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Contract NOnr 478 (00)

Our Case Number C51137

A STUDY OF TENSILE MECHANICS OF SOME BLENDED WOOLEN YARNS

by

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Technical Report Number 2

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71

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SUMMARY

Several aspects of the tensile behavior of "3-Run" woolen type blended wool-nylon and wool-viscose yarns have been examined and rationally interpreted in terms of the intrinsic fiber properties, their own geometry, and the geometry of the yarns. The last item was the subject of a study reported in Technical Report No. 1, Contract NOnr 478(00).

In the present report it is shown that very low-strain ease of extensibility--a characteristic believed to contribute to the "softness" of a yarn--is principally functional with fiber crimpiness and yarn twist. Whatever had been the nominal state of crimp prior to processing (both synthetics had been artificially crimped, and the wool was naturally crimped), fibers removed from yarns showed decreasing crimp in the order: wool, nylon, viscose. Yarns composed entirely of wool, nylon and viscose by themselves also exhibited crimpiness or low-strain ease of extensibility, in decreasing order: wool, nylon, viscose. In fact, both the viscose fibers and viscose yarn manifested negligible crimpiness.

The net effect in blended yarns was such that nylon blended with wool only partly depressed the yarn "softness". Viscose blended with wool had the effect of stiffening the yarn, at low strains, to the point where 50-50 wool viscose behaved like 100% viscose, insofar as low-strain softness is concerned.

The effect of blend, as just described, is most evident at the low to moderate twists. Increasing the twist decreases yarn low-strain softness for all blends until at about 12 or 14.5 t.p.i. they are all essentially "hard" yarns. Even at this level of twist, however, the greater crimpiness of the wool fiber retains its distinction in that the 100% wool yarns remain the most crimp in the group.

At strains up to 50% of rupture, the elastic recovery of yarns from repeated straining reflects very closely the elastic recovery of the fibers. Below 6%-8% extension, wool fibers exhibited a small superiority over nylon which, in turn, was superior to viscose. Above 6% strain, nylon becomes increasingly superior to wool and both are substantially more recoverable than viscose. The 100% wool, nylon, and viscose yarns at all twists exhibited almost exactly the same values of elastic recovery as the fibers.

The blended yarns had elastic recovery values intermediate between those of the constituent fibers. In the viscose series, there was a strictly proportional effect of blend composition on yarn recovery

decreasing from 100% wool to 100% viscose. In the nylon series, the reversal in superiority of wool and nylon was demonstrated in that at 5% strain there was a gradual decrease in elastic recovery with blend from 100% wool to 100% nylon, while at 10% and 15% strain recovery was improved by addition of nylon. Here, however, the effect was not proportional with composition. The effect of adding nylon was more pronounced in the earliest additions and at about 50%-75% nylon the blend was substantially as good as 100% nylon.

Although it is shown that twist has little or no effect on the elastic recovery of the yarns, it does have a decided influence on the decay in load associated with relaxation under repeated straining. Load decay is greatest at lowest twist, diminishing toward the level of the basic fiber load decay at about 14.5 t.p.i.

The mechanism postulated to explain this effect of twist is also important in explaining ultimate yarn strength. It involves an assumption already experimentally validated by the observations of Technical Report No. 1. It is simply that the yarn at any twist above a certain minimum, say 4.5 t.p.i., for the present yarns, has a cohesive "heart zone" surrounded by a fringe. In the heart, the packing density of the fibers is sufficiently high to obviate slippage during yarn straining. Hence, these fibers are strained and recover according to their intrinsic elastic and tensile properties. In the fringe, the fibers either uncrimp or slip, and on recovery of the yarn they either recrimp, slip back or buckle. In any event, the fringe does not seem to impede dimensional recovery of the heart fibers.

The effect of increasing twist is to reduce the fraction of fringe fibers in the average yarn cross-section. Hence, in repeated straining, the load decay occasioned by inelastic frictional resistance of the fringe is reduced with increasing twist.

By the same token, when ultimate yarn strength is considered, increasing twist increases the amount of load-bearing heart fibers in the average cross-section. Hence, increasing twist gradually improves yarn strength up to a so-called "optimum-twist". At the same time that twist improves strength by bringing more fiber into the high density heart zone of the yarn, it also increases the angulation of these fibers with the yarn axis. Because of this angulation, only a component part of the fiber tensile resistance is felt in the tensile strength of the yarns.

The component effect is one aspect of yarn geometry that interferes with full realization of fiber strength in spun yarns. Another aspect is related to the fact that the helix angle is greater on the outside of the yarn than the inside. As a result of this, during yarn straining there is a gradient of fiber straining from inside to outside of the heart zone, and some fibers will break before others. This is a geometric serigraph.

Besides geometric serigraph, there is the omnipresent fiber-to-fiber variability in elongation to rupture, which adds its influence in depressing yarn strength in the same manner as the geometric serigraph.

These effects are accounted for in an efficiency factor, η , calculated for the blends in this study. The method is described and is adapted for spun staple blends from the method originally developed for filament yarns and hard fibers in cordage structures.

The explanation for existence of an "optimum twist" is related to the fact that η decreases with increasing twist. At first, while twist is increasing, the heart zone fraction angulation effects are small. Eventually, angulation effects rapidly increase and a maximum strength is found--beyond about 9-1/2 t.p.i. yarn strength falls off.

