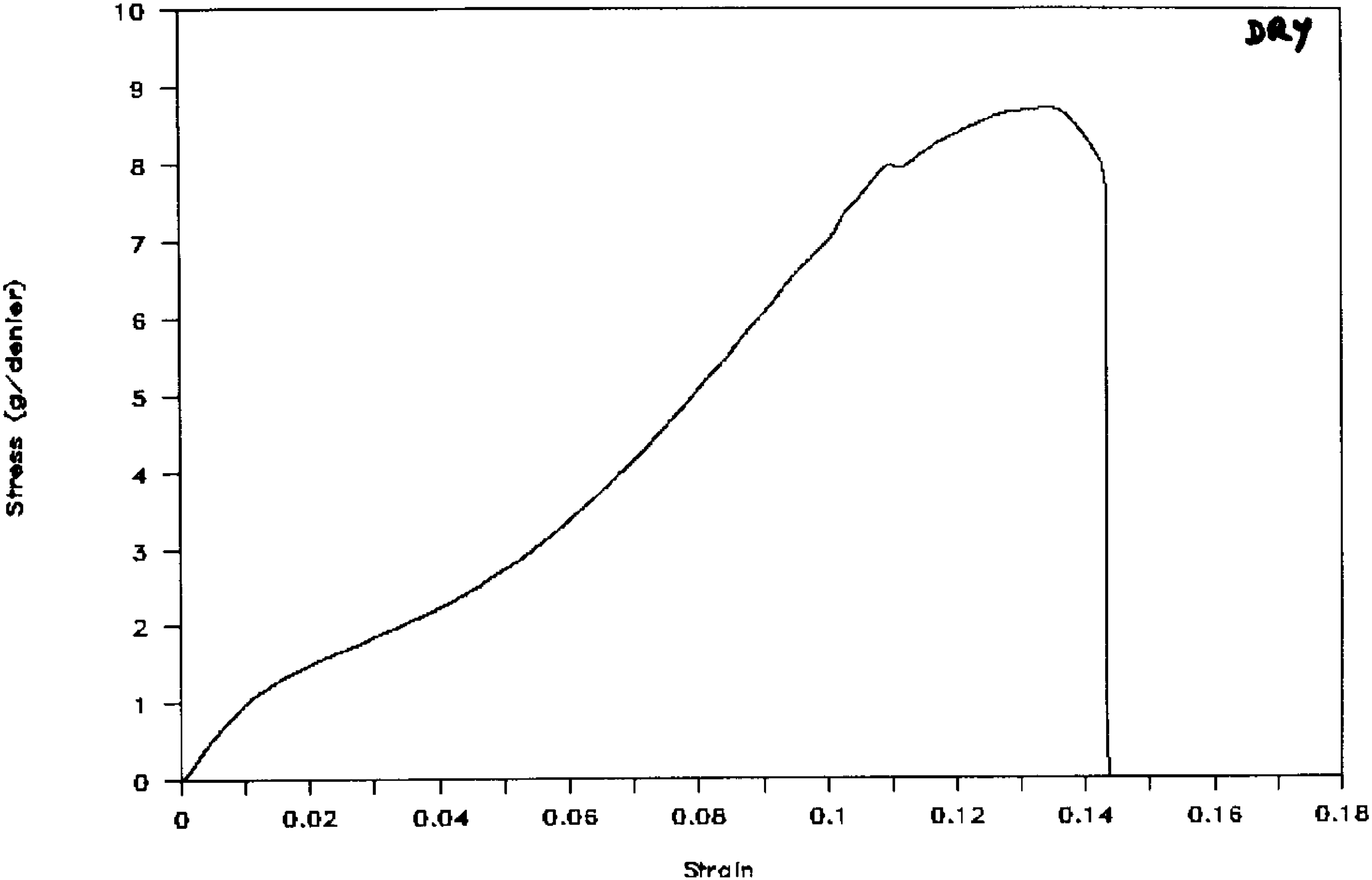




ENKA %%! Single Pull
Test 2
DRY
Stress (g/denier)
Strain
0
1
2
3
4
5
6
7
8
9
10
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18

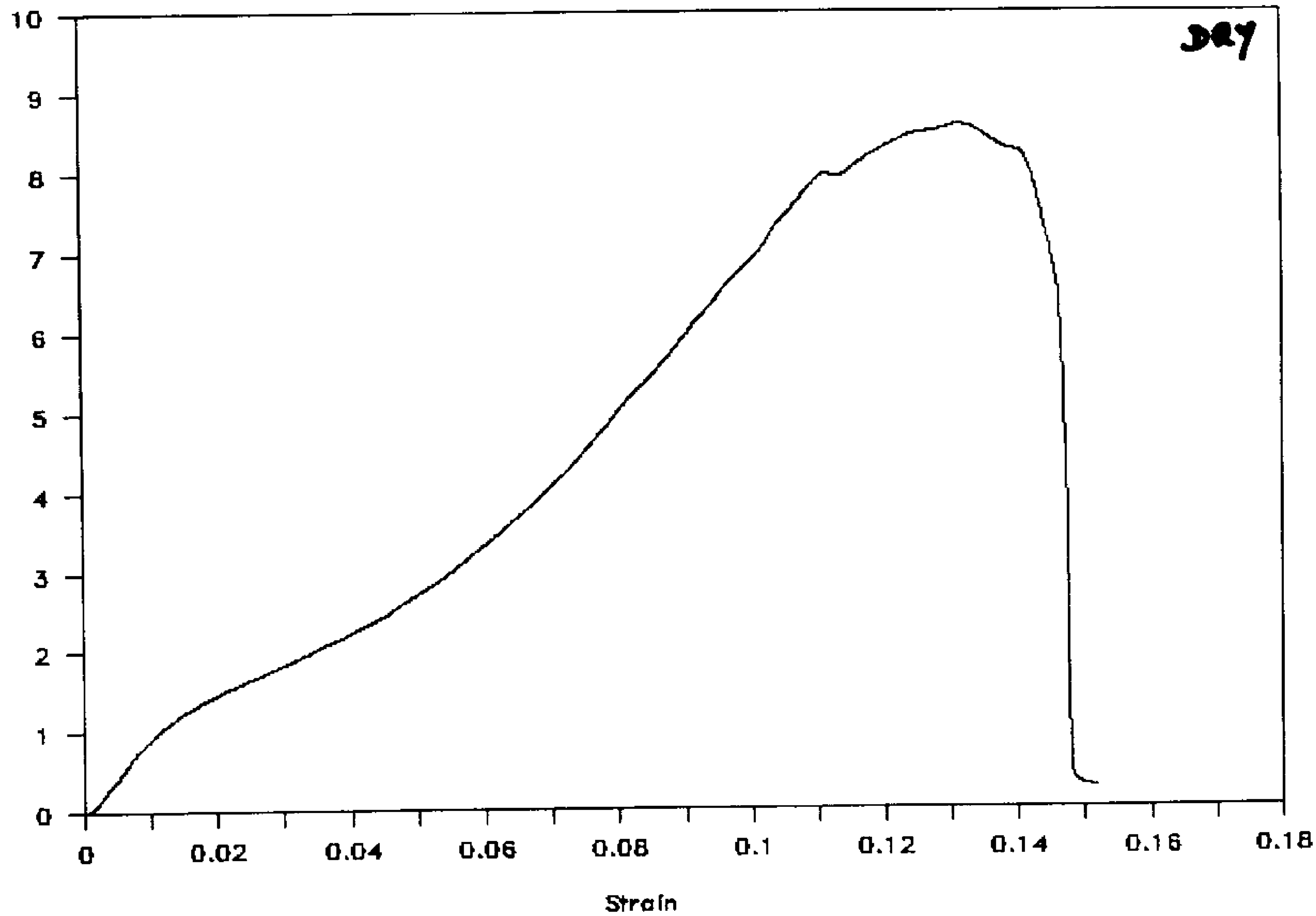
ENKA 551 Single Pull

Test 3

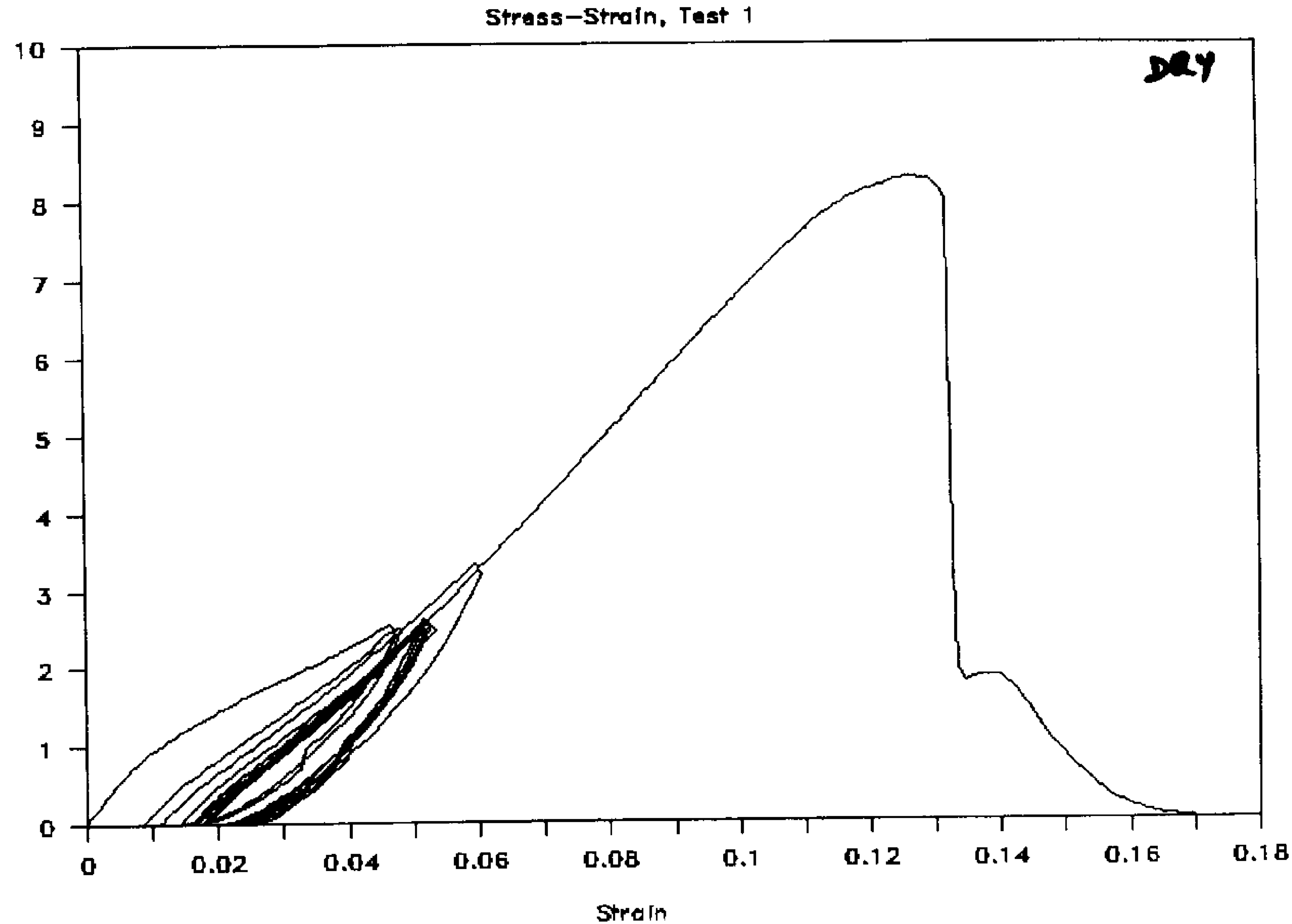


ENKA 551 Single Pull

Test 4

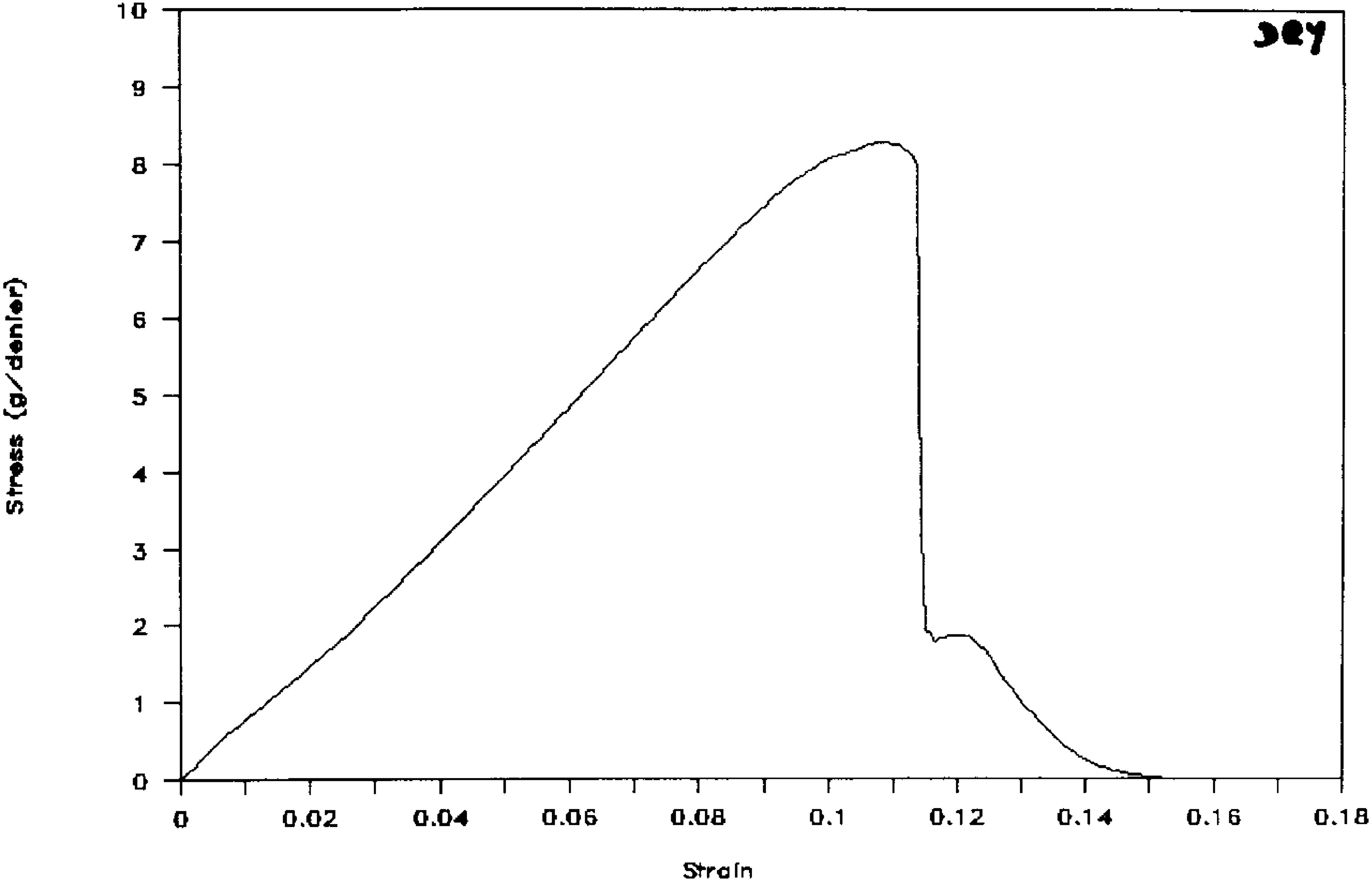


ENKA 551, 10 Cycles to 30% UTS



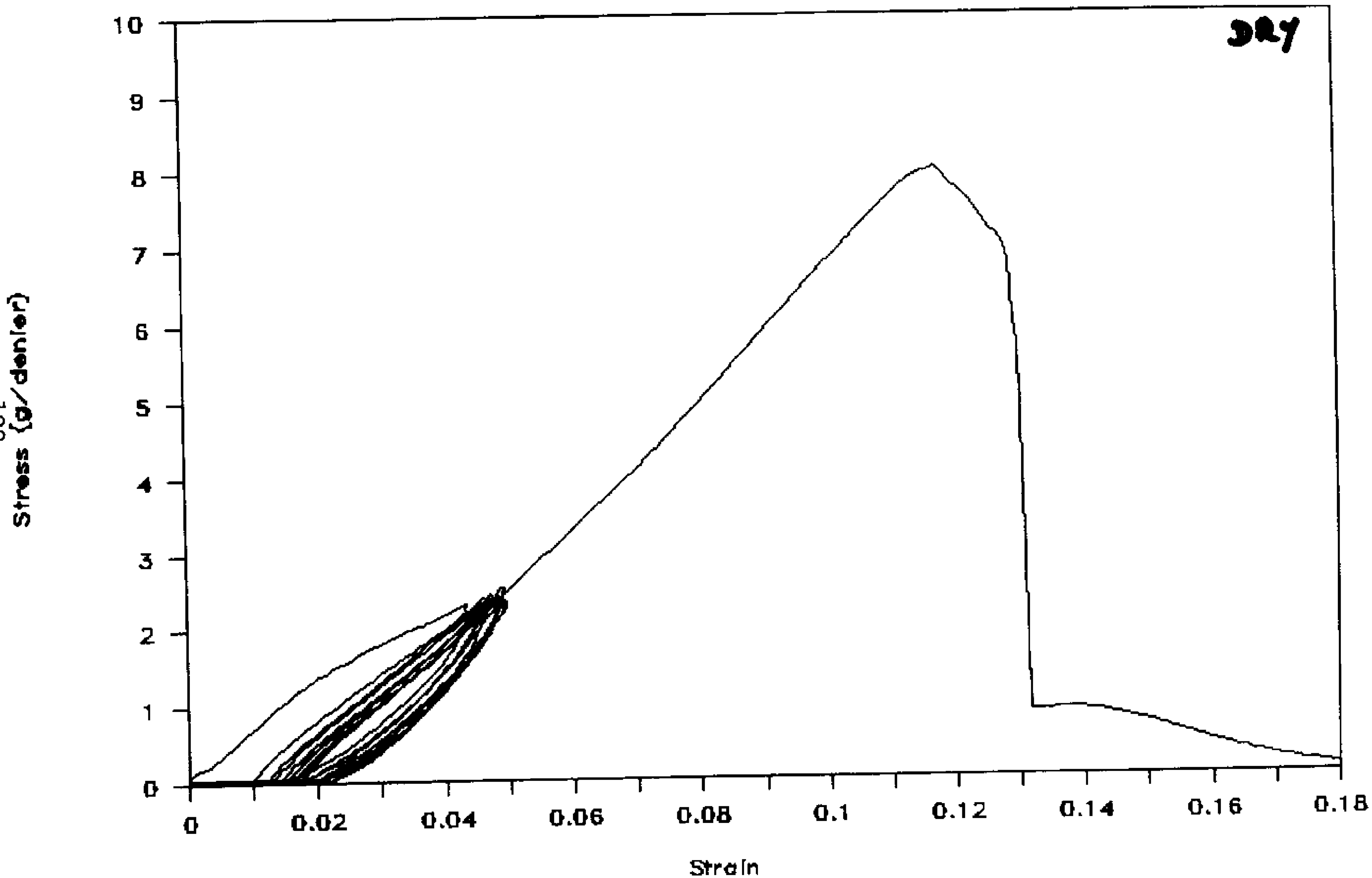
ENKA 551, 10 Cycles to 30% UTS

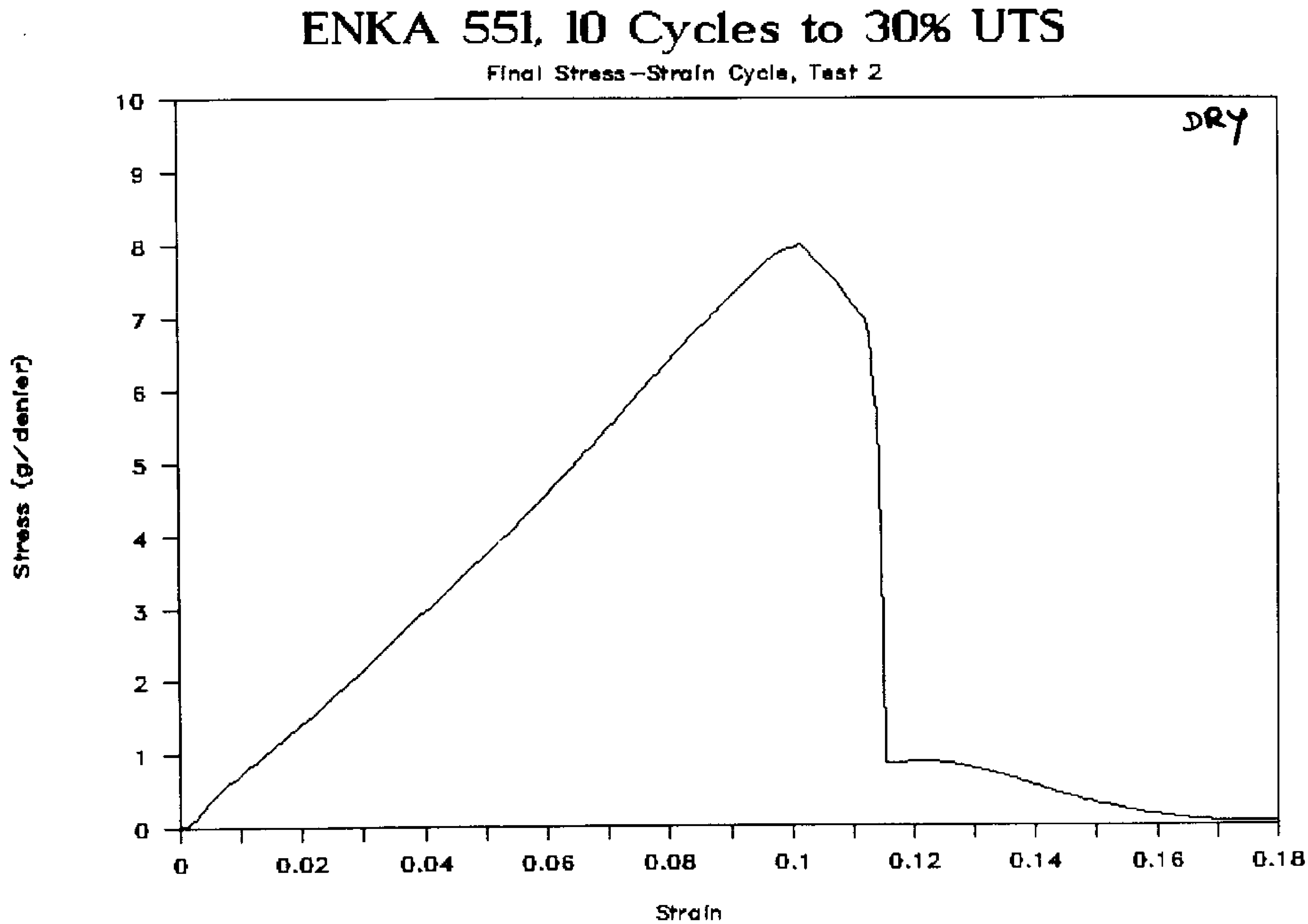
Final Stress—Strain Cycle, Test 1

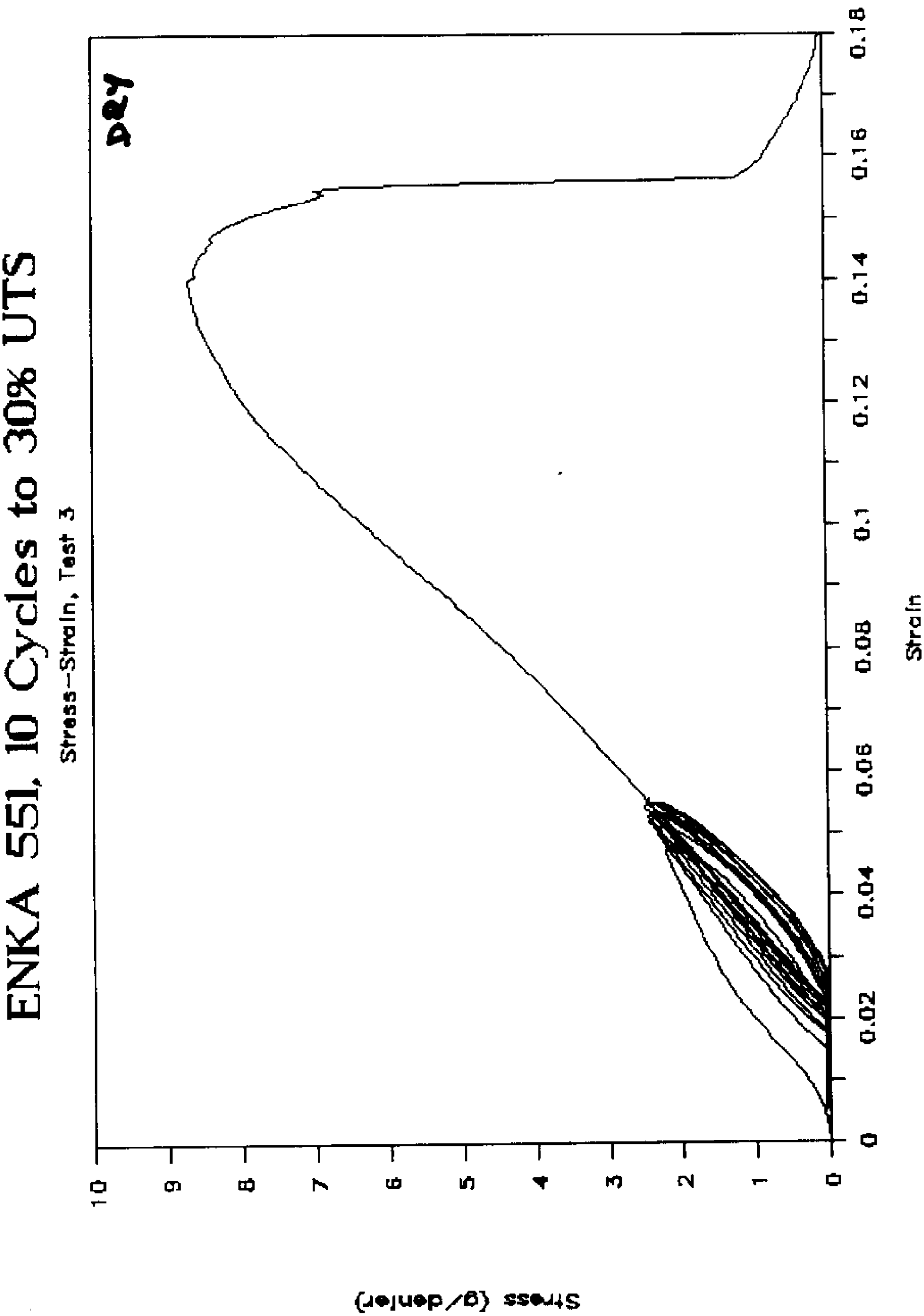


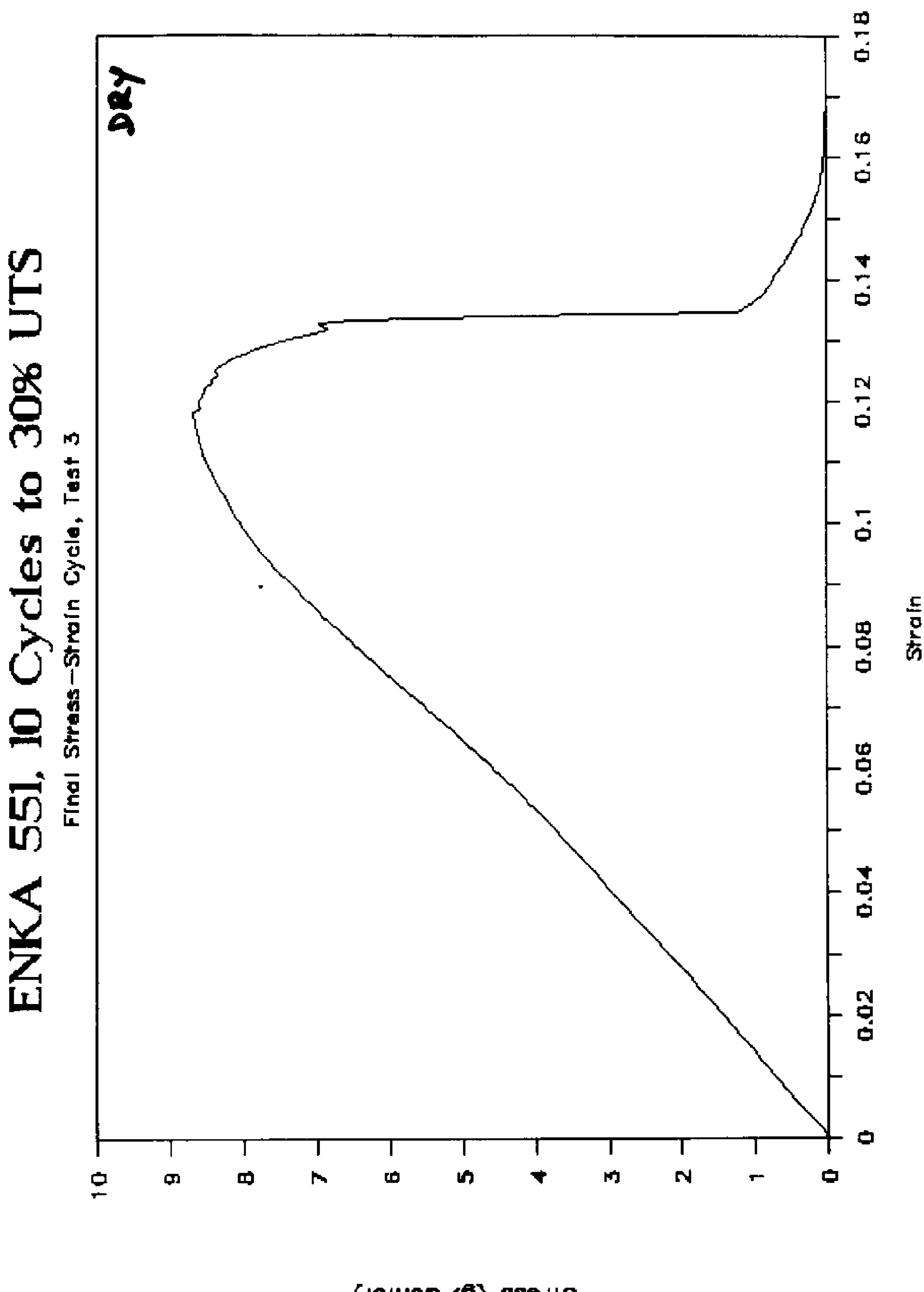
ENKA 551, 10 Cycles to 30% UTS

Stress–Strain, Test 2



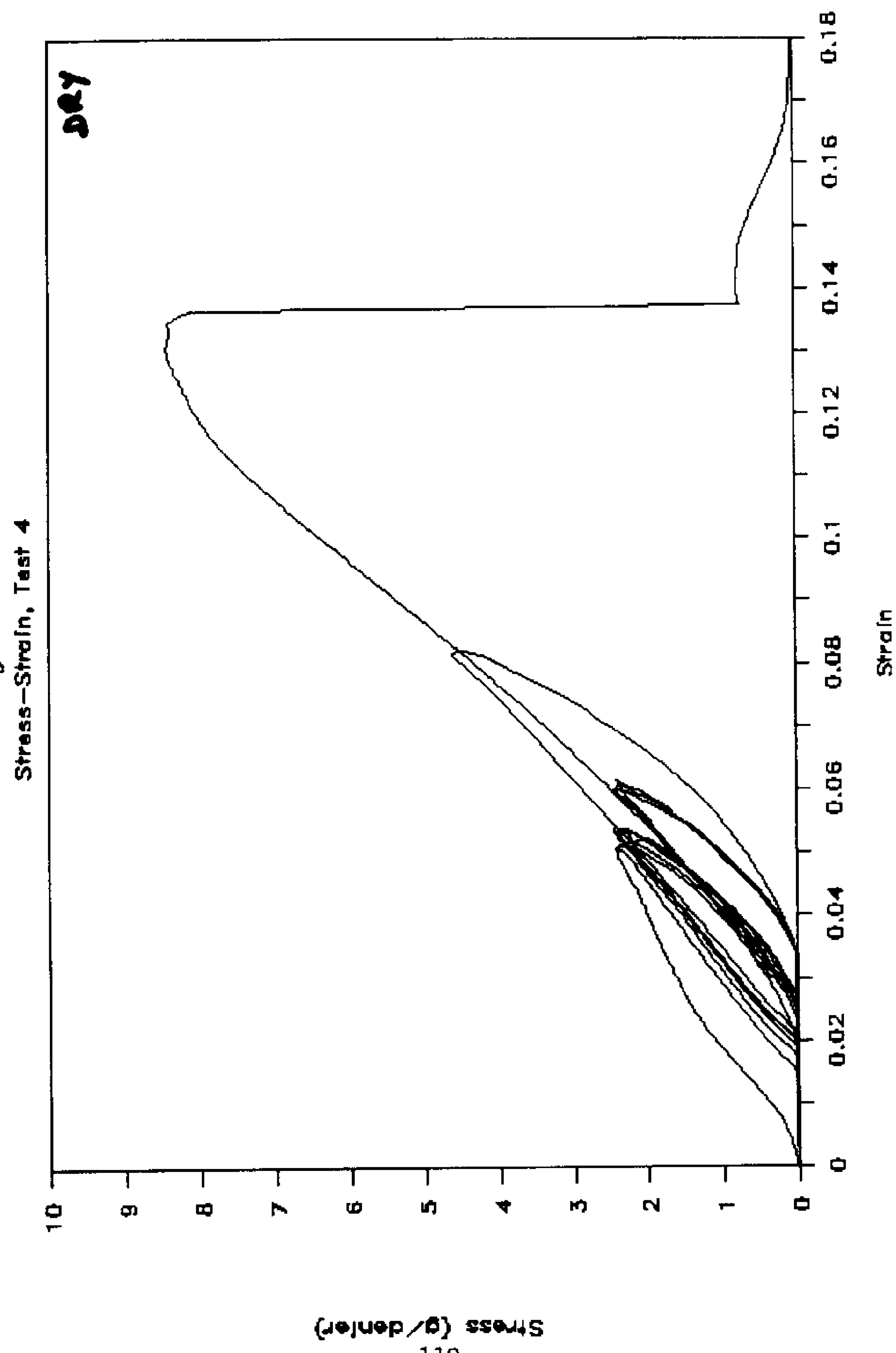

ENKA 551, 10 Cycles to 30% UTS
Final Stress-Strain Cycle, Test 2
DRY
Stress (g/denier)
Strain
10
9
8
7
6
5
4
3
2
1
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18


ENKA 551, 10 Cycles to 30% UTS
Stress—Strain, Test 3
DRY
Stress (g/denier)
Strain
0
1
2
3
4
5
6
7
8
9
10
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18



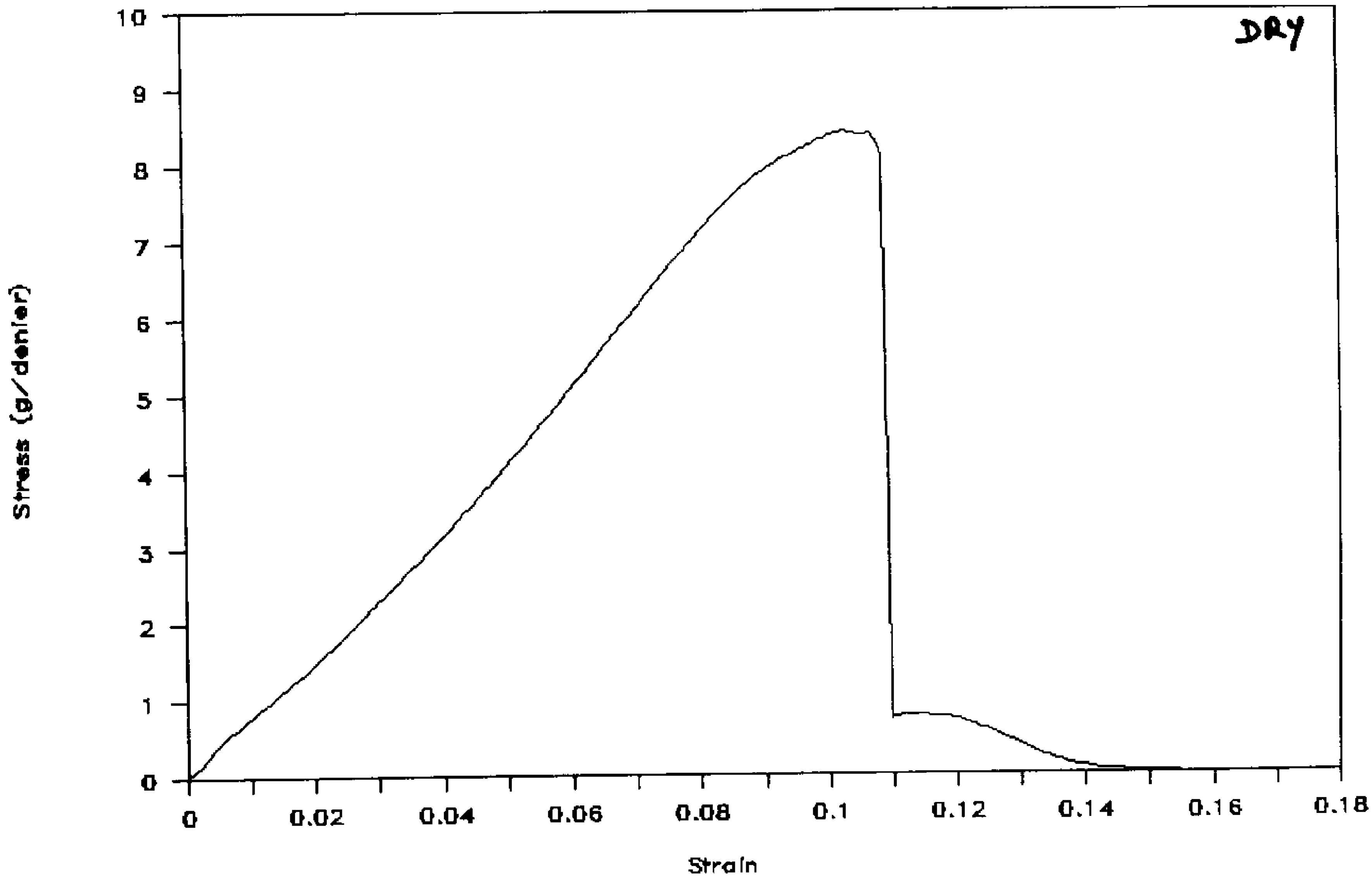
ENKA 551, 10 Cycles to 30% UTS
Final Stress–Strain Cycle, Test 3
DRY
Stress (g/denier)
Strain
0
1
2
3
4
5
6
7
8
9
10
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18

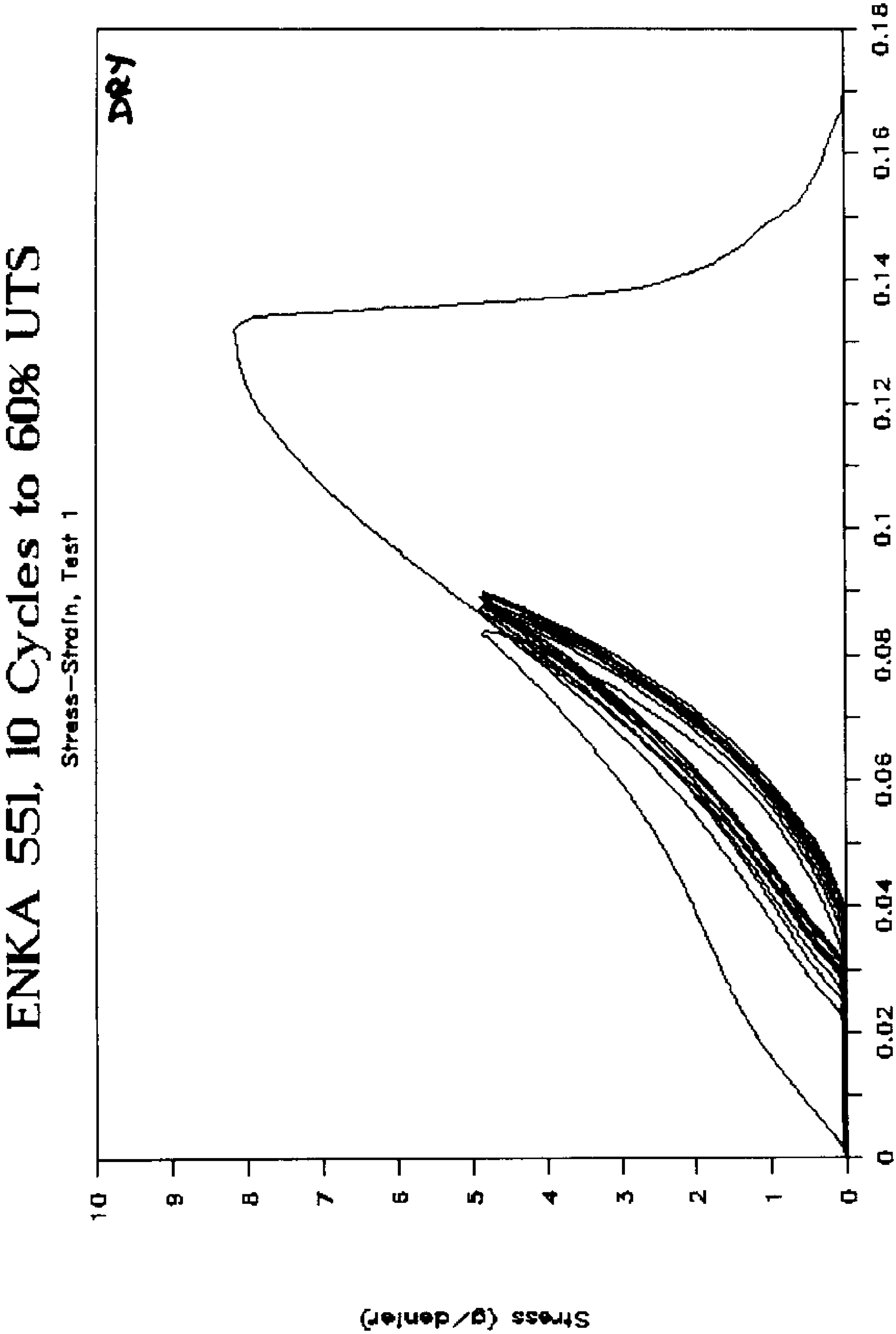
ENKA 551, 10 Cycles to 30% UTS



ENKA 551, 10 Cycles to 30% UTS

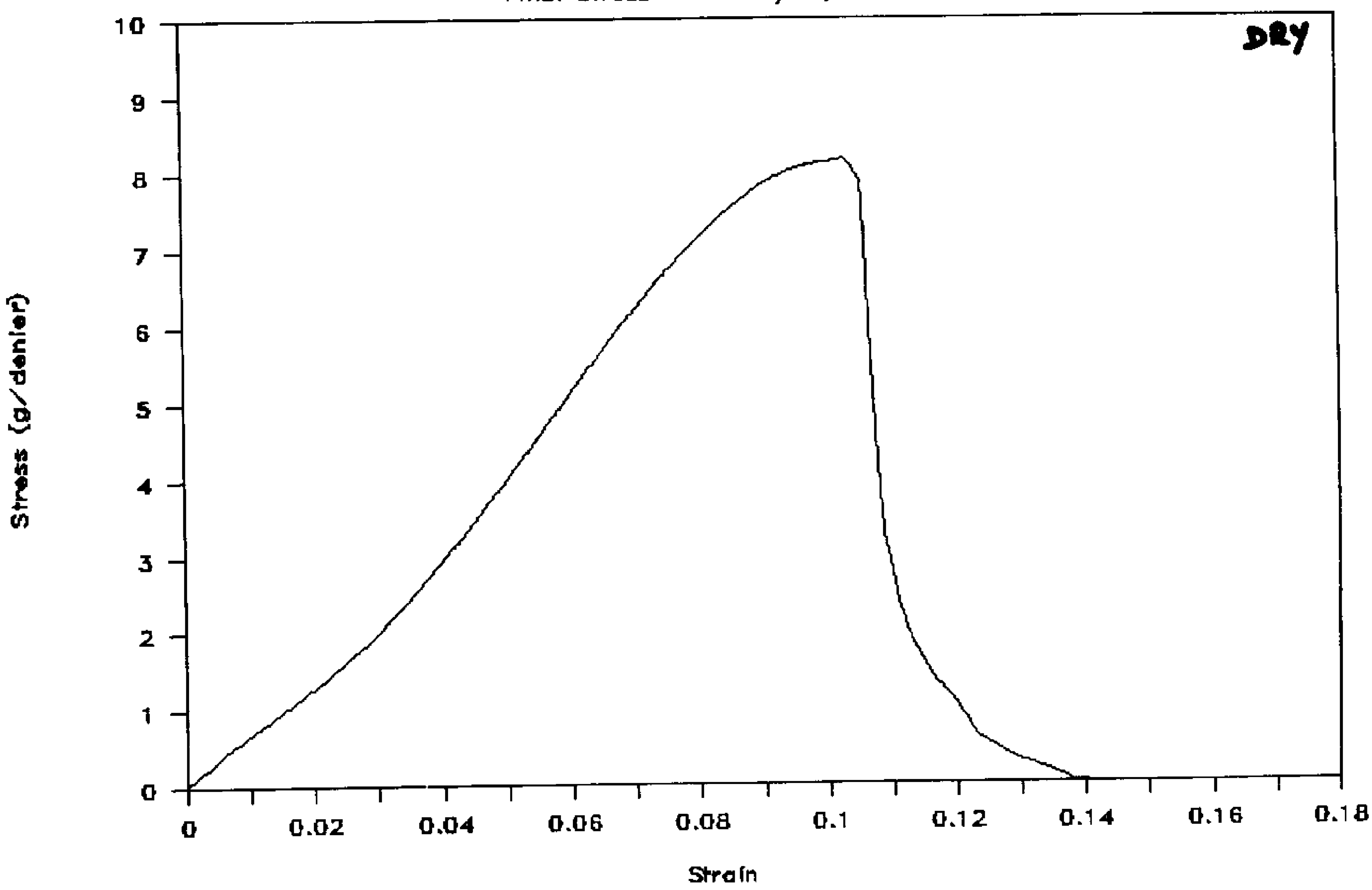
Final Stress—Strain Cycle, Test 4



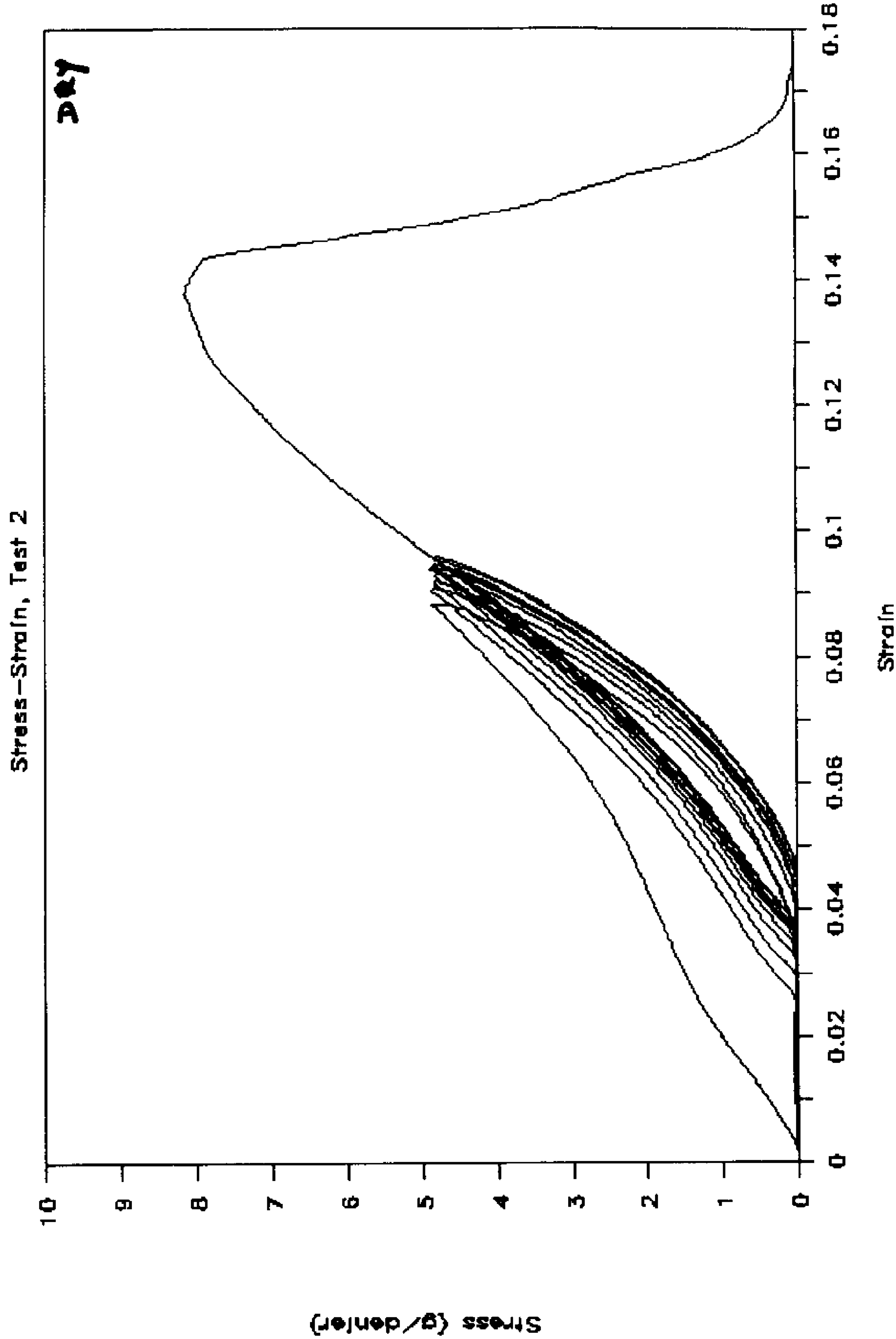

ENKA 551, 10 Cycles to 60% UTS
Stress-Strain, Test 1
DRY
Stress (g/denier)
Strain
0
1
2
3
4
5
6
7
8
9
10
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18

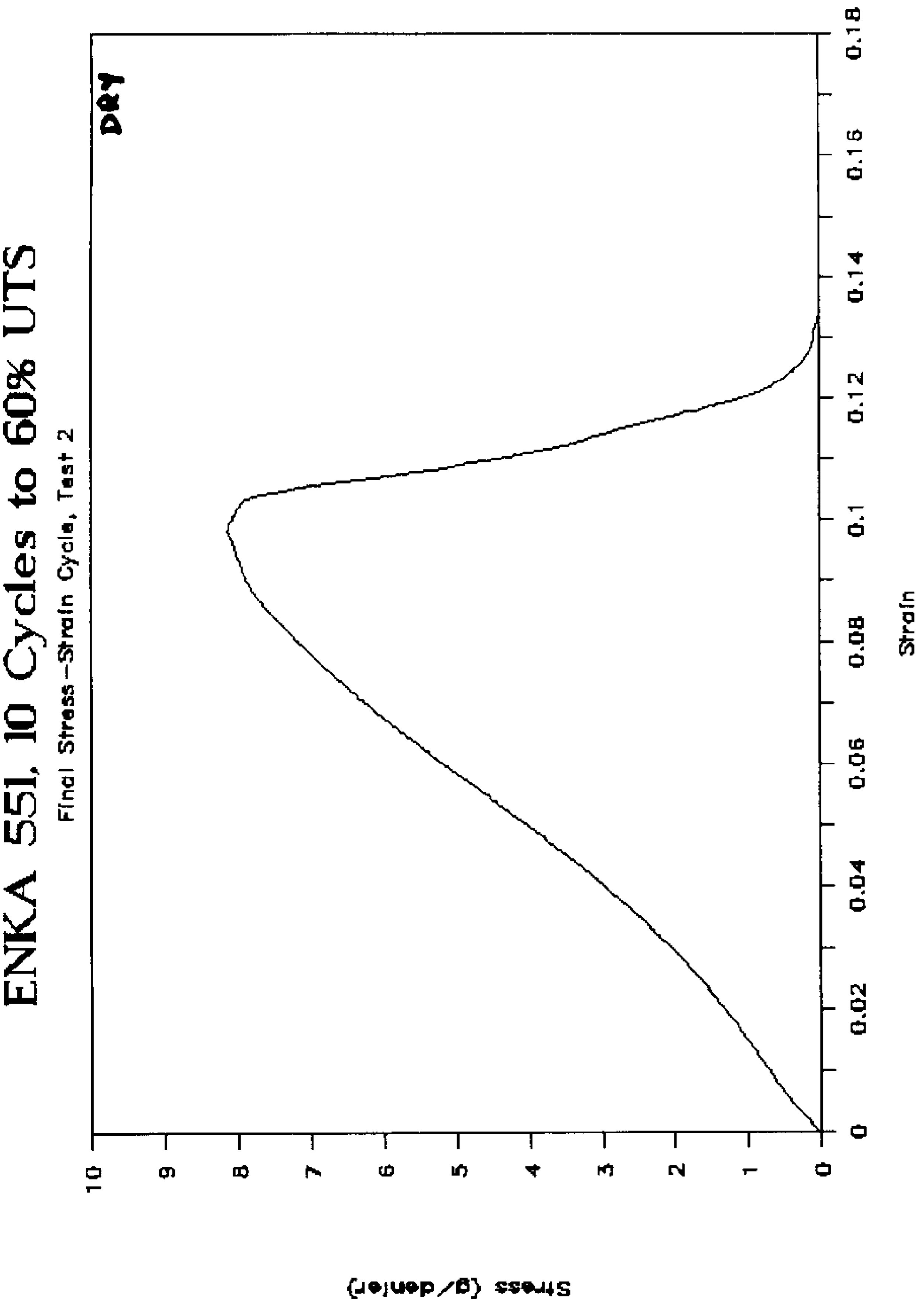
ENKA 551, 10 Cycles to 60% UTS

Final Stress—Strain Cycle, Test 1



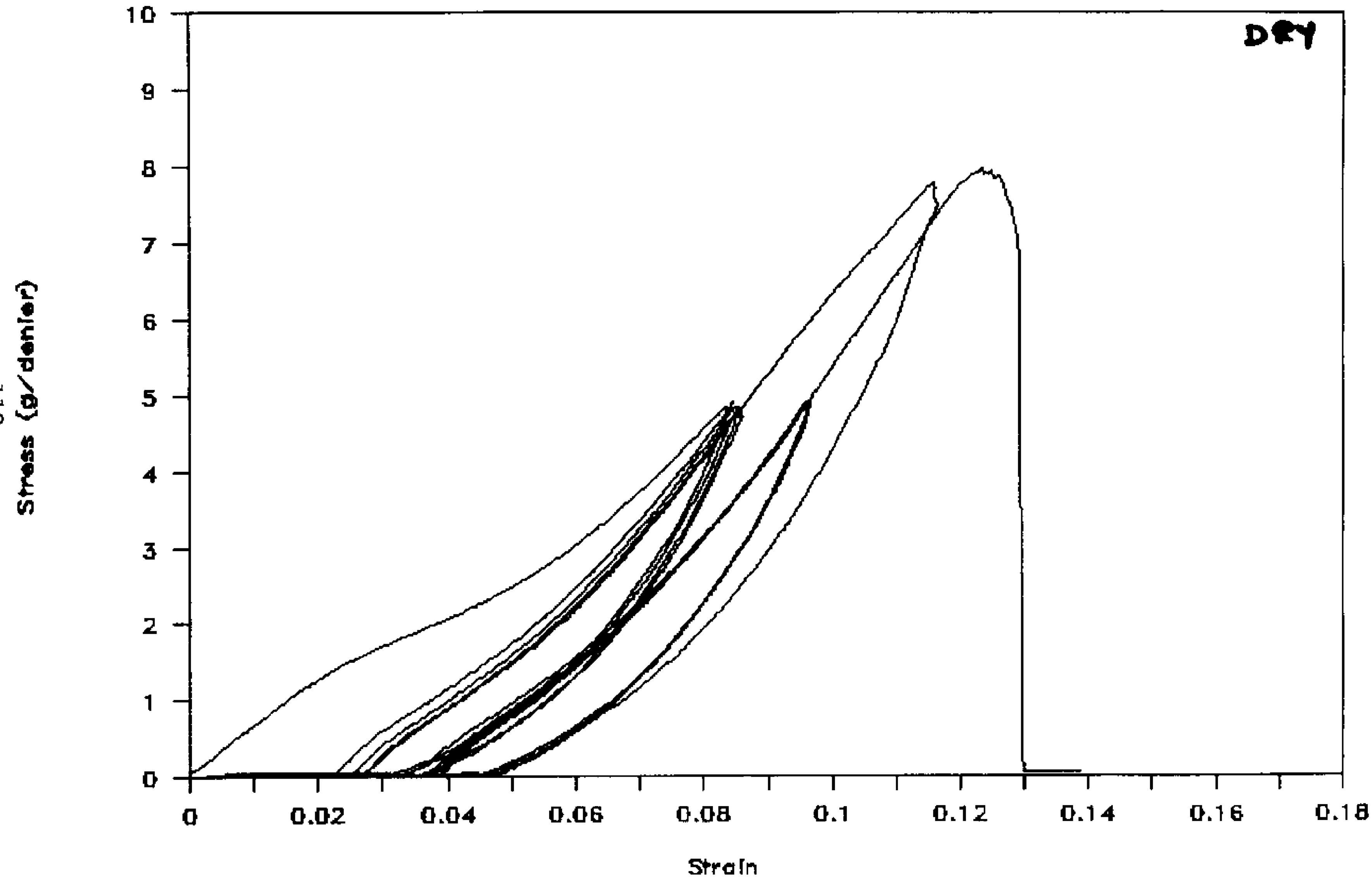
ENKA 551, 10 Cycles to 60% UTS




ENKA 551, 10 Cycles to 60% UTS
Final Stress—Strain Cycle, Test 2
DRY
Stress (g/denier)
Strain
0
1
2
3
4
5
6
7
8
9
10
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18

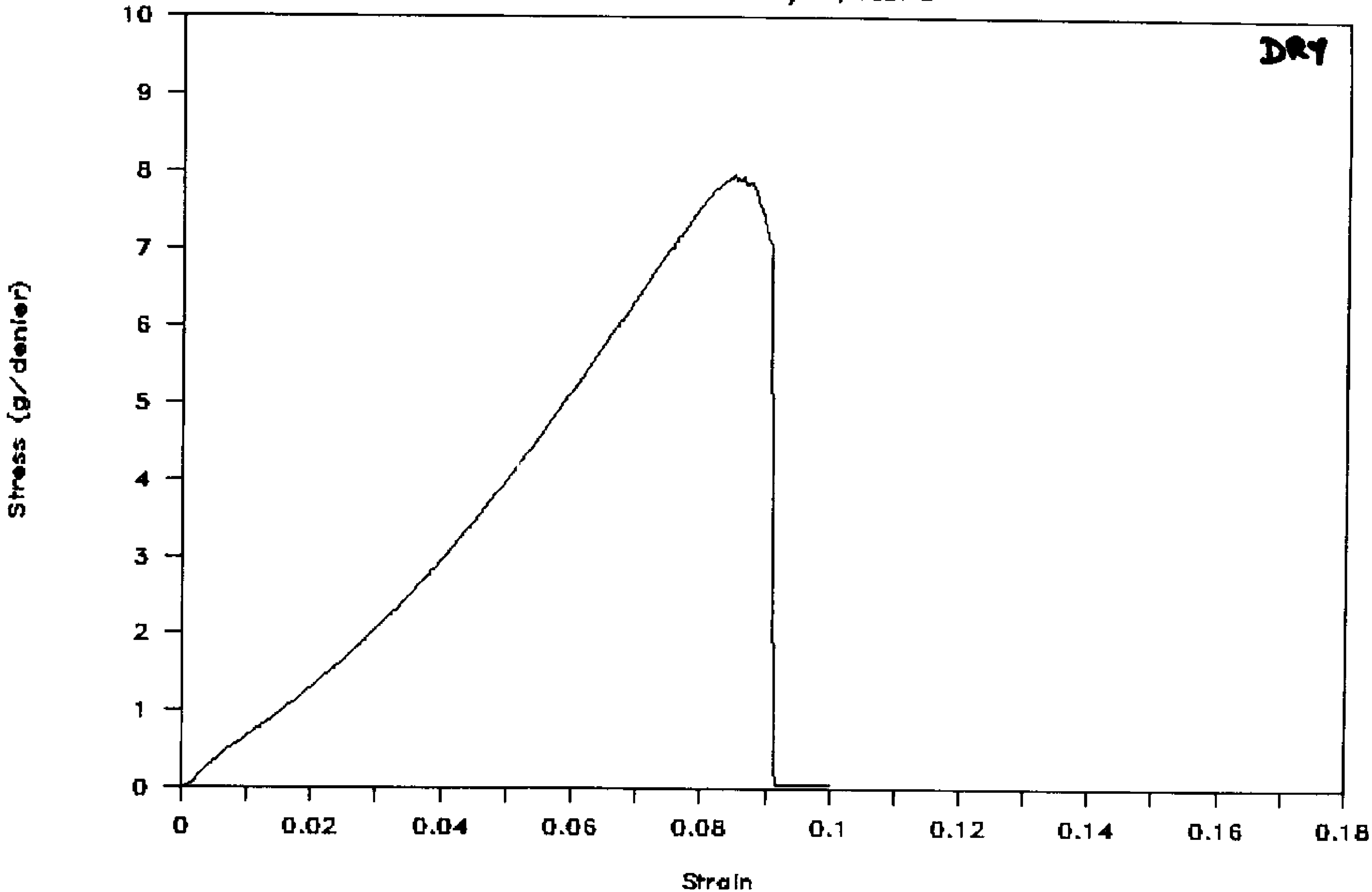
ENKA 551, 10 Cycles to 60% UTS

Stress—Strain, Test 3



ENKA 551, 10 Cycles to 60% UTS

Final Stress—Strain Cycle, Test 3



SINGLE LOAD STRESS STRAIN BEHAVIOR

ENKA Polyester (1000 Denier) 20 Ply

Dry and Wet Tests

SINGLE LOAD STRESS-STRAIN BEHAVIOR

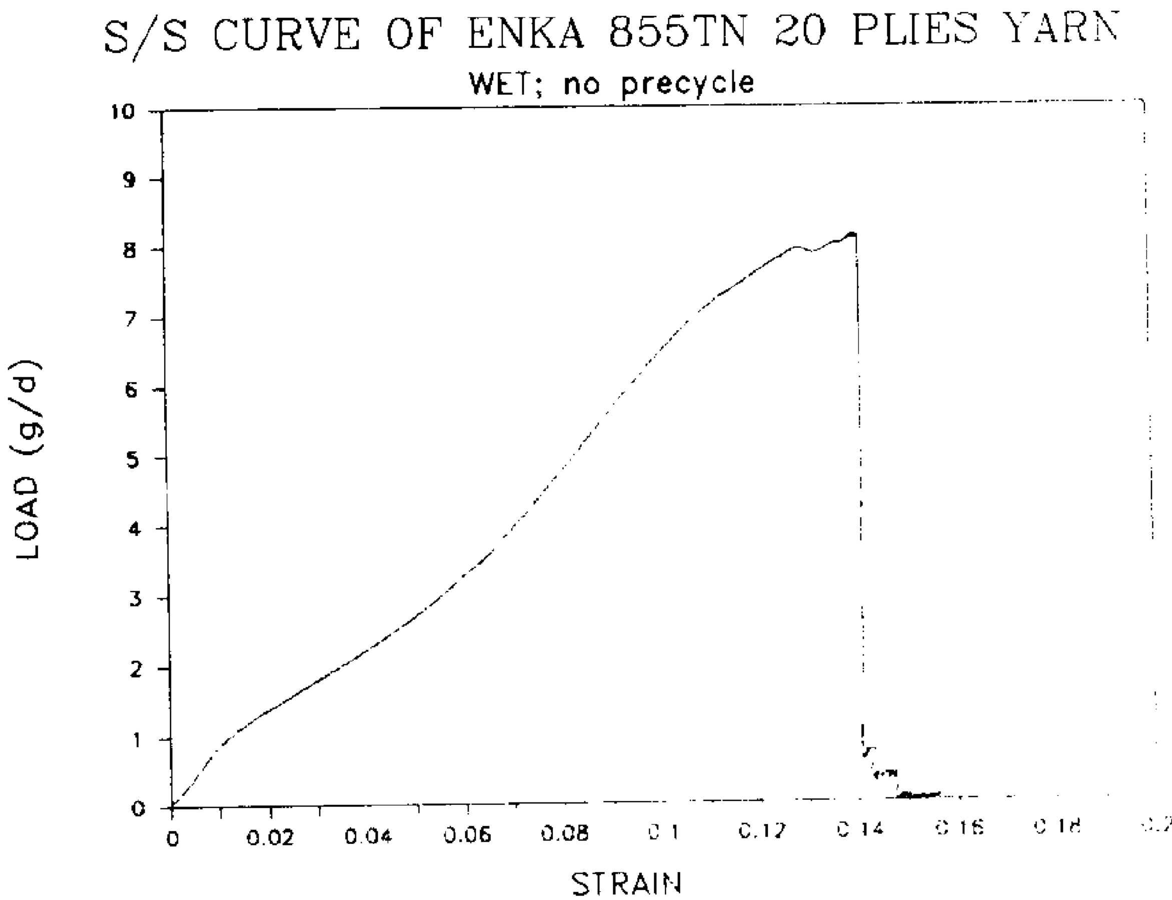
ENKA 855TN 20 PLIES YARN (WITH MARINE FINISH)

DRY YARN

	ORIGINAL		AFTER 30% B.S. 10 CYCLES		AFTER 60% B.S. 10 CYCLES	
	BREAKING STRESS GM/DENIER	BREAKING STRAIN	BREAKING STRESS GM/DENIER	BREAKING STRAIN	BREAKING STRESS GM/DENIER	BREAKING STRAIN
1	8.5	.141	8.1	.117	7.65	.098

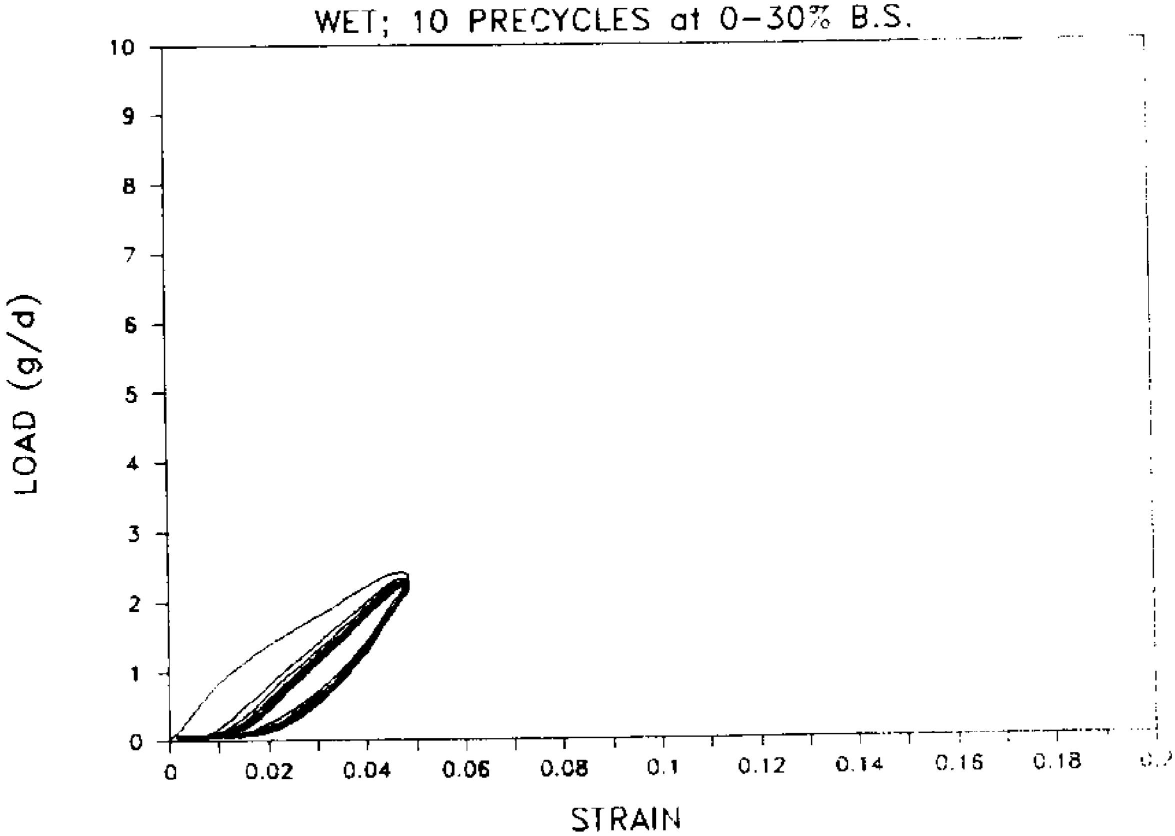
WET YARN

	ORIGINAL		AFTER 30% B.S. 10 CYCLES		AFTER 60% B.S. 10 CYCLES	
	BREAKING STRESS GM/DENIER	BREAKING STRAIN	BREAKING STRESS GM/DENIER	BREAKING STRAIN	BREAKING STRESS GM/DENIER	BREAKING STRAIN
1	8.6	.142	8.3	.13	7.6	.102



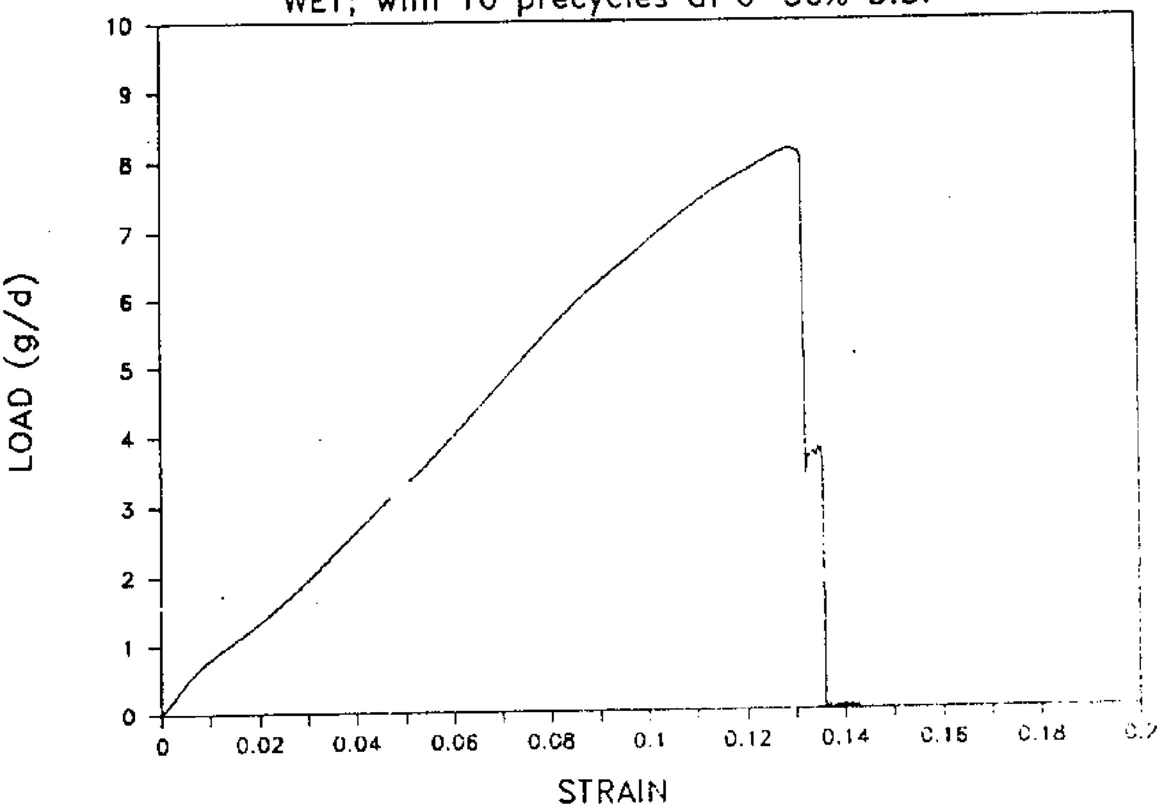
S/S CURVE OF ENKA 855TN 20 PLIES YARN
WET; no precycle
LOAD (g/d)
STRAIN
0
1
2
3
4
5
6
7
8
9
10
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2

PRECYCLE S/S CURVE OF ENKA 855TN 20 PLIES YARN

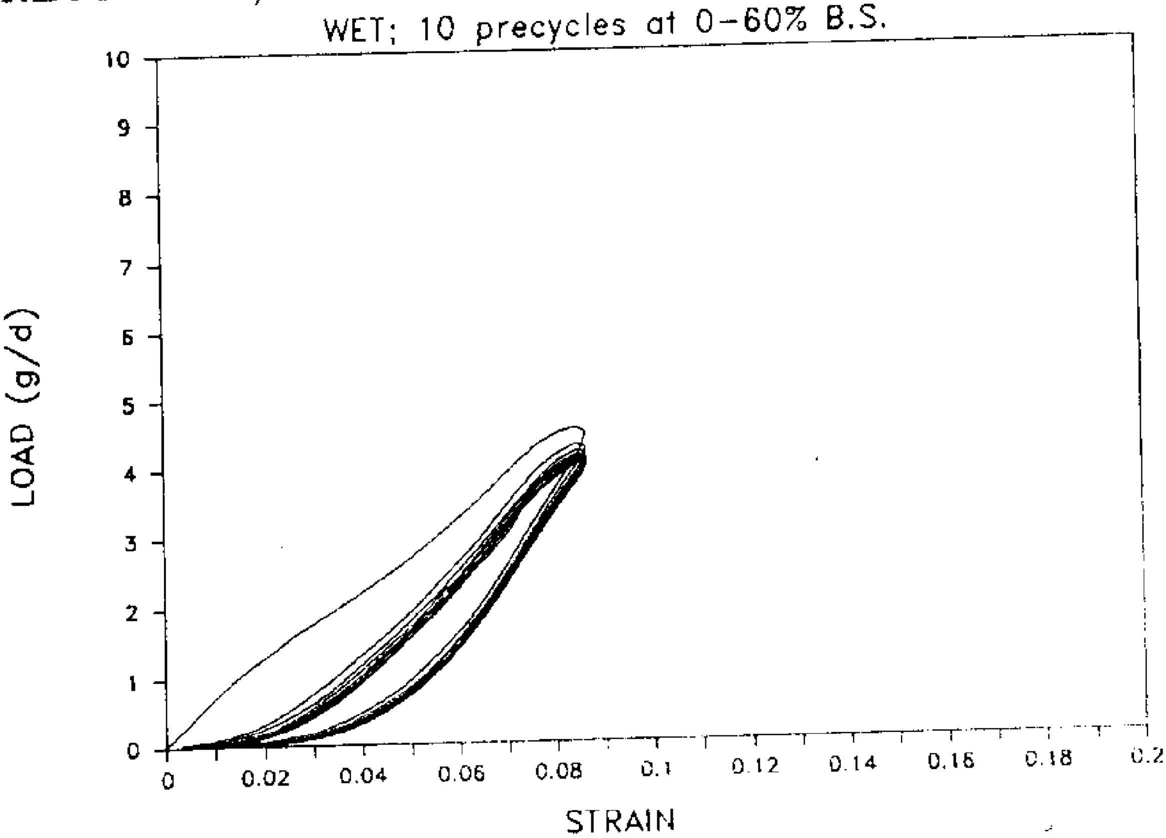


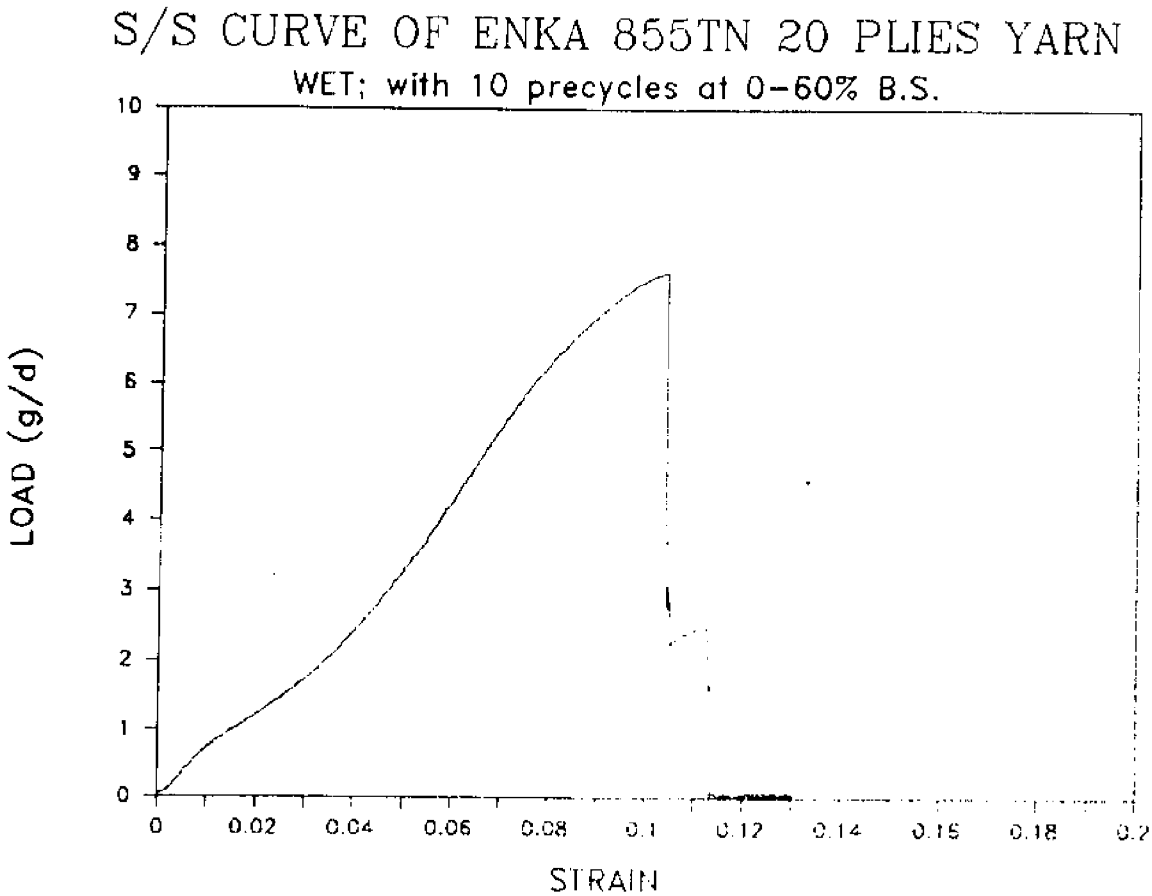
S/S CURVE OF ENKA 855TN 20 PLIES YARN

WET; with 10 precycles at 0–30% B.S.



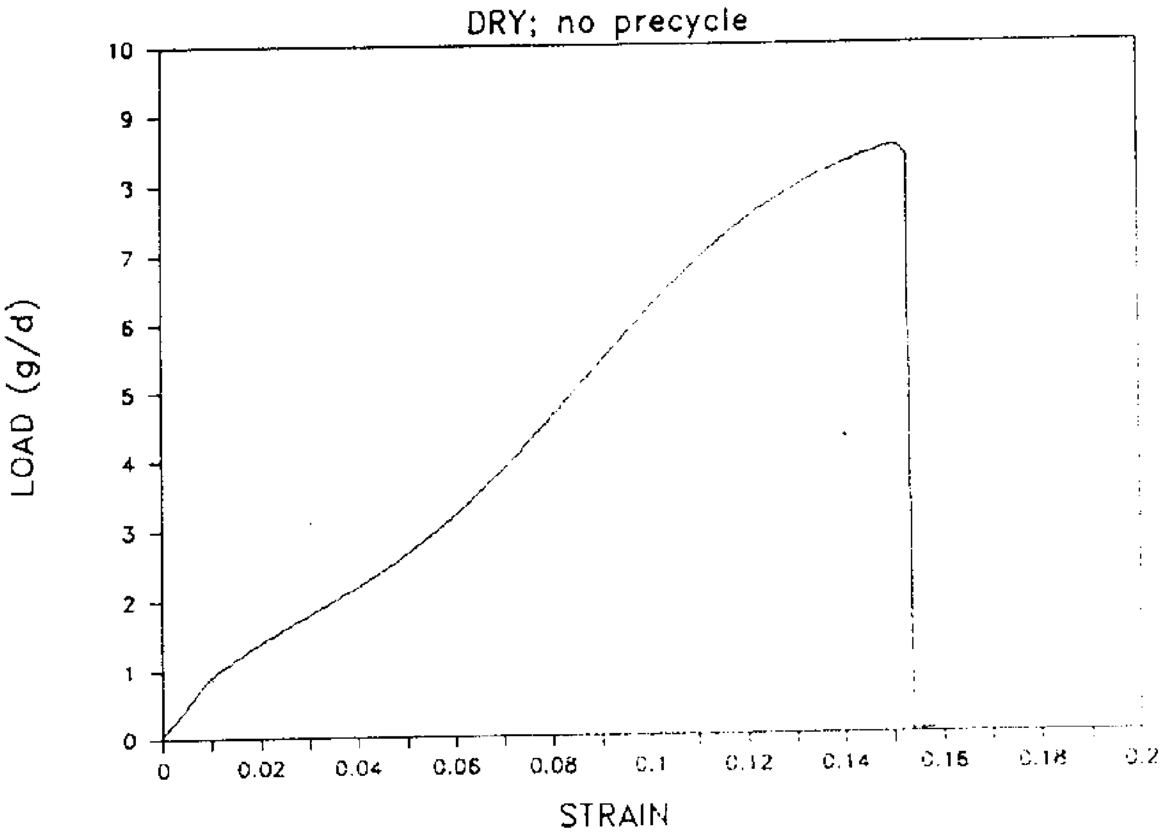
PRECYCLE S/S CURVE OF ENKA 855TN 20 PLIES YARN



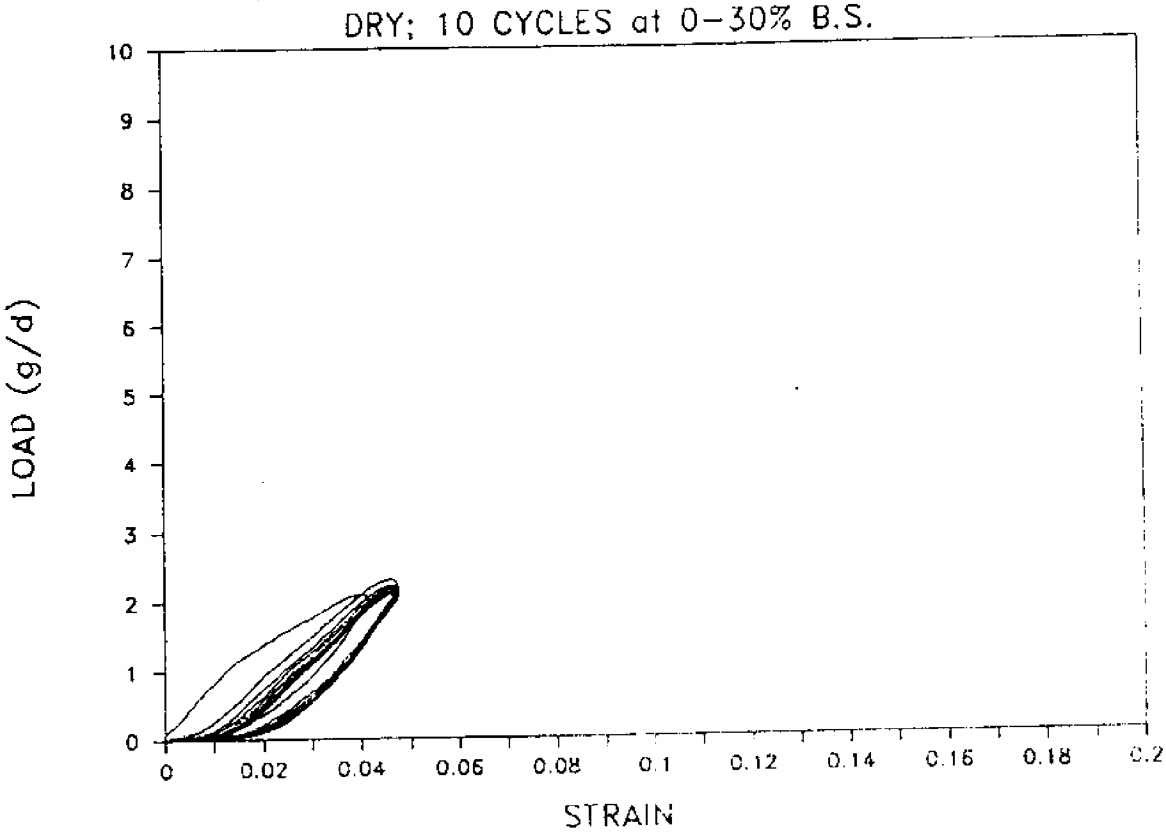


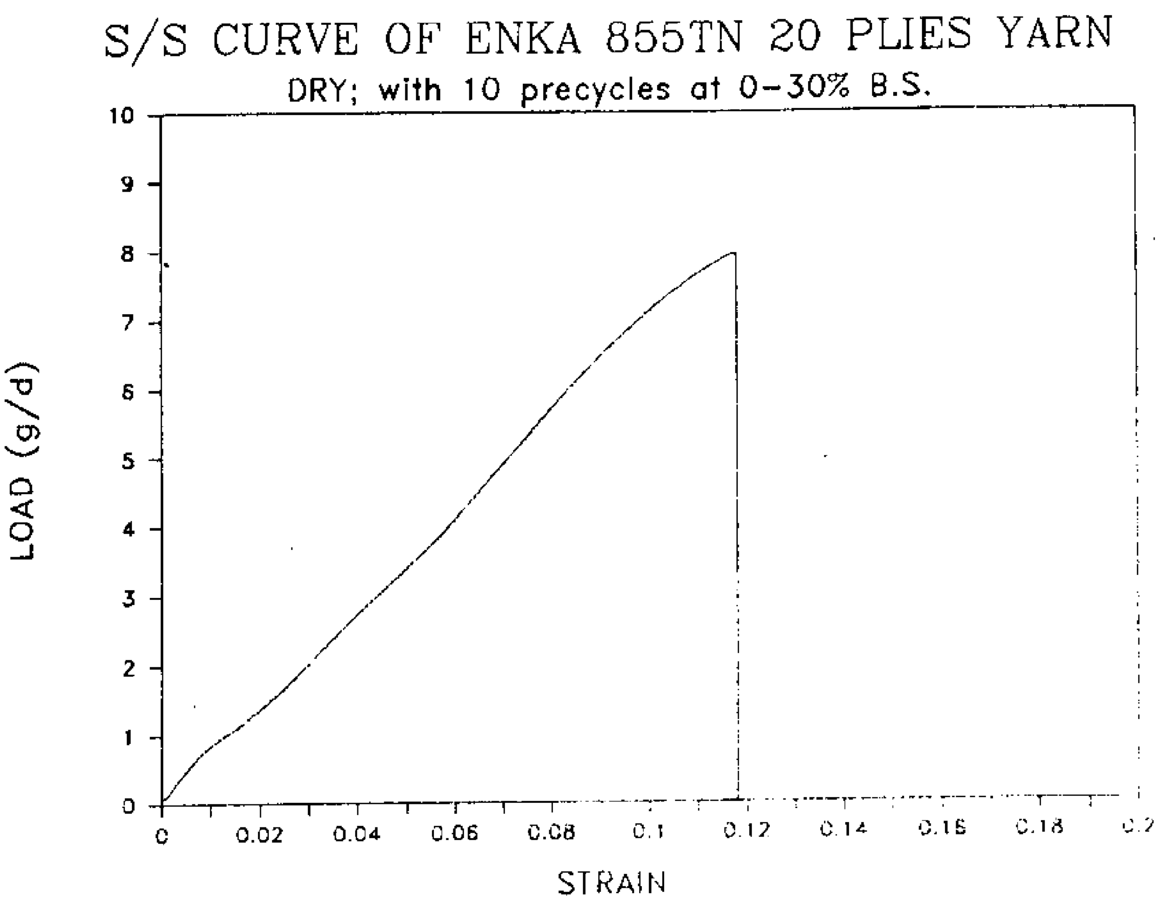
S/S CURVE OF ENKA 855TN 20 PLIES YARN
WET; with 10 precycles at 0-60% B.S.
LOAD (g/d)
10
9
8
7
6
5
4
3
2
1
0
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
STRAIN

STRESS-STRAIN CURVE OF ENKA 855TN 20 PLIES YARN



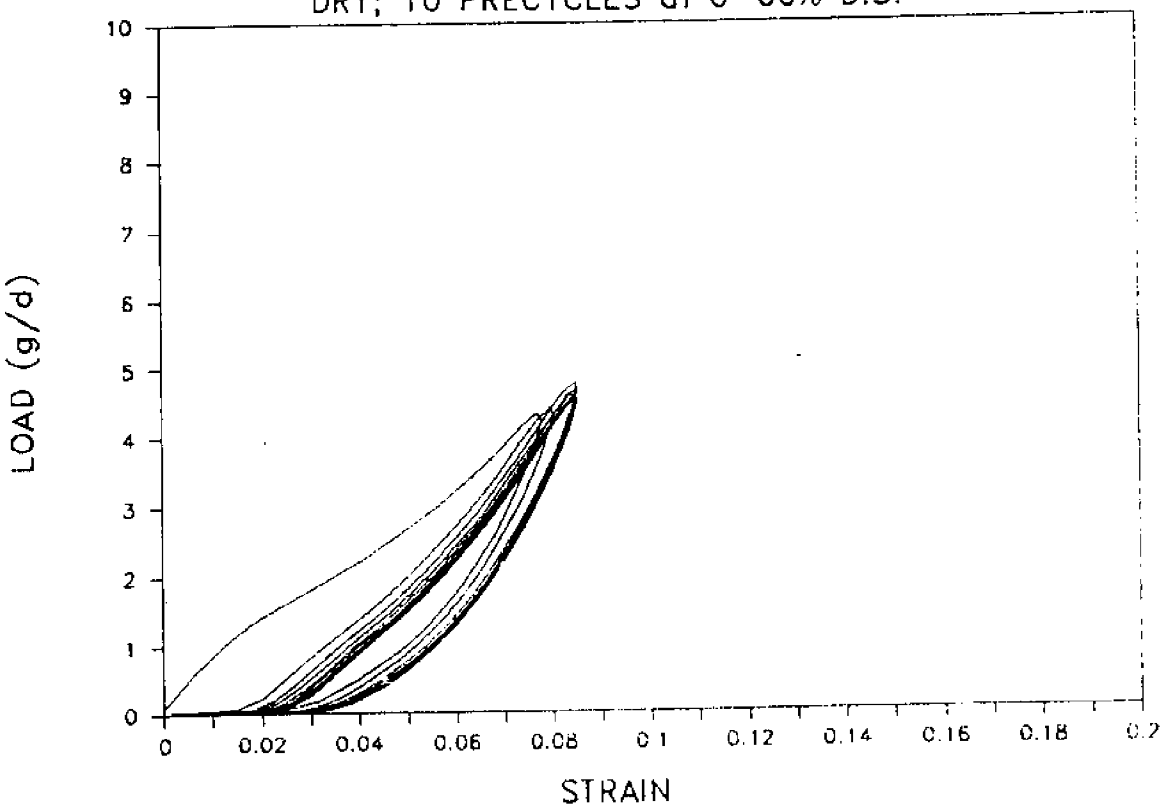
PRECYCLE S/S CURVE OF ENKA 855TN 20 PLIES YARN




S/S CURVE OF ENKA 855TN 20 PLIES YARN
DRY; with 10 precycles at 0-30% B.S.
LOAD (g/d)
STRAIN
0
1
2
3
4
5
6
7
8
9
10
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2

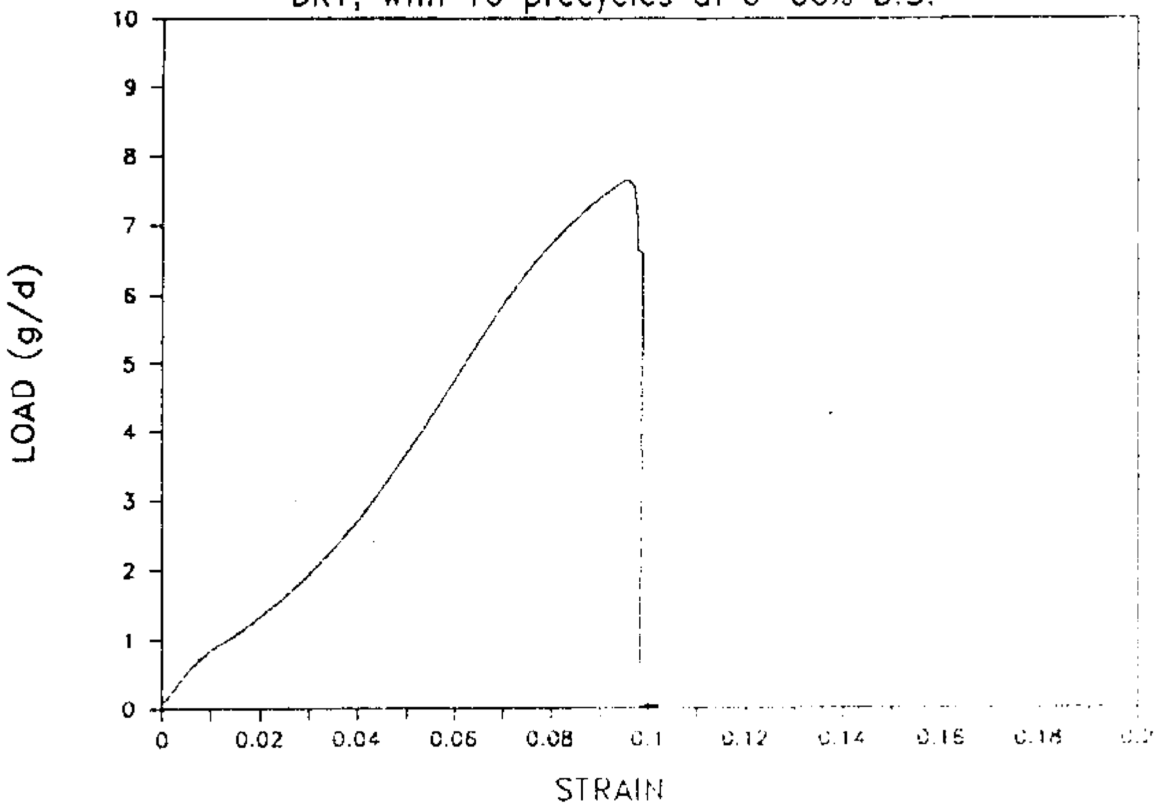
PRECYCLE S/S CURVE OF ENKA 855TN 20 PLIES YARN

DRY; 10 PRECYCLES at 0-60% B.S.