However, at optimum twist, 9-1/2 - 12 t.p.i. for the present yarns, it was shown that a certain fraction of fibers still form a non-working fringe zone, estimated to represent about 15% of the total of an average cross-section. The efficiency coefficient, η , must therefore apply only to the inner 85%, heart, of the yarn.

Beyond that, the existence of thin, or light-weight, regions within test samples of the yarn was also demonstrated. Strength of short specimens was shown to be closely dependent on their weight and hence the strength of a longer specimen would be governed by the presence of thin spots.

The fringe effect and the longitudinal weight variation effect are combined in a factor "X". When the weighted average tenacities of the fiber in the blends are corrected for both "X" and η , the real yarn strengths can be predicted with gratifying accuracy.

Adding nylon to wool increases yarn strength, but more slowly at first than at concentrations above 10%. This is predicted. Adding viscose to wool increases yarn strength to any worthwhile degree only beyond 50% concentration, and this too is predicted.

TABLE OF CONTENTS

<u>Subject</u>	<u>Page Number</u>
I. INTRODUCTION	1
II. EXPERIMENTAL WORK	3
A. Fiber Properties	3
1. One-Time Loading to Rupture	3
2. Summary of the Fiber Tenacity Study	6
3. The Average Stress-Strain Diagram of Fibers .	7
4. Fiber Repeated-Strain Tests	8
B. Yarn Tensile Studies - One Cycle To Rupture	9
C. Yarn Repeated-Strain Studies	11
III. DISCUSSION	13
A. General	13
B. Low-Strain Extensibility	17
C. Repeated-Strain Elasticity	18
D. Yarn Rupture Properties	25
1. Theoretical Maximum Translation Efficiency ..	25
2. Actual Yarn Efficiencies vs. Theoretical	31
IV. CONCLUSIONS	38
A. Low-Strain and Repeated Stress Behavior	38
B. Yarn Strength Considerations	40

LIST OF TABLES

<u>Table Number</u>	<u>Title</u>	<u>Page Number</u>
I	Fiber Properties	3a
II	Comparison of the Properties of Long and Short Wool Fibers Tested at 1/2" Gage Length	5a
III	Percent Elastic Recovery of Fibers and Percent Load Decay in Five Cycles	9a
IV-A	Effect of Gage Length on Tensile Properties of Extracted 100% Wool	10a
IV-B	Effect of Gage Length on Tensile Properties of Extracted 100% Nylon	10b
IV-C	Effect of Gage Length on Tensile Properties of Extracted 50% Wool/50% Nylon	10c
IV-D	Effect of Gage Length on Tensile Properties of Extracted 100% Rayon	10d
IV-E	Effect of Gage Length on Tensile Properties of Extracted 50% Wool/50% Viscose	10e
V-A	Tensile Properties of Blended Yarns at 10" Gage Length	11a and 11b
V-B	Tensile Properties of Blended Yarns at 10" Gage Length	11c and 11d
VI	Partial and Total Elongation of a Wool Fiber at Different Levels of Extension as Related to the Mean Diameters of the Segments	15a
VII	Comparison of Load Decay of 100% Yarns with Respective Fibers	19a
VIII	Fiber Parameters Employed in Efficiency Calculations	30a
IX	Experimentally Determined Yarn Efficiencies	31a
X	Comparison of Actual and Theoretical Efficiencies	32a
XI-A	Effect of Gage Length vs. Found Efficiency at 9-1/2 t.p.i.	34a
XI-B	Ratio "X" at 2.5 Gage Length, 9-1/2 t.p.i.	34a

LIST OF FIGURES

<u>Figure Number</u>	<u>Title</u>	<u>Page Number</u>
1	Frequency Distribution of Wool Fiber Deniers	5b
2	Average Fiber Stress-Elongation Diagrams	7a
3	Average Wool Fiber Load-Elongation Diagram	7b
4	Average Nylon Fiber Load-Elongation Diagram	7c
5	Average Viscose Fiber Load-Elongation Diagram	7d
6	Yarn Stress-Elongation Diagrams Wool-Nylon Series 4.5 tpi	11e
7	Yarn Stress-Elongation Diagrams Wool-Nylon Series 7 tpi	11f
8	Yarn Stress-Elongation Diagrams Wool-Nylon Series 9.5 tpi	11g
9	Yarn Stress-Elongation Diagrams Wool-Nylon Series 12 tpi	11h
10	Yarn Stress-Elongation Diagrams Wool-Nylon Series 14.5 tpi	11i
11	Yarn Stress-Elongation Diagrams Wool-Viscose Series 4.5 tpi	11j
12	Yarn Stress-Elongation Diagrams Wool-Viscose Series 7 tpi	11k
13	Yarn Stress-Elongation Diagrams Wool-Viscose Series 9.5 tpi	11-l
14	Yarn Stress-Elongation Diagrams Wool-Viscose Series 12 tpi	11m
15	Yarn Stress-Elongation Diagrams Wool-Viscose Series 14.5 tpi	11n
16	Effect of Twist on Rupture Stress Wool-Nylon Series	11o
17	Effect of Twist on Rupture Stress Wool-Viscose Series	11p
18	Effect of Blend on Elastic Recovery Wool-Nylon Series	12a
19	Effect of Blend on Elastic Recovery Wool-Viscose Series	12b
20	Effect of Twist on Elastic Recovery Wool-Nylon Series	12c
21	Effect of Twist on Elastic Recovery Wool-Viscose Series	12d
22	Effect of Twist on Load Decay Wool-Nylon Series	12e
23	Effect of Twist on Load Decay Wool-Viscose Series	12f
24	Effect of Blend on Load Decay Wool-Nylon Series	12g
25	Effect of Blend on Load Decay Wool-Viscose Series	12h
26	Effect of Repeated Straining on Yarn Tenacity Wool-Nylon Series	13a
27	Effect of Repeated Straining on Yarn Ten. Wool-Visc. Series	13b
28	Effect of Repeated Straining on Yarn Rupture Elongation Wool-Nylon Series	13c
29	Effect of Repeated Straining on Yarn Rupture Elongation Wool-Viscose Series	13d
30	Fiber Crimp and Effect of Twist on Yarn Crimp	17a
31	Summarized Effect of Blend on Yarn Elastic Recovery	18a
32	Effect of Strain on Elastic Response of Wool, Nylon and Viscose	18b