S/S CURVE OF ENKA 855TN 20 PLIES YARN

DRY; with 10 precycles at 0–60% B.S.



III. CREEP AND CREEP RECOVERY

KEVLAR AND ENKA POLYESTER

INTRODUCTION

Creep is the time-dependent strain that occurs when a material is subjected to a stress for a prolonged period of time. Some of this strain may be recoverable with time after the load has been removed. Instantaneously after the loading, the deformation due to creep increases rapidly for about a minute, and then the rate of deformation decreases gradually until a constant rate is reached. The first rapid increase in creep is referred to as the primary creep stage. The constant creep rate stage is the secondary creep stage. Secondary creep continues until a point when the rate starts to increase very rapidly and failure occurs. The last rapid increase stage is known as the tertiary phase. The failure because of creep is known as creep rupture. The time between the secondary and tertiary phase can vary from a few minutes to years depending on the stress level.

In addition to stress level, there are also environmental effects on creep rate. Temperature affects the creep rate of almost all materials. Materials which are hygroscopic (i.e., water-absorbing) are affected by humidity also.

Creep Phenomena in Filamentous Materials

Consider that a fixed constant longitudinal load is applied to a single filament. The resultant initial extension of the filament due to this load is not constant but increases gradually with time; that is, creep occurs. The rate of deformation decreases with time. On removal of the load, an immediate longitudinal contraction of the filament takes place. Subsequent to load removal further more gradual contraction is observed; that is, creep recovery takes place.

Complete recovery is time consuming and is not possible for many cases. Consequently a residual deformation is observed in almost all recovery processes. The typical deformation-time behavior for such filamentous material is shown in Figure 1.

In this report, the creep behavior of filamentous materials has been tested for four samples. The samples include ENKA 855T, ENKA 855TN, KEVLAR T960 and KEVLAR T961. The ENKAs are polyester yarns and the KEVLARs are aramids. Both ENKAs are similar in structure but the ENKA 855TN yarns are coated with a marine finish. Similarly, the KEVLAR T960 has a marine finish.

These yarns are the main constituents of selected ropes of interest. The creep behavior and the creep rupture tests of these yarns provide important information regarding the performance and failure mechanism of these ropes. Tests have been conducted under three different conditions for each of these samples.

— at room temperature (20°C) and relative humidity 62%.

— at room temperature (20°C), with sample completely immersed in water.

— sample completely immersed in water at 40°C.

We have also run creep rupture tests at different stress levels for all four samples in dry and in wet conditions.

Dry Creep Tests

Shown in Figure 2 is a steel frame of dimension 6.5' x 2.5' x 1'. Several aluminum rods were clamped on the top part of the frame. Plexiglass plates (2' x 1') were fixed on the frame as shown and graph paper was attached to the surface of the Plexiglass plates. This arrangement served as a measurement device for the creep rate.

Sample preparation:

A sample yarn of about 4 feet was taken. The two loose ends were inserted inside two rubber tubes of 5" long and 1/4" in diameter. The loose ends were pulled out and fixed to the outer wall of the tubes by small pieces of tape. The rubber tubes and the yarn ends were clamped between two Plexiglass plates (5" x 2.5") as shown in Figure 3. This process prevents the yarn from slipping. One end was used to suspend the sample from the top of the frame and load was applied at the other end as shown in Figure 2. Two pieces of tapes were then attached to the yarn at a distance of 90 to 100 cm. These were our initial reference points. A suitable load was applied and the extension was recorded at desired time intervals. The strain values were then calculated and plotted. In this experiment the time intervals for both creep and creep recovery were 30 sec, 60 sec, 5 minutes, 10 minutes, 30 minutes, 1 hour, 1 day, and 7 days. In a few cases we took measurements at 5 days instead of 7 days.

Wet Creep Test

In this set of experiments the sample was marked with ink at two points 90 to 100 cm apart. The sample was inserted inside a 3 feet long transparent plastic tube, a plastic connector, and then a rubber tube (5″ long and 1/4″ diameter). The diameter of the plastic tube was 3/8″. The plastic tube and the rubber tube were joined firmly by the connector. The loose end of the sample was pulled out and fixed to the outer wall of the rubber tube. The lower part of the rubber tube was clamped between two Plexiglass plates (5″ x 2.5″). The load was applied to this end. The other end was prepared as in the dry creep case. The sample was suspended from the top of the frame. The plastic tube was filled with tap water. The set up is shown in Figure 4. The two ink marks provided the initial reference points. Suitable loads were then hung, and the creep recovery was noted.

Hot Creep Test

An aluminum trough 6' x 4″ x 3″ was fixed firmly to the table (see Figure 5). Four thin steel rulers were glued on the bottom of the trough as shown in Figure 5. These rulers were used to measure the extension of the samples. A sample yarn of about 6.5' long was taken. One end was prepared as the weight-hanging end (as in the dry creep case). The other end was inserted through a rubber tube (as in the previous case) and fixed to the outer wall of the tube. This end was pressed between two aluminum plates (4″ x 2.5″) and clamped to the bottom surface of the trough by two "C" clamps. The sample was placed in the trough as shown in Figure 5. Teflon cylinder was used as a guide to keep the sample immersed in the water. Two points were marked on the sample as the initial reference points. The trough was filled up to 70% of its volume with water at 40°C from the constant temperature bath by siphoning action. Water was siphoned from the opposite end of the trough to a pump and then circulated back to the constant temperature bath. Both flow rates in and out of the pump were adjusted such that the sample was immersed in water during the entire period of 14 days (7 days of creep and 7 days of creep recovery). Loads were applied and the extension of the yarn was recorded. The creep rate was calculated and plotted.

RESULTS OF CREEP AND CREEP RECOVERY TESTS

Graphs for creep, creep recovery, and creep rupture tests at room temperature are given for different stress levels in Figures 6 to 17 inclusive. Because of the direct line arrangement illustrated in Figures 2,3, and 4, friction was not a factor in these tests. However in test conducted wet and at a higher temperature (40°C) a special longitudinal trough arrangement was necessary as shown in Figure 5. In this case however, friction entered as an unknown quantity and could not be eliminated despite a series of experiments with different bearings, pulleys and Teflon rods. It was therefore decided to conduct all tests on the same set up, that of Figure 5 for dry creep, wet creep (room temperature), and hot wet (at 40°C). The results obtained in this series of tests are plotted in Figures 18 to 28 but these cannot be considered as absolute values, rather they indicate the relative creep behavior of the selected fibers under the designated experimental conditions.

DISCUSSION OF CREEP RESULTS

The creep and creep recovery graphs plotted in Figures 6 to 17 inclusive reflect the most direct plotting of creep data. An alternate method would be to plot strain versus load for a given creep period, and this will result in a series of essentially linear plots. But it is more instructive to compare yarn responses to individual changes in test condition or in yarn treatment, i.e., with or without marine finish.

Consider the water effects. For both the polyester and for aramid yarns, creep rates were higher for wet tests than for dry. The increase in wet creep rates were reflected in a higher slope of the strain versus log time curves as is noted in comparison of Figure 12 versus 13 for dry versus wet KEVLAR T960 with marine finish. The level of the strain/time curves of these plots is significantly different for wet versus dry KEVLAR. And it should be noted that the wet KEVLAR T960 could not sustain creep loads above 11.5 kg whereas the dry KEVLAR samples were intact in creep tests of 16.2 kg.

Similar behavior was noted in the KEVLAR T961 (without marine finish) as seen in Figures 15 and 16. The slope of the strain versus time curves are higher for the wet tests as are the overall strain levels. In addition the wet samples could not be creep tested at loads above 15 kg.

The ENKA polyester yarns show little difference in the slope of the strain versus time curves as seen in Figures 6 and 7, although overall strain levels are somewhat higher in the wet tests. As for allowable load levels in the creep tests, the wet ENKA yarns without marine finish failed at loads above 5.2 kg but the dry ENKA yarns survived at 6.2 kg as shown in Figure 6. The same can be said for the ENKA TN specimen with finish.

Creep tests at 40°C were considered necessary and here the horizontal trough device for Figure 5 was employed. The test results for 40°C wet immersion are plotted in Figures 8, 11, 14, and 17. Comparison of these data with the creep results for dry tests run at room temperature as plotted in Figures 6, 9, 12, and 15 shows the hot creep to less than the room temperature, dry creep contrary to expectation. This reversal was attributed to the friction incurred in the change of threadline direction. Accordingly it was decided to run a full set of creep tests with the same threadline path but with nominal friction. Data from such tests would be relative, not absolute. Such data are plotted in Figures 18 - 28. A consistent pattern of behavior is noted.

Creep of dry polyester and aramid yarns is minimal run at room temperature, and creep recovery is generally maximum. Creep of wet yarns at room temperature exceeds that of dry yarns at room temperature as seen for example in Figures 18-28. Creep recovery of wet yarns at room temperature is less than that for dry yarns.

Creep of hot wet yarn is generally greater than that of wet room temperature yarns both in the case of polyester and aramid. Creep recovery of the hot wet yarns is less or greater than that of the cold wet and the dry yarns depending on the loads applied during the test.

CREEP, CREEP RECOVERY AND CREEP RUPTURE TESTS

ENKA 855T, ENKA 855TN, KEVLAR T960 and KEVLAR T961

DEFORMATION-TIME GRAPH

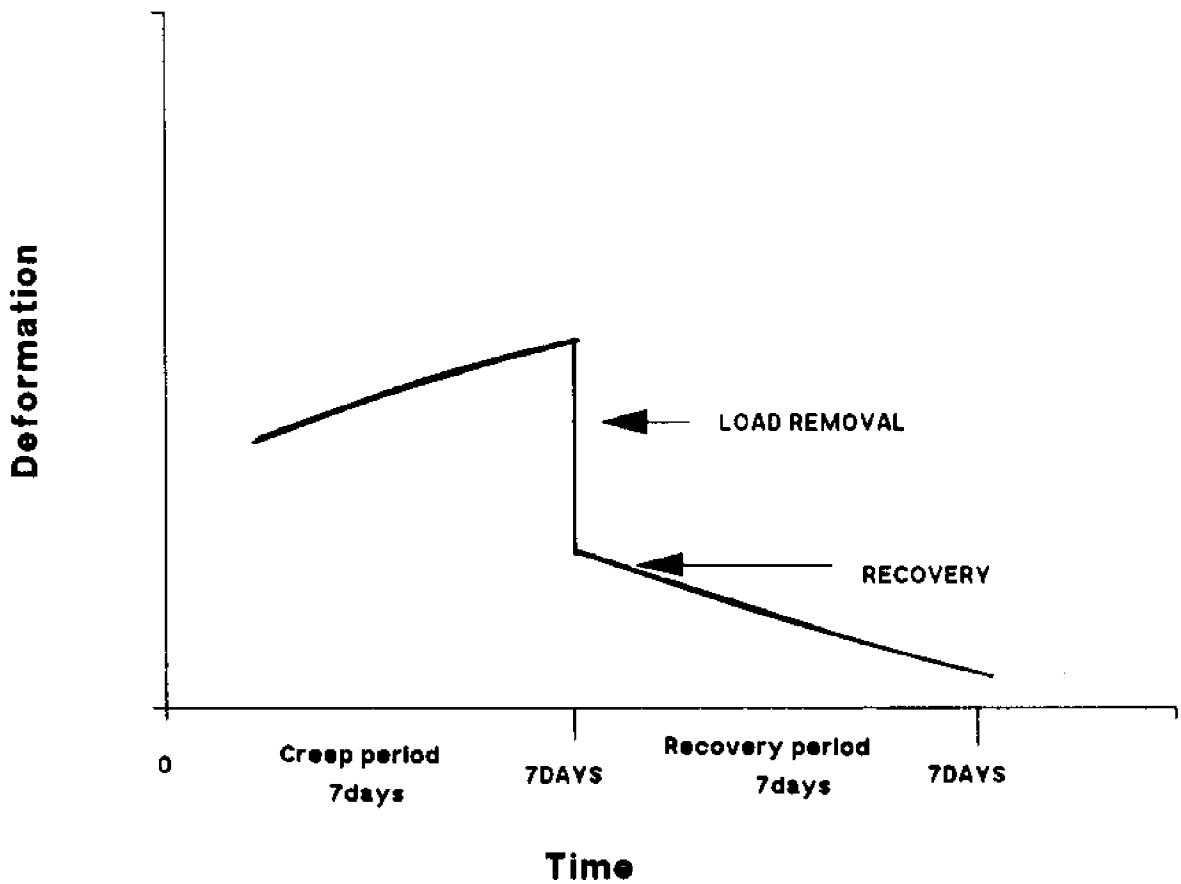


Figure 1

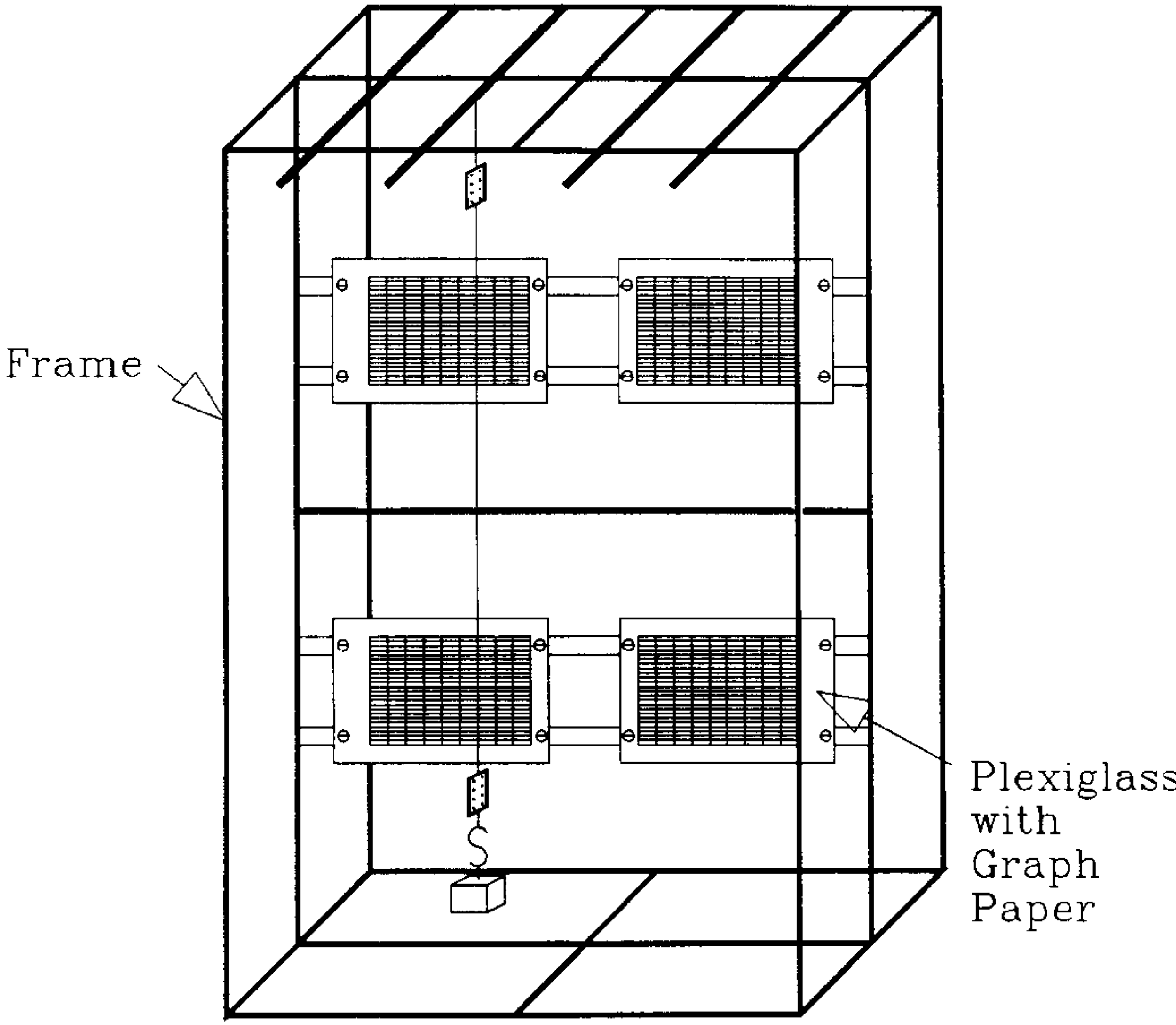


Figure 2 -- Filament Creep Frame

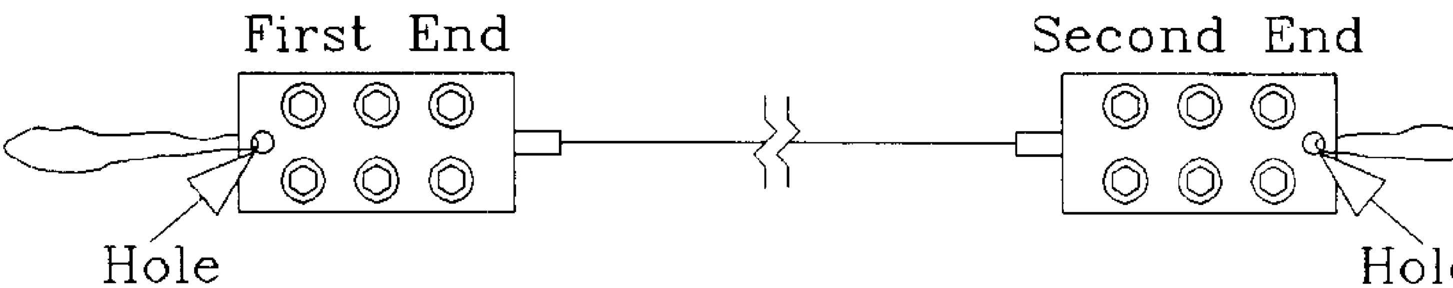


Figure 3 -- Plexiglass Specimen Clamps

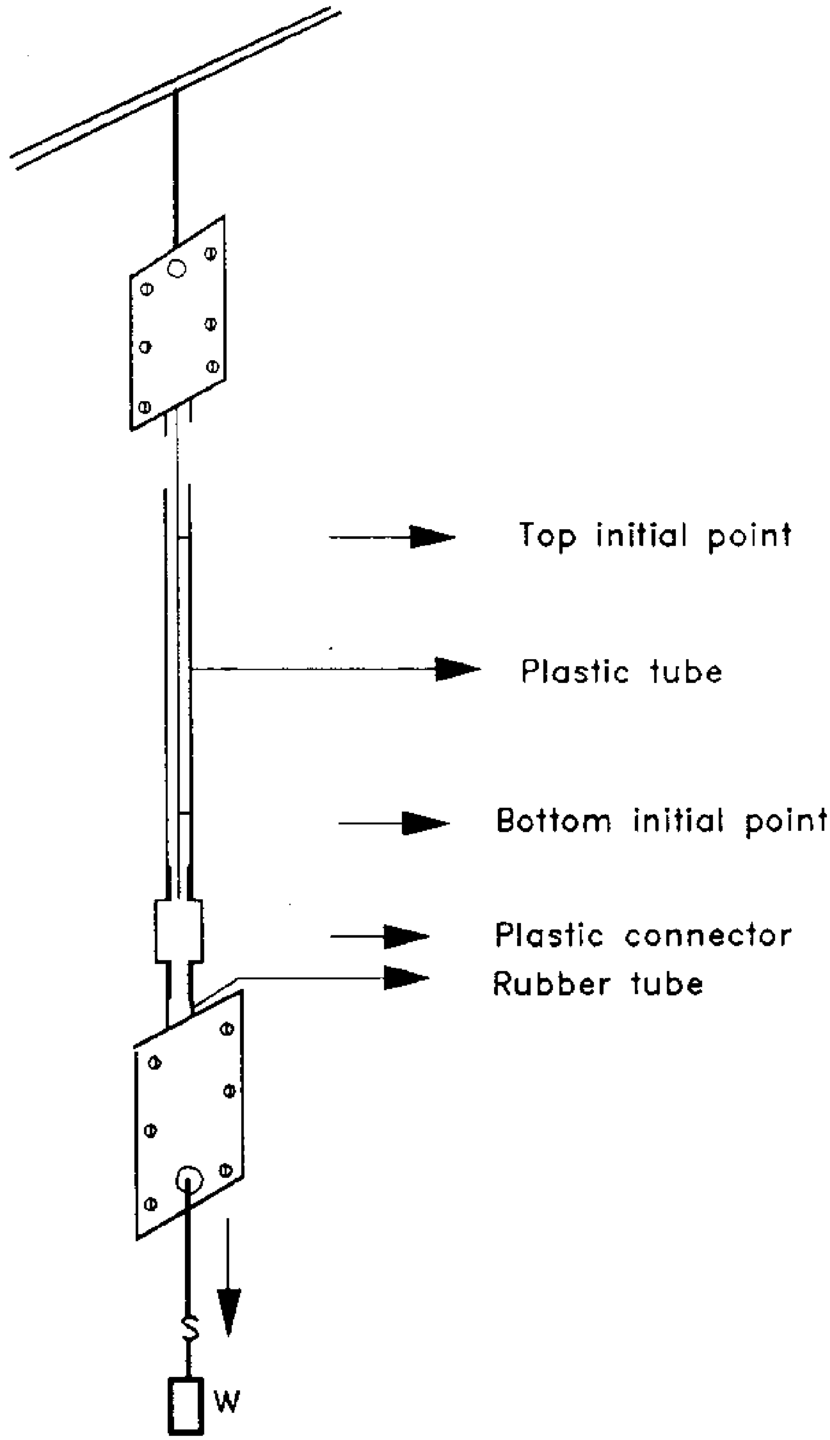


FIGURE 4 --- WET CREEP ARRANGEMENT

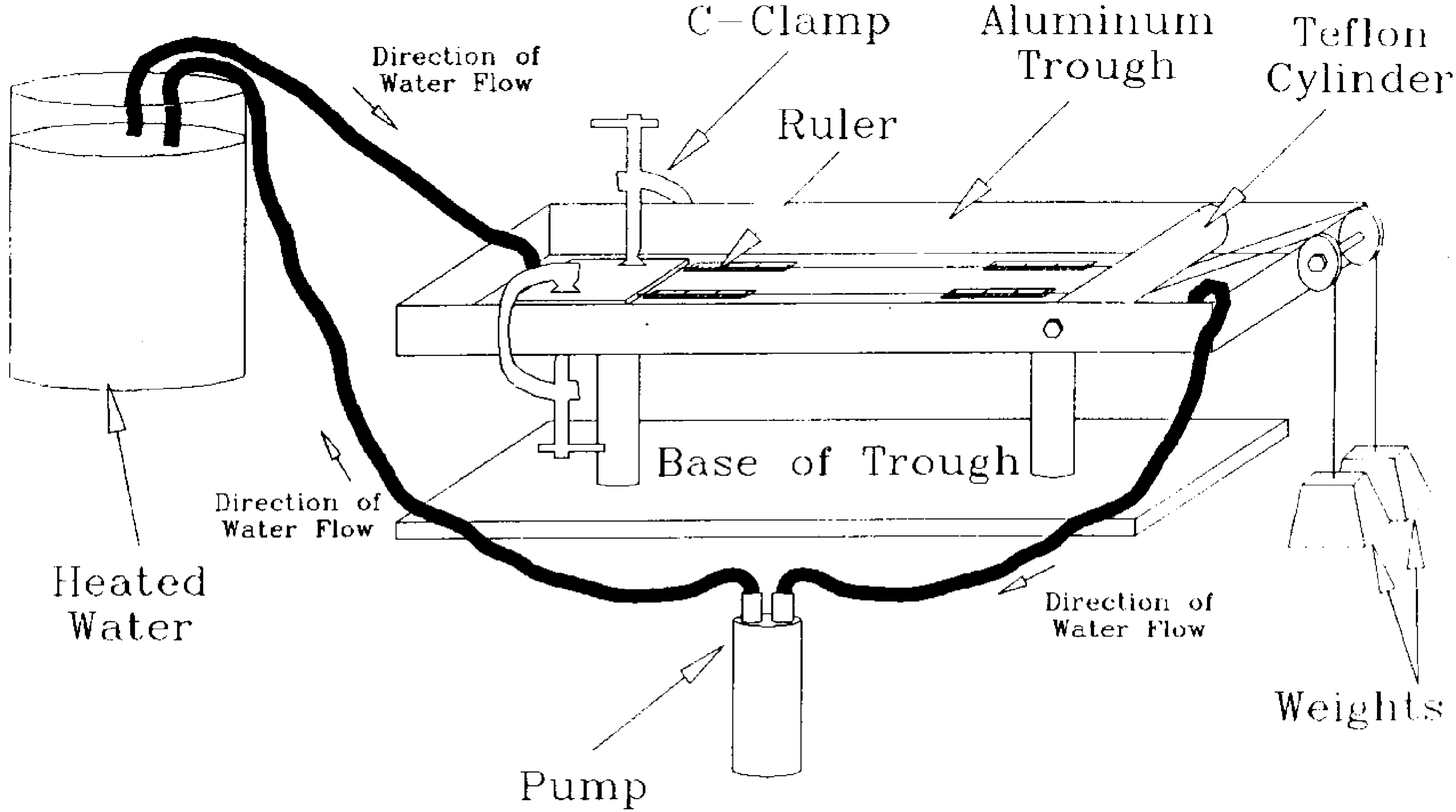


Figure 5 HOT WET CREEP ARRANGEMENT

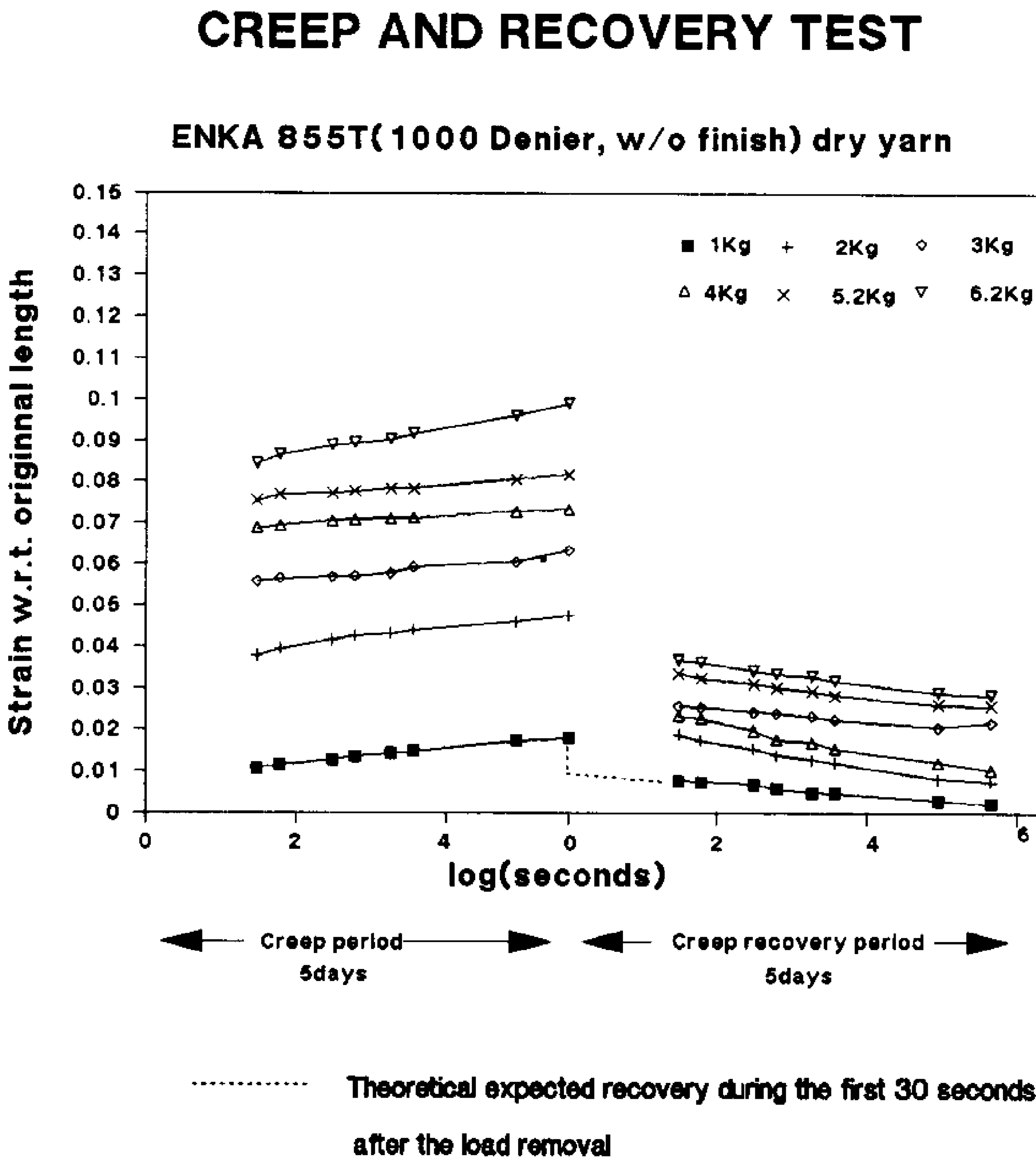
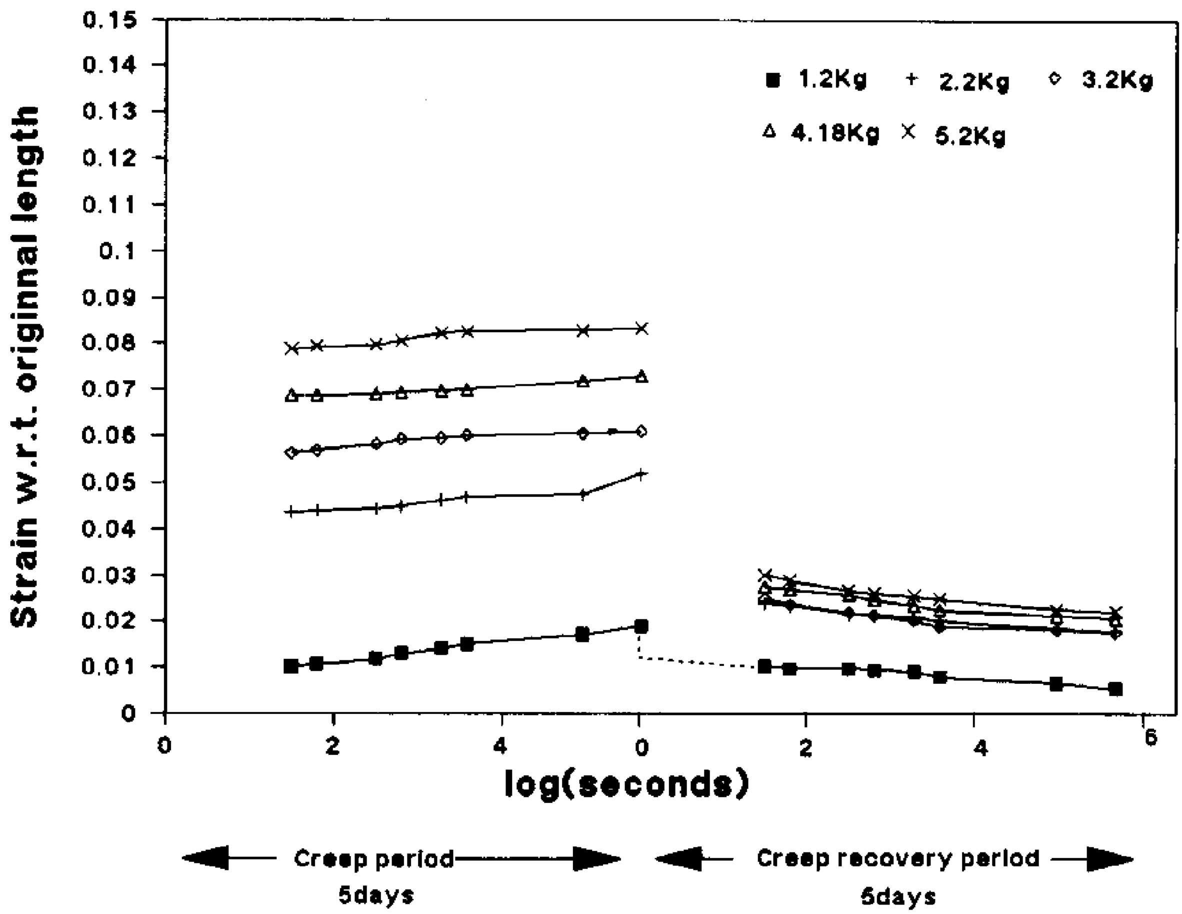

CREEP AND RECOVERY TEST
ENKA 855T(1000 Denier, w/o finish) dry yarn
Strain w.r.t. originnal length
0.15
0.14
0.13
0.12
0.11
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
1Kg
2Kg
3Kg
4Kg
5.2Kg
6.2Kg
0
2
4
0
2
4
6
log(seconds)
Creep period
5days
Creep recovery period
5days
Theoretical expected recovery during the first 30 seconds
after the load removal

Figure 6

CREEP AND RECOVERY TEST

ENKA 855T (1000 Denier, w/o finish) wet yarn



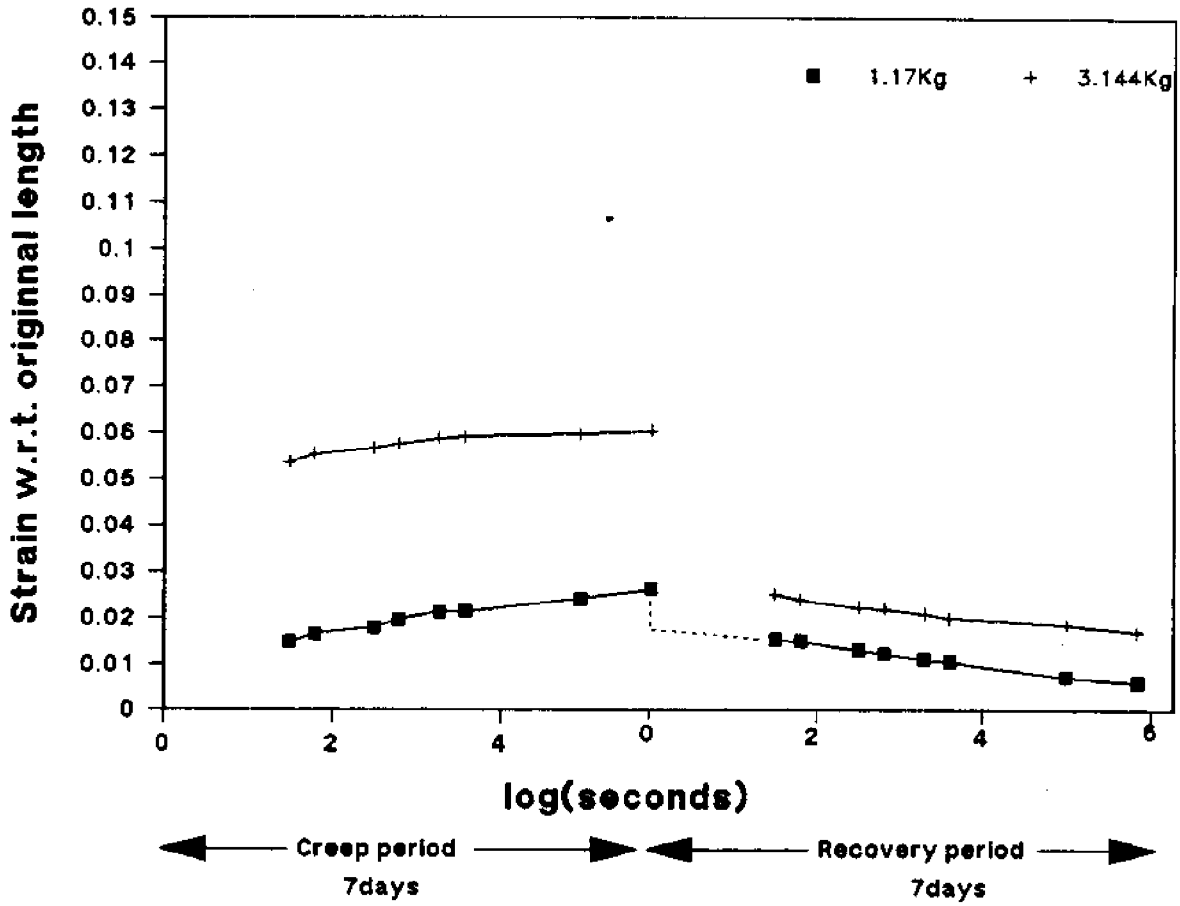
.... Theoretical expected recovery during the first 30 seconds after the load removal

Figure 7

CREEP AND RECOVERY TEST

ENKA 855T (1000 Denier w/o finish) wet yarn

(Test at 40 degrees C)

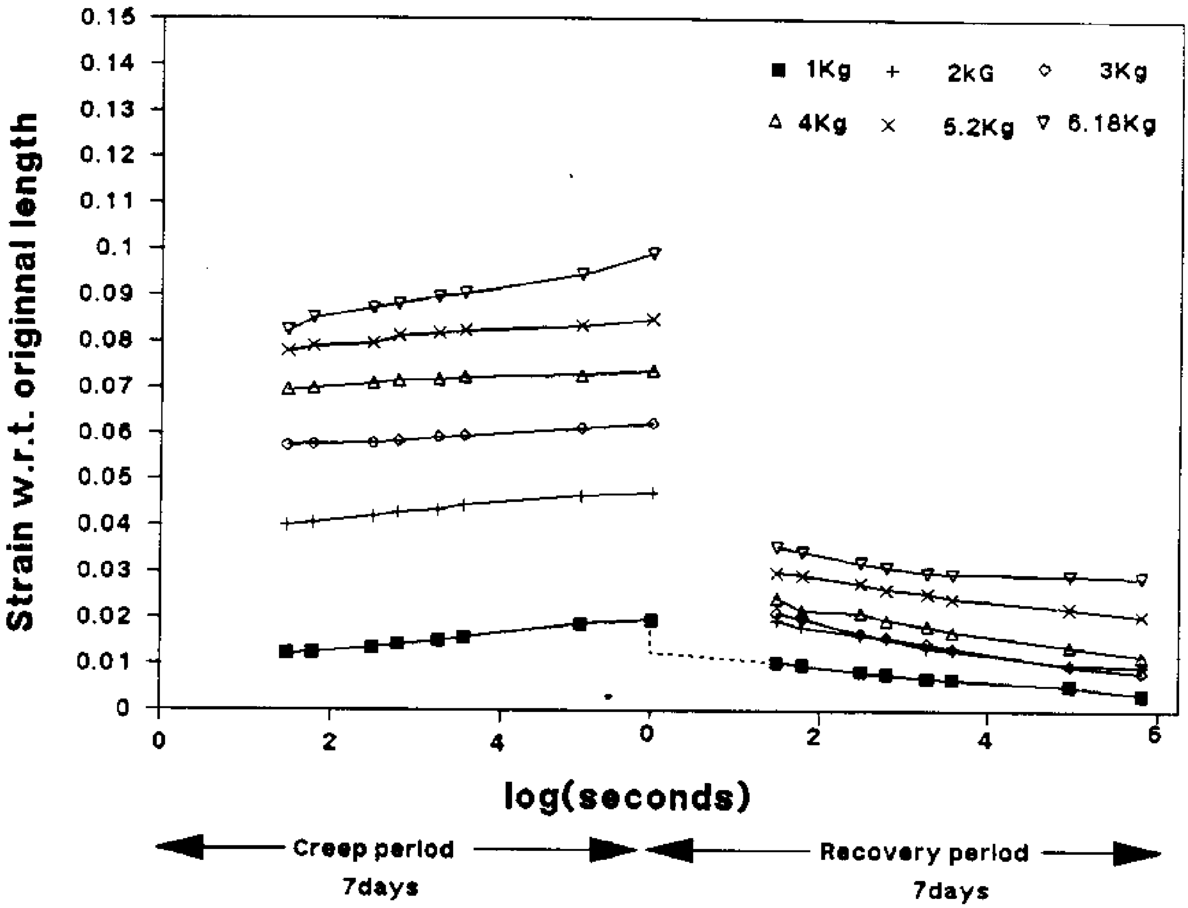


.... Theoretical expected recovery during the first 30 seconds after the load removal

Figure 8

CREEP AND RECOVERY TEST

ENKA 855TN (1000 Denier, w/ finish) dry yarn



.... Theoretical expected recovery during the first 30 seconds after the load removal

Figure 9

CREEP AND RECOVERY TEST

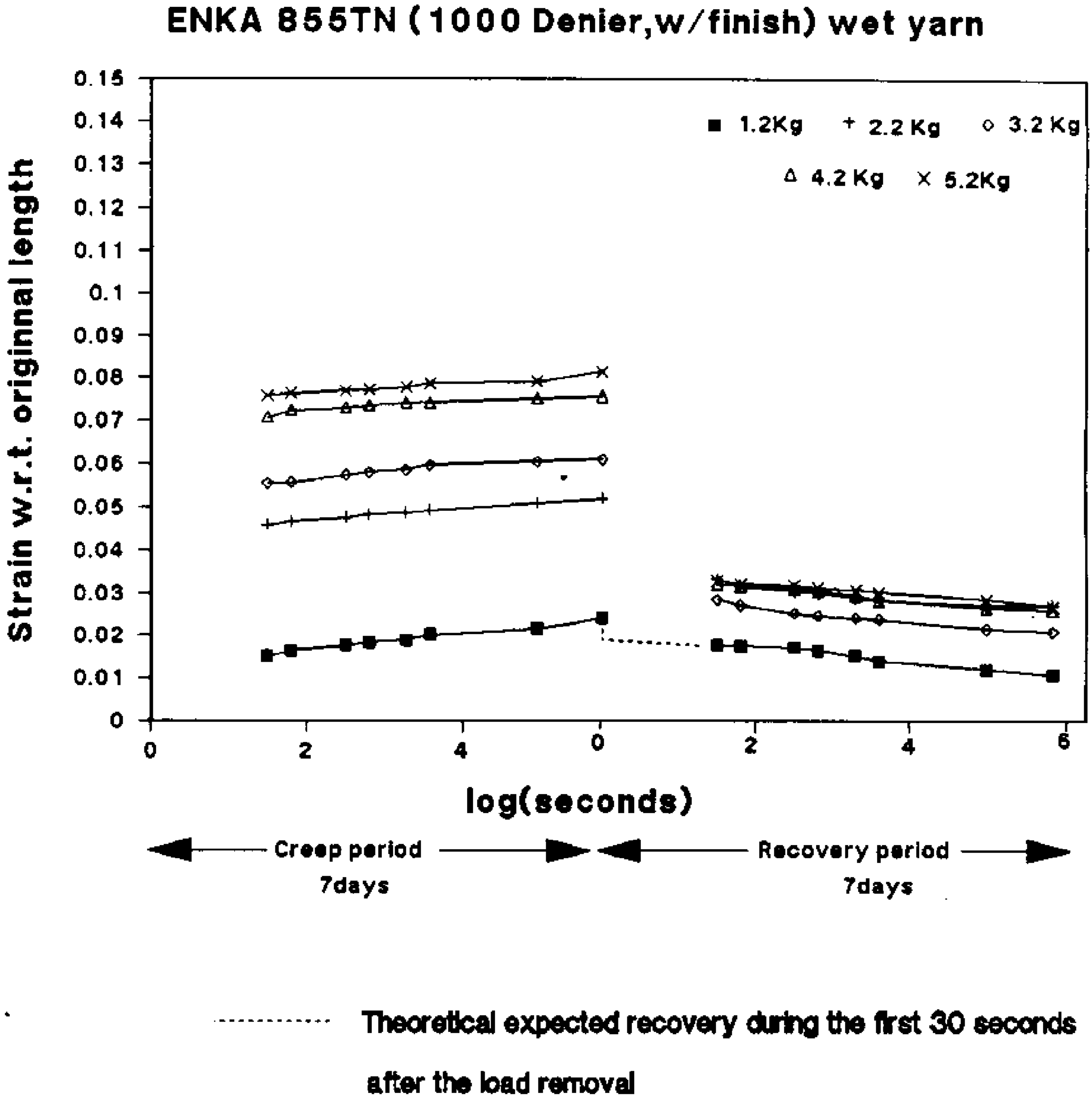


Figure 10

CREEP AND RECOVERY TEST

ENKA 855 TN (1000 Denier, w/finish) wet yarn

(Test at 40 degrees C)