LIST OF FIGURES (Continued)

<u>Figure Number</u>	<u>Title</u>	<u>Page Number</u>
33	Effect of Strain on Elastic Response of Wool, Nylon, and Viscose	18c
34	Diagrammatic Version of the Heart-Fringe Effect	20a
35	Effect of Strain Level on Load Decay Wool-Nylon Series	22a
36	Effect of Strain Level on Load Decay Wool-Viscose Series	22b
37	Graphical Method of Compositing Two Fiber Species	30b
38	Effect of Twist on Translation Efficiency (Theoretical for several blends)	31b
39	Effect of Blend on Translation Efficiency Nylon Series (Theoretical for several twists)	32b
40	Effect of Blend on Translation Efficiency Viscose Series (Theoretical for several twists)	32c
41	Effect of Gage Length on Yarn Tenacity	34b
42	Dependence of Strength on Yarn Weight at Different Gage Lengths Nylon Series	34c
43	Dependence of Strength on Yarn Weight at Different Gage Lengths Nylon Series	34d
44	Dependence of Strength on Yarn Weight at Different Gage Lengths Viscose Series	34e
45	Dependence of Strength on Yarn Weight at Different Gage Lengths Viscose Series	34f
46	Comparison of Predicted and Experimental Yarn Strengths Nylon Series	36a
47	Comparison of Predicted and Experimental Yarn Strengths Viscose Series	36b
48	Tenacity vs. Blend for Six Different Wool-Nylon Series Compared with Yarns of Present Study	37a

I. INTRODUCTION

Yarn strength has been one of the principal gages of product quality employed by yarn spinners for decades, if not centuries. It is pretty safe to assume that not one spinning mill in a thousand--including cotton, woollen, worsted, and synthetic mills--runs a day without testing the tensile strength of its yarn. Yet, in contrast with the functional requirements of cordage and industrial fabrics, the major uses of apparel textiles rarely contemplate failure in service directly from simple tensile loading.

A rope must be built strong enough to hold a loaded cargo net; a conveyor belt fabric is required to sustain severe tensile stresses. On the other hand, suiting fabric is not intended to support the wearer's weight in tension and has no minimum strength specification that can be calculated on such a basis. One is entitled to enquire, therefore, why the apparel yarn spinner is concerned with yarn strength.

In answer to this question, it may probably be said with some certainty that mill operators have learned from their own experience that, with all other things held constant, a stronger yarn can be warped, quilled, wound, beared and woven more efficiently and with fewer fabric seconds. For two very cogent reasons, namely plant efficiency and product quality, the strength of yarns would be important to the manufacturer of apparel fabrics.

Interest in yarn tensile strength, however, is not confined to considerations of manufacturing economics. There are some apparel service conditions which do impose significant tensile loads on the fabric and its yarns. In such instances, although the fabric durability may also depend on such factors as yarn extensibility and fabric geometry, the strength of the yarns is unquestionably a first order factor.

Beyond simply the tensile strength of yarns, their elastic behavior in tension at low loads and in repeated straining are also matters of fundamental importance to serviceability of fabrics. In a broad program directed toward the improvement of Navy fabrics through fiber blending, a study of the effect of blend composition on yarn tensile properties is of major importance. To appreciate this, consider what contributes to apparel fabric serviceability and the role of yarn tensile properties in this respect.

In general, the serviceability of apparel is judged in three

areas, the relative importance of each varying with the type of garment, as will be apparent. These areas are: 1) durability, 2) comfort, and 3) aesthetics. A lady's cocktail gown, for example, calls for a fabric of maximum aesthetic appeal, almost always accomplished at the cost of reduced durability and comfort. Undergarments for Arctic military service demand a maximum of comfort and durability; no comments about their aesthetics is required.

In the area of fabric durability, yarn strength and extensibility are functionally related to fabric tear-resistance. Thus, although simple tensile rupture of apparel may be very unusual, certainly resistance to tearing, which involves yarn tensile failure, is an important durability factor. Certain conditions of abrasion also may involve tensile loading of yarns, and therefore resistance to tension-abrasion will also contribute to fabric durability.