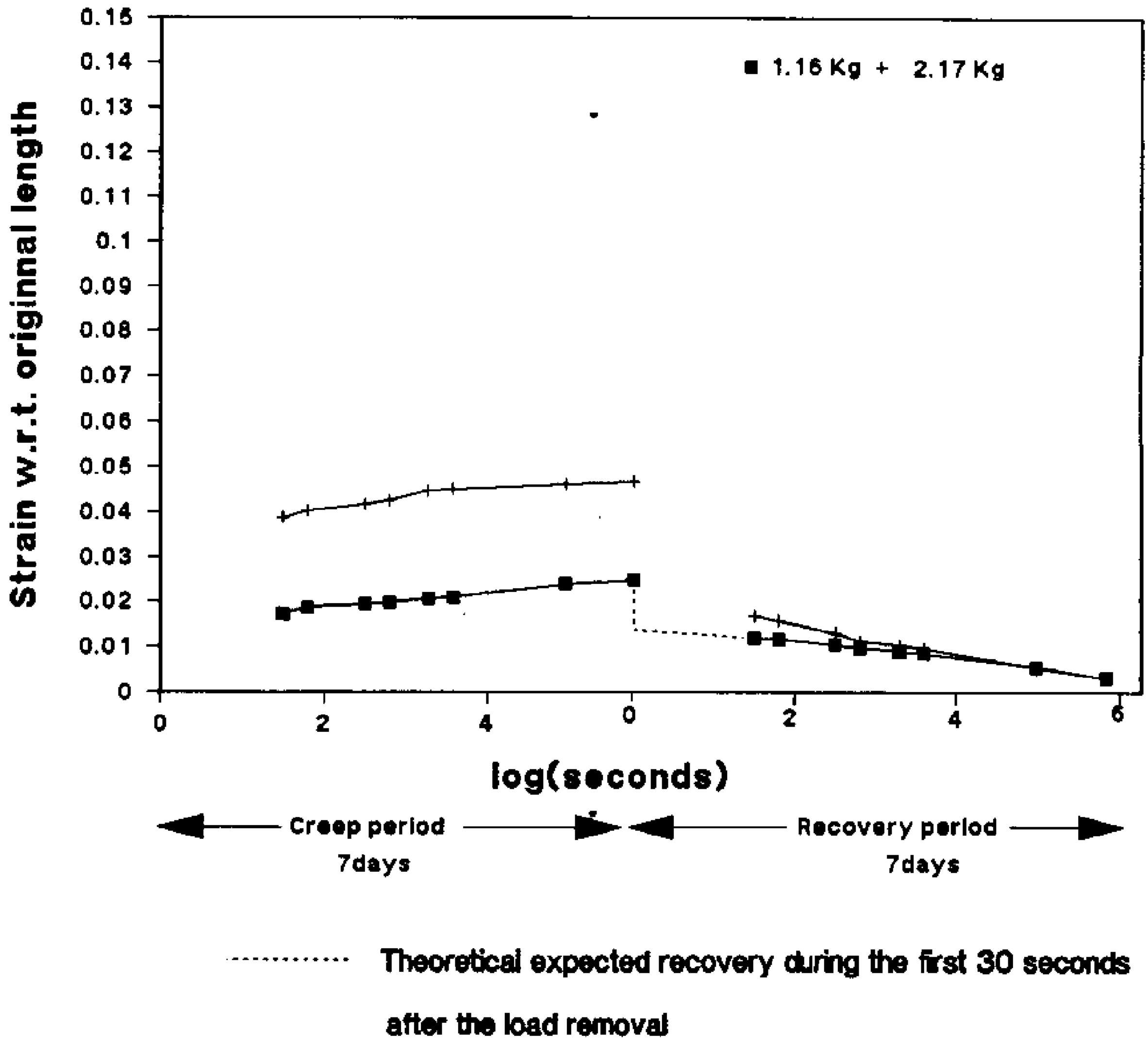


Figure 11

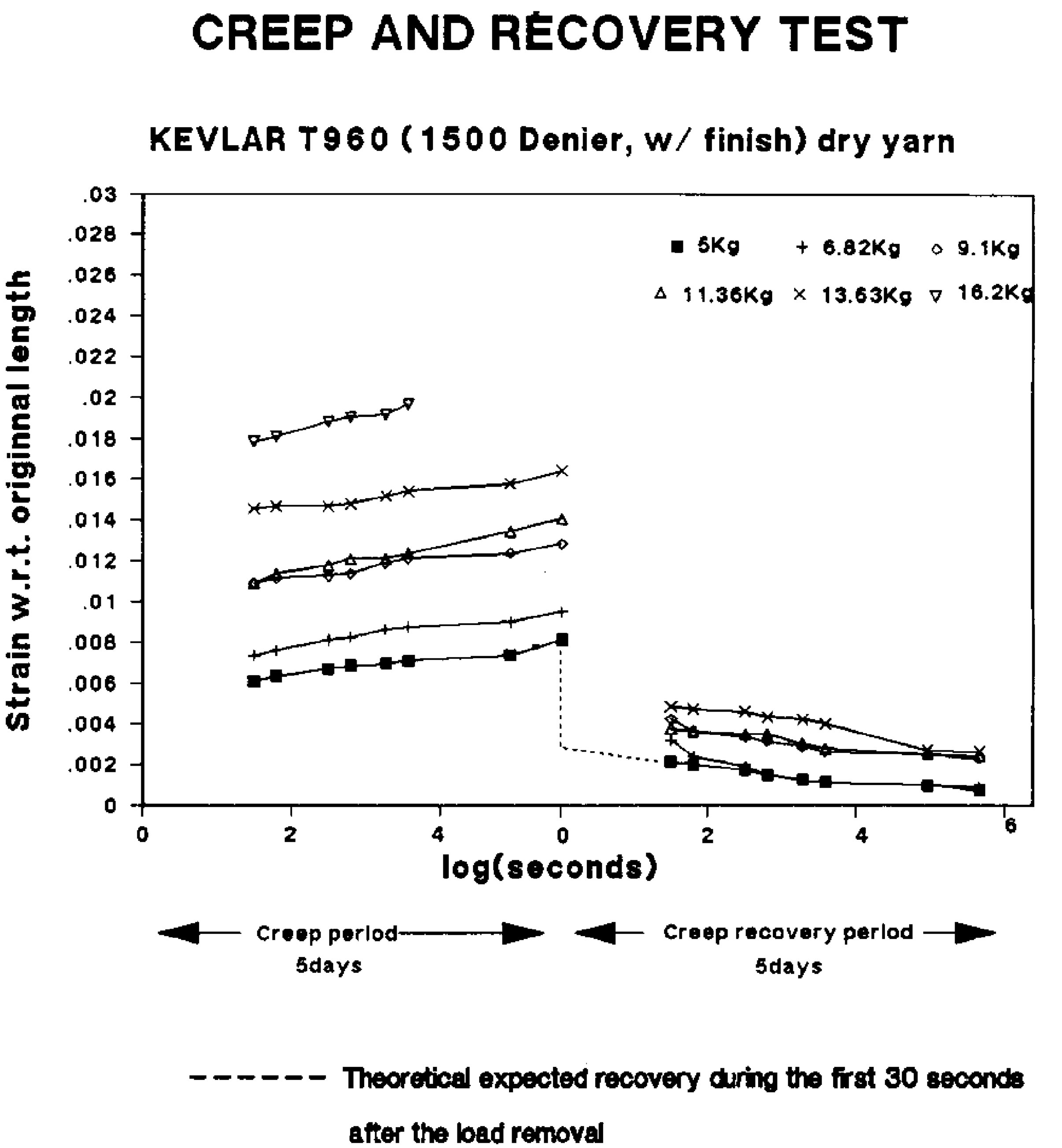

CREEP AND RECOVERY TEST
KEVLAR T960 (1500 Denier, w/ finish) dry yarn
Strain w.r.t. originnal length
log(seconds)
5Kg
6.82Kg
9.1Kg
11.36Kg
13.63Kg
16.2Kg
Creep period
5days
Creep recovery period
5days
Theoretical expected recovery during the first 30 seconds after the load removal

Figure 12

CREEP AND RECOVERY TEST

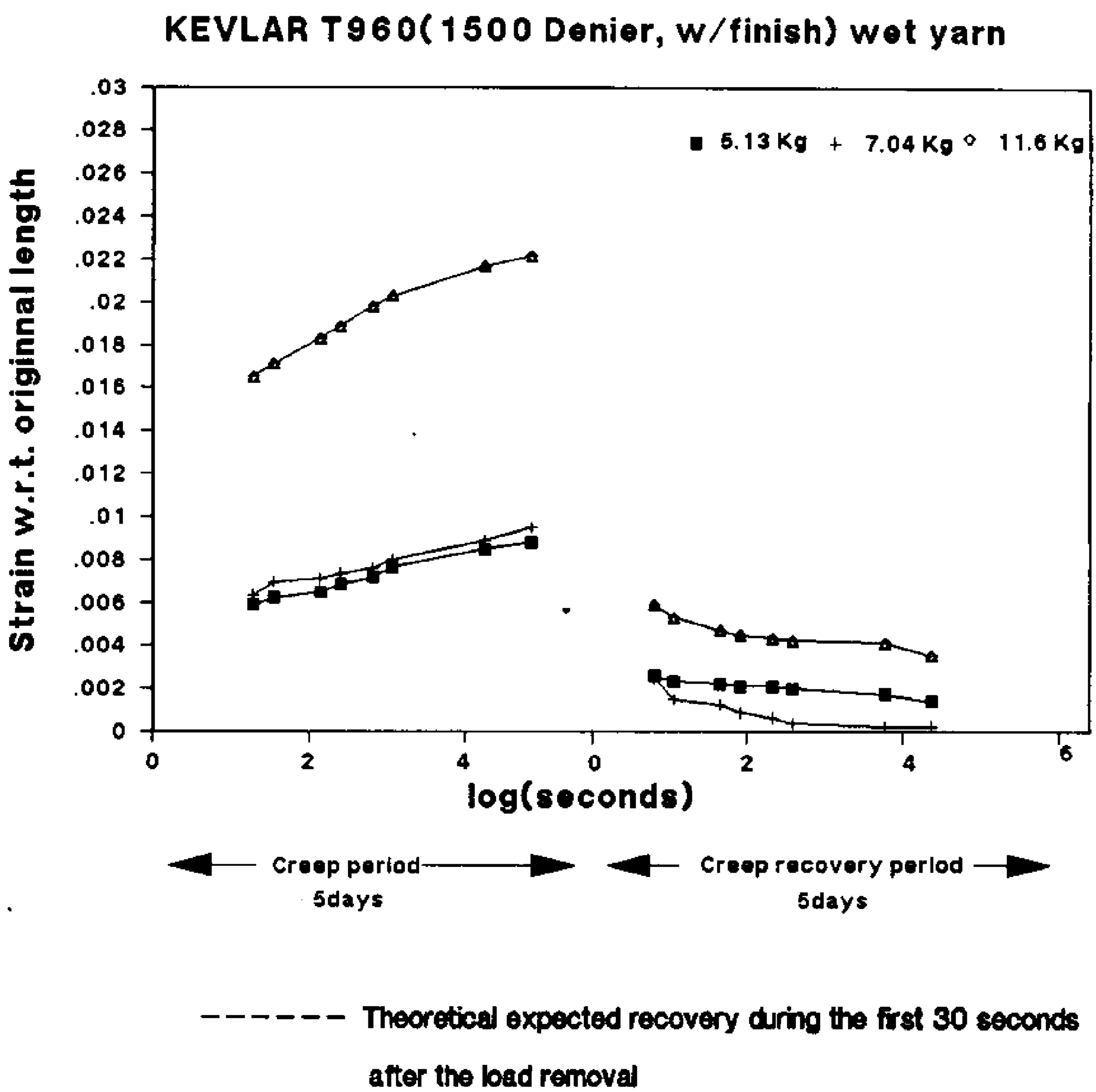
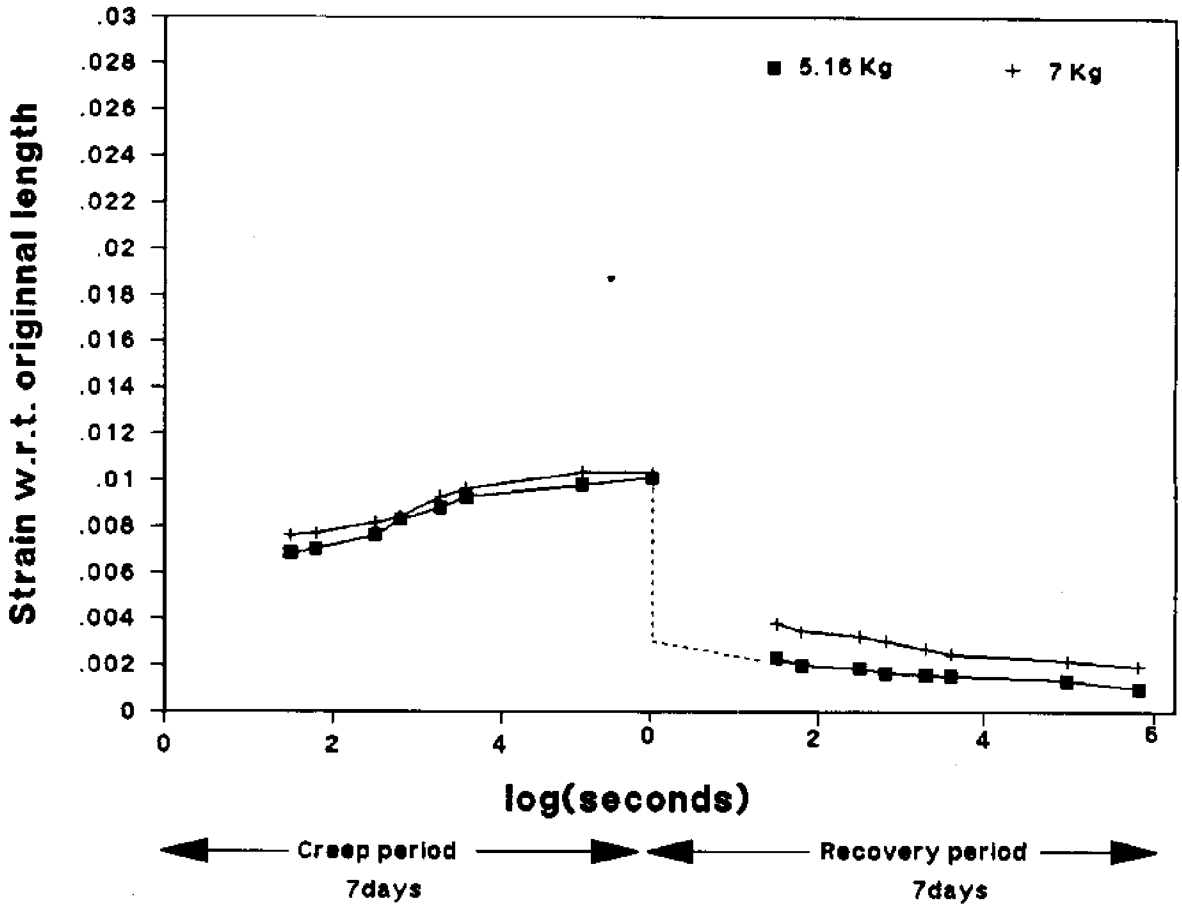


Figure 13

CREEP AND RECOVERY TEST

KEVLAR T960 (1500 Denier, w/ finish) wet yarn

(Test at 40 degrees C)



------------ Theoretical expected recovery during the first 30 seconds after the load removal

Figure 14

CREEP AND RECOVERY TEST

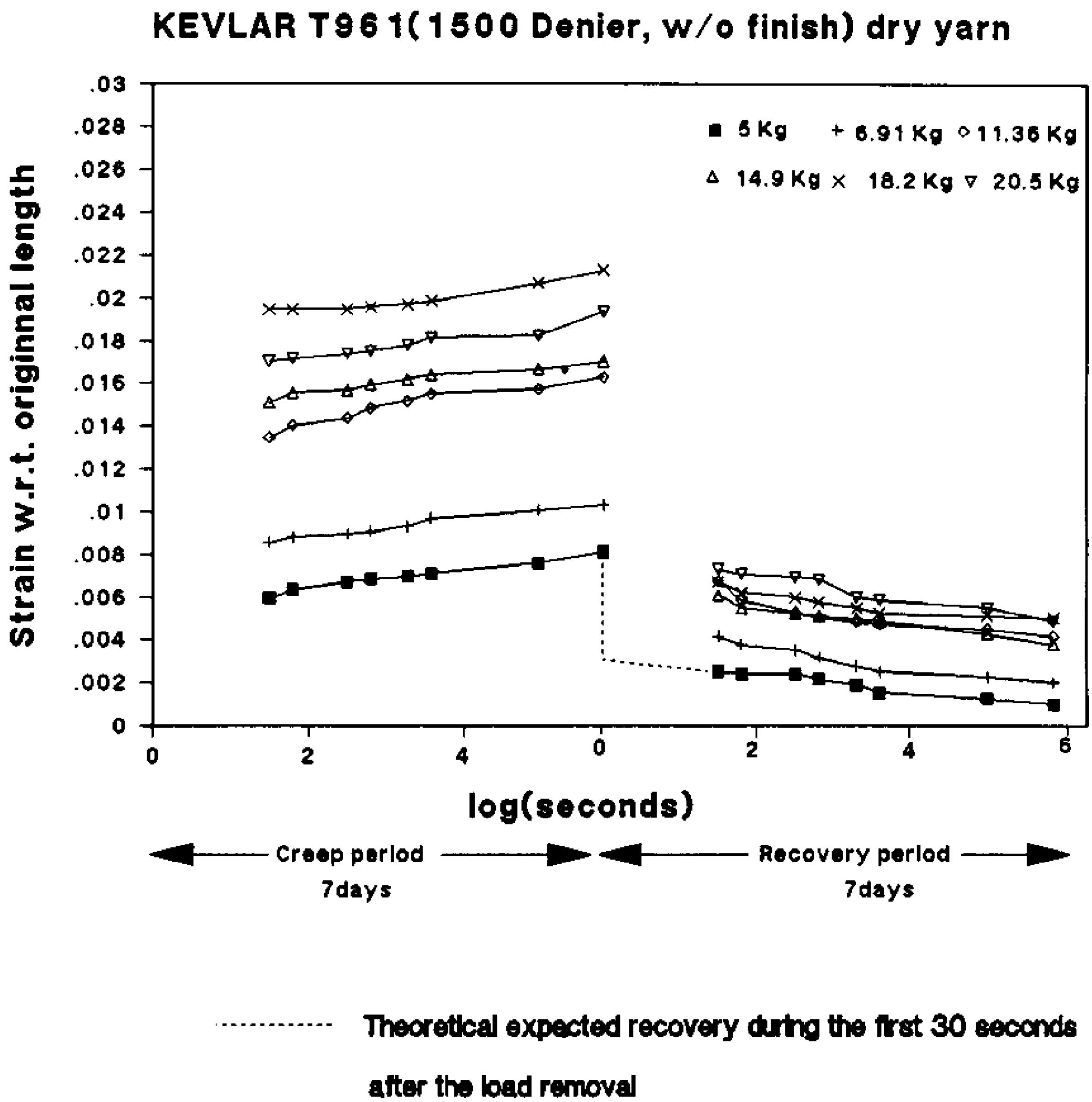
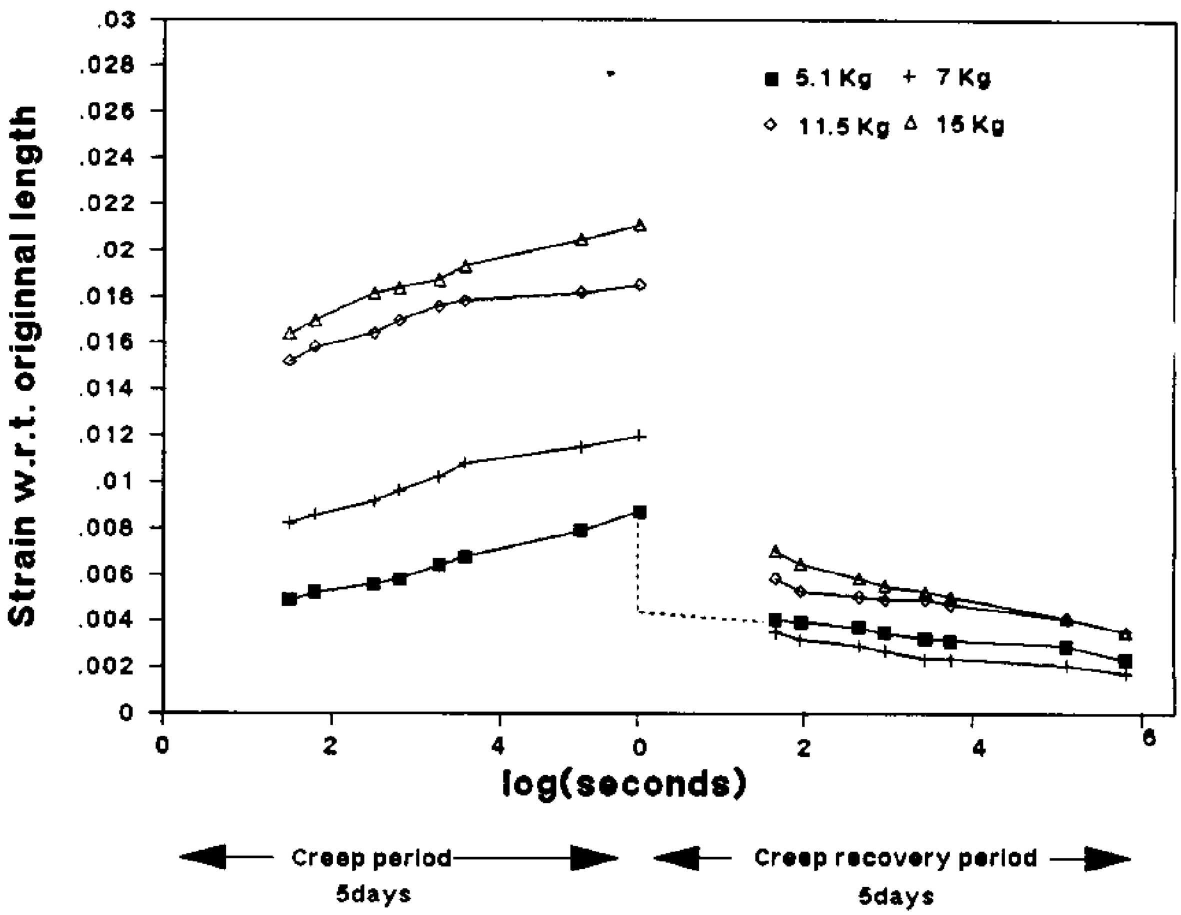


Figure 15

CREEP AND RECOVERY TEST

KEVLAR T961(1500 Denier, w/o finish) wet yarn



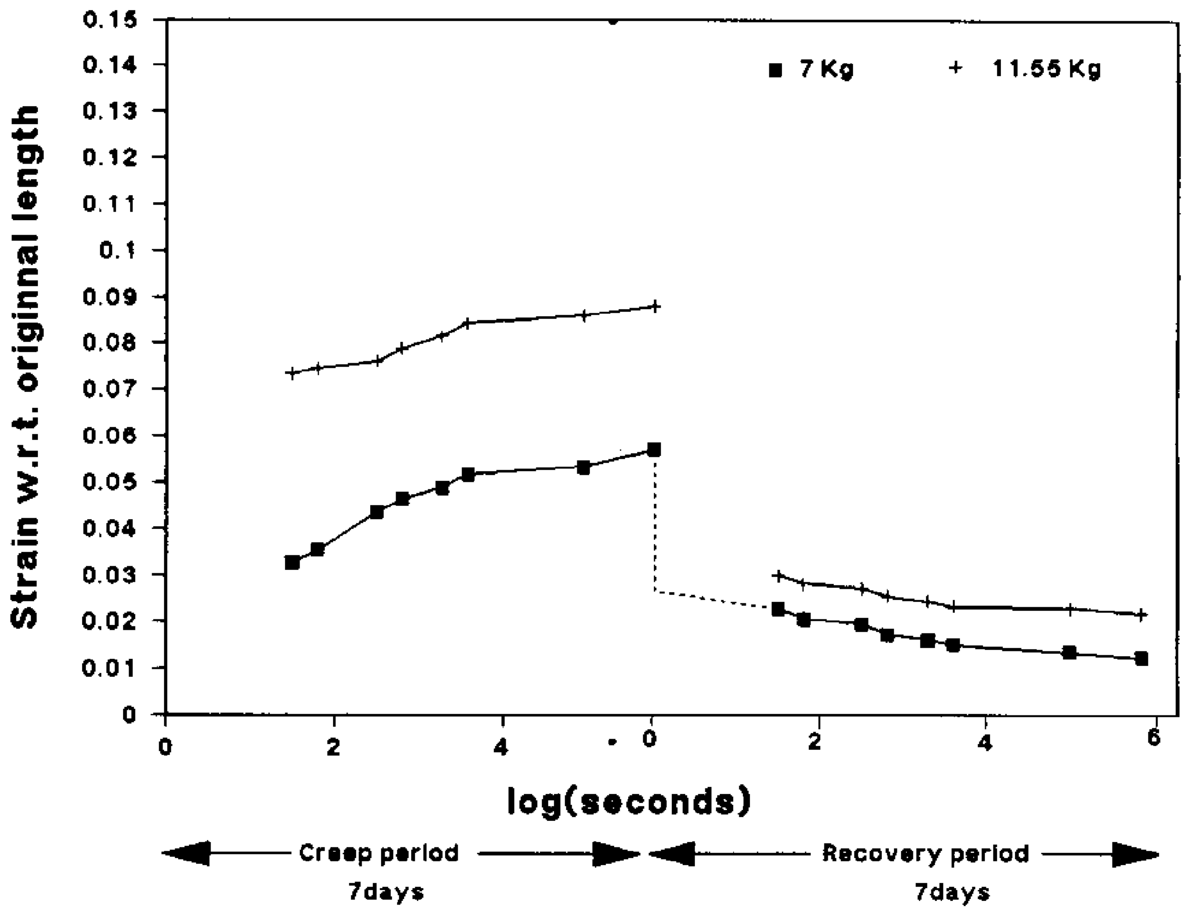
------ Theoretical expected recovery during the first 30 seconds after the load removal

Figure 16

CREEP AND RECOVERY TEST

KEVLAR T961(1500 DENIER) WET YARN

(TEST AT 40 DEGREES C)



.... **Theoretical expected recovery during the first 30 seconds after the load removal**

Figure 17

CREEP AND RECOVERY TEST

ENKA 855T (1000 Denier yarn, w/o finish)

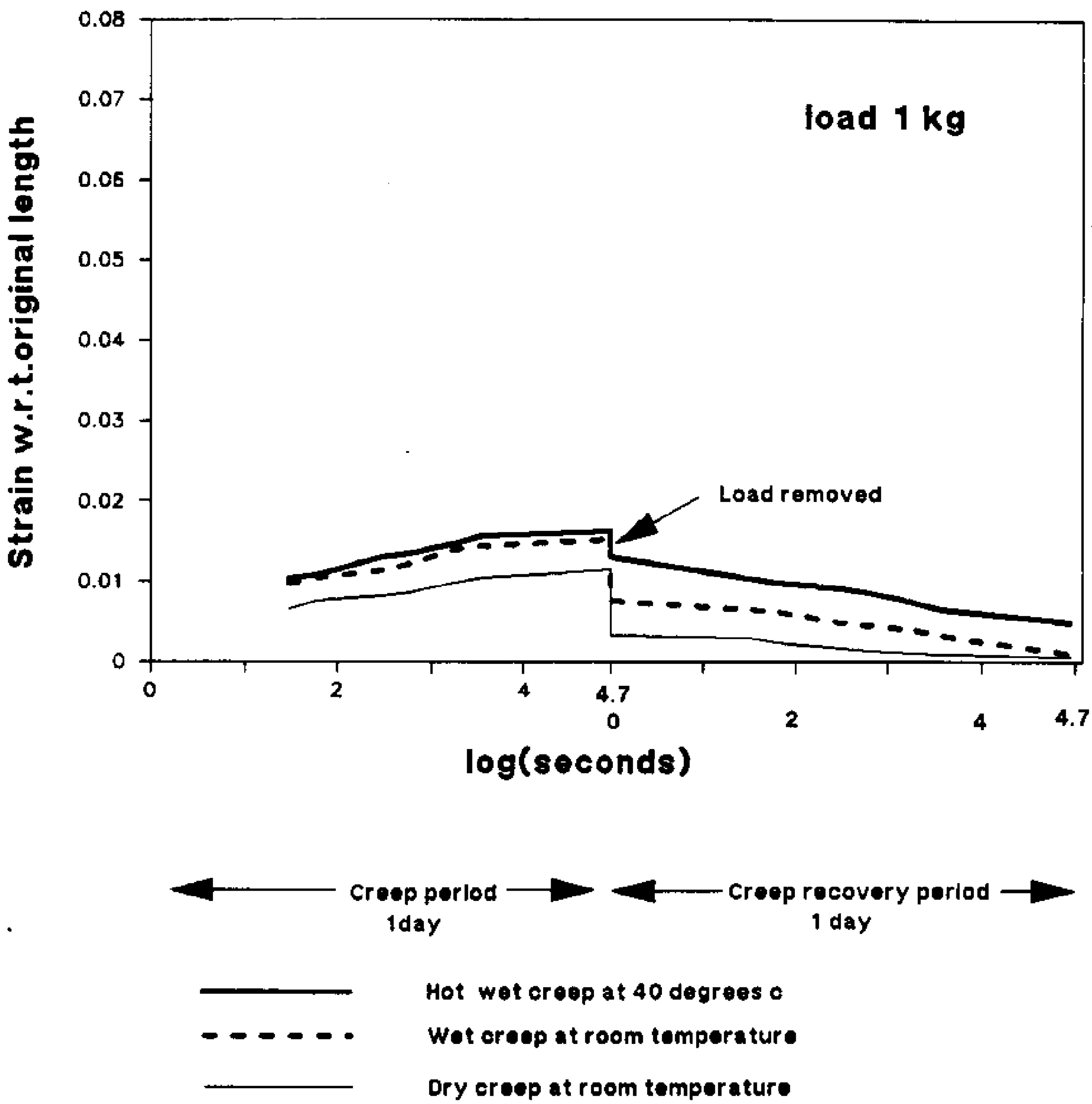


Figure 18

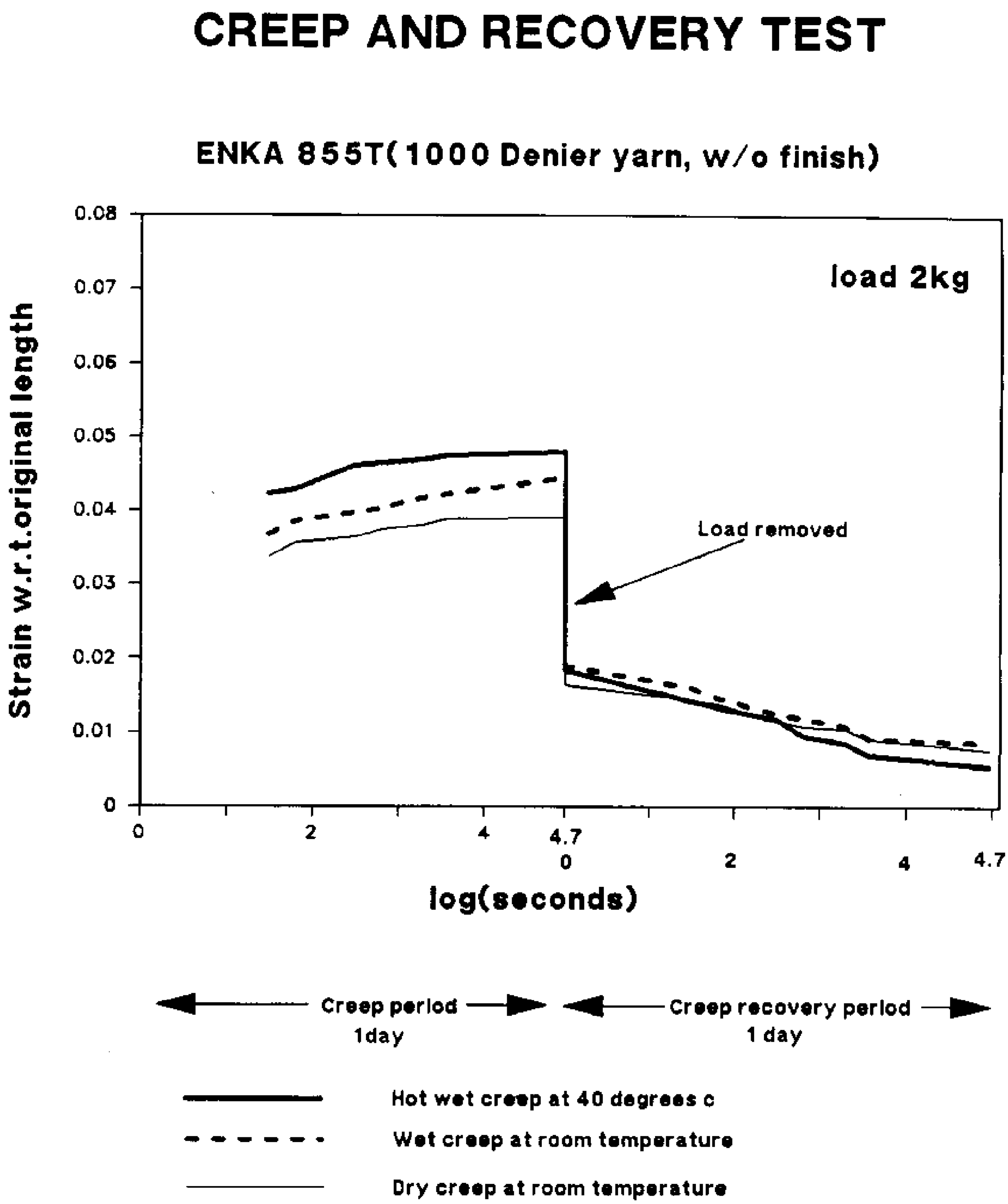

CREEP AND RECOVERY TEST
ENKA 855T(1000 Denier yarn, w/o finish)
load 2kg
Load removed
Strain w.r.t.original length
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0
2
4
4.7
0
2
4
4.7
log(seconds)
Creep period
1day
Creep recovery period
1 day
Hot wet creep at 40 degrees c
Wet creep at room temperature
Dry creep at room temperature

Figure 19

CREEP AND RECOVERY TEST

ENKA 855T (1000 Denier yarn, w/o finish)

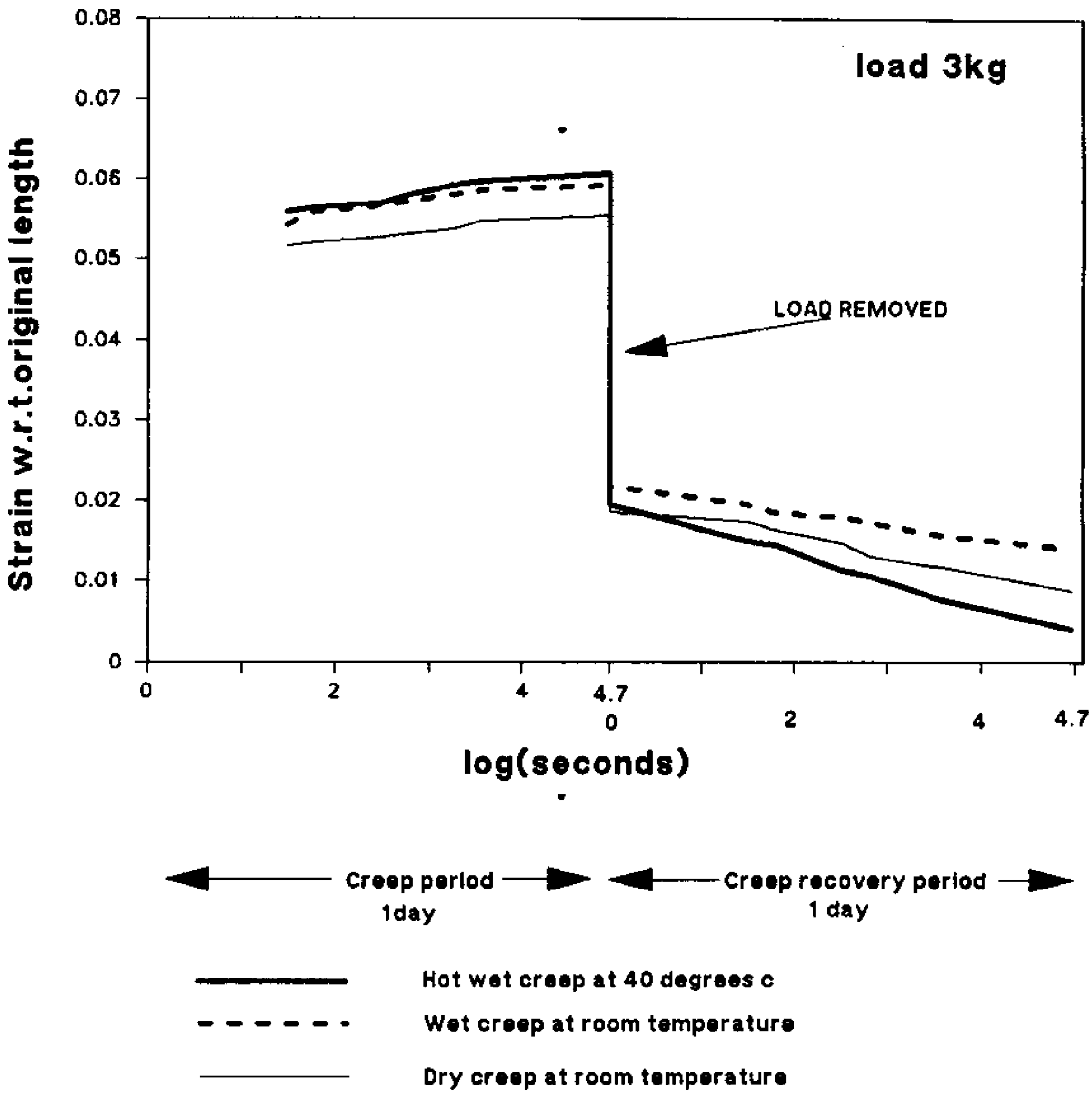


Figure 20

CREEP AND RECOVERY TEST

ENKA 855 TN (1000 Denier yarn w/ finish)

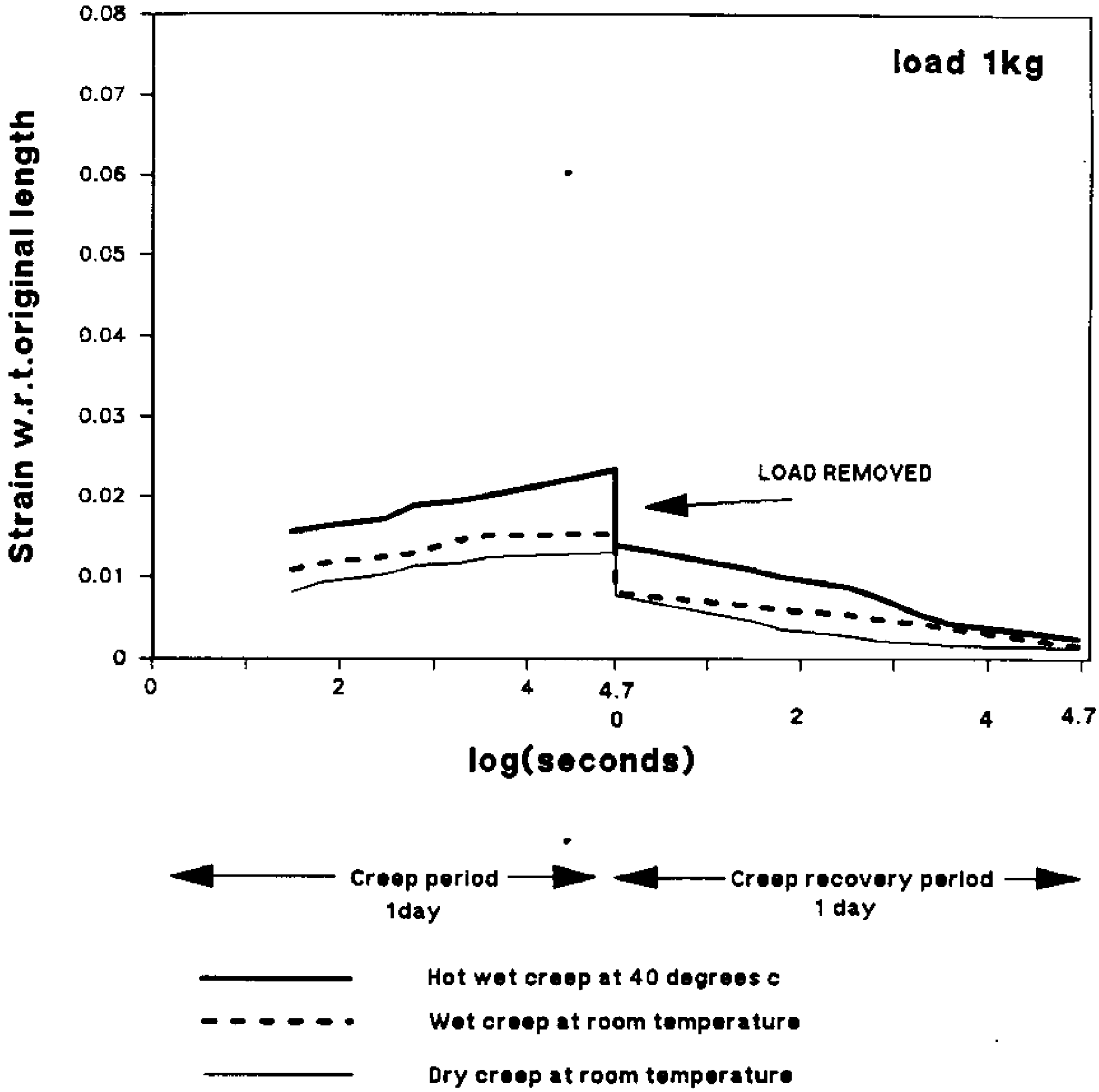


Figure 21

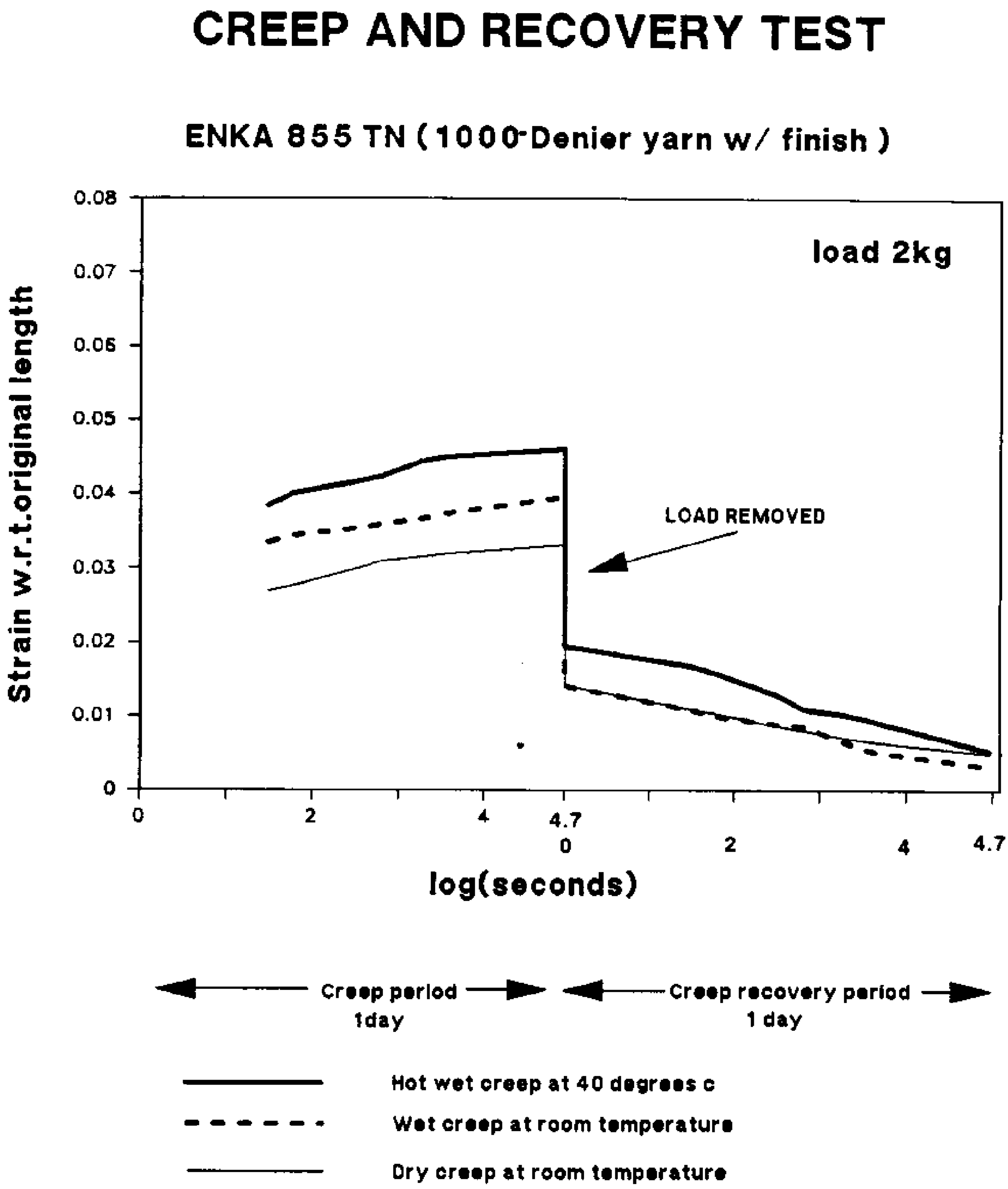

CREEP AND RECOVERY TEST
ENKA 855 TN (1000-Denier yarn w/ finish)
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
Strain w.r.t.original length
load 2kg
LOAD REMOVED
0
2
4
4.7
0
2
4
4.7
log(seconds)
Creep period
1day
Creep recovery period
1 day
Hot wet creep at 40 degrees c
Wet creep at room temperature
Dry creep at room temperature

Figure 22

CREEP AND RECOVERY TEST

ENKA 855TN (1000 Denier yarn w/ finish)

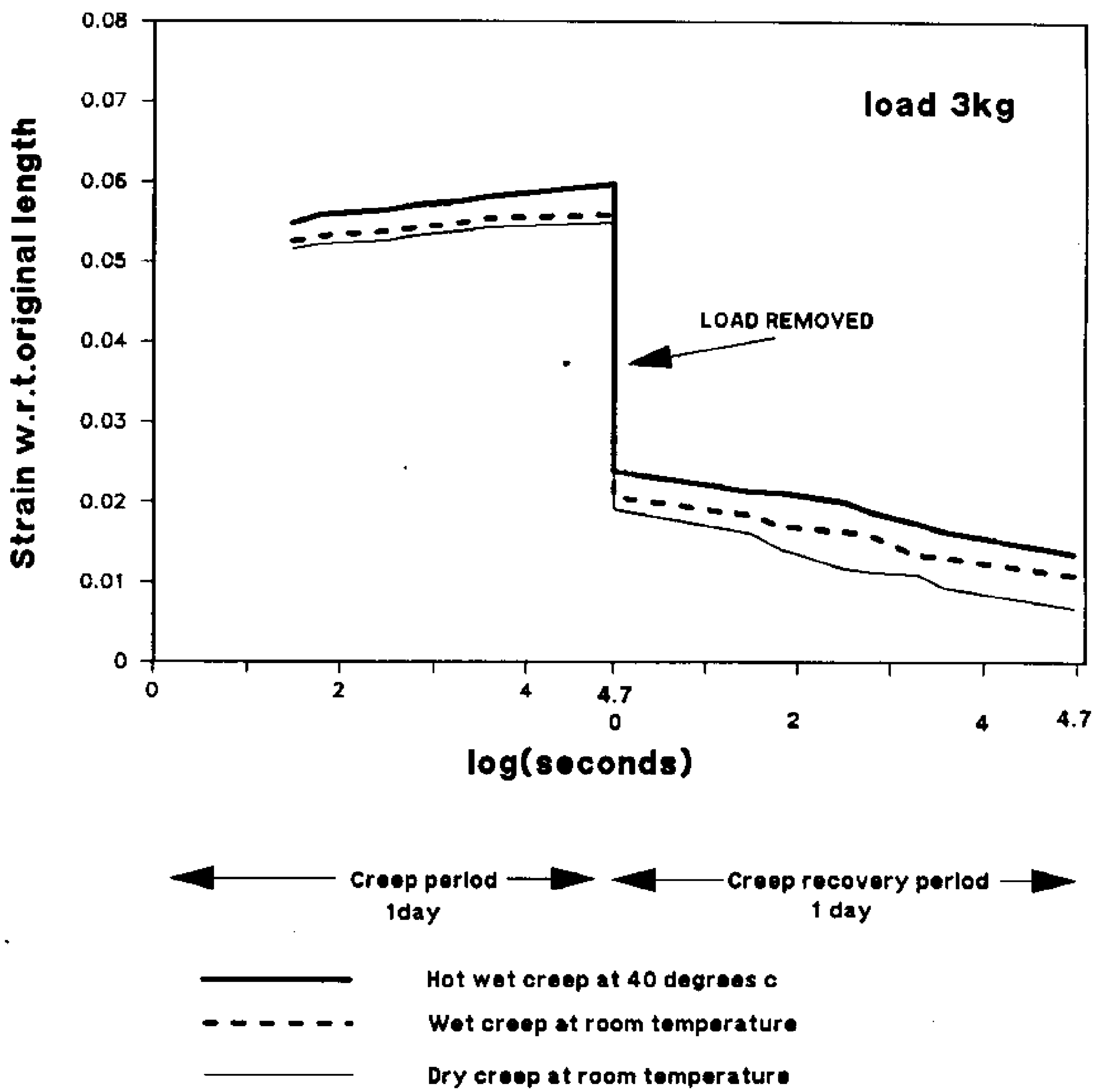


Figure 23

CREEP AND RECOVERY TEST

KEVLAR T960 (1500 Denier yarn w/ finish)

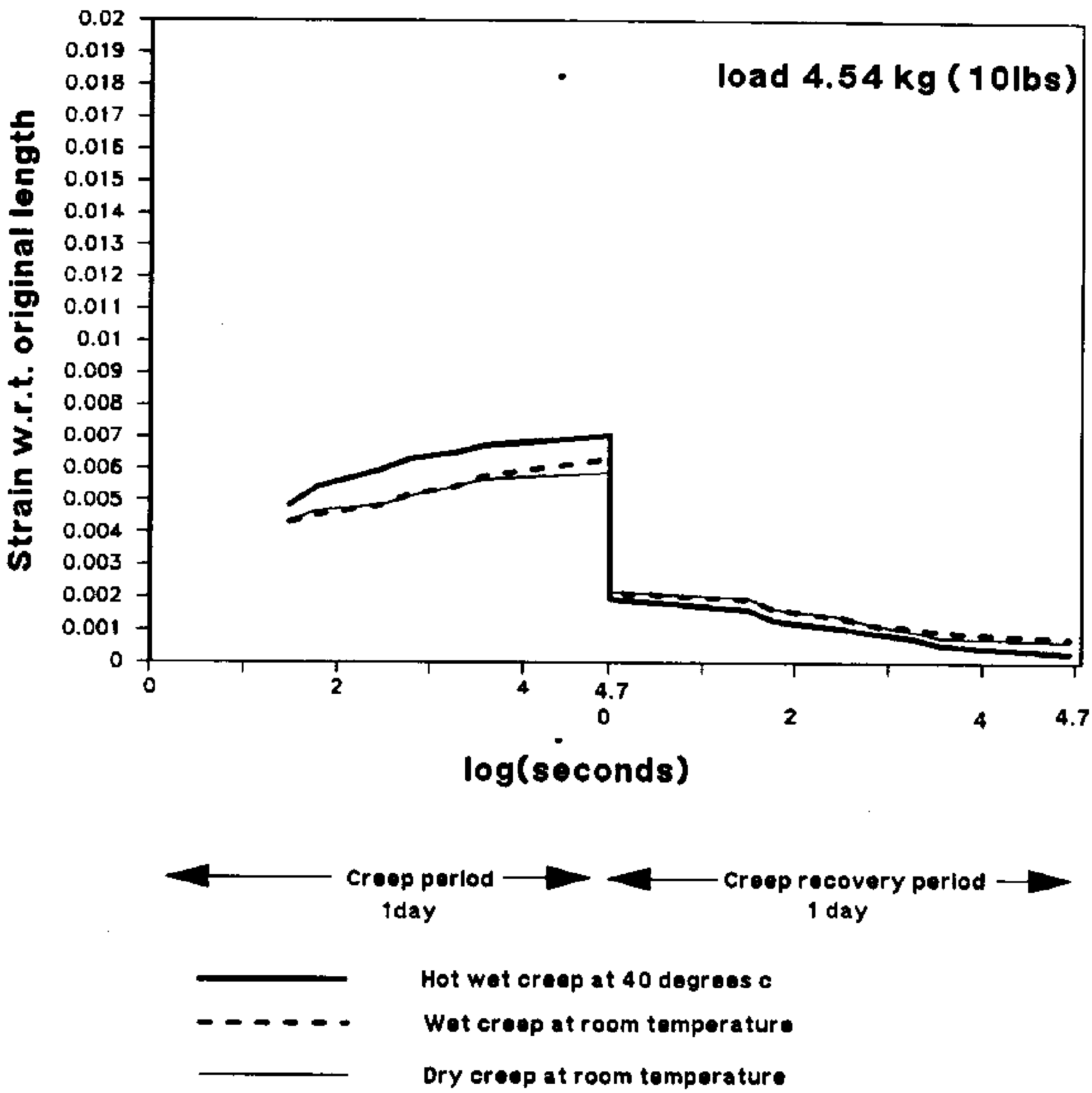


Figure 24

CREEP AND RECOVERY TEST

KEVLAR T960 (1500 Denier yarn w/ finish)

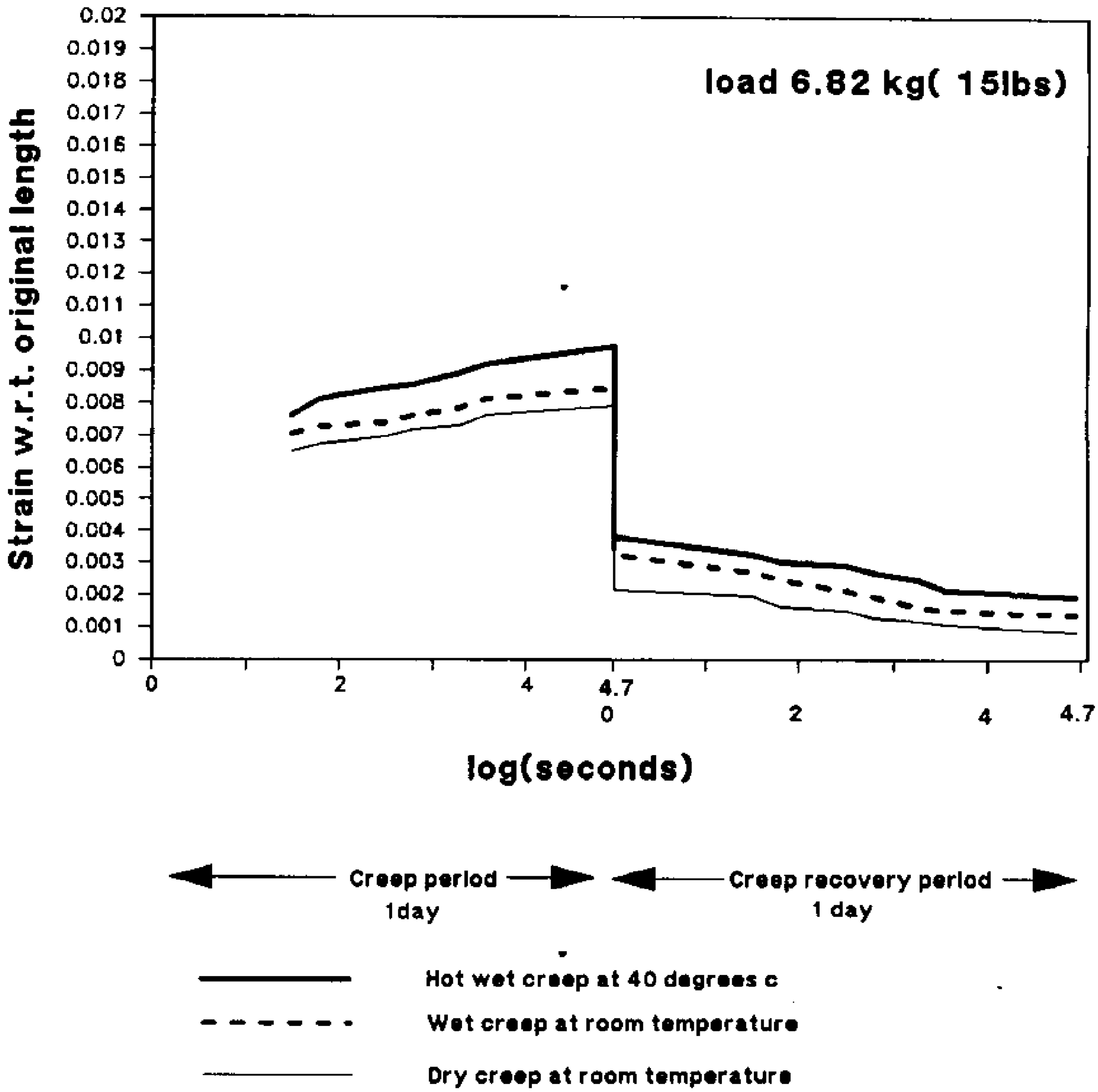


Figure 25

CREEP AND RECOVERY TEST

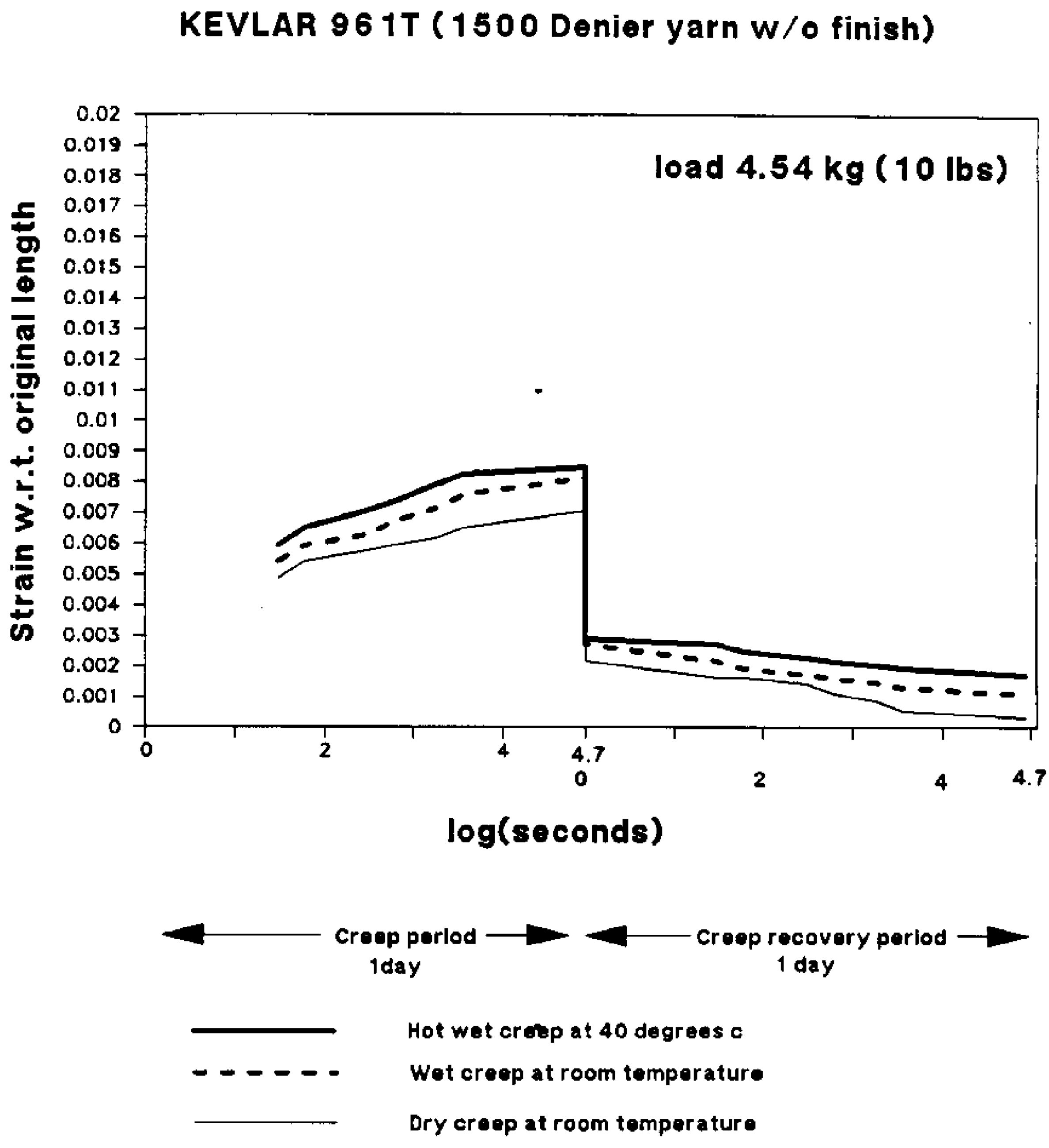


Figure 26

CREEP AND RECOVERY TEST

KEVLAR T961(1500 Denier yarn w/o finish)

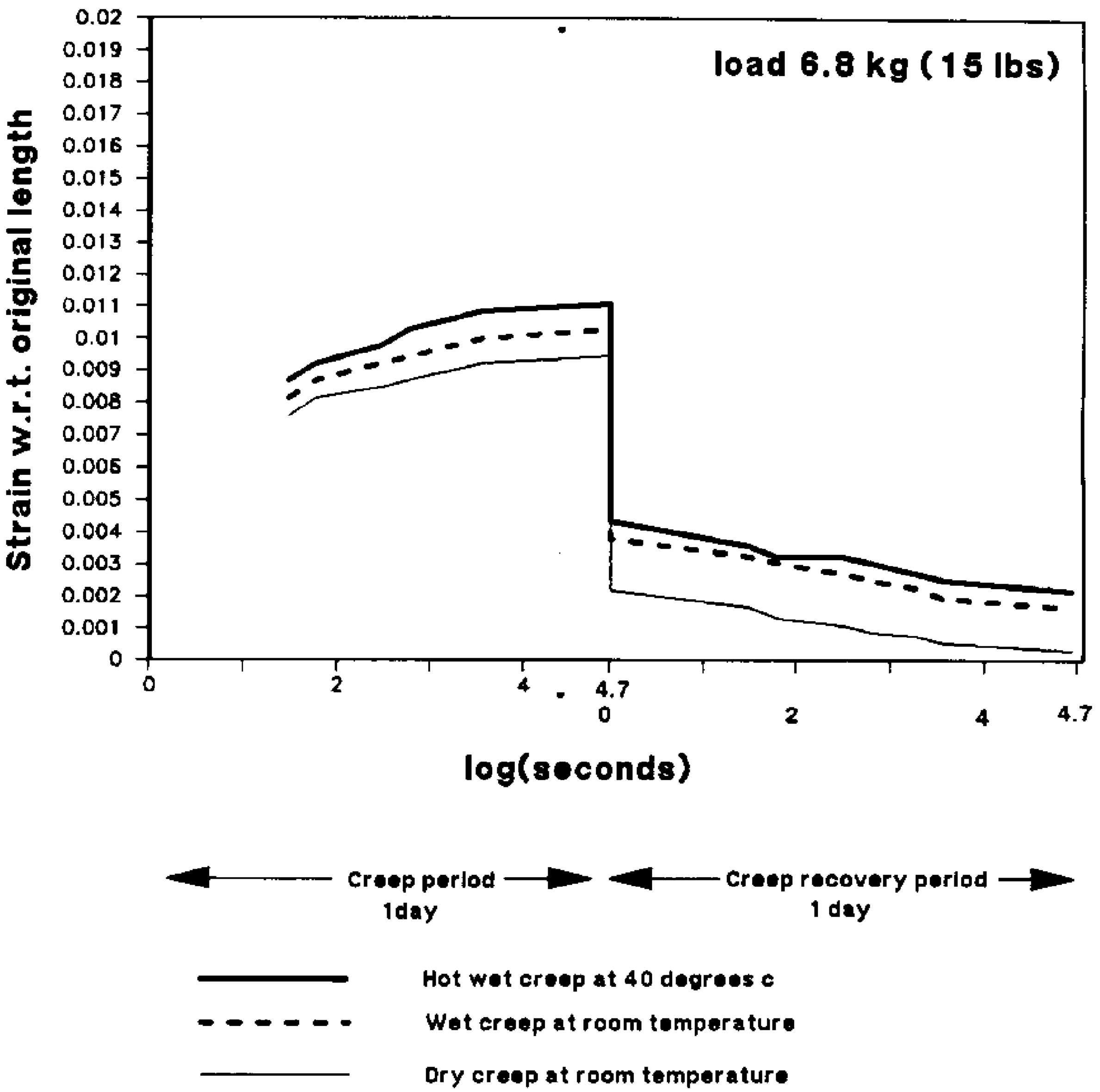


Figure 27

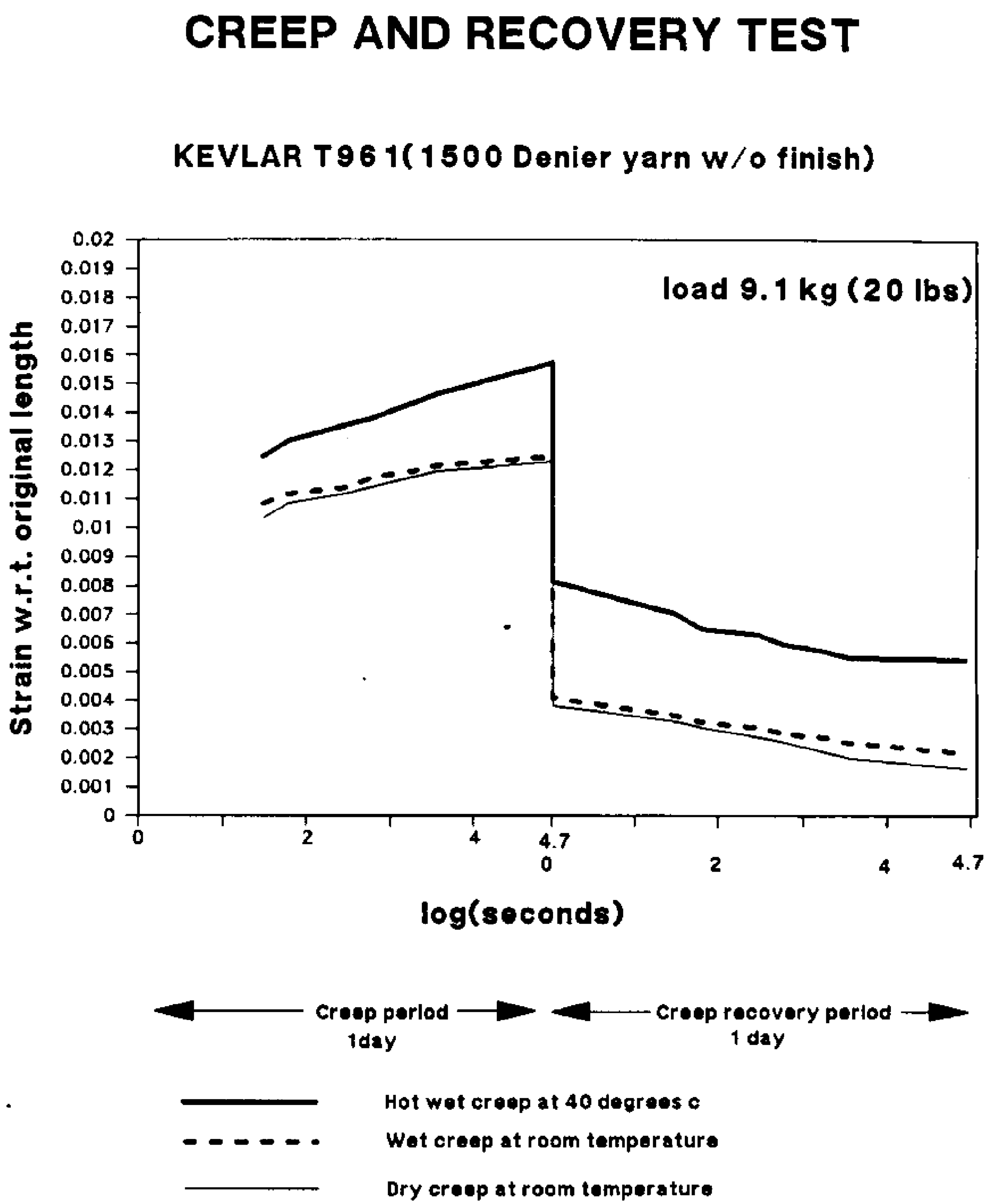

CREEP AND RECOVERY TEST
KEVLAR T96 1(1500 Denier yarn w/o finish)
load 9.1 kg (20 lbs)
Strain w.r.t. original length
0.02
0.019
0.018
0.017
0.016
0.015
0.014
0.013
0.012
0.011
0.01
0.009
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0
0
2
4
4.7
0
2
4
4.7
log(seconds)
Creep period
1day
Creep recovery period
1 day
Hot wet creep at 40 degrees c
Wet creep at room temperature
Dry creep at room temperature

Figure 28

CREEP AND RECOVERY TEST

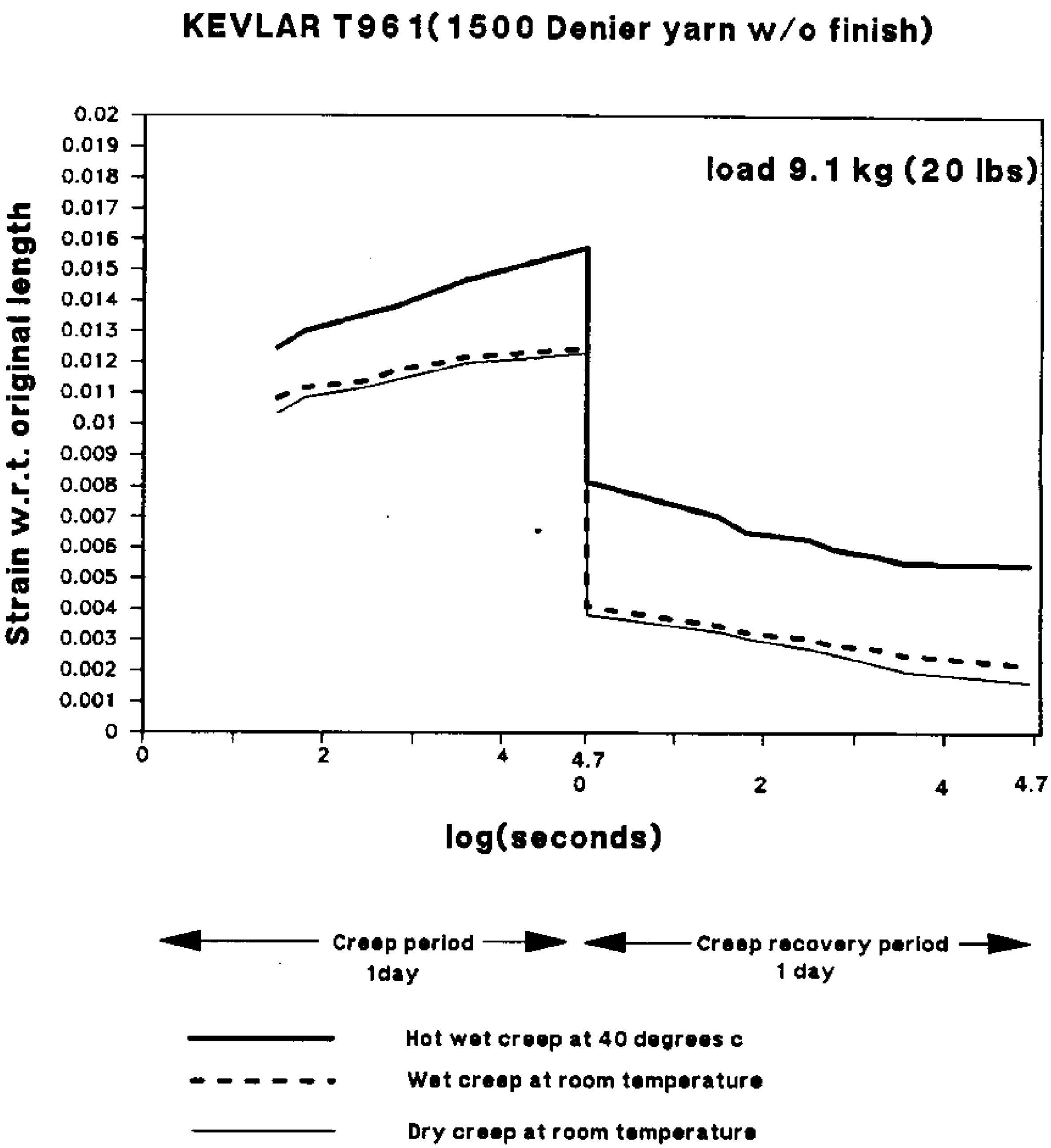


Figure 28

IV. CREEP RUPTURE

KEVLAR AND ENKA POLYESTER

Application of a dead load to a polymeric fiber will in time cause its failure even though the load is well below the conventionally tested breaking strength. The phenomenon is that of creep, with the end point the fracture of the fiber or yarn designated in time to rupture for a given dead load.

For the creep rupture tests run for ENKA Polyester and KEVLAR Aramid both with and without finish and both wet and dry, the dead loads were expressed as percentages of normally run breaking strengths. Because of the statistical variation in yarn properties it was found that creep rupture times covered a range for each fractional (percentage) load.

As expected the creep rupture times increased significantly as the dead loads were decreased. This is reflected in the creep rupture tables and in the graphs plotted of the data. Clearly more data on this yarn behavior is warranted but the time requirements for such tests were a barrier to providing a complete performance pattern.

CREEP RUPTURE

KEVLAR AND ENKA POLYESTER

CREEP RUPTURE RANGES

KEVLAR T960 (w/ finish)

DRY		WET	
% B.S.	log (SEC)	% B.S.	log (SEC)
76 %	4.8 → 5.8	91 %	0 → 4.2
68 %	6.5 → 7.0	88 %	1.5 → 3.5
		83 %	2.4 → 3.3
		78 %	3.8 → 4.3
		73 %	4.3
		70 %	6.0 → 6.2
		68 %	6.6

KEVLAR T961 (w/o finish)

DRY		WET	
% B.S.	log (SEC)	% B.S.	log (SEC)
78 %	4.7 → 5.1	83 %	0 → 3.2
76 %	5.0 → 5.2	81 %	6.2
71 %	5.3 → 5.6	80 %	5.3 → 6.0
70 %	6.2 → 7.0		

CREEP RUPTURE RANGES

ENKA TN (w/ finish)

DRY		WET	
% B.S.	log (SEC)	% B.S.	log (SEC)
90 %	1.8 → 2.8	80 %	3.3 → 4.4
86 %	2.3 → 3.3		
75 %	4.2		

ENKA T (w/o finish)

DRY		WET	
% B.S.	log (SEC)	% B.S.	log (SEC)
83 %	2.5 → 3.3	87 %	1.05 → 3.2
70 %	7.4	86 %	0.8 → 2.9
		79 %	2.7
		75 %	3.3 → 5.3
		73 %	2.8 → 4.7
		70 %	6.7
		58 %	7.6

ENKA 855T (1000 denier, w /o finish) YARN

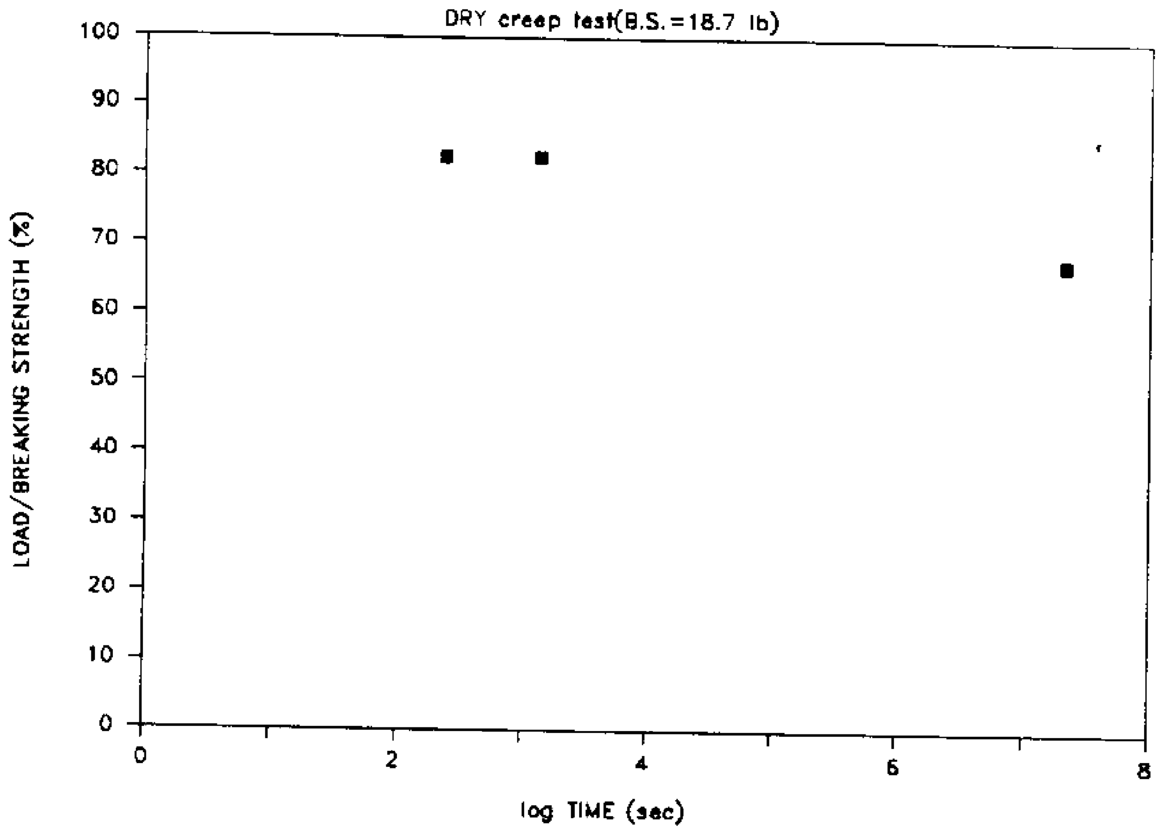


Figure 1

ENKA 855T(1000 denier,w/o finish) YARN

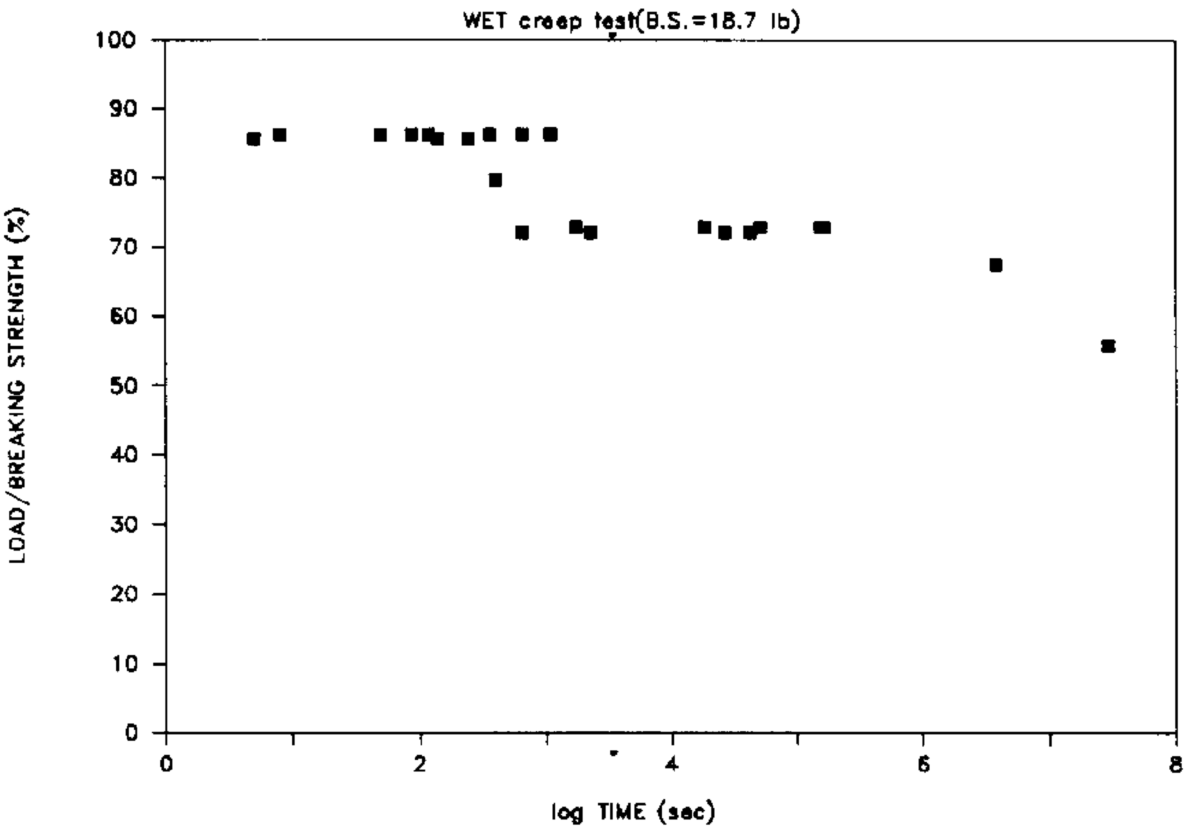


Figure 2

ENKA 855TN(1000 denier,w/finish) YARN

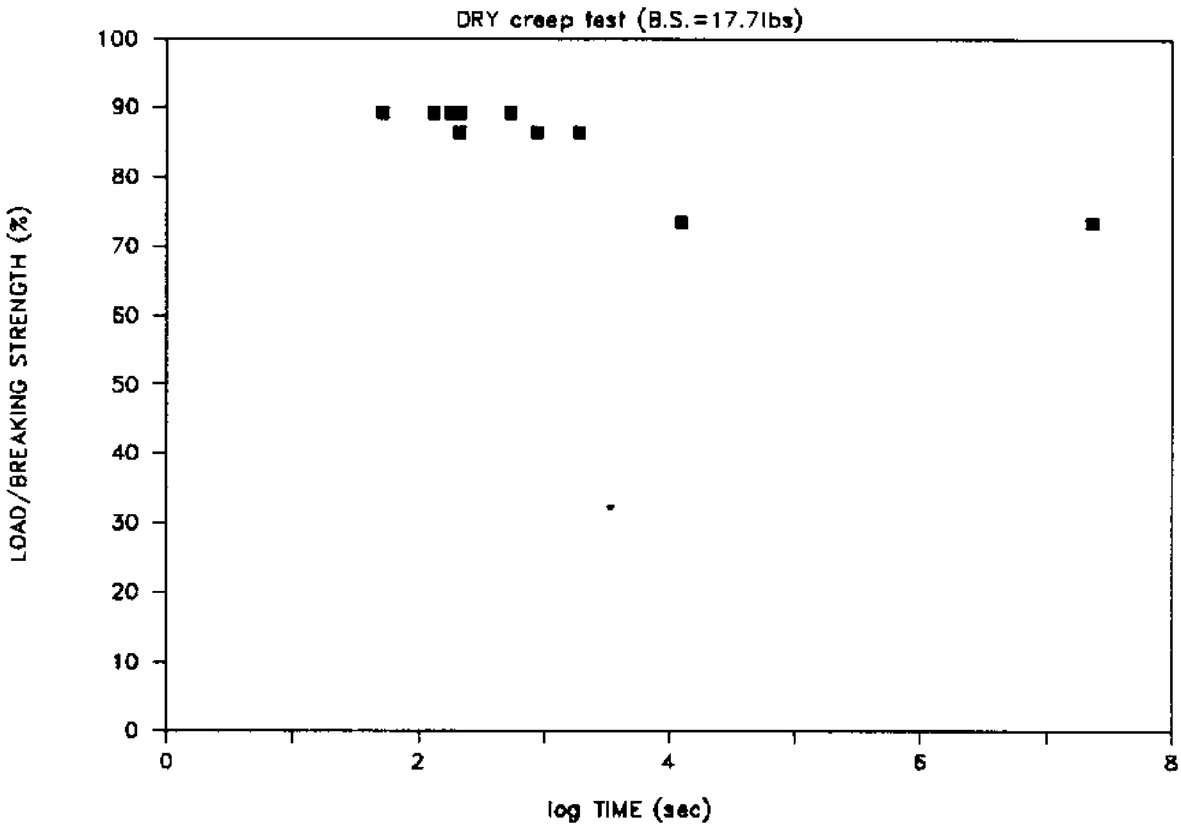


Figure 3

ENKA 855TN(1000 denier,w/finish) YARN

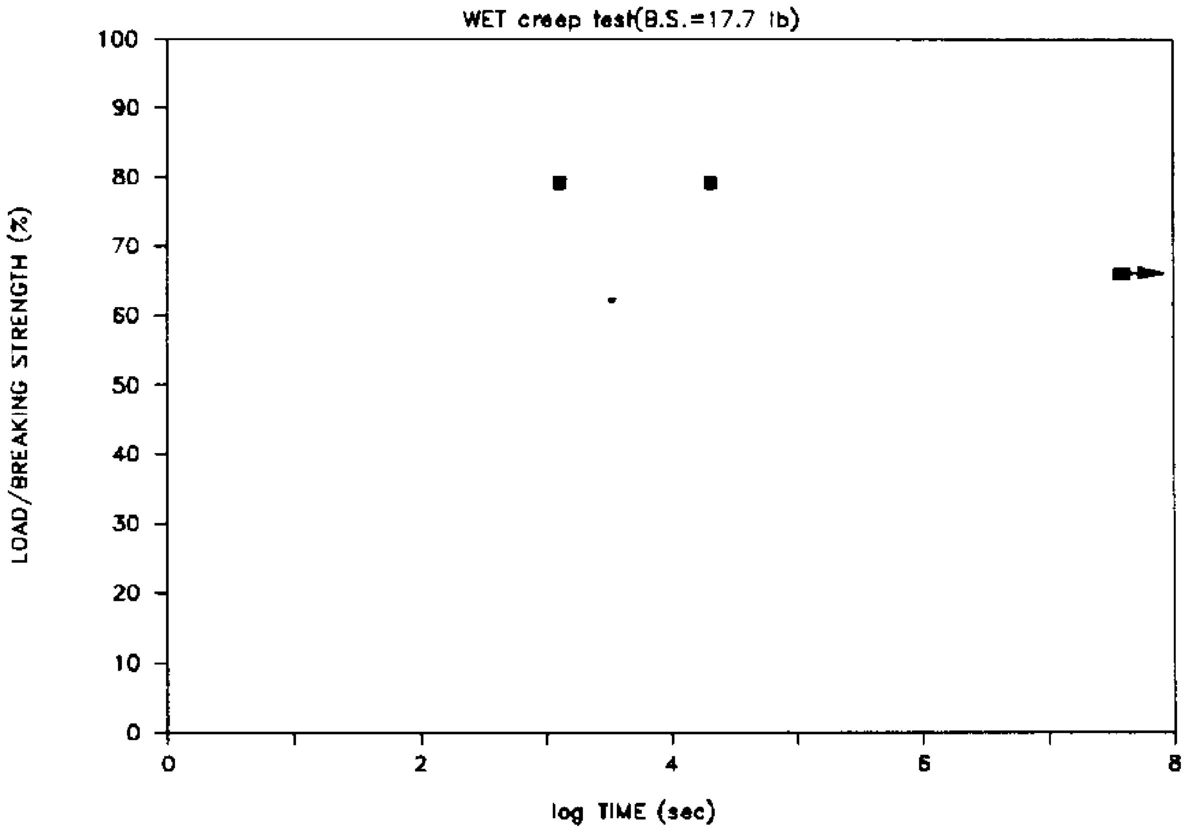


Figure 4

KEVLAR(T960, 1500 denier w/finish) YARN

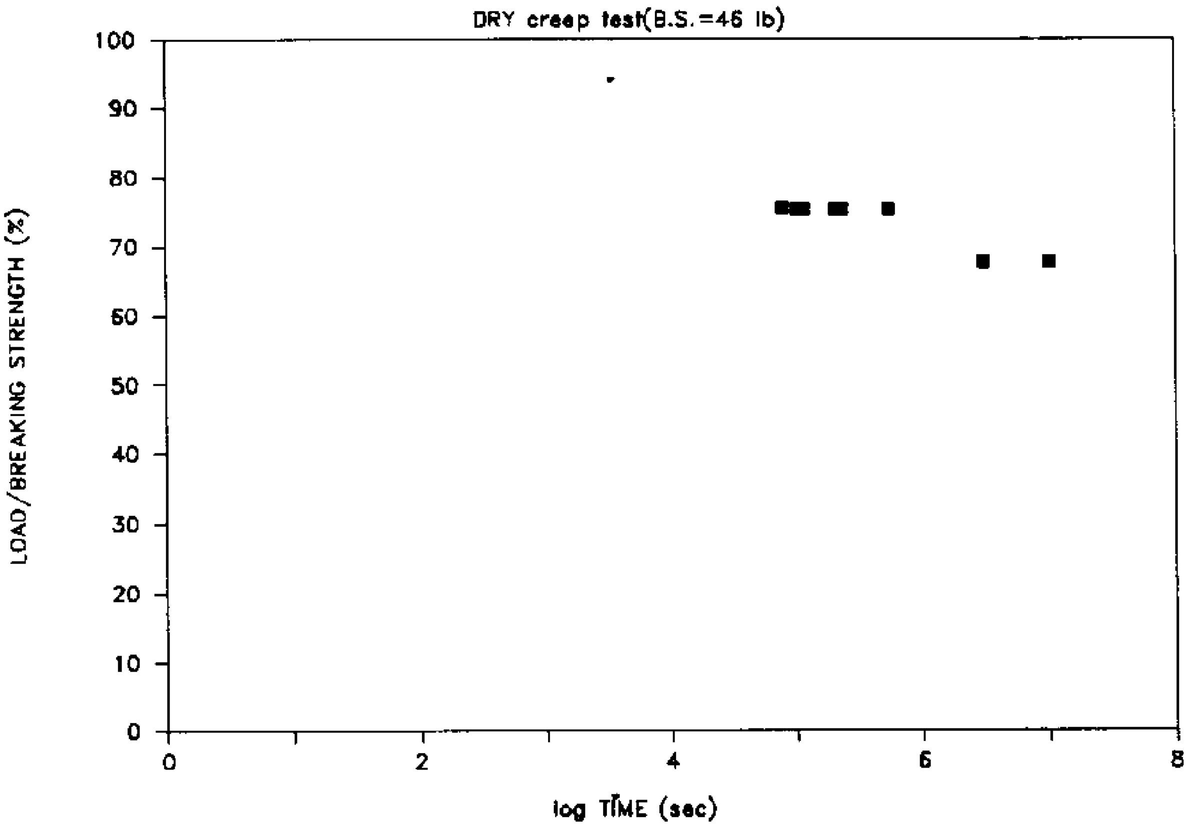


Figure 5

KEVLAR(T960 ,1500 denier w/ finish) YARN

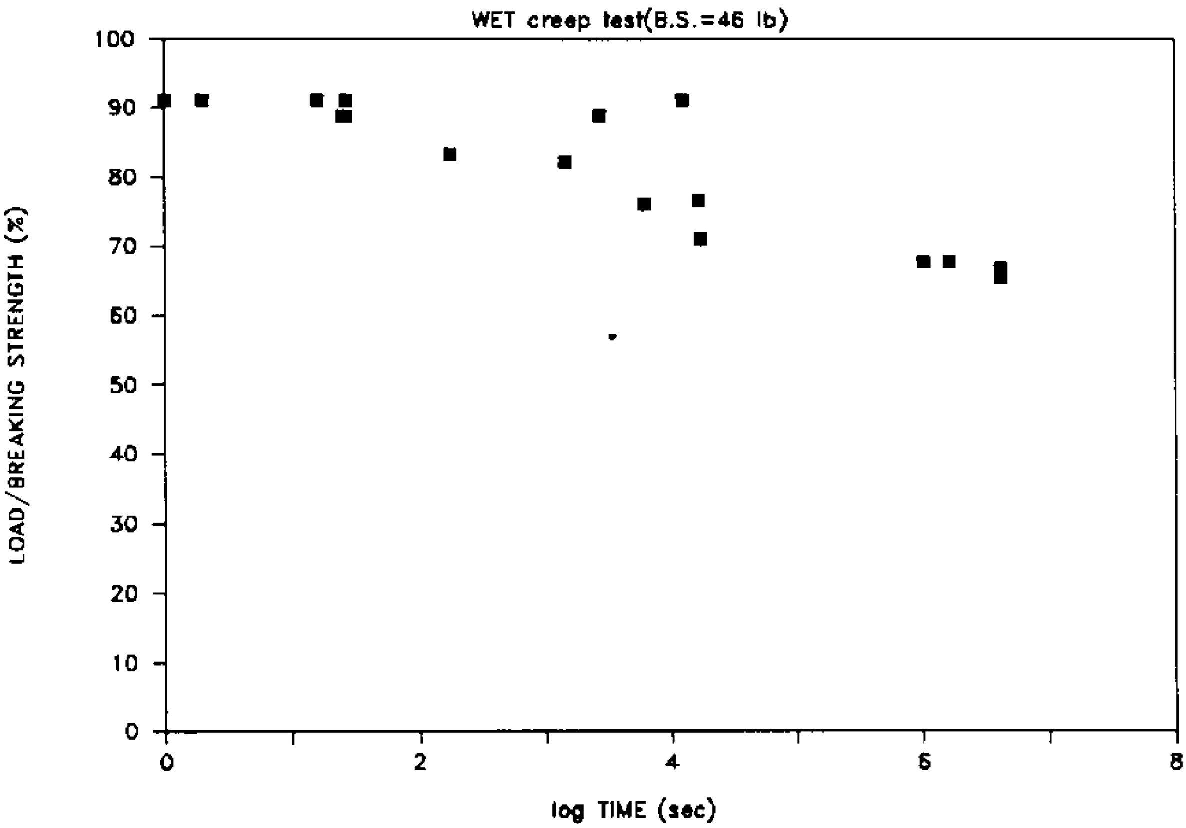


Figure 6

KEVLAR(T961, 1500 denier,w/o finish) YARN

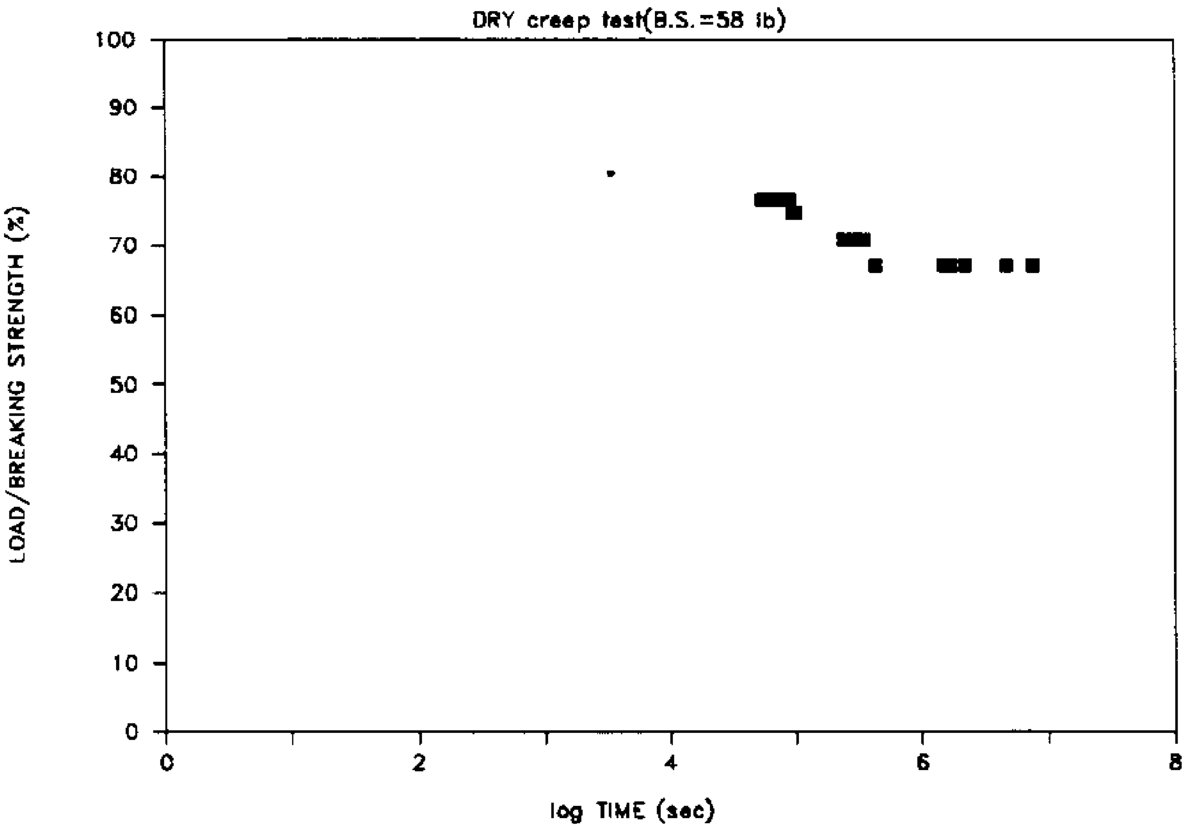


Figure 7

KEVLAR(T961, 1500 denier, w/o finish) YARN

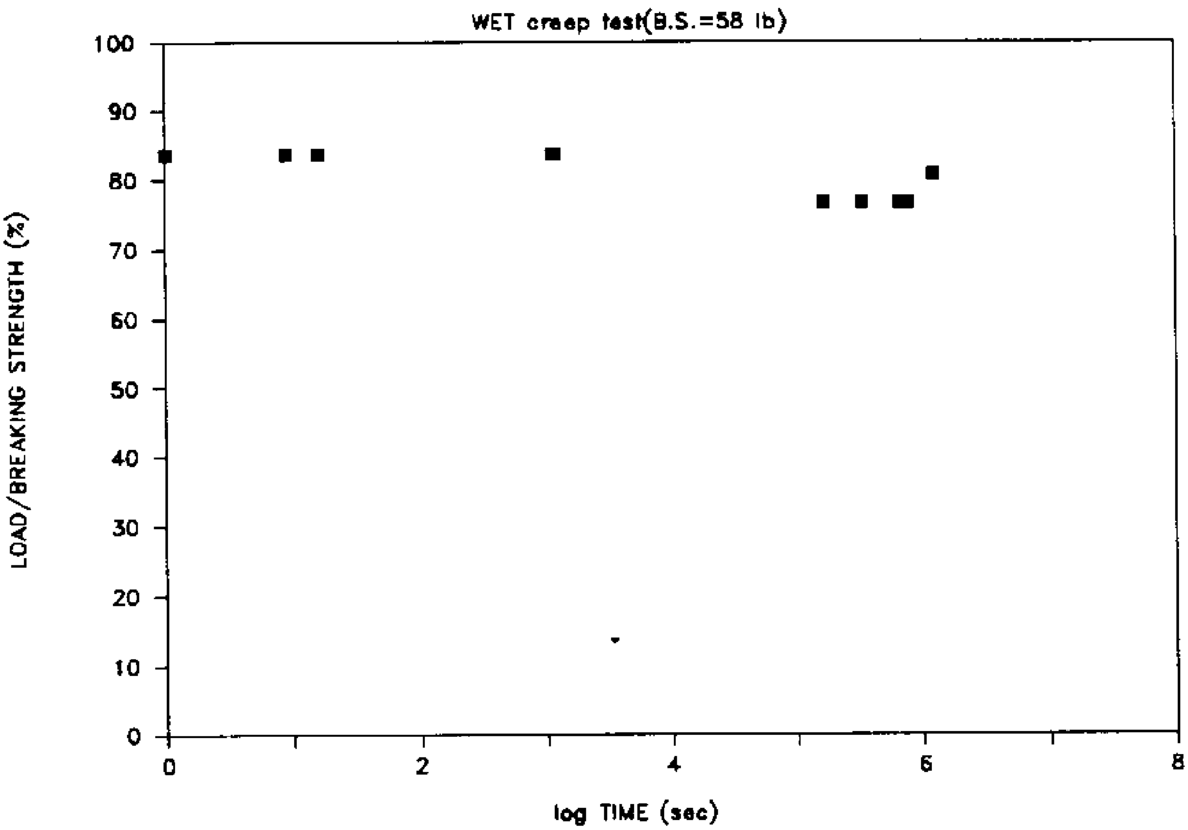


Figure 8

V. FRICTIONAL PROPERTIES

KEVLAR AND ENKA POLYESTER

INTRODUCTION

Friction is one of the major causes of deterioration in machines and material systems. In the case of ropes and other tensile structure friction has been shown to be a key factor leading to internal abrasion, which in turn leads to premature failure [1]. Frictional force between solids is a function of contact surface materials, the surrounding media and the external applied forces. In the case of fibers and yarns it is also a function of orientation of the surfaces. To understand the process of frictional deterioration this force has to be studied and the effects evaluated. In the present experiment we have used a yarn-on-yarn test to study the effect of surface fiction on ENKA 855T, ENKA 855TN, KEVLAR T960, and KEVLAR T961 yarns. These yarns are all made up of continuous filaments and are the main constituents of several ropes of interest. The goal is to gain some insight into the frictional deterioration and failure mechanisms of ropes constituted of these yarns.