Service use of garments frequently includes conditions imposing repeated low-strain exertions which the fabric must sustain without failure. These strains may be set up in a variety of ways at button-holes, elbows and knees, at under-arm seams, etc. While fabric failure or severe distortion in such regions may be markedly influenced by garment tailoring as well as fabric construction, it is certainly to be expected that the elastic response of yarns in repeated-strain will be of major significance.

In the area of comfort, the subjective sensation of softness or harshness will depend to a moderate extent on tensile stiffness. Perhaps bending stiffness and bending resilience are more directly controlling, but these are probably in turn related to their tensile counterparts. Again, fabric geometry will play a prime role, but certainly not an exclusive one. Similarly, dimensional stability--a comfort as well as an aesthetic consideration--will be in large measure determined by yarn tensile recovery characteristics.

Taken altogether, therefore, yarn tensile stiffness, strength, extensibility and repeated-strain resilience and recovery may be considered important to the serviceability of apparel fabrics. Any attempt at improvement through blending together of fibers should eventually call on a background of information on the effects of blend composition on yarn tensile properties.

The work reported herein was undertaken with this viewpoint in mind. A series of 55 blended woolen type wool-nylon and wool-viscose yarns varying in twist and composition were examined. These yarns and the manufacturing procedure were more fully described in Technical Report No. 1 (4).

The present report is concerned with:

- a) Single fiber properties.
- b) Yarn tensile strength and elongation in one cycle of loading to rupture.
- c) Yarn repeated-strain behavior at low and moderately high loads.

Presentation of experimental data will be made for each of these phases separately with a brief discussion of the significance of the several different items. A semi-quantitative mechanistic interpretation of the tensile response characteristics of these yarns will follow.

It was desired, among other objectives, to relate the present knowledge and theories of fiber-yarn mechanics as developed for yarns composed of a single fiber type to yarns composed of two different fiber types. More specifically, analytical techniques for predicting translation efficiency of fiber strength into such products as filament yarn and cordage structures (14, 15) are to be applied here for the case of wool-viscose and wool-nylon blends.

II. EXPERIMENTAL WORK

A. Fiber Properties

Commercial stocks of fiber of the following designations were used in the preparation of the pedigreed series of yarns:

Wool - 6 months Texas 64's (nominal 0.5% grease)

Nylon - type 200 - 3 denier - 2 1/2" semi-dull

Viscose - Grade A - 3 denier - 2 1/2" dull

Samples of fiber for testing were taken from both raw stock and low-twist (4 1/2 t.p.i.) yarn after solvent extraction of spinning oils.

1. One-Time Loading to Rupture

Determinations were made of single-fiber denier by means of the vibroscope. Tensile stress-strain tests were performed on the Instron tester at several gage lengths. The results of these tests are given in Table I. It is obvious that a large number of repeat tests were run on the wool. This was done for a number of reasons.

TABLE I

FIBER PROPERTIES

<u>Sample</u>	<u>Operator</u>	<u>No. of Fibers</u>	<u>Gage Length Inches</u>	<u>Strength Gms.</u>	<u>Denier</u>	<u>Tenacity</u>		<u>Rupture Elongation</u>	
						<u>Gms/Den</u>	<u>% C.V.</u>	<u>%</u>	<u>% C.V.</u>
<u>Wool</u>									
Grease stock	I.E.	38	1	4.27	4.86	0.88	41	30.3	28
Extracted stock #1	I.E.	41	1	4.58	3.76	1.22	18	34.3	31
Extracted stock #2	I.E.	46	1	4.50	4.09	1.10	16	31.6	32
Extracted stock #1	H.R.	44	1	5.46	4.34	1.26	14	34.4	23
Extracted stock #2	H.R.	40	1	5.59	4.40	1.27	15	32.8	34
Extracted yarn	C.W.	47	1	5.01	3.95	1.28	19	25.5	42
Extracted yarn	C.W.	53	1	5.10	4.01	1.29	22	29.3	36
Extracted yarn	P.T.	51	1	4.58	4.02	1.15	22	28.7	18
Extracted yarn	C.C.	22(S)	1/2	5.88	4.78*	1.23	18	33.0	26
Extracted yarn	C.C.	22(L)	1/2	6.64	4.80*	1.38	16	35.1	23
<u>Viscose</u>									
Stock	J.C.	25	2	6.82	3.54	1.95	23	13.1	23
Extracted yarn	H.R.	44	1	6.92 (7.17)	3.33	2.14	14	12.0	19
Extracted yarn	C.W.	54	1	6.67	2.86	2.37	21	12.6	22
Extracted yarn	C.C.	25	1/2	7.29	--	--	--	14.9	24
Extracted yarn	C.C.	15	1/4	7.40	--	--	--	14.0	24
<u>Nylon</u>									
Stock	J.C.	25	2	12.99	3.37	3.86	16	37	25
Extracted yarn	C.C.	50	1	12.28	3.35	3.70	11	42.8	24
Extracted yarn	J.R.	42	1	12.25	3.24	3.83	11	46.9	12

*See text for explanation of these values.

First, the original sampling from wool stock (line 1 of Table I) gave evidence of being unusually weak (tenacity 0.88 gms./den.) for virgin wool. In view of the low nominal grease content (0.5%) no effort had been made to degrease the fibers prior to testing. However, in subsequent testing of fibers from yarns, the apparent tenacity increased to about 1.2 gms./den. while the apparent average denier dropped from 4.9 to about 4.1. For reasons having to do with yarn testing, the yarns had all been extracted with carbon tetrachloride. It seemed likely, then, that the original wool stock sample had given spurious results due to the presence of solvent extractable impurities. This would have accounted for the superfluous weight and low apparent tenacity.