LABORATORY SET UP

Figure 1 shows the experimental set up. The experimental apparatus is comprised of three parts.

Friction measurement

This consists of a frame with several bearings and pulleys attached to control the direction of the test yarn and to allow the yarn to twist on itself at a given helix angle. Three different sets of bearings are provided to allow for changing the helix angle. Other bearings and pulleys connect the sample yarn to the applied load (i.e., the dead weight) at one end and the load cell at the other end. The entire frame is attached to the crosshead of the Instron tensile tester. As the crosshead is raised and lowered the yarns in the helix twist zone rub past each other causing friction and wear. The configuration of the contact point is shown in Figure 2 in enlarged form.

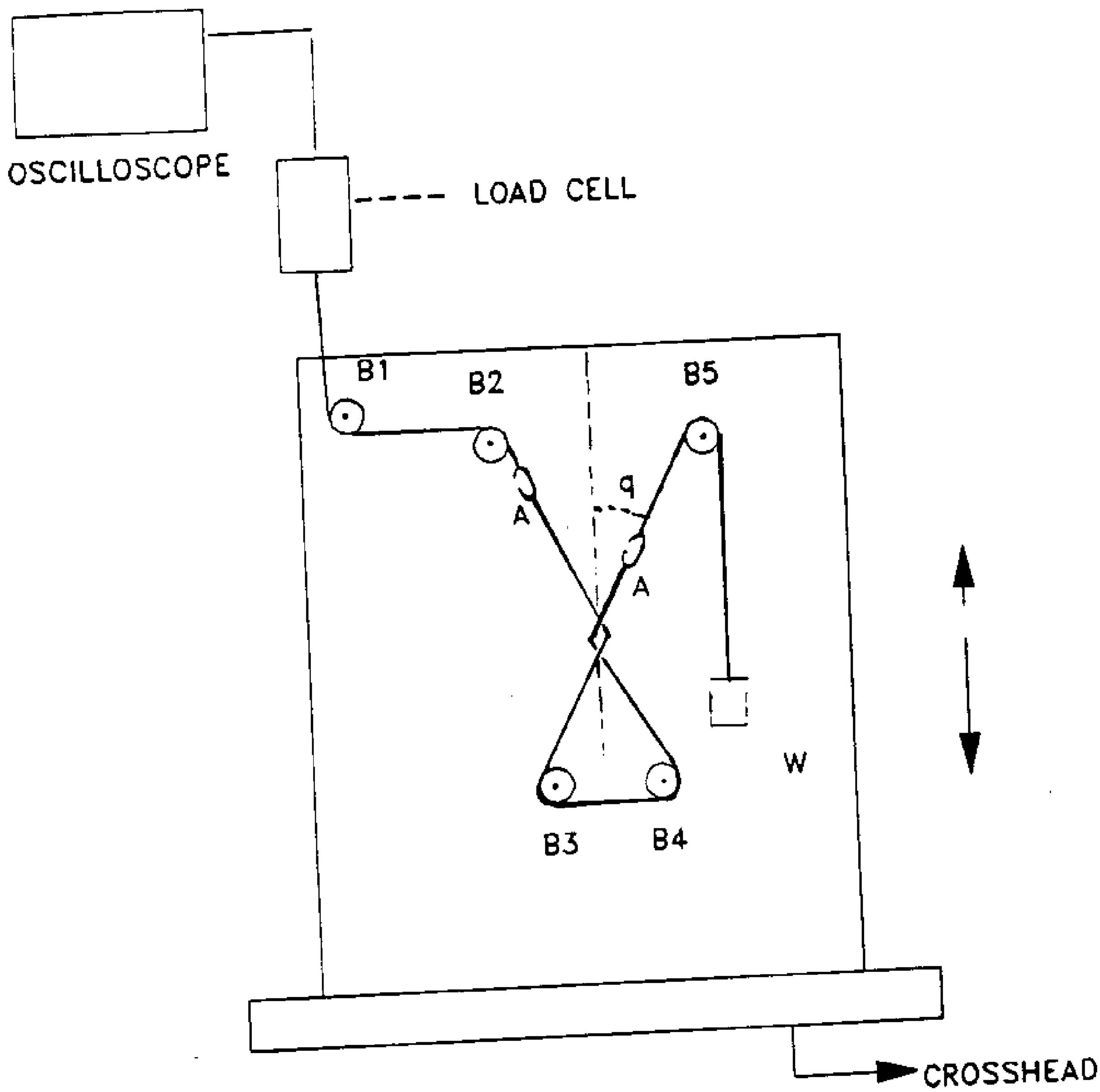
Driving system.

The system is driven by the Instron machine. By selecting a proper crosshead speed (10"/minute) we can produce the required motion of the contact point of the yarn in the interwrapped zone under each given load (see Figure 1).

Recording System.

The load cell of the Instron machine is connected to a NICOLET oscilloscope. The oscilloscope recorded the tensile force registered by the load cell in terms of volts as a function of time for a few cycles. The data are stored on a floppy disk and are then processed on an IBM PC with Lotus 1-2-3 software. The results are presented for a typical case in Figure 3.

EXPERIMENTAL SET UP



B1,B2,B3,B4,B5--------BEARINGS

W ------------------DEAD WEIGHT

AA- -----------------TEST YARN

q- ------------------HELIX ANGLE

FIG 1

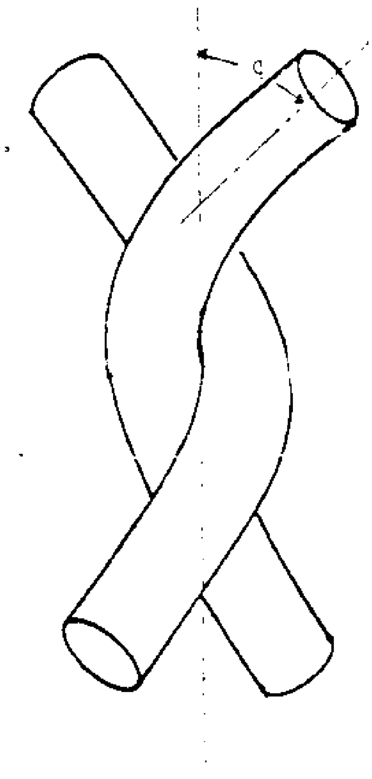


DIAGRAM OF CONTACT POINT

FIG 2

TIME VS AMPLITUDE FOR ENKA 855T YARN

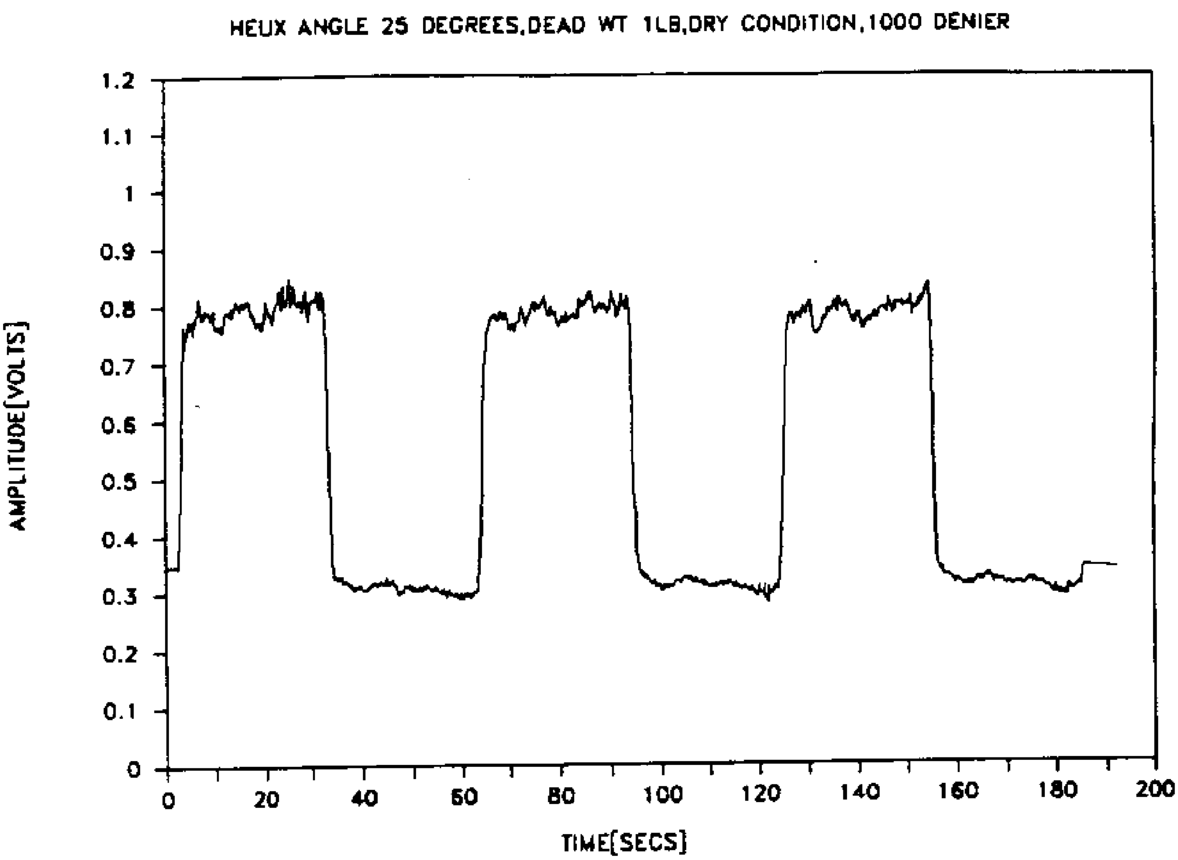


FIG 3

THEORY

The present experiment was done in both wet and dry conditions. In the wet conditions the test yarns were immersed in tap water 24 hrs prior to the experiment. Care was taken to keep the contact point covered with thin film of water during the entire experiment. This was done by regularly adding drops of water to the contact point.

In the course of these experiments the helix angle was changed to three different values and the magnitude of dead weight was also changed to three different values for each yarn type mentioned above. For each yarn type for a given helix angle and dead weight three samples were tested. Combined with wet and dry testing each yarn type for each sample underwent 18 different test variations.

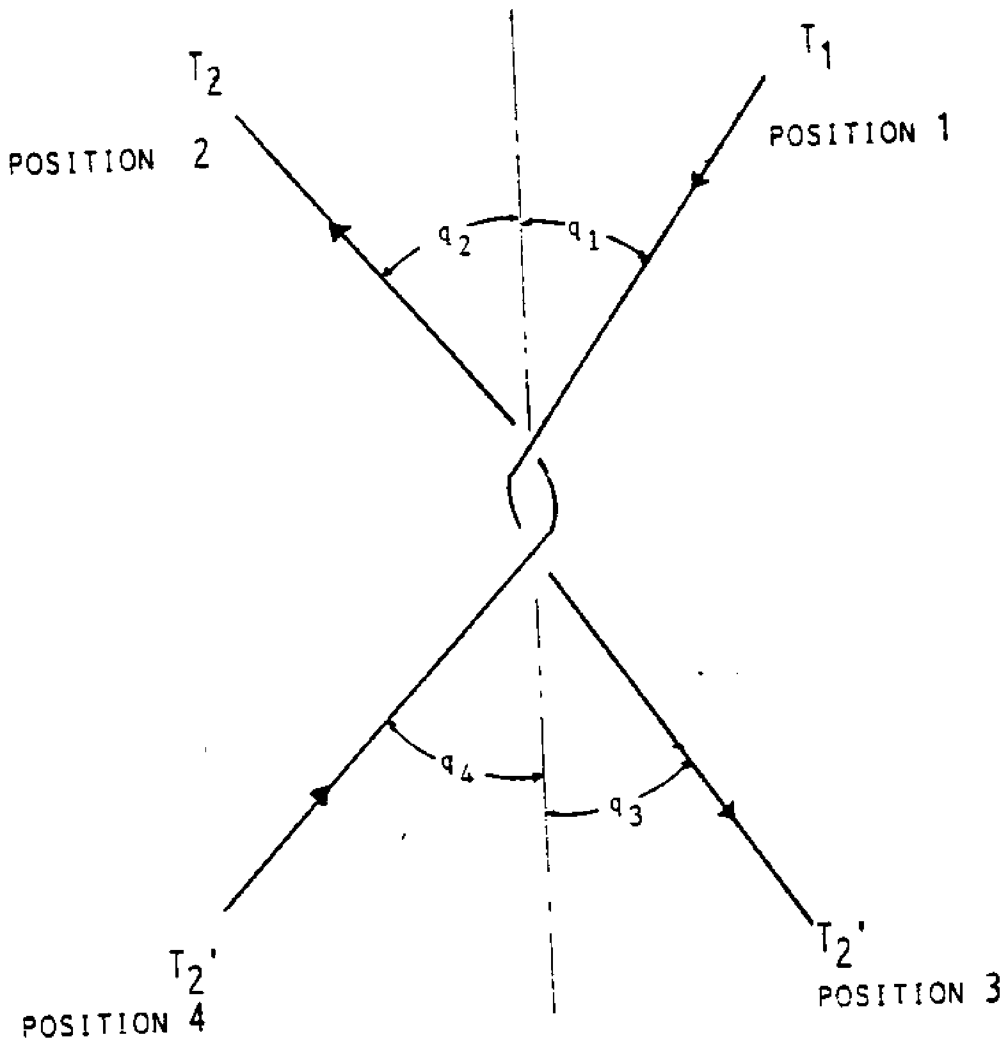
The coefficient of friction can be estimated from the geometrical relationships and the tension T1 and T2 (see Figure 4). The derivation of the friction coefficient is based on a single yarn wrapped over a cylinder with a constant helix angle q. For the differential element of a yarn along the yarn path, illustrated in Figures 5a and 5b, equilibrium of the force can be written as [2].

1) Along the yarn path

$$\left((T+dT)\cos\left(\frac{d\theta}{2}\right) - T\cos\left(\frac{d\theta}{2}\right)\right) - \mu f_n dL_n = 0 \tag{1}$$

2) Perpendicular to the yarn path

$$\left((T+dT)\sin\left(\frac{d\theta}{2}\right) + T\sin\left(\frac{d\theta}{2}\right)\right) - f_n dL_n = 0 \tag{2}$$



q_i'S : HELIX ANGLES

T 'S : TENSIONS

DIAGRAM OF CONTACT POINT OF YOY TESTER
SHOWING VARIABLE ANGLES

FIG 4

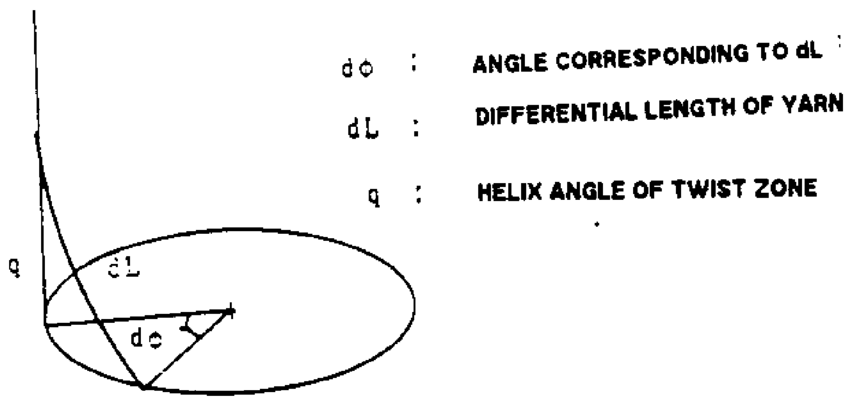


FIG 5a

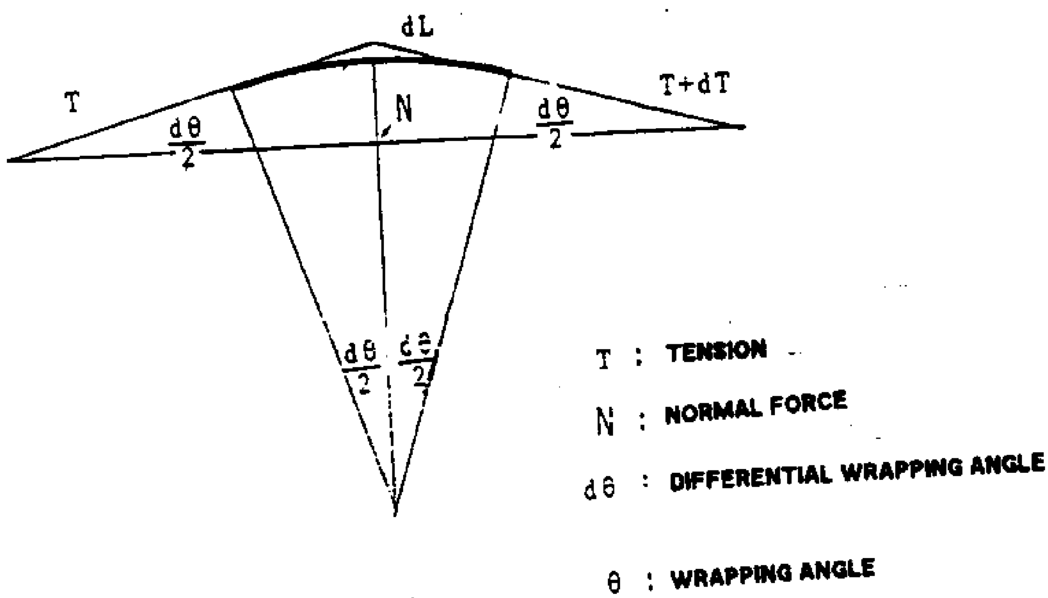


FIG 5b

DIAGRAMSOF DIFFERENTIAL ELEMENT IN YOY TESTER where

T, dT: increment of local tension as the differential wrapping angle increases, differential increment of local tension as the differential wrapping angle increases.

$d\theta$: wrapping angle along the yarn path on differential element

l: differential length of yarn

f_n: normal force per unit length at θ

Since $d\theta$ is vanishingly small, equation (1) and (2) can be written as

$$f_n = \frac{dT}{\mu dl} \tag{3}$$

$$f_n = \frac{Td\theta}{dl} \tag{4}$$

From the two above equations we can obtain

$$\frac{dT}{T} = \mu d\theta \tag{5}$$

Since $d\theta/dl$ is equal to the local curvature k

$$\frac{d\theta}{dl} = k \tag{6}$$

The normal force per unit length can be expressed as

$$f_n = Tk \tag{7}$$

Since the wrapping angle, θ is the angle measured along the helical path, it cannot be measured directly; however, it can be related to base angle, ϕ, which is the twist angle with respect to the axis of the twist zone, from geometrical constraints. The differential yarn length, dl, corresponding to a differential base angle, $d\phi$, and $d\theta$, can be expressed as:

$$dl = \left((rd\phi)^2 + \left(\frac{rd\phi}{\tan(q)} \right)^2 \right)^{1/2} \tag{8}$$

$$= \frac{rd\phi}{\sin(q)} \tag{9}$$

where

r: radius of the cylinder

ϕ: base angle

q: local helix angle

From the differential geometry, the local curvature of a circular helix can be expressed as

$$k = \frac{\sin^2(q)}{r} \tag{10}$$

From the equations 6, 9, and 10 the relationship between θ and ϕ can be derived as

$$d\theta = \sin(q)\, d\phi \tag{11}$$

The differential relationship between tension and twist angle, and local normal force per unit length can be expressed as:

$$\frac{dT}{T} = \mu \sin(q)\, d\phi \tag{12}$$

$$f_n = T \frac{\sin^2(q)}{r} \tag{13}$$

Integrating equation (12) for constant q and considering both twist sides we get

$$\ln\left(\frac{T_{2'}}{T_1}\right) = \mu \sin(q)\, \phi_{t1} \tag{14}$$

$$ln\left(\frac{T_2}{T_{2'}}\right) = \mu sin(q)\,\phi_{t2} \tag{15}$$

where

ϕ_{t1}: total wrapping base angle between point 1 and 3.

ϕ_{t2}: total wrapping base angle between point 4 and 2.

Since the total wrapping angle can be expressed as the number of turns in the contact zone, ϕ_{t1}, and ϕ_{t2} are the same and can be expressed as ϕ_t.

$$\phi_t = \phi_{t1} = \phi_{t2} \tag{16}$$

$$\phi_t = 2\pi N_t \tag{17}$$

where

N_t: total number of turns in the YOY test

Then the friction coefficient of the YOY tester can be expressed as:

$$\mu = \frac{ln\left(\frac{T_2}{T_1}\right)}{\left(4\pi N_t sin(q)\right)} \tag{18}$$

The number of wraps in the entire experiment is kept constant at a value of 1/2. By using equation (18) we have calculated the coefficient of friction, μ, in all cases. Then μ was plotted against the displacement of the contact point from the initial starting position. Because of time constraints it has not been possible to plot the entire data shown in Figure 3 for all the tests, instead only the first half cycle is plotted, i.e., the lifting of the dead weight by the sample from the lowest position to the highest position. The coefficient of friction μ is plotted as function of displacement for ENKA 855T dry yarn and are presented in Figures 6, 7, and 8. The values of μ for all different conditions for the four yarn types are tabulated and presented in Tables 1, 2, 3, and 4.

RESULTS

In this study specimens of two categories have been studied. The ENKA yarns are one category and the KEVLAR yarns are the other. Both ENKA yarns are the same material and structure except ENKA TN has been given a marine surface finish. Similarly both KEVLAR yarns are same material and structure and T960 has a marine surface finish.

Friction coefficient, μ varies inversely with both helix angle and dead weight according to equation (18). The plots of μ vs dead weight for a helix angle of 25 degrees are shown in Figures 9, 10, 11, and 12. These results agree with the theory. The variation of μ with helix angle as seen in Tables 1, 2, 3, and 4 has a few discrepancies. The value of μ for helix angle of 29 degrees is expected to have a slightly lower value than for 25 degrees, but in almost all cases there are slightly higher values for 29 degrees than 25 degrees. The reason for this behavior of the yarn is not clear.

Examination of Tables 1 and 2 shows that ENKA 855T has a higher value of coefficient of friction than ENKA 855TN both in dry and in wet conditions. The marine finish applied to the ENKA 855TN is likely the cause of its lower value of coefficient of friction.

Similarly examination of Tables 3 and 4 shows that KEVLAR T960 has a greater value of μ than KEVLAR T961 under dry conditions but in the wet condition the effect is reversed. It was observed that when immersed in water the fibers in T960 yarn stick together compactly but the fibers in T961 yarn spreads out completely. This behavior of the two yarns in water environment leads to their difference in frictional properties. We can speculate that the marine finish given on T960 increases the coefficient of friction in dry conditions where as decreases the same in wet condition by keeping the fibers together.

The last effect is the stick-slip effect which is present in almost all cases in different magnitudes. The effect is because of the pulsatory motion of the contact point under an applied load. In general the effect increases with applied load. This can be seen from

Figures 6, 7, and 8. This effect arises when the static coefficient of friction is markedly greater than kinetic coefficient of friction [3].

REFERENCES

1. Seo, M., "Mechanical Mechanism of Syntheic Fiber Rope Deterioration", Ph.D. Thesis, Department of Mechanical Engineering, MIT, 1988.
2. Crandall, S.H., Sahl, N.C., and Lardner, T.J., *An Introduction to the Mechanics of Solids*, 2nd Ed, McGraw-Hill, 1978.
3. Rabinowicz, E., *Friction and Wear of Materials*, John Wiley and Sons, Inc., 1966.

TABLE 1

FRICTION COEFFICIENT OF ENKA 855T YARN

HELIX ANGLE 29 DEGREES

DEAD WEIGHT	DRY CONDITION				WET CONDITION			
	FRICTION COEFFICIENT			MEAN	FRICTION COEFFICIENT			MEAN
1lb	.19	.177	.193	.186	.165	.166	.143	.158
3lbs	.127	.131	.147	.135	.135	.145	.137	.137
5lbs	.09	.141	.118	.116	yarn broke			

HELIX ANGLE 25 DEGREES

DEAD WEIGHT	DRY CONDITION				WET CONDITION			
	FRICTION COEFFICIENT			MEAN	FRICTION COEFFICIENT			MEAN
1lb	.171	.187	.178	.178	.157	.159	.156	.158
3lbs	.129	.128	.138	.131	.140	.141	.143	.141
5lbs	.111	.112	.105	.109	.111	.105	.138	.118

HELIX ANGLE 21 DEGREES

DEAD WEIGHT	DRY CONDITION				WET CONDITION			
	FRICTION COEFFICIENT			MEAN	FRICTION COEFFICIENT			MEAN
1lb	.202	.207	.212	.207	.169	.172	.161	.167
3lbs	.159	.155	.179	.164	.149	.148	.154	.150
5lbs	.118	.127	.148	.131	.133	.12	.137	.13

TABLE 2
FRICTION COEFFICIENT OF ENKA 855TN YARN

HELIX ANGLE 29 DEGREES

DEAD WEIGHT	DRY CONDITION				WET CONDITION			
	FRICTION COEFFICIENT			MEAN	FRICTION COEFFICIENT			MEAN
1lb	.144	.145	.138	.142	.138	.134	.113	.138
3lbs	.117	.118	.116	.117	.115	.114	.098	.109
5lbs	.096	.098	.107	.1	.101	.096	.15	.116

HELIX ANGLE 25 DEGREES

DEAD WEIGHT	DRY CONDITION				WET CONDITION			
	FRICTION COEFFICIENT			MEAN	FRICTION COEFFICIENT			MEAN
1lb	.126	.128	.120	.124	.117	.119	.119	.118
3lbs	.111	.116	.107	.11	.114	.112	.113	.113
5lbs	.099	.098	.096	.097	.107	.107	.105	.106

HELIX ANGLE 21 DEGREES

DEAD WEIGHT	DRY CONDITION				WET CONDITION			
	FRICTION COEFFICIENT			MEAN	FRICTION COEFFICIENT			MEAN
1lb	.149	.151	.163	.154	.136	.133	.12	.129
3lbs	.132	.129	.144	.135	.118	.117	.125	.12
5lbs	.109	.107	.124	.113	.11	.11	.111	.11

TABLE 3

FRICTION COEFFICIENT OF KEVLAR T960 YARN

HELIX ANGLE 29 DEGREES

DEAD WEIGHT	DRY CONDITION				WET CONDITION			
	FRICTION COEFFICIENT			MEAN	FRICTION COEFFICIENT			MEAN
1lb	.195	.2	.202	.199	.217	.20	.16	.192
5lbs	.154	.156	.148	.152	.178	.175	.154	.169
10lbs	.133	.133	.123	.129	.145	.150	.125	.14

HELIX ANGLE 25 DEGREES

DEAD WEIGHT	DRY CONDITION				WET CONDITION			
	FRICTION COEFFICIENT			MEAN	FRICTION COEFFICIENT			MEAN
1lb	.185	.183	.176	.181	.187	.183	.172	.18
5lbs	.163	.157	.163	.161	.165	.153	.158	.158
10lbs	.133	.134	.134	.133	.142	.134	.144	.14

HELIX ANGLE 21 DEGREES

DEAD WEIGHT	DRY CONDITION				WET CONDITION			
	FRICTION COEFFICIENT			MEAN	FRICTION COEFFICIENT			MEAN
1lb	.217	.231	.215	.221	.2	.198	.213	.203
5lbs	.175	.165	.168	.169	.169	.162	.181	.170
10lbs	.140	.142	.159	.147	.152	.152	.15	.151

TABLE 4
FRICTION COEFFICIENT OF KEVLAR T961 YARN

HELIX ANGLE 29 DEGREES

DEAD WEIGHT	DRY CONDITION				WET CONDITION			
	FRICTION COEFFICIENT			MEAN	FRICTION COEFFICIENT			MEAN
1lb	.195	.196	.184	.192	.278	.242	.214	.244
5lbs	.147	.15	.148	.148	.176	.176	.16	.17
10lbs	.124	.126	.123	.124	.15	.151	.134	.145

HELIX ANGLE 25 DEGREES

DEAD WEIGHT	DRY CONDITION				WET CONDITION			
	FRICTION COEFFICIENT			MEAN	FRICTION COEFFICIENT			MEAN
1lb	.184	.184	.169	.179	.233	.208	.216	.219
5lbs	.144	.146	.145	.145	.174	.17	.172	.172
10lbs	.126	.124	.134	.133	.148	.145	.169	.154

HELIX ANGLE 21 DEGREES

DEAD WEIGHT	DRY CONDITION				WET CONDITION			
	FRICTION COEFFICIENT			MEAN	FRICTION COEFFICIENT			MEAN
1lb	.216	.213	.215	.214	.232	.233	.201	.222
6lbs	.153	.152	.174	.159	.182	.197	.182	.187
10lbs	.215	.174	.144	.113	.153	.152	.15	.152

TABLE 5

FRICTION COEFFICIENT OF ENKA 855T YARN

HELIX ANGLE 10 DEGREES

DEAD WEIGHT	DRY CONDITION				WET CONDITION			
	FRICTION COEFFICIENT			MEAN	FRICTION COEFFICIENT			MEAN
1lb	.199	.213	.21	.207	.184	.188	.187	.184
3lbs	.208	.194	.207	.203	.166	.177	.171	.169
5lbs	.173	.183	.186	.180	.164	.175	.167	.168

FRICTION COEFFICIENT OF ENKA 855TN YARN

HELIX ANGLE 10 DEGREES

DEAD WEIGHT	DRY CONDITION				WET CONDITION			
	FRICTION COEFFICIENT			MEAN	FRICTION COEFFICIENT			MEAN
1lb	.168	.169	.173	.17	.178	.180	.165	.174
3lbs	.159	.166	.159	.161	.158	.162	.158	.159
5lbs	.162	.163	.152	.159	.140	.143	.143	.142

TABLE 6

FRICTION COEFFICIENT OF KEVLAR T960 YARN

HELIX ANGLE 10 DEGREES

DEAD WEIGHT	DRY CONDITION				WET CONDITION			
	FRICTION COEFFICIENT			MEAN	FRICTION COEFFICIENT			MEAN
1lb	.212	.210	.214	.212	.201	.225	.198	.208
5lbs	.19	.192	.18	.187	.187	.197	.183	.189
0lbs	.177	.188	.187	.184	.158	.164	.168	.163

FRICTION COEFFICIENT OF KEVLAR T961 YARN

HELIX ANGLE 10 DEGREES

DEAD WEIGHT	DRY CONDITION				WET CONDITION			
	FRICTION COEFFICIENT			MEAN	FRICTION COEFFICIENT			MEAN
1lb	.206	.212	.213	.210	.212	.204	.229	.215
5lbs	.173	.172	.172	.172	.2	.197	.209	.202
10lbs	.159	.164	.163	.162	.196	.195	.19	.193

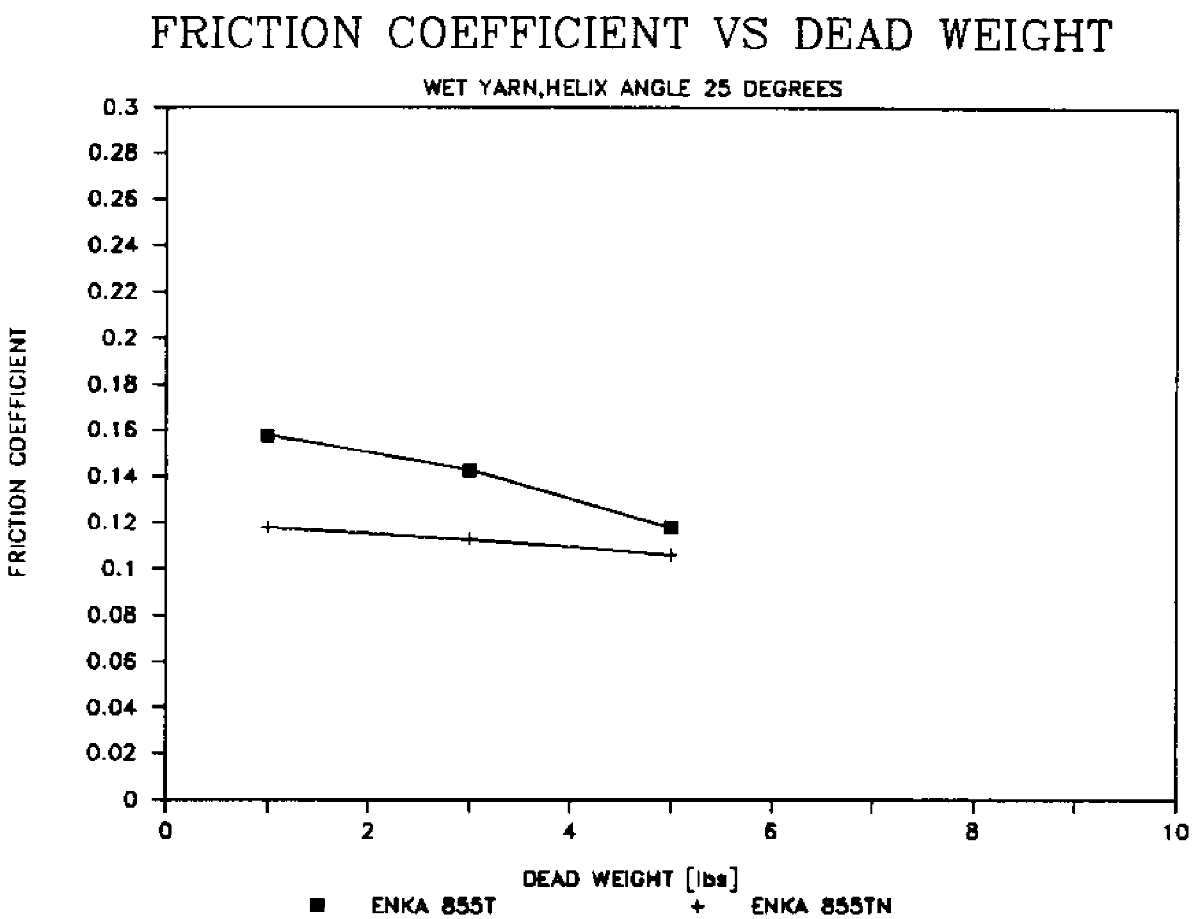

FRICTION COEFFICIENT VS DEAD WEIGHT
WET YARN,HELIX ANGLE 25 DEGREES
FRICTION COEFFICIENT
DEAD WEIGHT [lbs]
ENKA 855T
ENKA 855TN

FIG 10

FRICTION COEFFICIENT VS DEAD WEIGHT

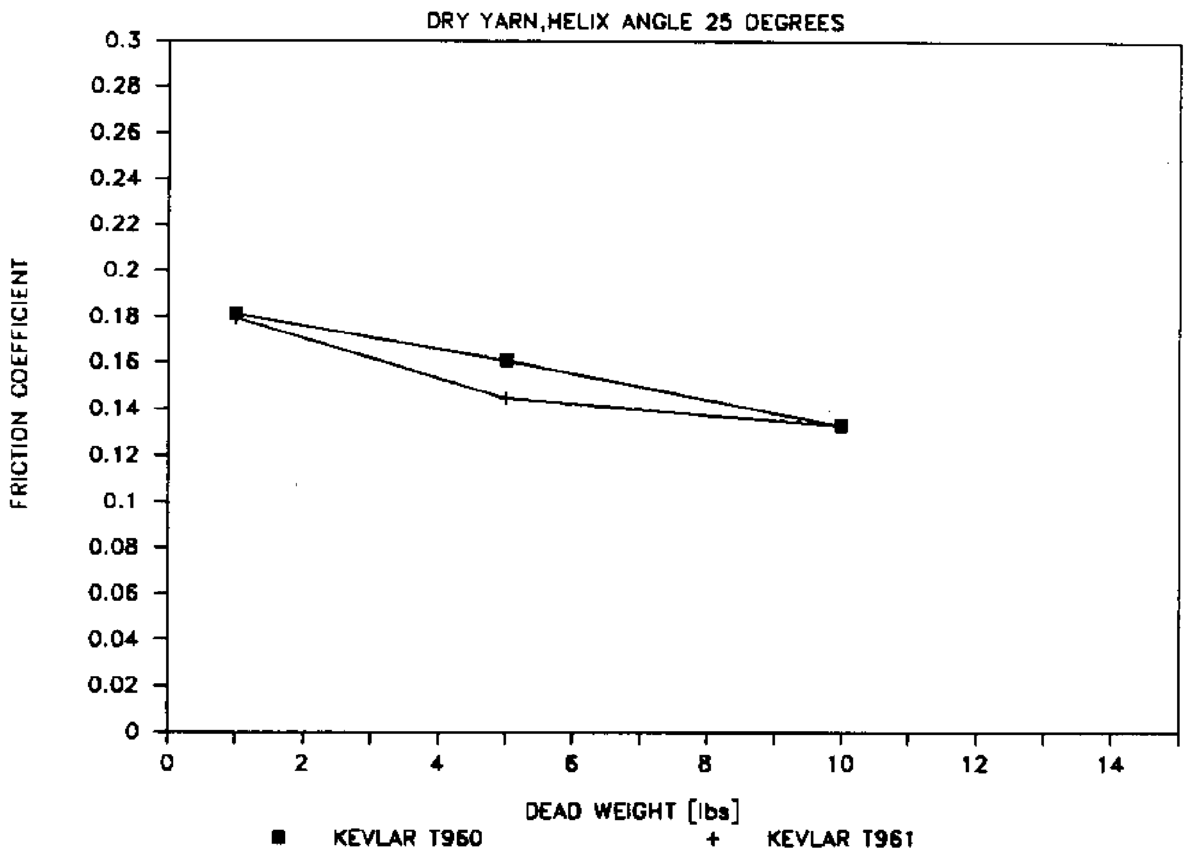


FIG 11

FRICTION COEFFICIENT VS DISPLACEMENT

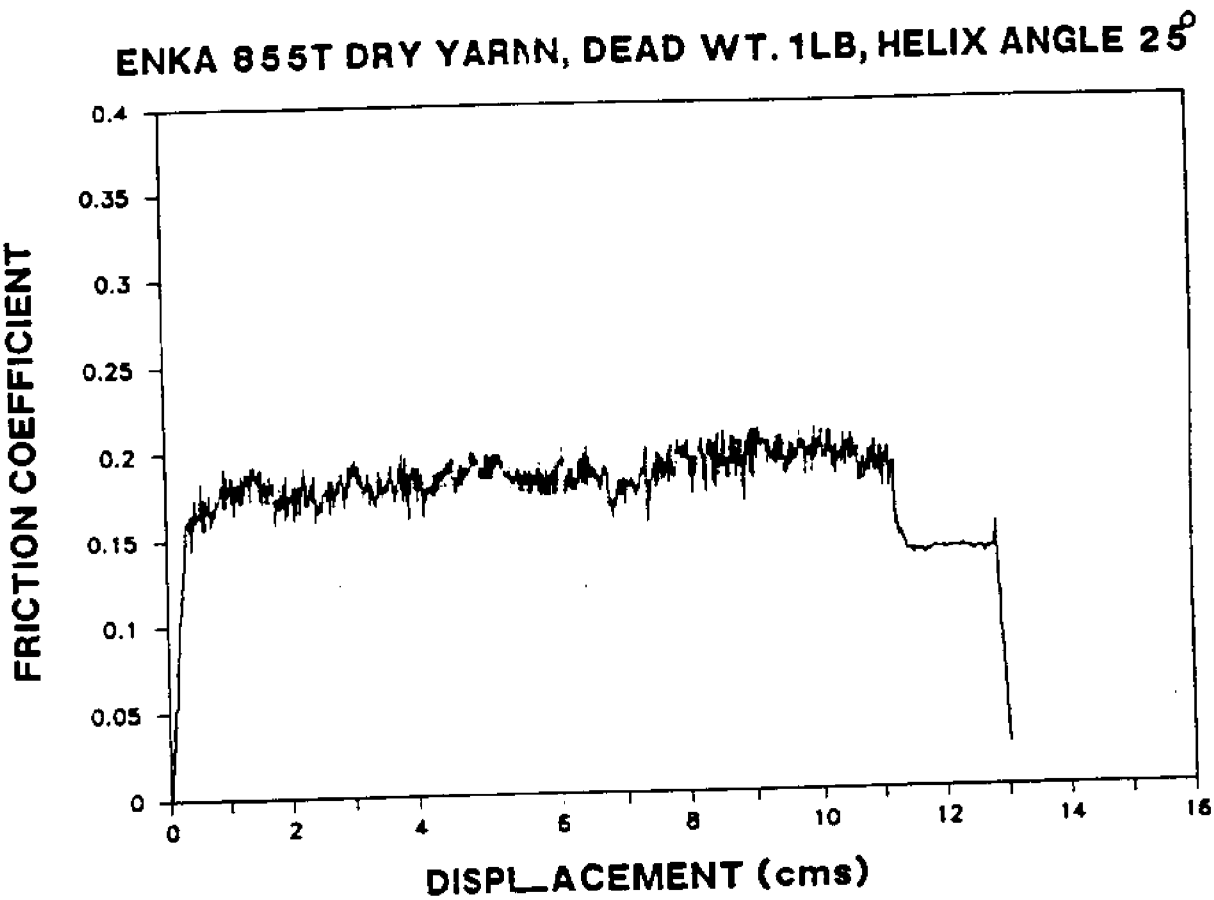


FIG 6

FRICTION COEFFICIENT VS DISPLACEMENT

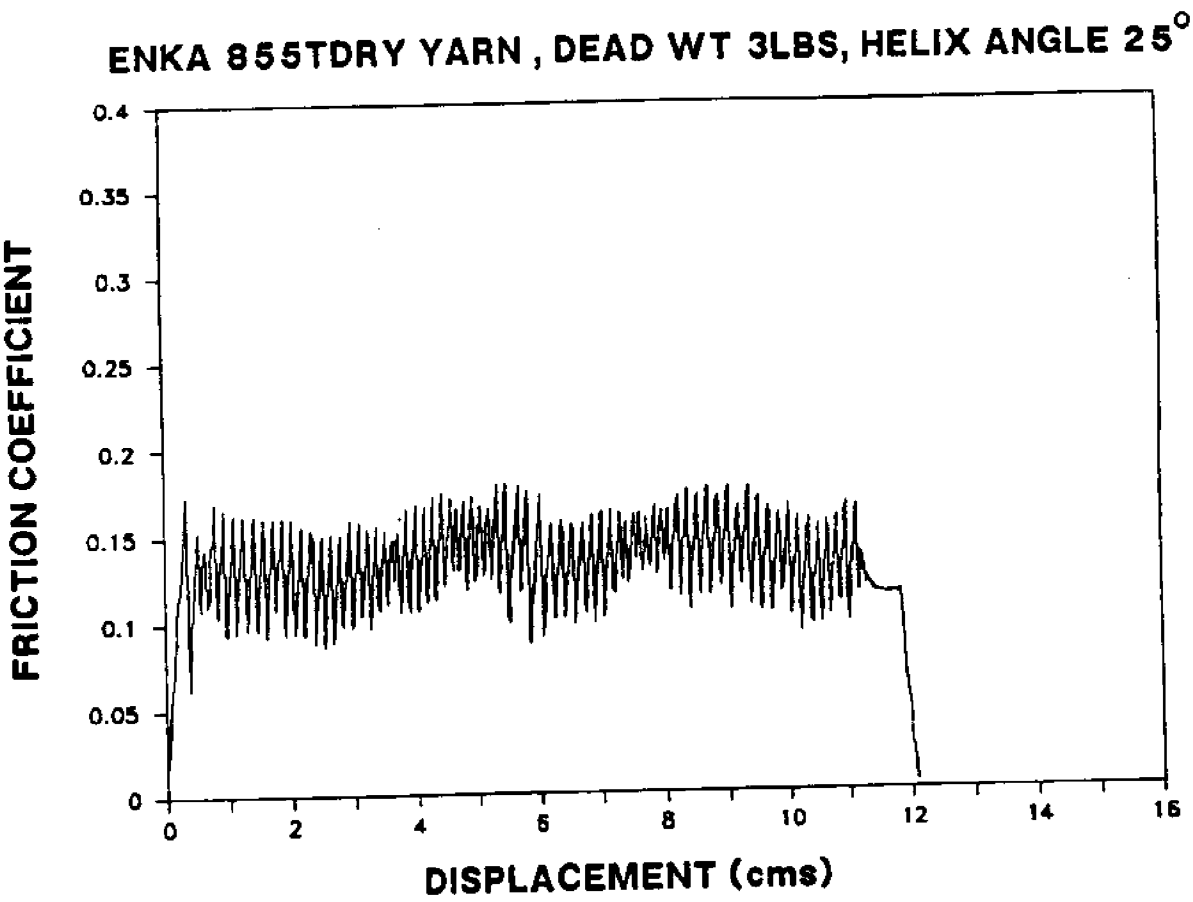


FIG 7

FRICTION COEFFICIENT VS DISPLACEMENT

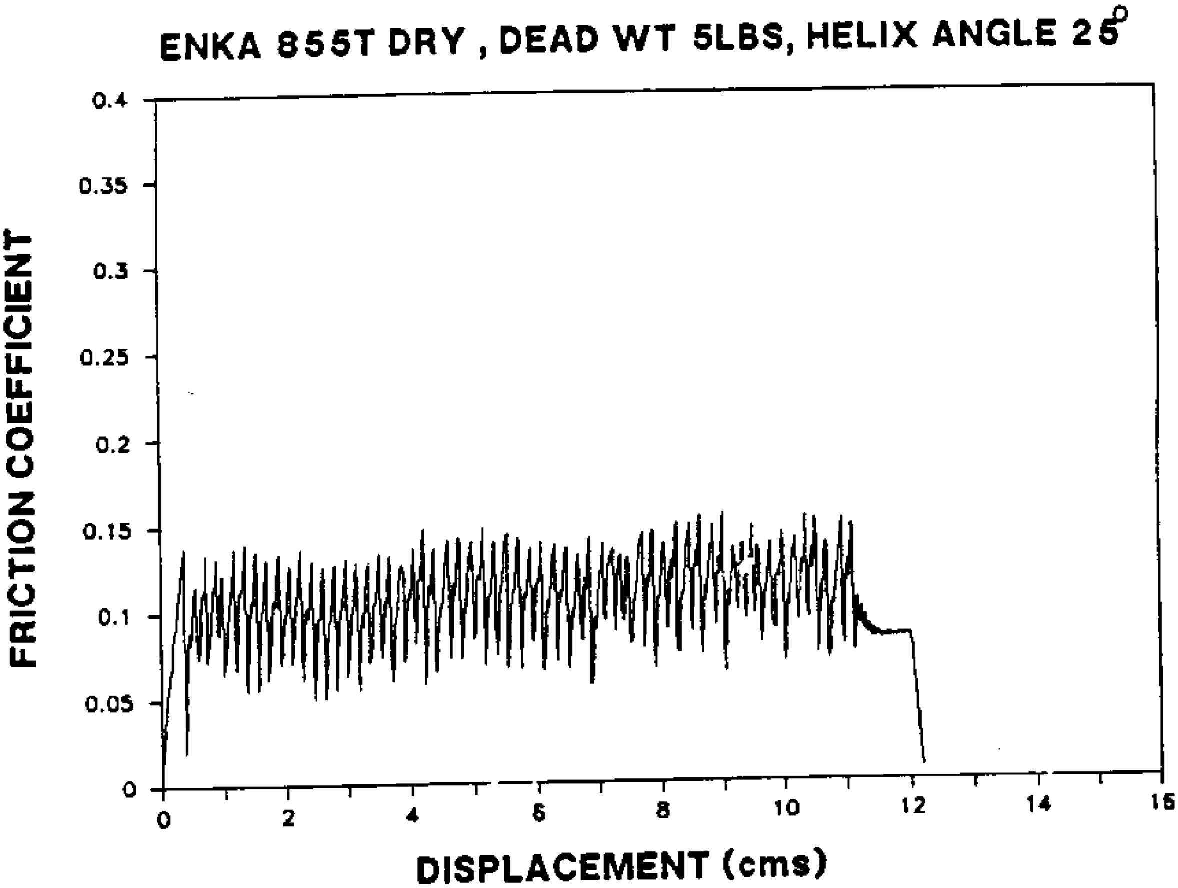


FIG 8

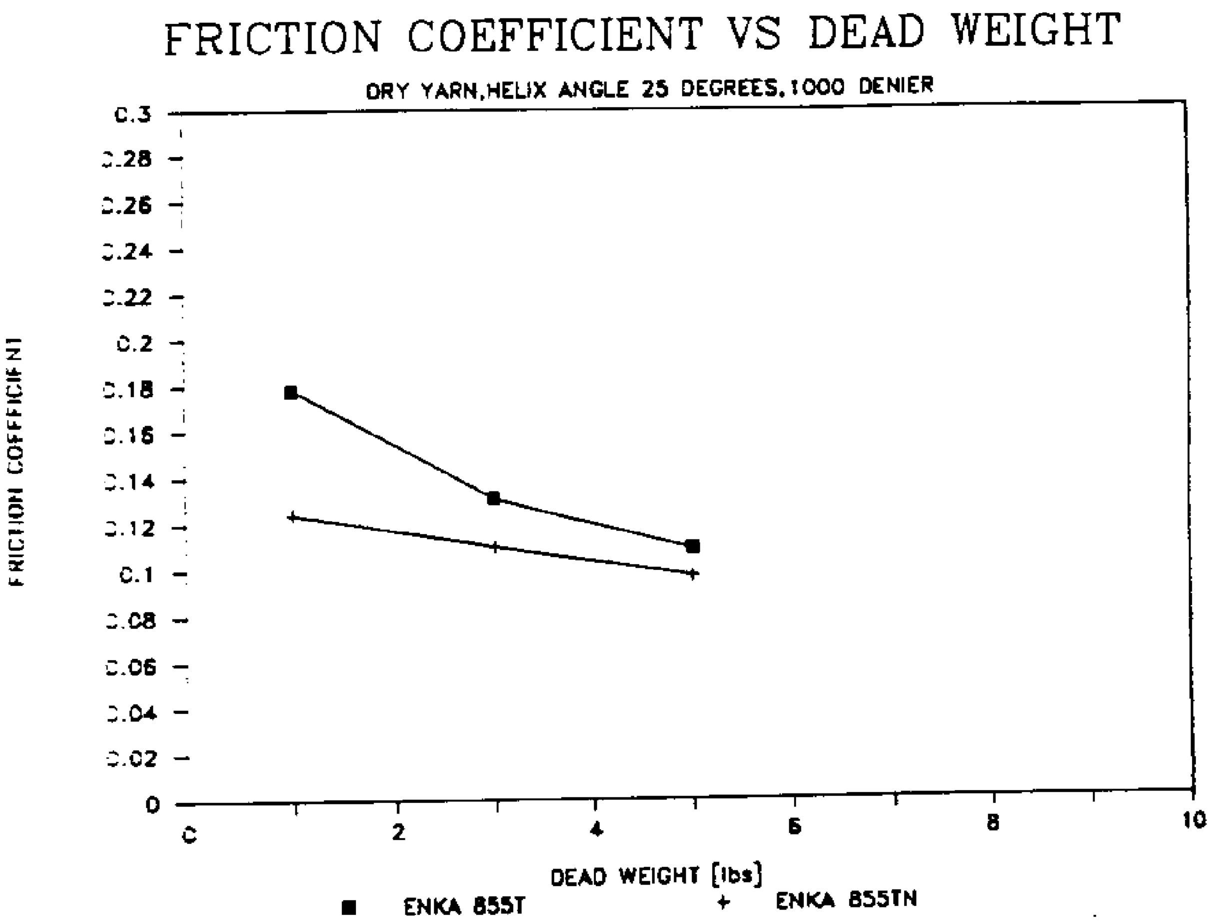

FRICTION COEFFICIENT VS DEAD WEIGHT
DRY YARN,HELIX ANGLE 25 DEGREES,1000 DENIER
FRICTION COEFFICIENT
0.3
0.28
0.26
0.24
0.22
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0
2
4
6
8
10
DEAD WEIGHT [lbs]
ENKA 855T
ENKA 855TN

FIG 9

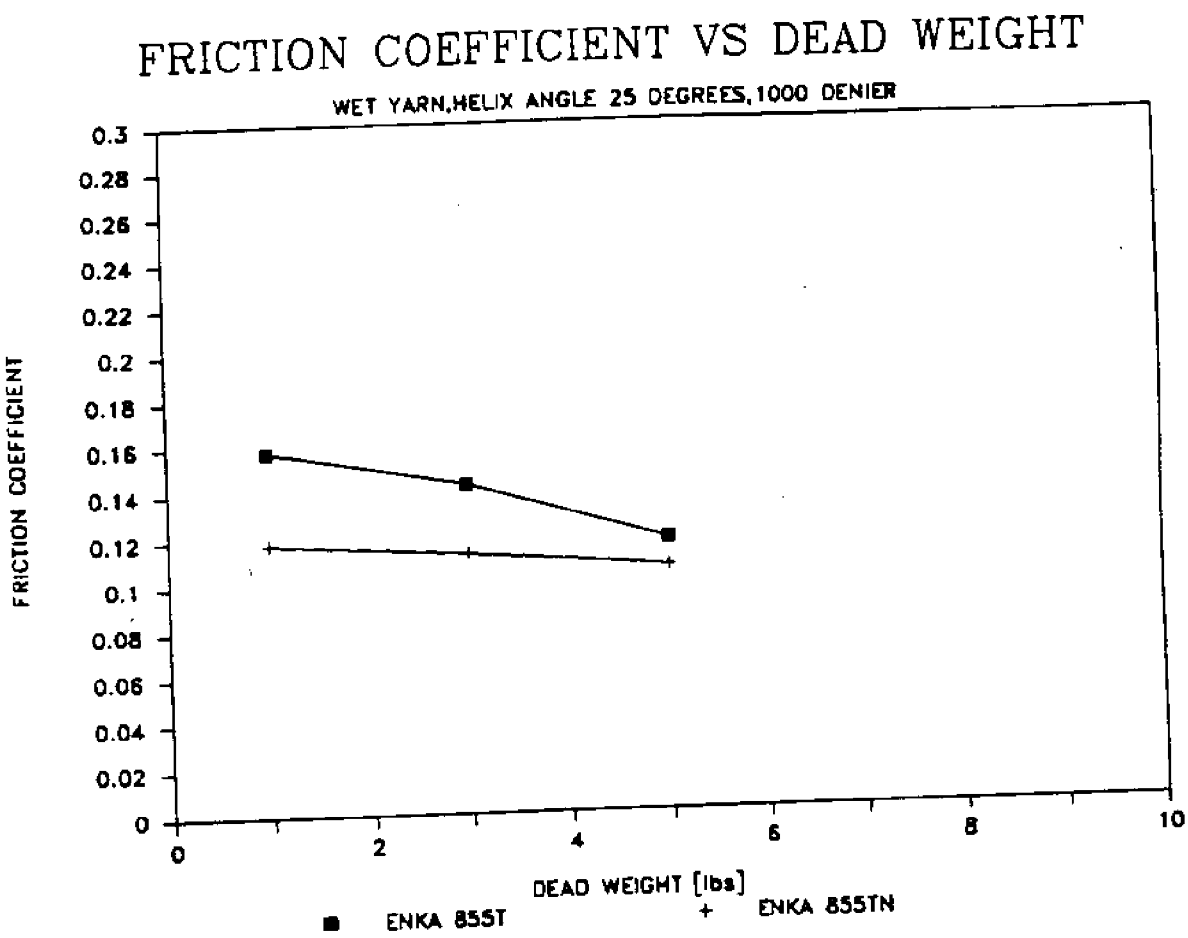

FRICTION COEFFICIENT VS DEAD WEIGHT
WET YARN, HELIX ANGLE 25 DEGREES, 1000 DENIER
FRICTION COEFFICIENT
0.3
0.28
0.26
0.24
0.22
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0
2
4
6
8
10
DEAD WEIGHT [lbs]
ENKA 855T
ENKA 855TN

FIG 10

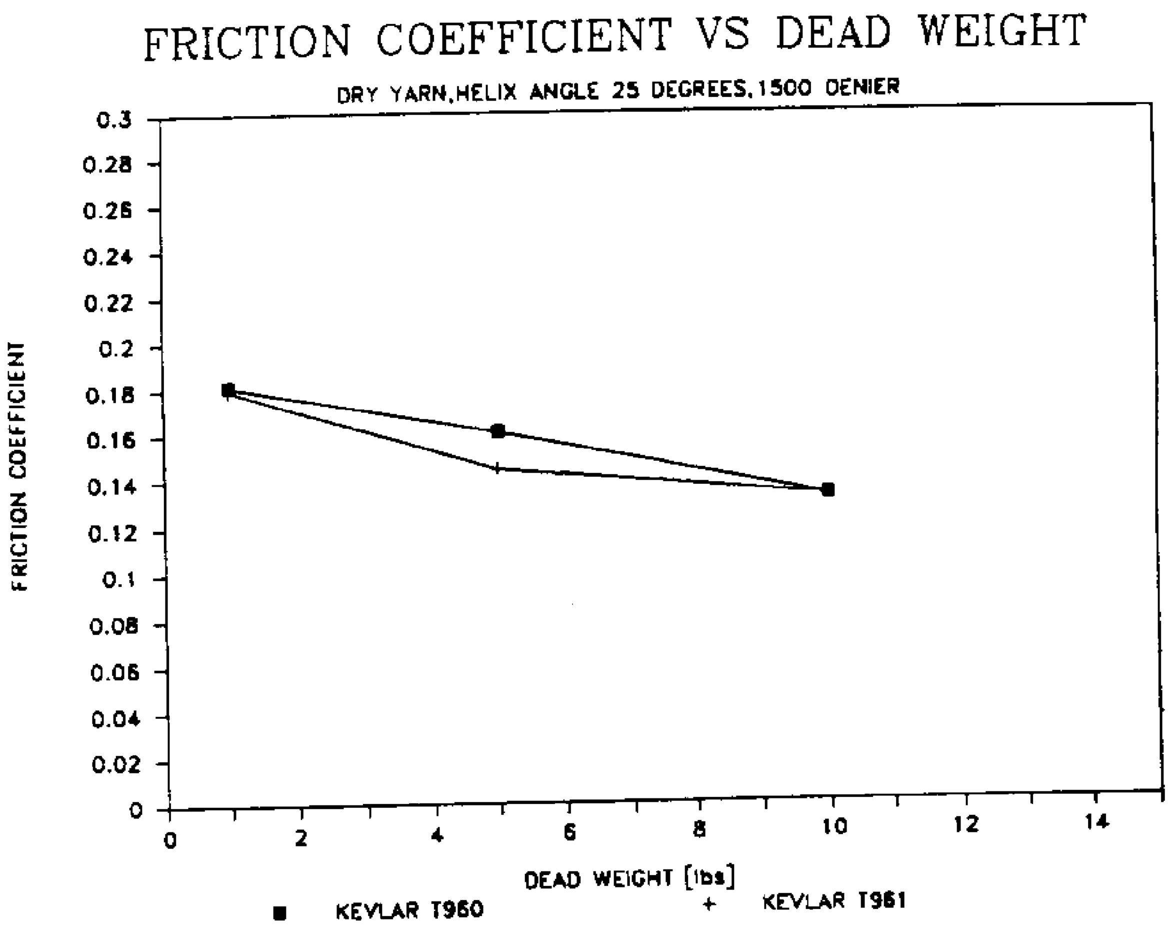
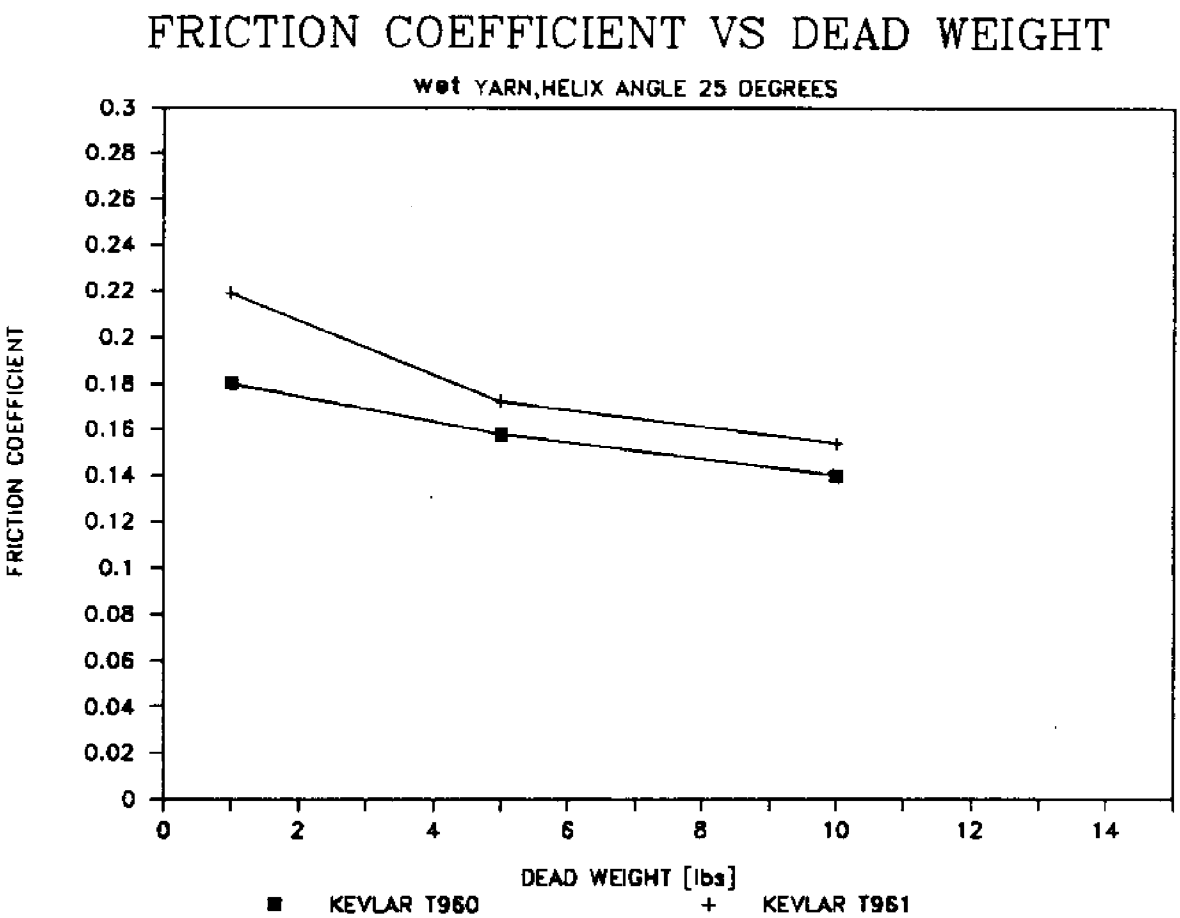

FRICTION COEFFICIENT VS DEAD WEIGHT
DRY YARN, HELIX ANGLE 25 DEGREES, 1500 DENIER
FRICTION COEFFICIENT
0.3
0.28
0.26
0.24
0.22
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0
2
4
6
8
10
12
14
DEAD WEIGHT [lbs]
KEVLAR T960
KEVLAR T961

FIG 11



FRICTION COEFFICIENT VS DEAD WEIGHT
wet YARN,HELIX ANGLE 25 DEGREES
FRICTION COEFFICIENT
0.3
0.28
0.26
0.24
0.22
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0
2
4
6
8
10
12
14
DEAD WEIGHT [lbs]
KEVLAR T960
KEVLAR T961

FIG 12

VI. YARN ON YARN ABRASION

KEVLAR AND ENKA POLYESTER

INTRODUCTION

Ropes in use are subjected to various loading conditions depending upon environmental conditions. During the deployment of marine ropes relative movements occur between rope components (i.e., plied yarns, yarns, and fibers). These relative movements cause friction and abrasion leading to ultimate failure even in the absence of external abrasion due to foreign objects and surfaces. Thus the study of abrasion phenomena is essential to determine the efficiency and performance of various types of ropes.

Yarn-on-yarn abrasion testing is common and is considered to be a method preferred to the fiber-on-fiber tests since the yarns are easier to handle.

In this report yarn-on-yarn abrasion tests are conducted for 4 types of yarns. They are ENKA 855T, ENKA 855TN, KEVLAR T960 and KEVLAR T961. The ENKAs are polyester yarns of similar structure except the ENKA 855TN is coated with a marine finish. The KEVLARs are aramid yarns, similar in structure with KEVLAR T960 has a marine finish on it.

EXPERIMENTAL SET UP

The experimental set up and the forces acting on the yarn at different points are sketched in Figures 1A and 1B. With the movement of the driving end, the yarn surfaces rub against each other. The direction of rubbing changes with each half cycle. The frictional force at the point of contact causes the abrasion of the yarn. The cycle of rubber was counted by an electronic counter.

Operational data as per Figures 1A and 1B:

— Number of yarn wraps

— Frequency of test, 30 cycles/minute

— Stroke length 3 inches

— Helix angle q = 25°

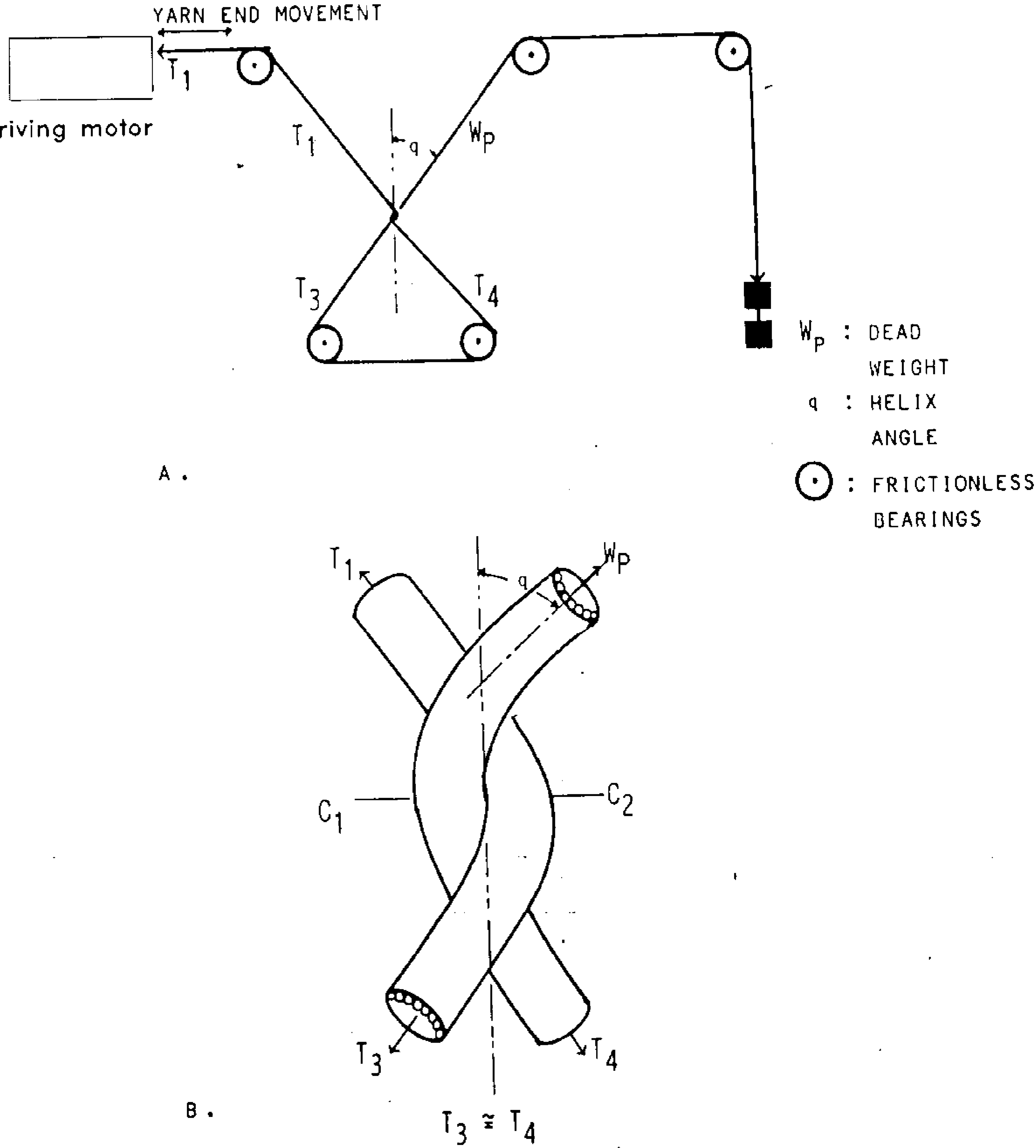


Figure 1 A,B DIAGRAM OF YARN–ON–YARN TESTER (YOY) AND ITS CONTACT POINT.

RESULTS

The results are plotted and the numerical values are given in Tables 1 and 2.

From Figure 2 it is seen ENKA 855TN has slightly higher abrasion resistance than ENKA 855T. Similarly Figure 4 shows that KEVLAR T961 has a higher value of abrasion resistance than KEVLAR T960.

Abrasion resistance of KEVLAR yarns are much less than that of ENKA yarns. ENKAs can sustain 30% of their breaking load where as KEVLARs can take only up to 15% of their breaking load (Figure 7).

Figure 7 shows that ENKAs have two distinct regions of abrasion resistance. The turning point is seen to be as approximately 15% of their breaking load. Below this region both the ENKAs are similar. Above this point ENKAs show different behavior. The slopes of the curves are different in both regions. KEVLARs do not have this characteristic.

TABLE 1

Yarn-on-Yarn Abrasion Test for ENKA 855T Yarn (1000denier, w/o finish)
B.S(breaking stress) of ENKA 855T is 8.7 gm/denier.

Wgt (kgs)	wt in% of B.S.	Number of Cycles n1	n2	n3	n4	n5	Avg (#cycles)	log(avg # cycles)
2.50	28.7	2	1	2	2	1	1.6	0 0.204
2.00	22.98	307	166	179	176	200	205.6	2.313
1.50	17.24	2449	1520	1750	1821	1899	1887.8	3.275
1.00	11.49	5192	4594	4364	4277	4955	4676.4	3.669
0.50	5.74	16327	13015	17565	17254	16515	16135.2	4.207
0.10	1.14	244611	218382	132508	103052		174638.2	5.242
0.05	.574	316471	752412		453020		507301.0	5.705

Yarn-on-Yarn Abrasion Test for ENKA 855TN Yarn (1000denier, w/ finish)
B.S.(breaking stress) of ENKA 855TN is 8.48 gm/denier.

Wgt (kgs)	wt in% of B.S.	Number of Cycles n1	n2	n3	n4	n5	Avg (#cycles)	log(avg # cycles)
2.50	29.4	26	7	22	16	15	17.2	1.235
2.00	23.5	512	387	463	511	722	519	2.715
1.50	17.6	1871	1946	1758	1763	1840	1835.6	3.263
1.00	11.7	3401	4707	5547	5033	4721	4681.8	3.670
0.50	5.89	10618	14418	23342	12197	18177	15750.4	4197
0.10	1.18	244611	218382	132508	103052		174638.2	5.33
0.05	0.58	316471	752412		453020		507301.0	5.63

TABLE 2

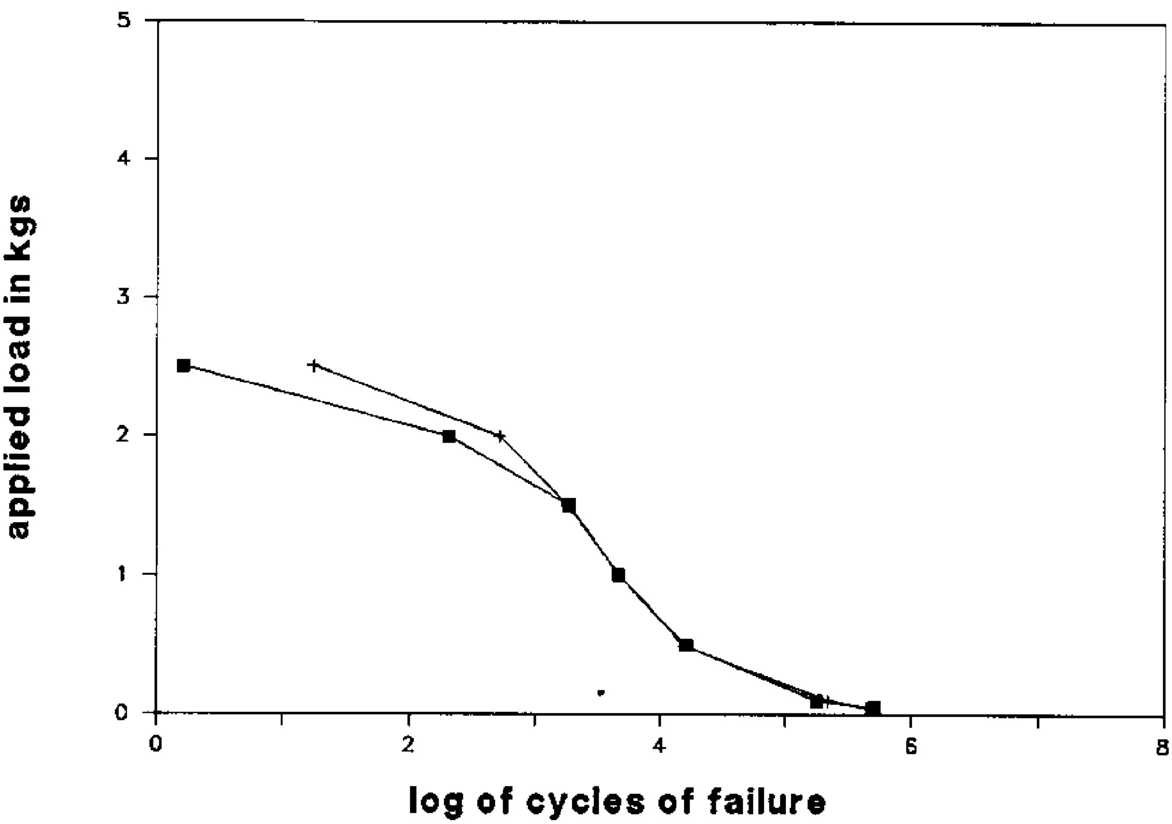
Yarn-on-Yarn Abrasion Test for KEVLAR T960 yarn (1500denier w/ finish)
B.S.(breaking stress) of KEVLAR T960 yarn is 15.02 gm/denier.

Wgt (kgs)	wt in % of B.S.	Number of Cycles n1	n2	n3	n4	n5	Avg (#cycles)	log(avg # cycles)
3.0	12.31	12	11	12	13	11	11.8	1.07
2.5	10.25	19	17	22	18	16	18.4	1.26
2.0	8.20	31	30	29	26	30	29.2	1.46
1.5	6.15	64	76	62	82	70	70.8	1.85
1.0	4.1	606	561	639	336	305	489.4	2.69
0.5	2.05	1562	1216	1381	941	1318	1283.6	3.11
0.2	0.82	6319	5796	8511	7484	7032	7028.4	3.84
0.1	0.41	20095	19723	19177	15054	10317	16873.2	4.22
0.05	0.205	59243	46493	42185	52351	53381	50730.6	4.7

Yarn-on-Yarn Abrasion Test for KEVLAR T961 (1500 denier w/o finish)
B.S.(breaking stress) of KEVLAR T961 yarn is 16.26 gm/denier.

Wgt (kgs)	wt in % of B.S.	Number of Cycles n1	n2	n3	n4	n5	Avg (#cycles)	log(avg # cycles)
3.5	14.36	13	12	13	11	14	12.6	1.1
3.0	12.31	17	15	19	16	16	16.6	1.22
2.5	10.2	24	29	27	22	27	25.8	1.41
2.0	8.2	31	40	40	40	42	38.6	1.58
1.5	6.1	79	89	90	104	127	97.8	1.99
1.0	4.1	285	295	273	330	270	290.6	2.46
0.5	2.0	1556	1272	1291	1075	265	1091.8	3.03
0.2	0.82	5839	7991	4995	3854	3842	5304.2	3.72
0.1	0.41	14598	130805	16973	14669	13369	38082.8	4.58
0.05	0.20	33880	32380	39769	33893	.....	34980.5	4.54

YOY TEST FOR ENKA 855T AND 855TN YARN



■ ENKA 855T(1000 denier w/o finish)

\+ ENKA 855TN (1000 denier w/ finish)

Figure 2

YOY TEST FOR KEVLAR T960 AND T961 YARN

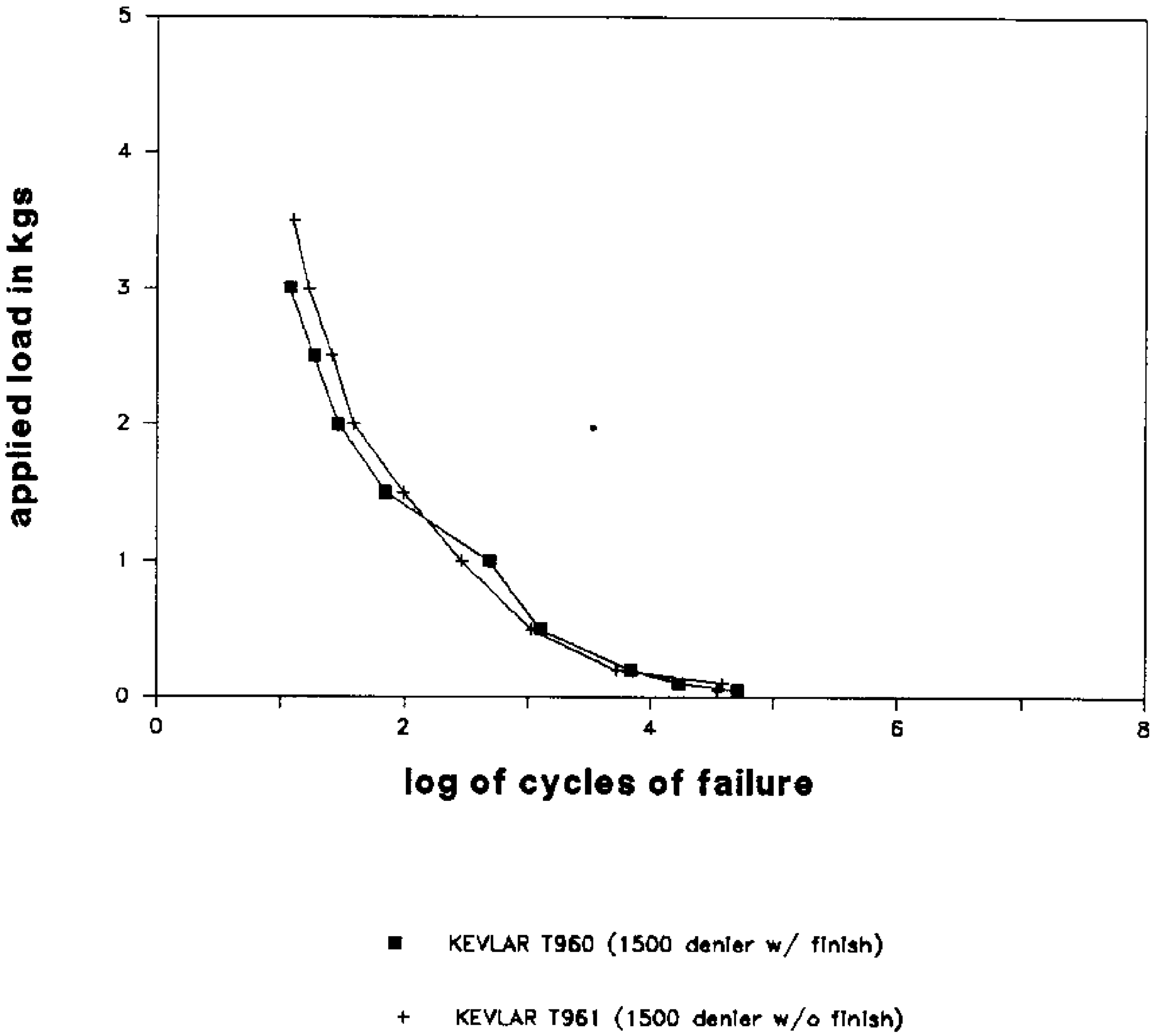


Figure 3

YOY TEST FOR KEVLAR AND ENKA YARN

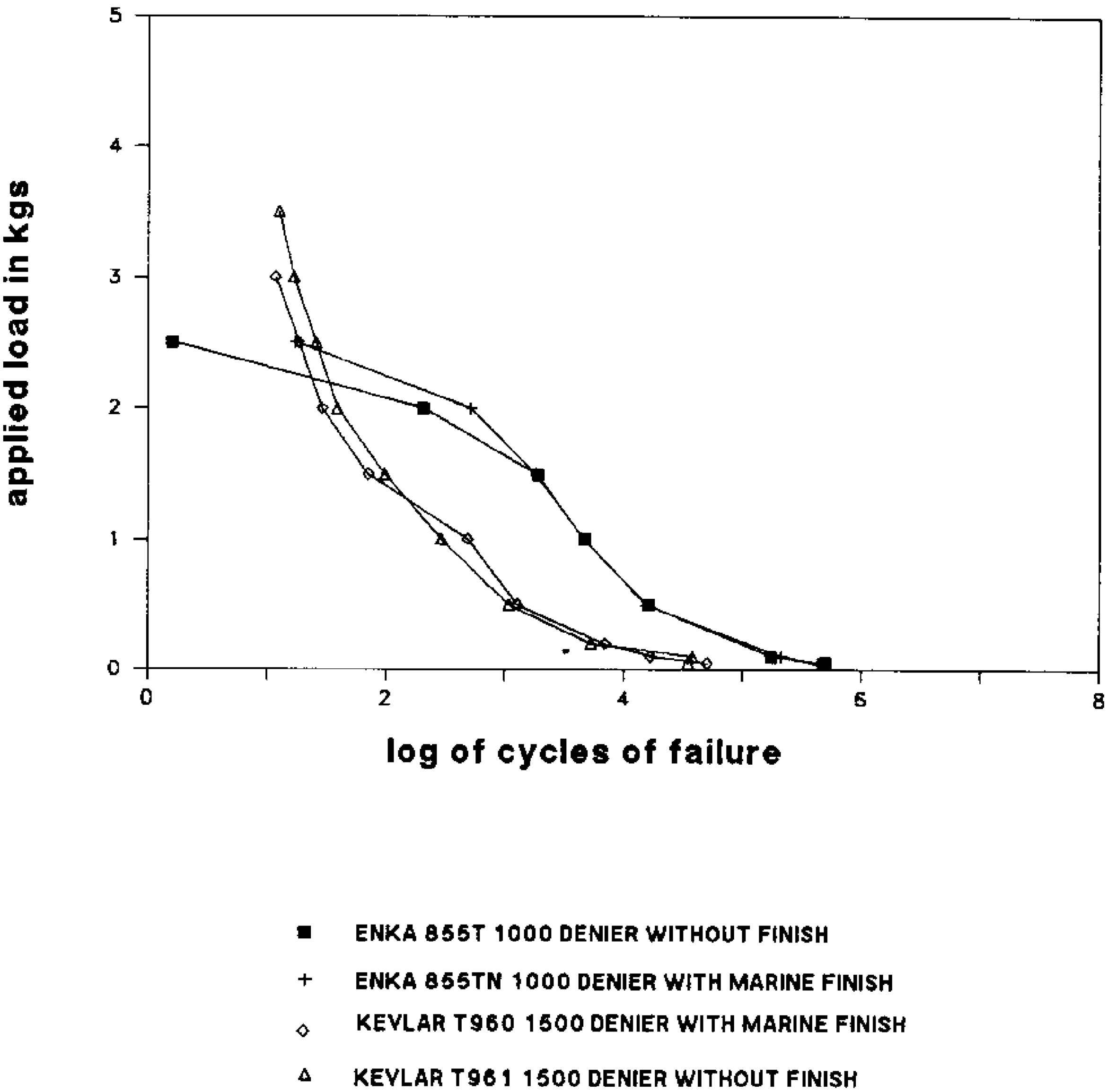


Figure 4

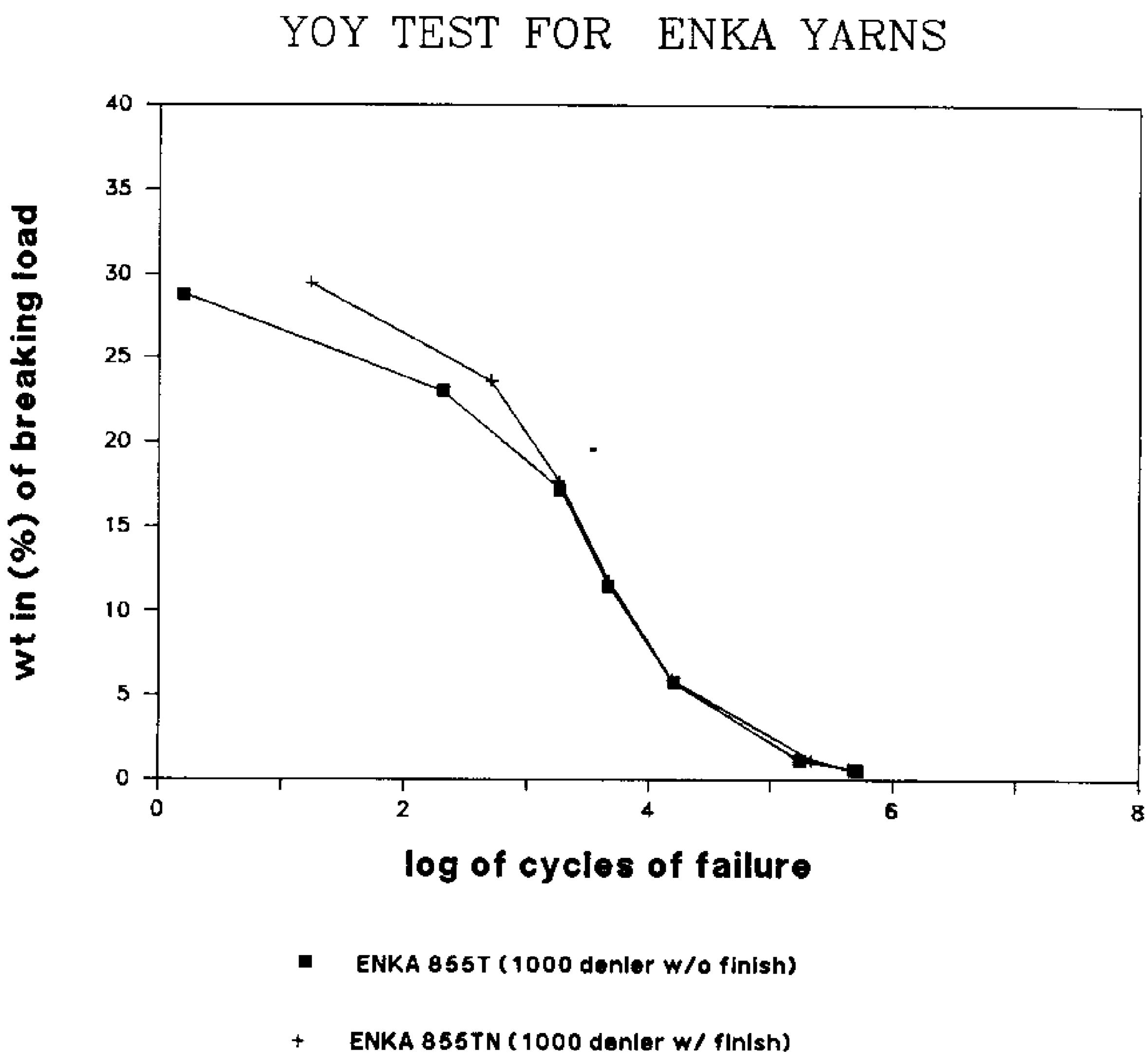

YOY TEST FOR ENKA YARNS
wt in (%) of breaking load
40
35
30
25
20
15
10
5
0
0
2
4
6
8
log of cycles of failure
ENKA 855T (1000 denier w/o finish)
ENKA 855TN (1000 denier w/ finish)