To verify this, samplings were again taken from original stock and this time solvent extracted. Moreover, since there were actually two separately identified bags of wool, these were each tested separately. Lines 2 through 5 give the data for these tests. It will be seen that the average tenacities do not vary much among these four, although operator H.R. gave results on both stocks #1 and #2 which seemed to indicate a bias in favor of selecting heavier fibers.

By this time fiber testing from extracted yarn had been repeated at 1" gage length twice more to verify the original favorable tenacity findings. Several questions had now been raised and some of these settled. First, it was almost certain that the original grease-wool data was not useful in connection with subsequent work. Second, it was fairly certain that stocks #1 and #2 did not show any reliable differences. Third, there was evidence of operator bias in selecting fibers. It was understood that any one sampling could include principally the heavier-than-average fibers in a tuft. But the evidence seemed to indicate that such a biased sample probably would not yield unusual tenacity or elongation data.

The question had yet to be resolved, however, as to whether a sampling bias in favor of picking longer-than-average fibers might influence the average tenacity and elongation results. The last two lines pertaining to wool fiber tests concern this experiment. A 6" length of yarn was gently untwisted and clamped across its middle. All the fibers not held in the clamp were carefully teased out of the fiber "beard" on each side of the clamp. What remained then were only those fibers and all of those fibers which traversed a particular random cross-section of yarn.

These fibers were then sorted into three length groups: under one inch long, between one and about 1-3/4" long, and those over 1-3/4" long. It was desired to compare the properties of the short group with the long group. To do so required that both be tested at a common gage length and in similar circumstances. Therefore, both sets were tested at 1/2" gage length.

In examining these data three significant features developed. First, of all the samples of wool tested after solvent extraction (i.e., excluding line 1) both of the tests run at 1/2" gage length indicated the highest fiber deniers. Consideration of the limitations on the vibrascope technique for measuring fiber deniers suggested that in measuring 1/2" long wool fibers the method had been "pushed" somewhat. In calculating fiber weight by the "vibrating string" equation a correction for stiffness of the string is ordinarily insignificant and therefore ignored. In the case of the wool fibers tested at 1/2" gage length the stiffness of the fibers was probably introducing some inaccuracies. While this might have been taken care of by applying a suitable correction, there was little reliable information on the value of stiffness and other items which had to be employed. The correction was therefore not applied, but it was concluded that denier measurements on fibers shorter than 1" gage length would no longer be attempted.

A second feature of the experiment comparing long and short fibers is also noteworthy. It will be seen that both sets of data taken at 1/2" gage length give absolute strength values sensibly greater than tests run at 1". This was not entirely unexpected, since it is fairly well understood that the natural fibers are not uniform along their length, but have periodic or randomly spaced "weak spots" or weak regions. In testing at progressively shorter gage lengths the frequency of occurrence of weak spots in test specimens must go down. In consequence, the average strength of an assortment of short lengths will be greater than the average strength of long lengths of fibers. A similar effect was noted in the series of tests run on viscose fibers, namely an increase in measured strength with decreasing gage length. This situation has considerable bearing on subsequent calculations of yarn efficiency and will be dealt with again in Section III.

The third feature of the particular experiment under discussion relates directly to the comparison of properties of the long and short fibers. For convenience in discussion, this information is repeated in Table II with some amplification in regard to the long fibers. It was noted in scrutinizing the data for the long fibers that among the 22 which had been selected was a 9.5 denier fiber. Reference to Figure 1, a frequency histogram of wool fiber deniers for all 400+ extracted fibers measured, will confirm the fact that this denier occurs very rarely in the general population. The short fibers included none of such high denier.

Whatever the error in denier measurement that might be due to stiffness, as mentioned above, both the short and long fiber tests were subject to the same effect except in the case of the very heavy fiber. It appeared unreasonable to retain the "super-heavy" fiber in the long fiber group for comparison purposes. Table II, therefore, gives the properties of the long fiber group calculated first in its entirety, then with the 9.5 denier fiber discarded.

TABLE IICOMPARISON OF THE PROPERTIES OF LONG AND SHORT WOOL
FIBERS TESTED AT 1/2" GAGE LENGTH

<u>Property</u>	<u>A</u> <u>22 Long</u>	<u>B</u> <u>21 Long</u>	<u>C</u> <u>22 Short</u>	<u>Comment</u>
Average Denier	4.80	4.58	4.78	No significant differences.
CV of Denier	31%	24%	18%	
Average Strength	6.64	6.36	5.88	A vs. C barely significant.
CV of Strength	35%	31%	26%	
Average Tenacity	1.38	1.39	1.23	C significantly different from B and A.
CV of Tenacity	16%	17%	18%	
Average Elongation	35.1	35.2	33.0	No significant differences.
CV of Elongation	23%	24%	26%	