Figure 5

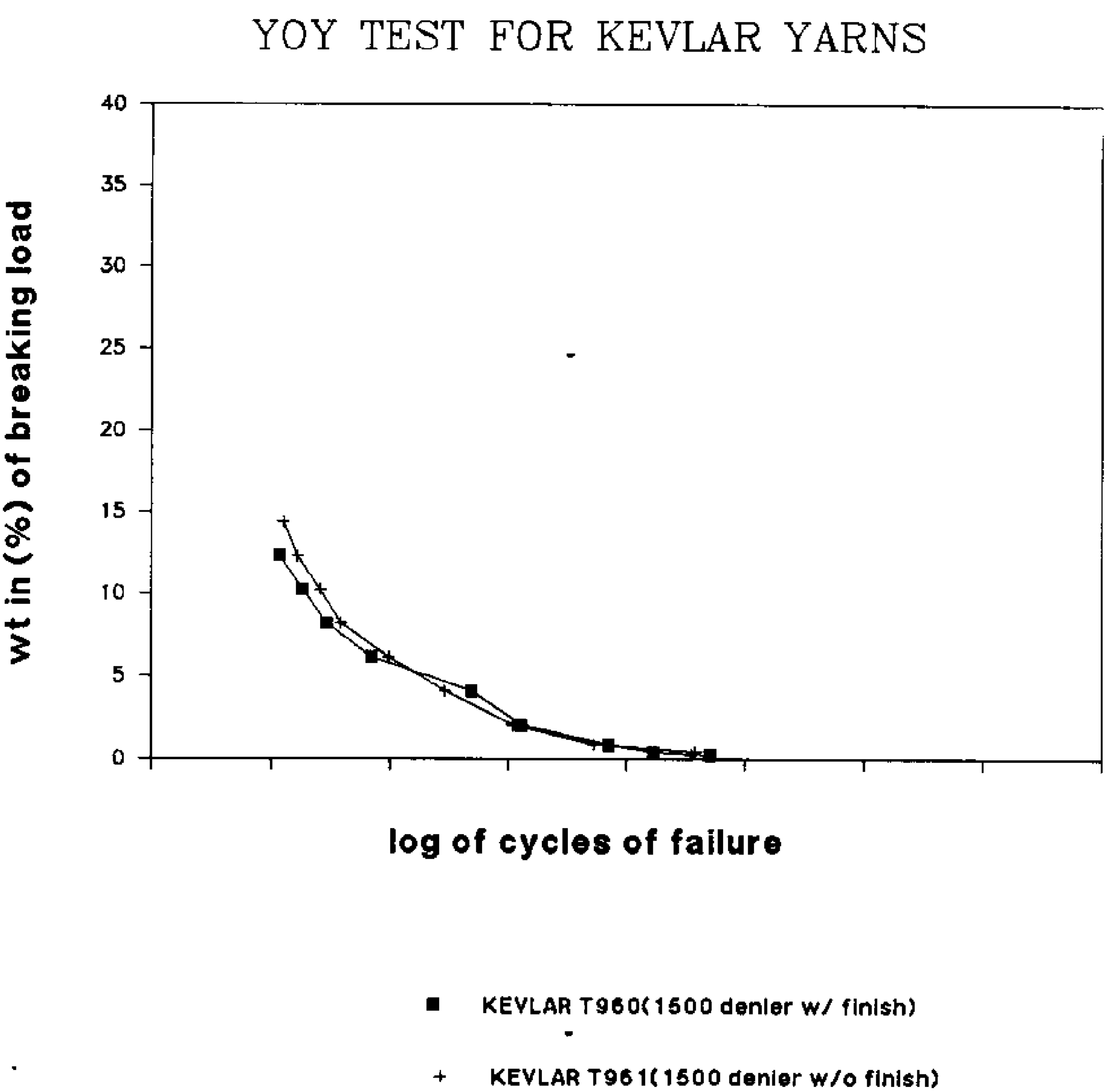

YOY TEST FOR KEVLAR YARNS
40
35
30
25
20
15
10
5
0
wt in (%) of breaking load
log of cycles of failure
KEVLAR T960(1500 denier w/ finish)
KEVLAR T961(1500 denier w/o finish)

Figure 6

YOY TEST FOR KEVLAR AND ENKA YARN

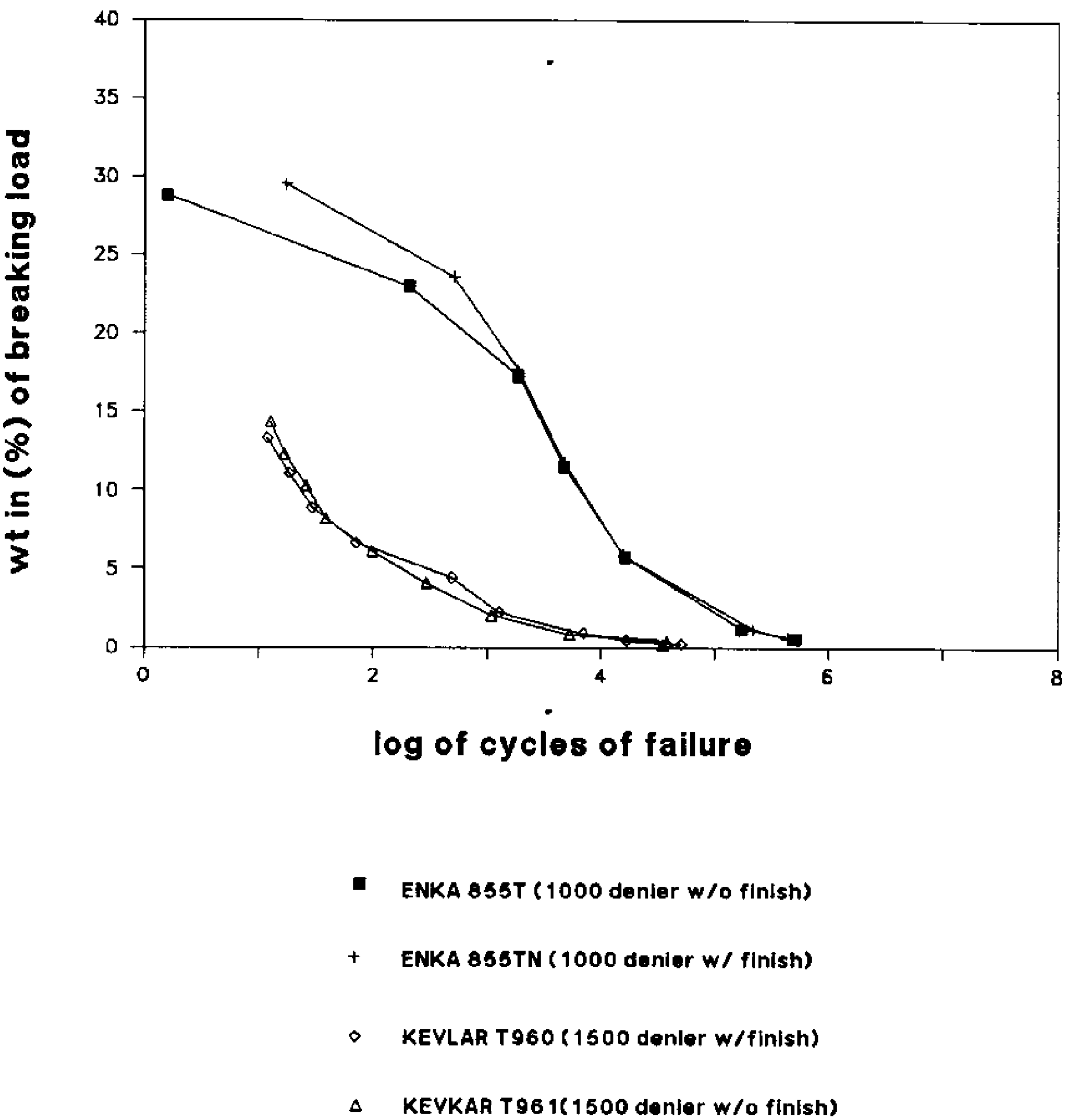


Figure 7

VII. LATERAL DEFORMATION

KEVLAR AND ENKA POLYESTER

COMPRESSION TEST

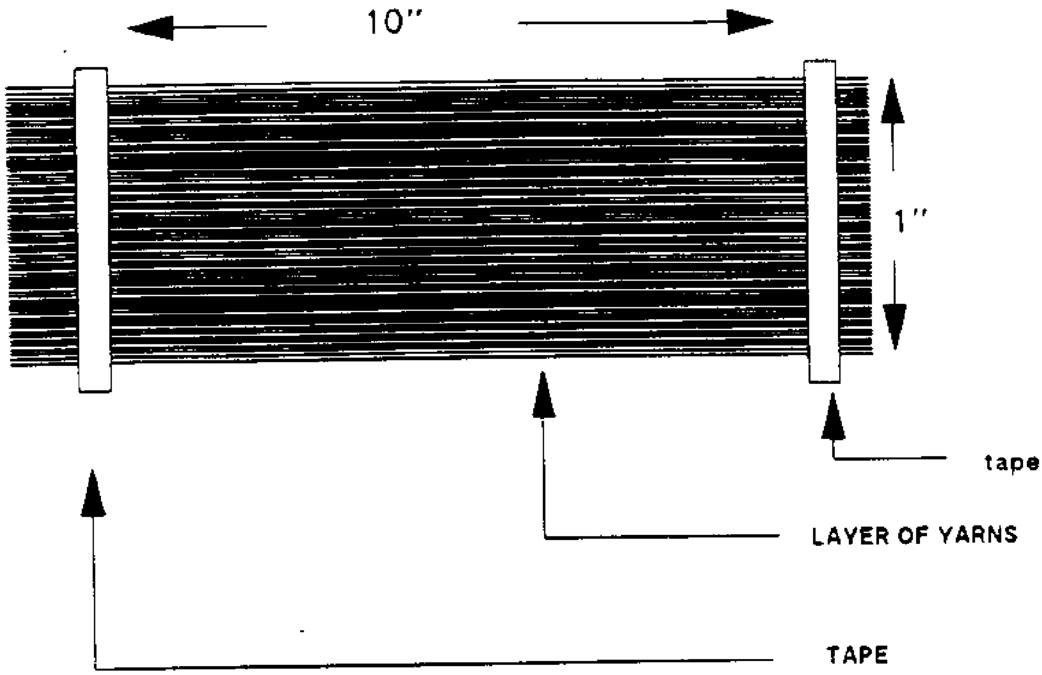
Sample Preparation

The yarn sample prepared for the compression test is shown in Figure 1. One layer of yarns was formed by winding the yarn on a skein winder. The layer then was taped and cut at suitable places to provide the desired sample length. The width of the layer was determined by the number of windings and the space between the yarns. In this experiment the width of the samples was one inch and the length of the sample was ten inches. The number of windings for all samples in this test was 60, except for the ENKA 855TN. ENKA TN was used in the form of a plied yarn and the number of windings was 13.

Experimental Set Up

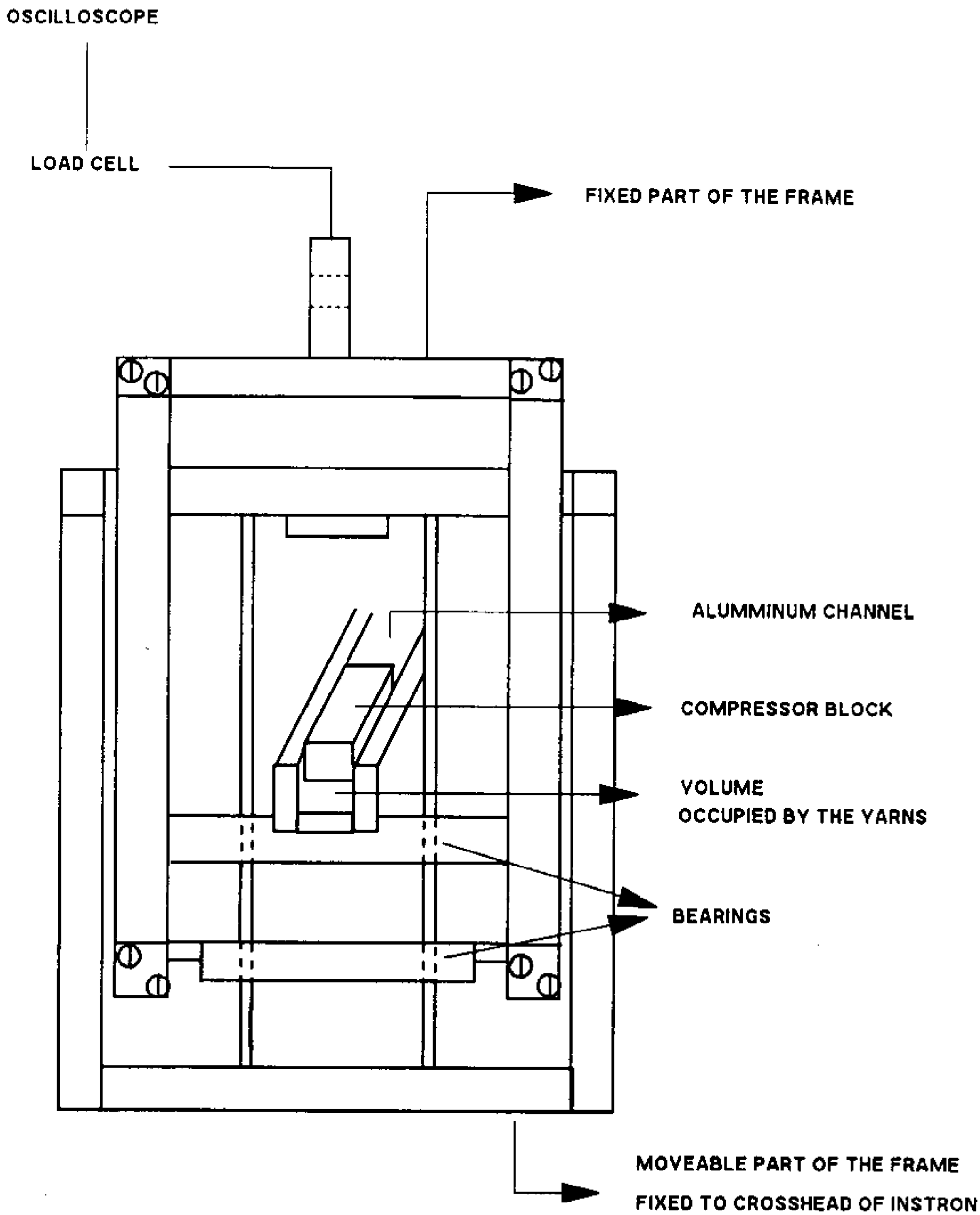
The equipment for the compression test is shown in Figure 2. The frame consists of two parts which move relative to each other. The fixed part of the frame was connected to the load cell which was continuously monitored by a digital oscilloscope. The moveable part of the frame was clamped to the crosshead of a screw driven Instron. An aluminum channel was firmly placed between these two parts of the frame as shown in Figure 2. The width of the channel was one inch and the length was five inches.

The yarn samples were gathered in parallel and placed in the channel to fill about 2/3rd of its volume. A block dimensioned to fit the channel piece closely was placed over the bundle of yarns. When the crosshead of the Instron was moved downward the block was pressed by the top edge of the moving part of the frame. The pressure was recorded by the load cell along with the oscilloscope. Displacement of the block down into the channel was converted to fiber/yarn volume. The recorded trace of the oscilloscope (voltage vs. time) was converted to pressure vs. volume fraction of fiber. A typical case of five compression cycles is shown in Figure 3. Each assembly was run through multiload cycles. The initial and the final cycles were plotted for most of the samples. Then a few layers were removed from the channel and the whole process was repeated. This test was done for four types of yarns — ENKA 855T, ENKA 955TN, KEVLAR T960, and KEVLAR T961. The results are plotted and given in the following figures.



SAMPLE OF YARN LAYER

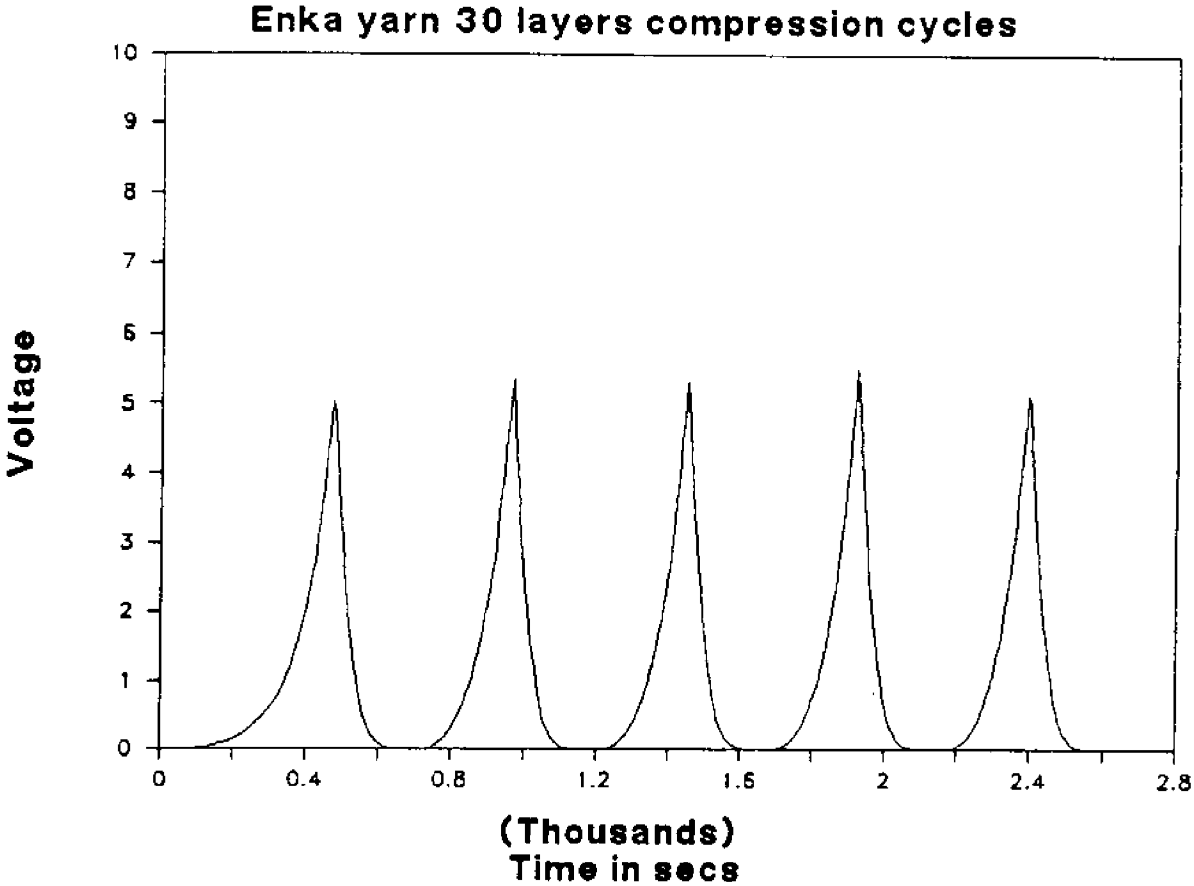
Figure 1



EXPERIMENTAL SETUP FOR COMPRESSION TEST

Figure 2

Voltage vs Time Graph

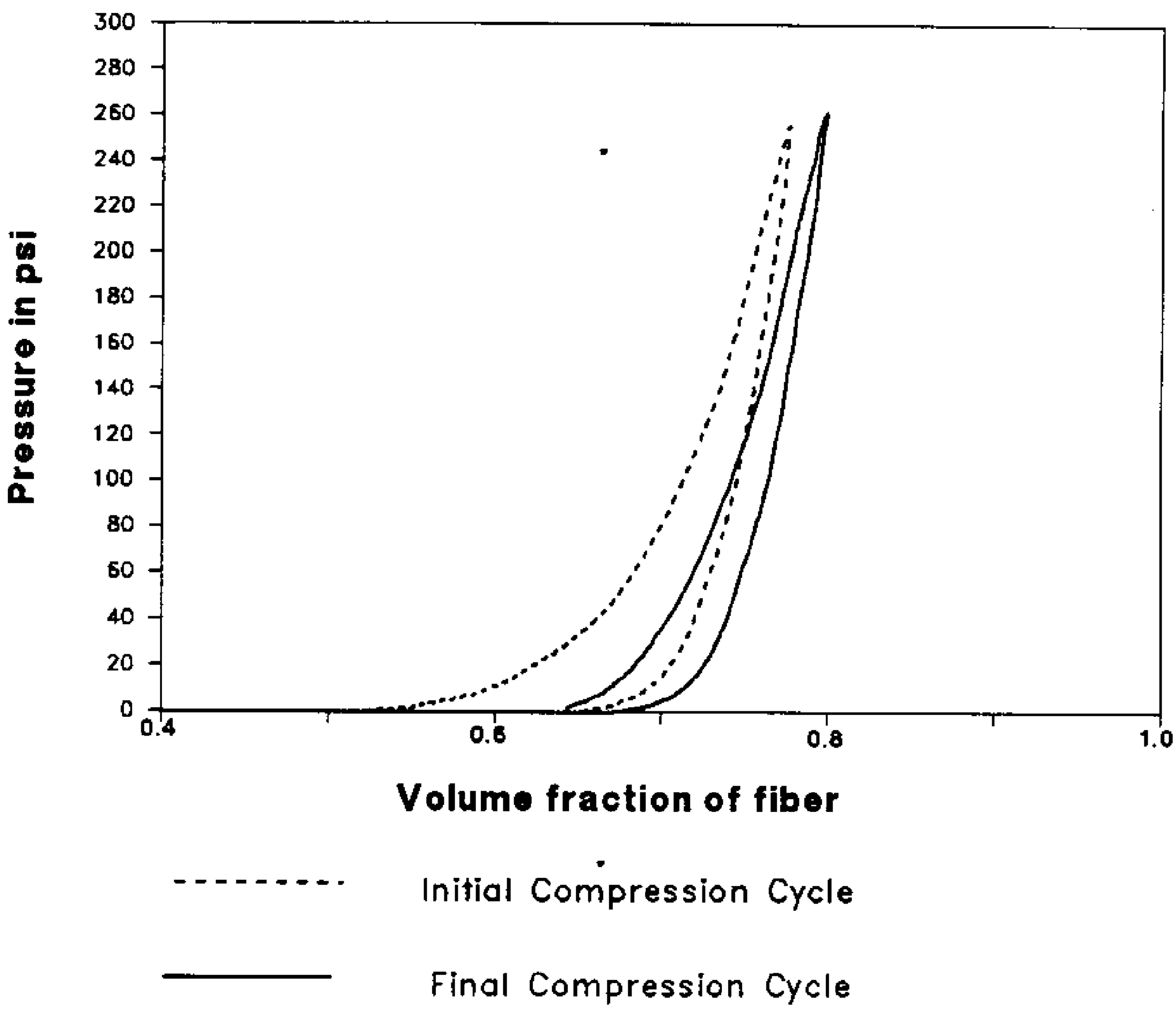


1 volts = 100lb

Figure 3

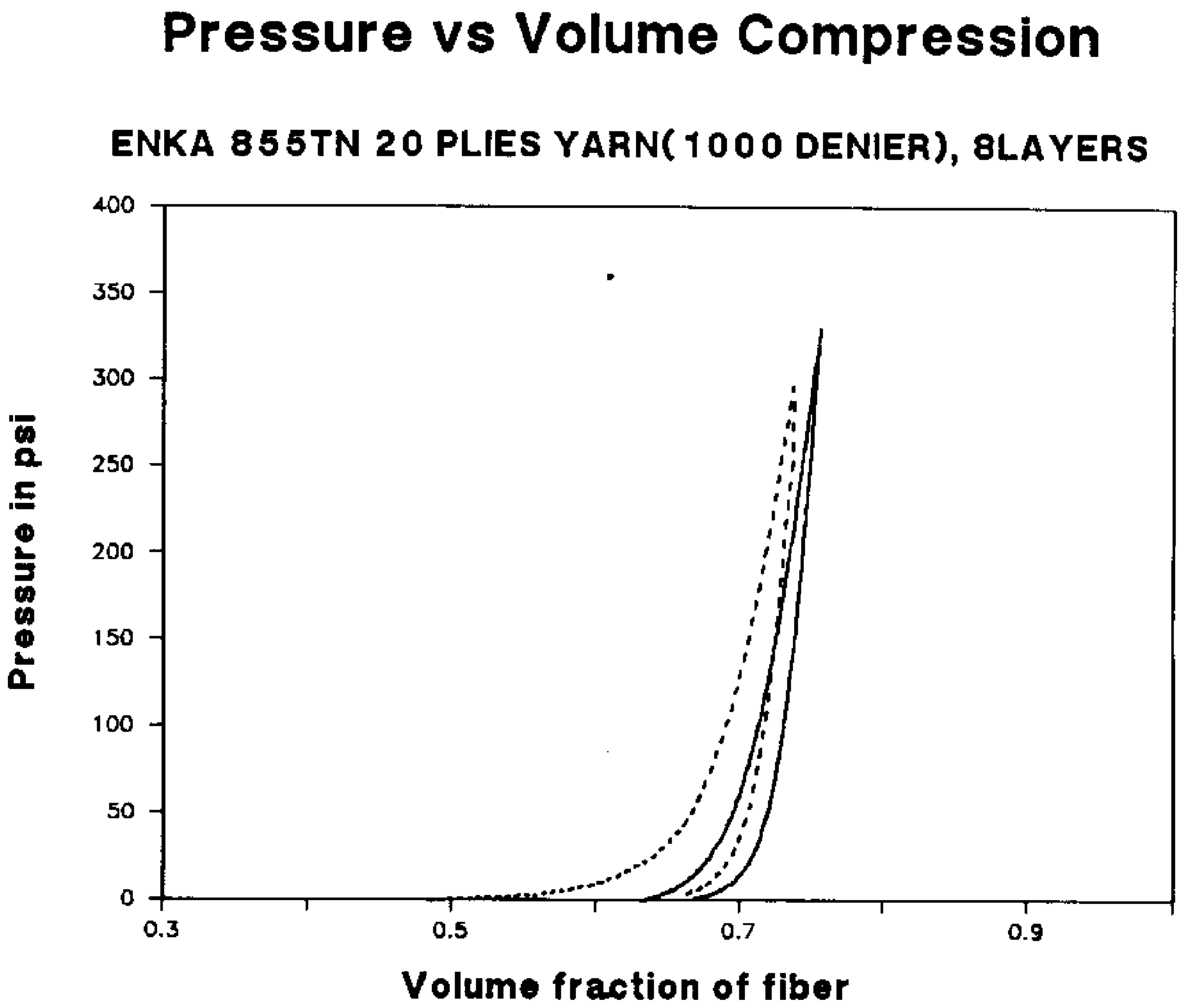
Pressure vs Volume Fraction

ENKA 855T YARN (1000 DENIER), 30 LAYERS



Number of compression cycles was 5

Figure 4



------------ Initial Compression Cycle

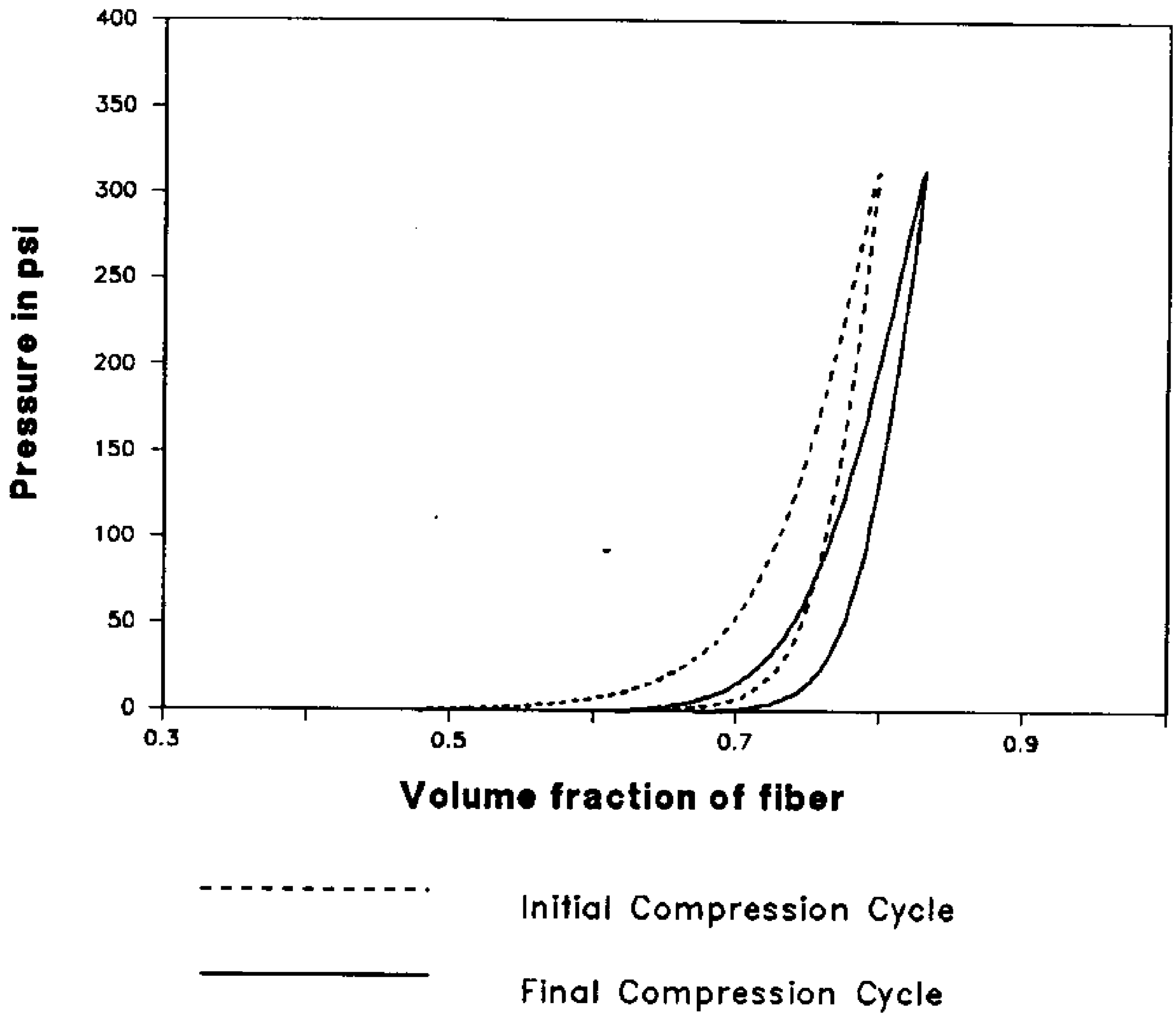
——————— Final Compression Cycle

Number of compression cycles was 4

Figure 5

Pressure vs Volume Compression

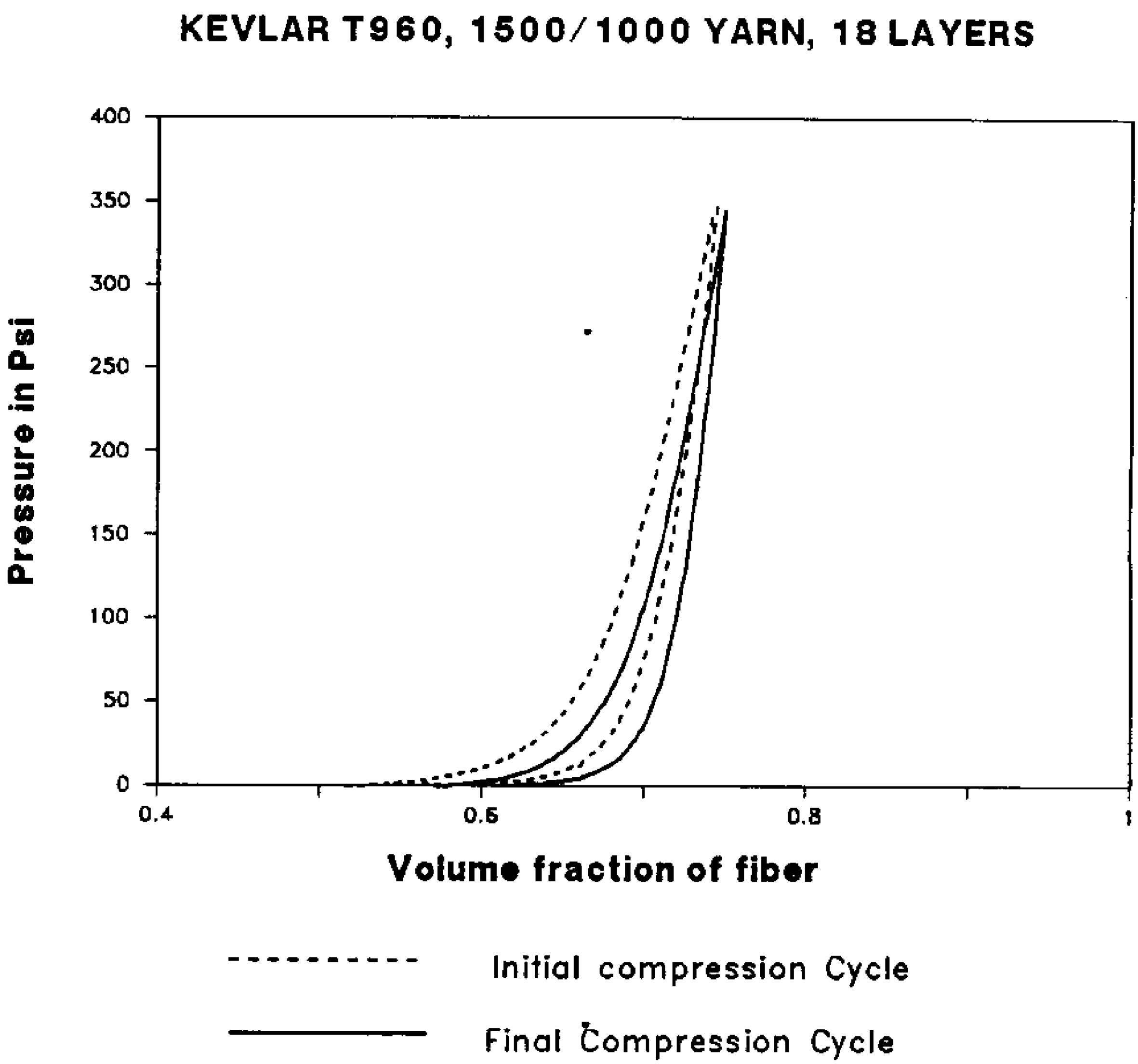
ENKA 855TN 20 PLIES YARN(1000 DENIER), 5 LAYERS



Number of compression cycles was 3

Figure 6

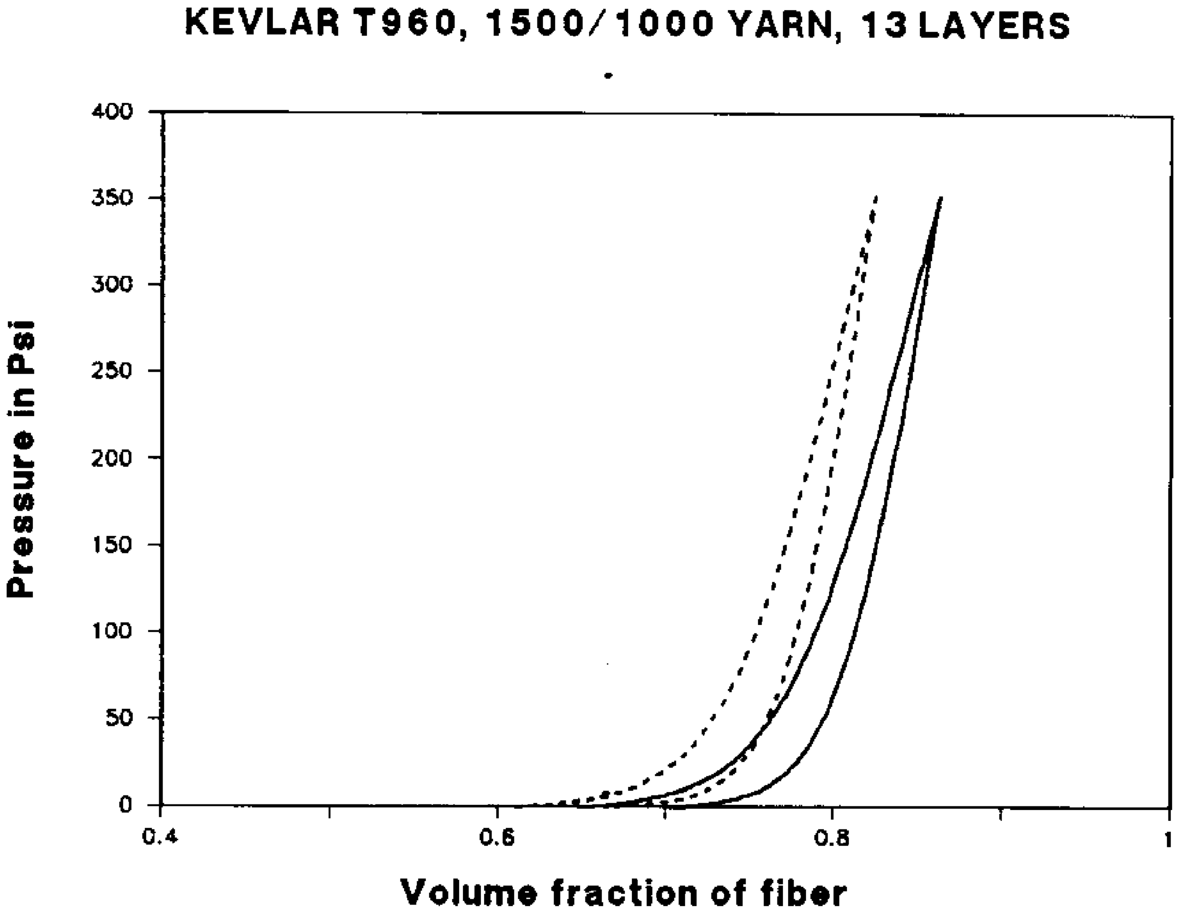
Pressure vs Volume Fraction



Number of Compression Cycles was 3

Figure 7

Pressure vs Volume Fraction



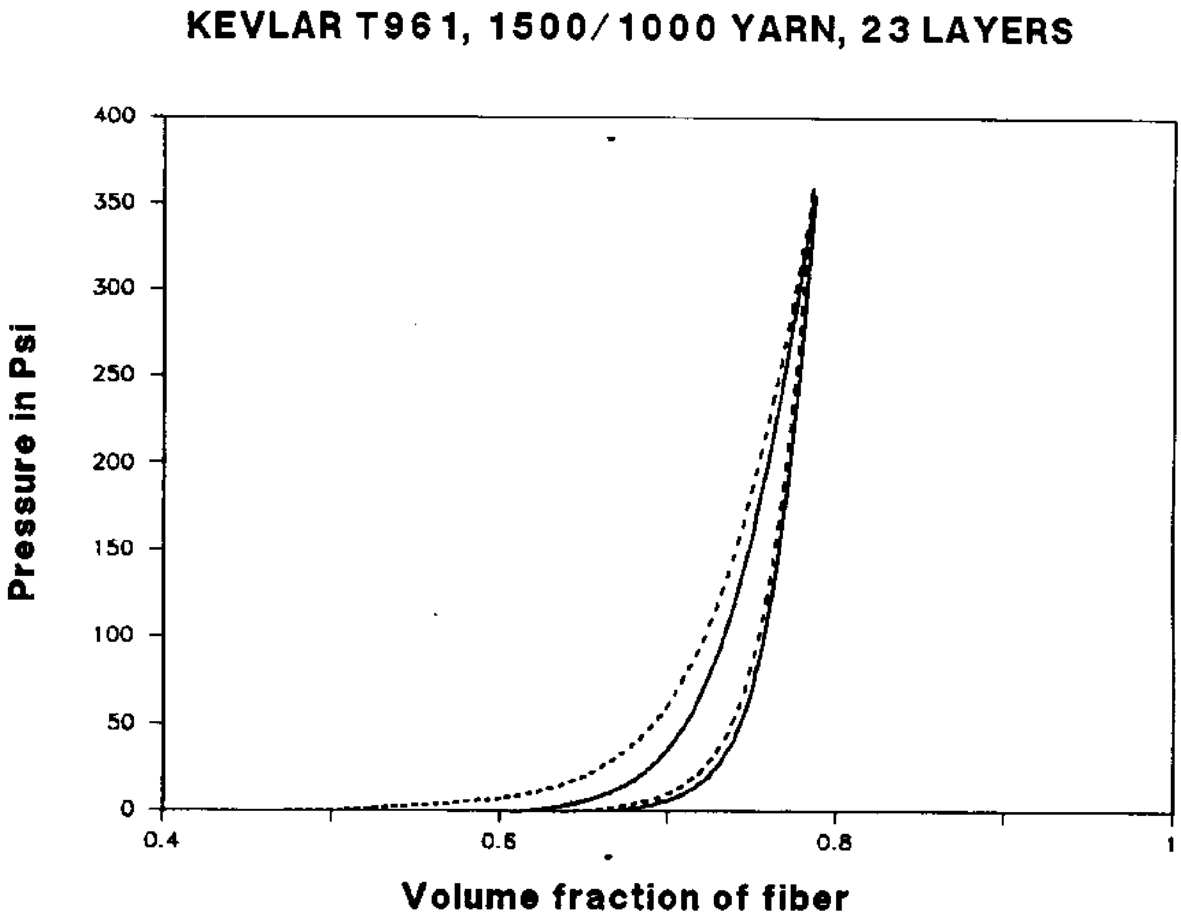
- - - - - - - - - -   Initial compression Cycle

————————   Final Compression Cycle

Number of Compression Cycles was 3

Figure 8

Pressure vs Volume Fraction



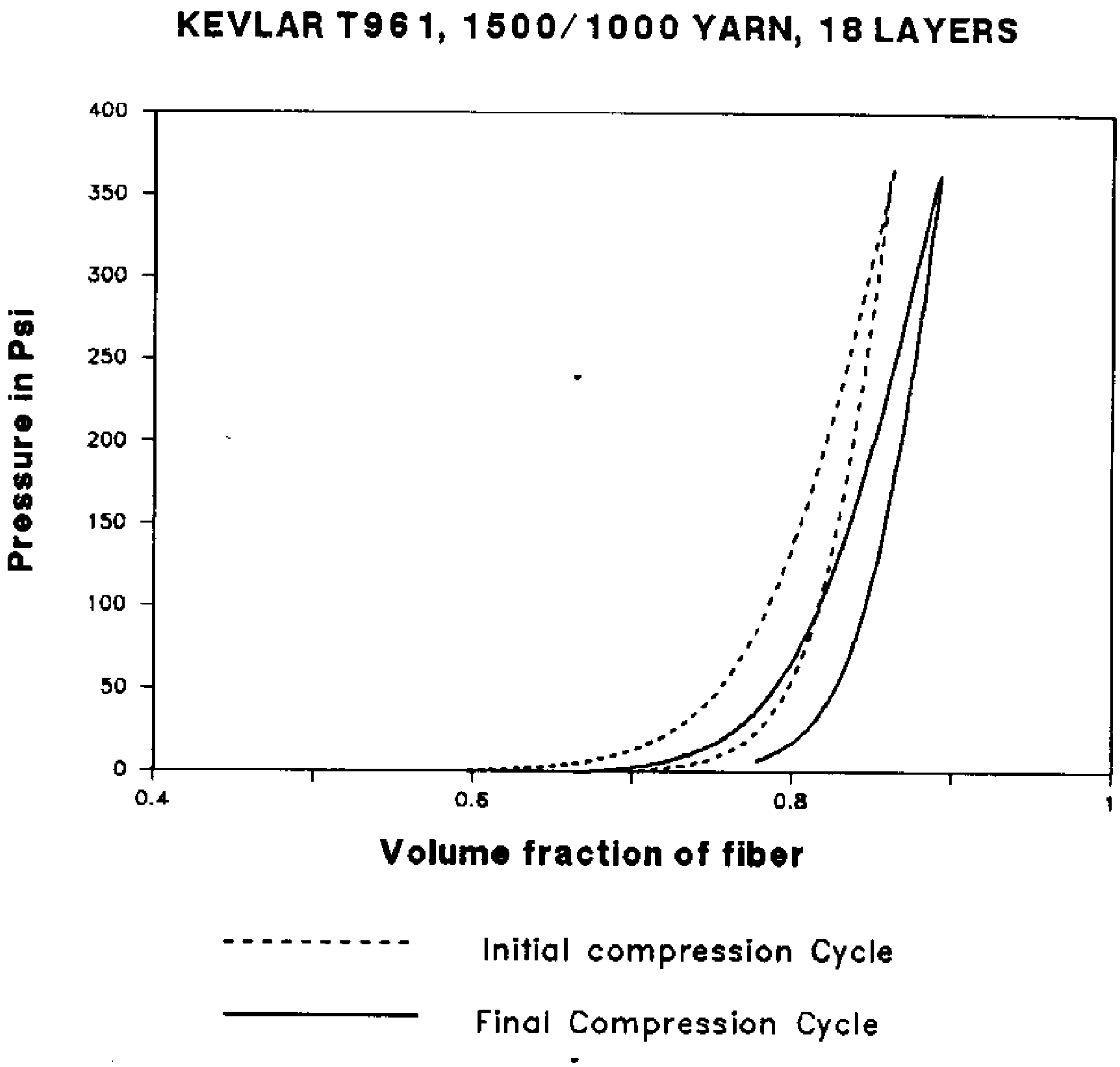
- - - - - - - - - - Initial compression Cycle

——— Final Compression Cycle

Number of Compression Cycles was 3

Figure 9

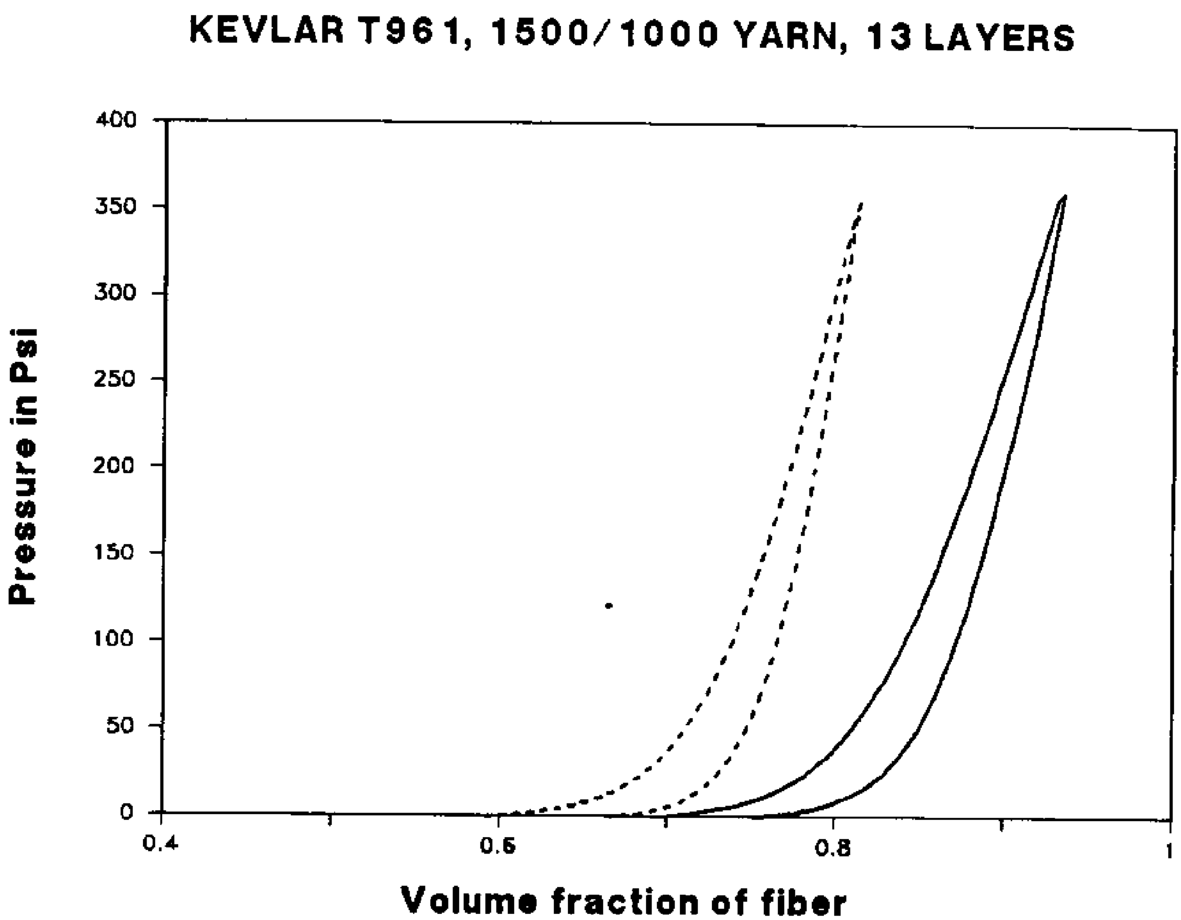
Pressure vs Volume Fraction



Number of Compression Cycles was 3

Figure 10

Pressure vs Volume Fraction



- - - - - - - - - - Initial compression Cycle

———————— Final Compression Cycle

Number of Compression Cycles was 3

Figure 11