FREQUENCY DISTRIBUTION OF WOOL FIBER DENIERS

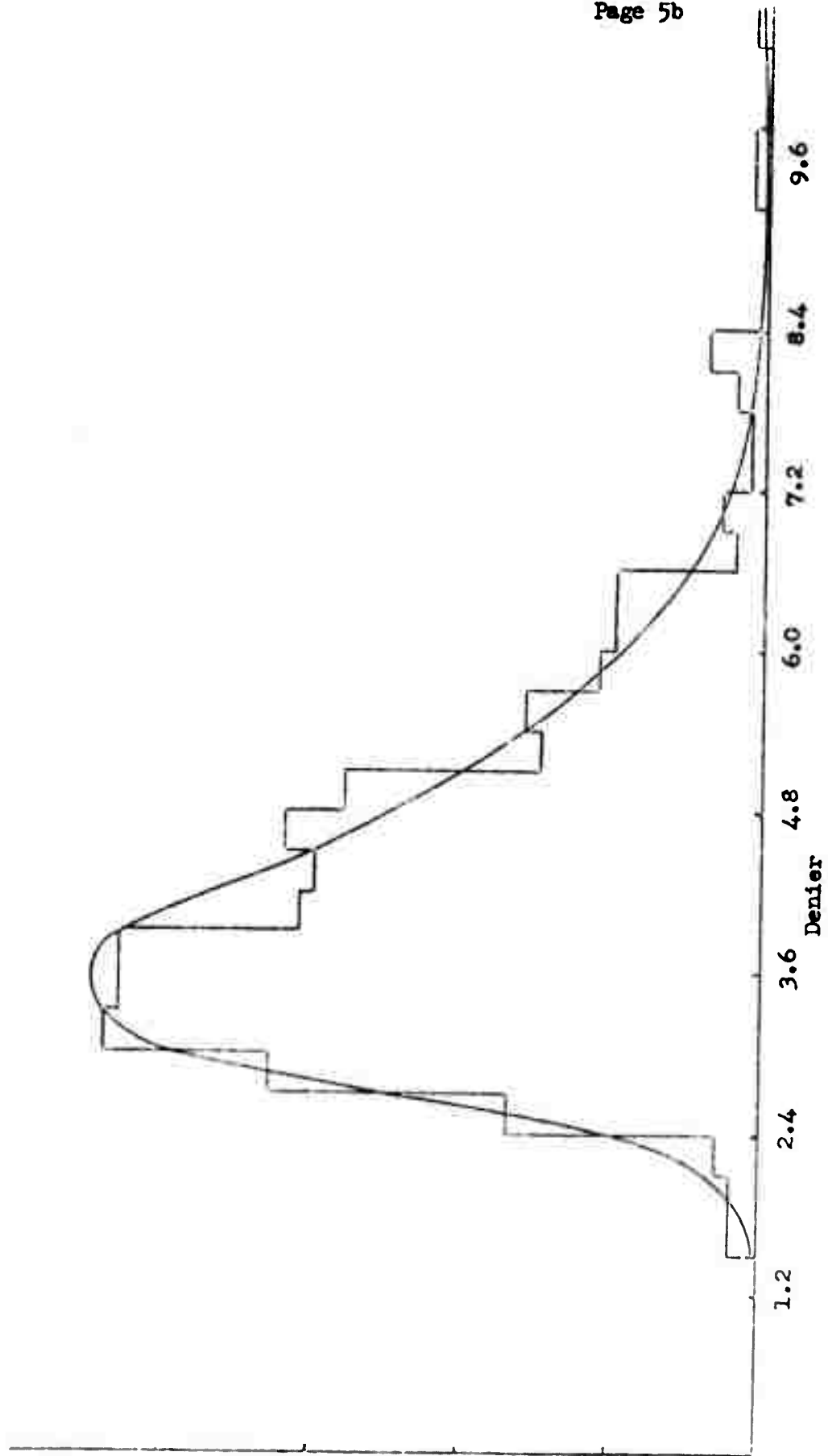


FIGURE 1
Lorenberg

Tests of statistical significance were applied to the several properties being compared. In the first place, whether or not the super-heavy fiber found among the long sample was included, there was no difference in average denier detected between the short and long groups. Second, whereas there was at first a barely significant difference in absolute strength between the short and long fibers, after rejecting the very over-weight fiber the average strength dropped enough to wash out the statistical significance of the difference in mean strengths. However, in the third property compared, namely tenacity, there was a statistically significant difference between the short fiber group and the long. This remained unchanged by discarding the exceptionally heavy fiber. The general importance of these results is given below in the Summary.

2. Summary Of The Fiber Tenacity Study

Because of testing technique limitations, fiber data taken at 1" gage length was considered the most reliable. It would, perhaps, have been desirable to accumulate better data at much shorter gage lengths. There is undoubtedly a gage length effect on the apparent strength of the fibers, part of which effect was detected in the tests at 1/2 and 1/4" gage length. This, as has been mentioned, will be of consequence in later discussion, although it was not feasible to secure the data desired. Tests at 1" gage length were therefore accepted as the most accurate.

Aside from the gage length effect, however, testing at 1" might also suffer from biased sampling since, obviously, fibers shorter than about 1-1/4 inches could not possibly be represented in any sample. If there were a correlation between fiber length and tenacity, this would introduce a bias in the test data.

Some inkling of this was uncovered when the tenacities of "short" and "long" wool fibers taken from yarn were compared at 1/2" gage length. The long fibers showed a tenacity of 1.39 gms./den. while the short were 1.23 gms./den. This latter figure was not much different from the average tenacity of some 300 fibers tested at 1" gage length, while the 1.39 figure was significantly higher. But it must be remembered that the short-long comparison was run at 1/2" gage length. If all of the fibers tested at 1" had been tested at 1/2" they would undoubtedly have yielded higher tenacities than at 1"--perhaps somewhere between 1.23 and 1.39 gms./den. More than likely, however, they would have been biased towards 1.39 rather than 1.23.

However, consider one of the causes of fiber "shortness". During processing of stock into yarn, there is an inadvertant reduction in average fiber staple length. This reduction in length is probably a partially selective process wherein particularly weak fibers, or fibers with inordinately weak regions are broken. It can be presumed, therefore, that of all the possible fibers in a sample of stock which could be selected for testing at 1" gage length, many will have been broken during processing into yarn. In sampling the yarn, these fragments of fiber will not be selected due to the length-bias. Thus, samples taken from stock and tested at 1" gage length would probably include many fibers that were length-biased out of the yarn sampling. Tests on stock at 1" gage length, therefore, might compensate for the error due to fiber length-tenacity correlation. If so, they would be more representative of the entire fiber population of the yarn than a similar sampling from the yarn itself. To overcome possible length-bias effects, therefore, wherever possible data from tests on fiber stock was combined with data on fibers taken from yarn.

Finally, there was indication that the wool fiber population included a very minor number of excessively high denier fibers. There might have been some tendency for operators to be biased in favor of selecting these (they were also probably among the longest fibers). However, although they were unusually strong, simply because of their weight, they were not of unusually high tenacity. Therefore, no effort was made to exclude them from computation of the best average stress-strain properties.

Tensile testing of both the nylon and viscose fibers was accomplished without event in accordance with the method finally adopted for the wool fibers, and requires no particular commentary.

3. The Average Stress-Strain Diagram Of Fibers

For reasons already discussed, fiber data taken at 1" gage length is to be used. In all cases solvent-extracted fibers only are included, and where possible representative data from both stock and yarn fibers are included. The best average stress-strain curves of the three fiber types are given together for contrast in Figure 2. They are obviously quite different in their shapes.

In applying the theories of fiber strength translation, several parameters must be calculated from average fiber stress-strain curves. For this purpose, enlarged diagrams of each fiber type individually are given in Figures 3 - 5. The features of these curves important to subsequent efficiency calculations are indicated thereon and will appear eventually in Table VIII. These data are to be used in the discussion of strength translation in Section III, and further comment is reserved for that section. The curves of Figures 2-5 do not indicate fiber uncrisping, this part of the strain epoch having been determined separately and rationalized.

AVERAGE FIBER STRESS-ELONGATION DIAGRAMS

+Wool
OViscose
ΔNylon

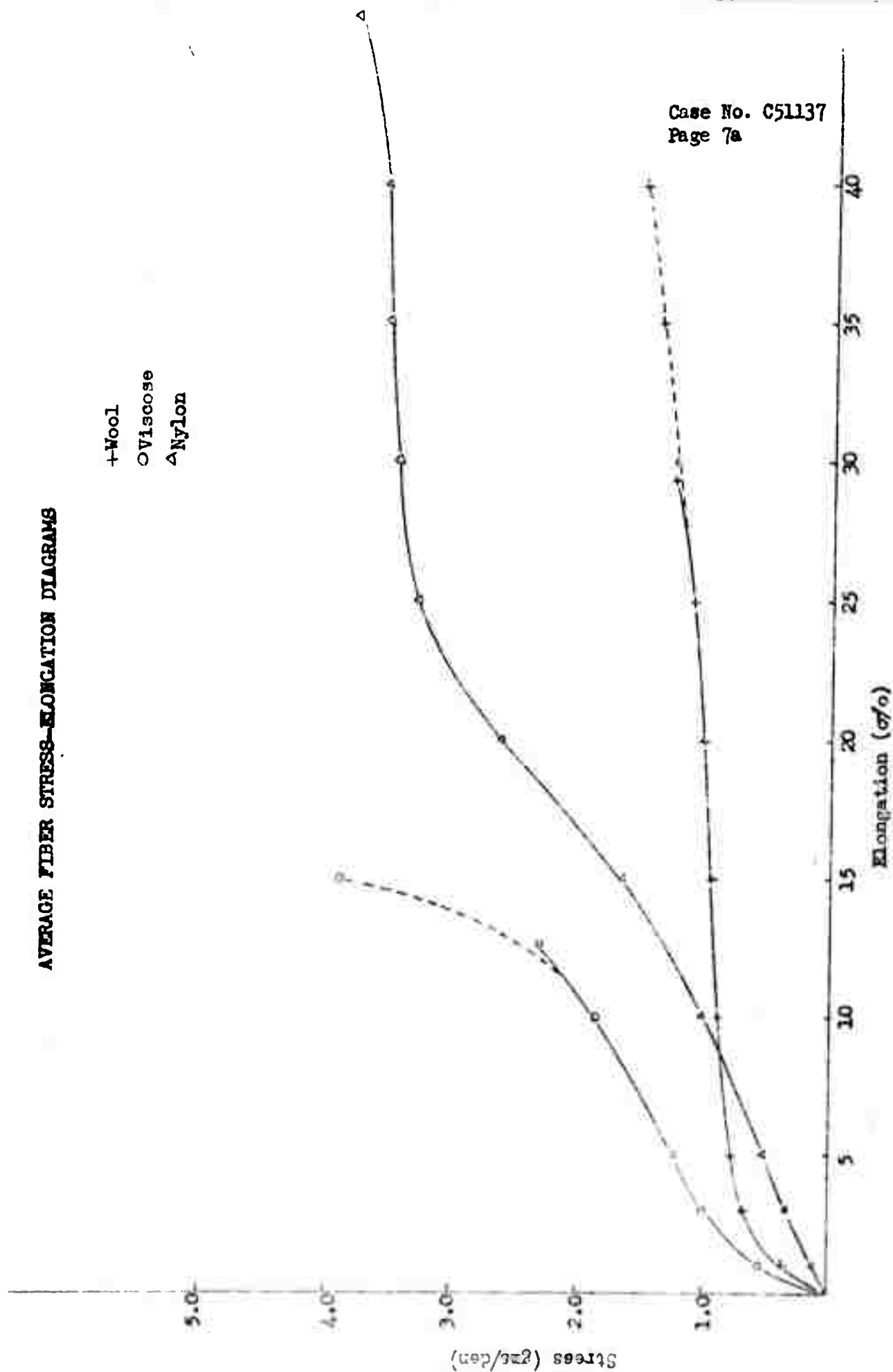


FIGURE 2

AVERAGE WOOL FIBER LOAD-ELONGATION DIAGRAM

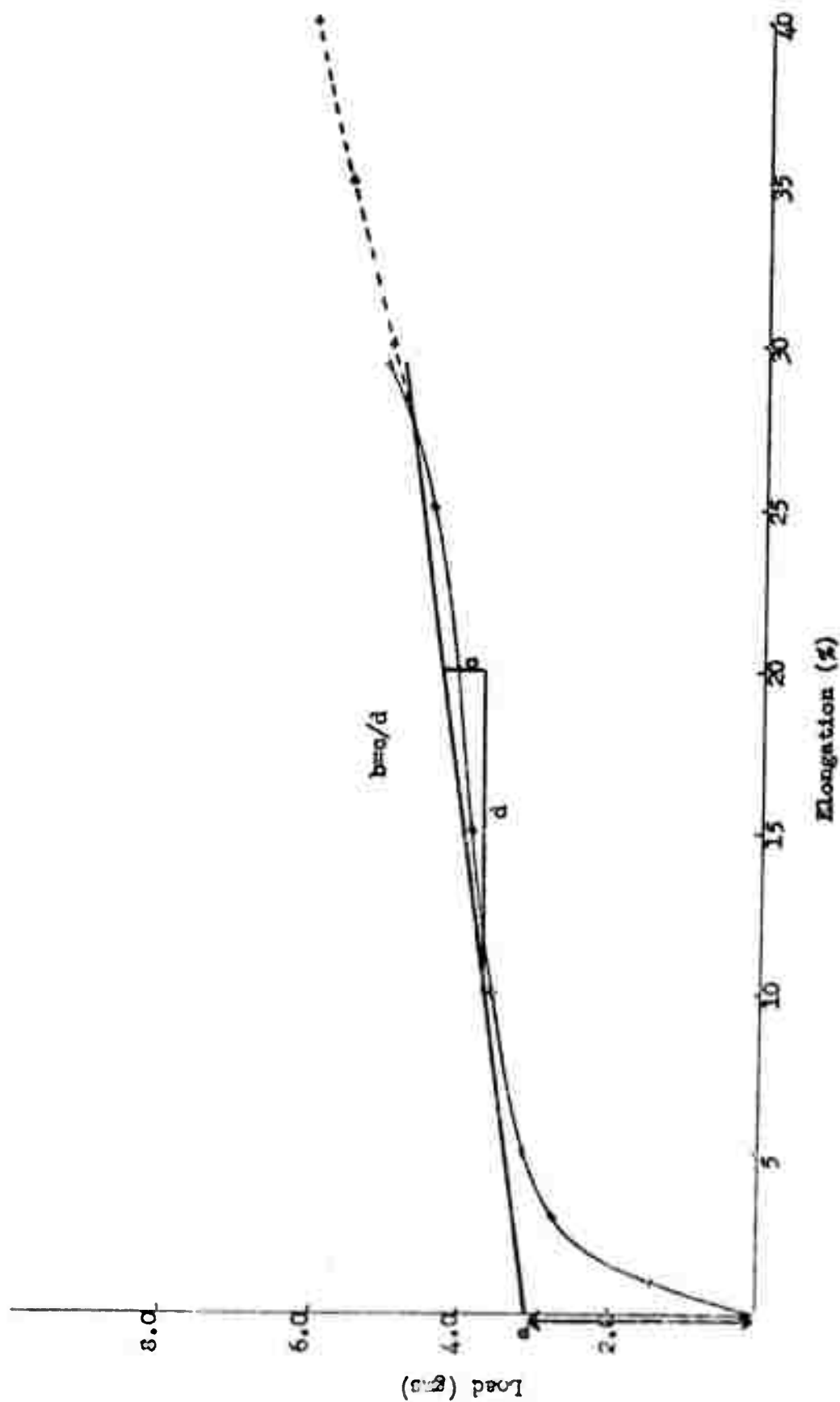


FIGURE 3

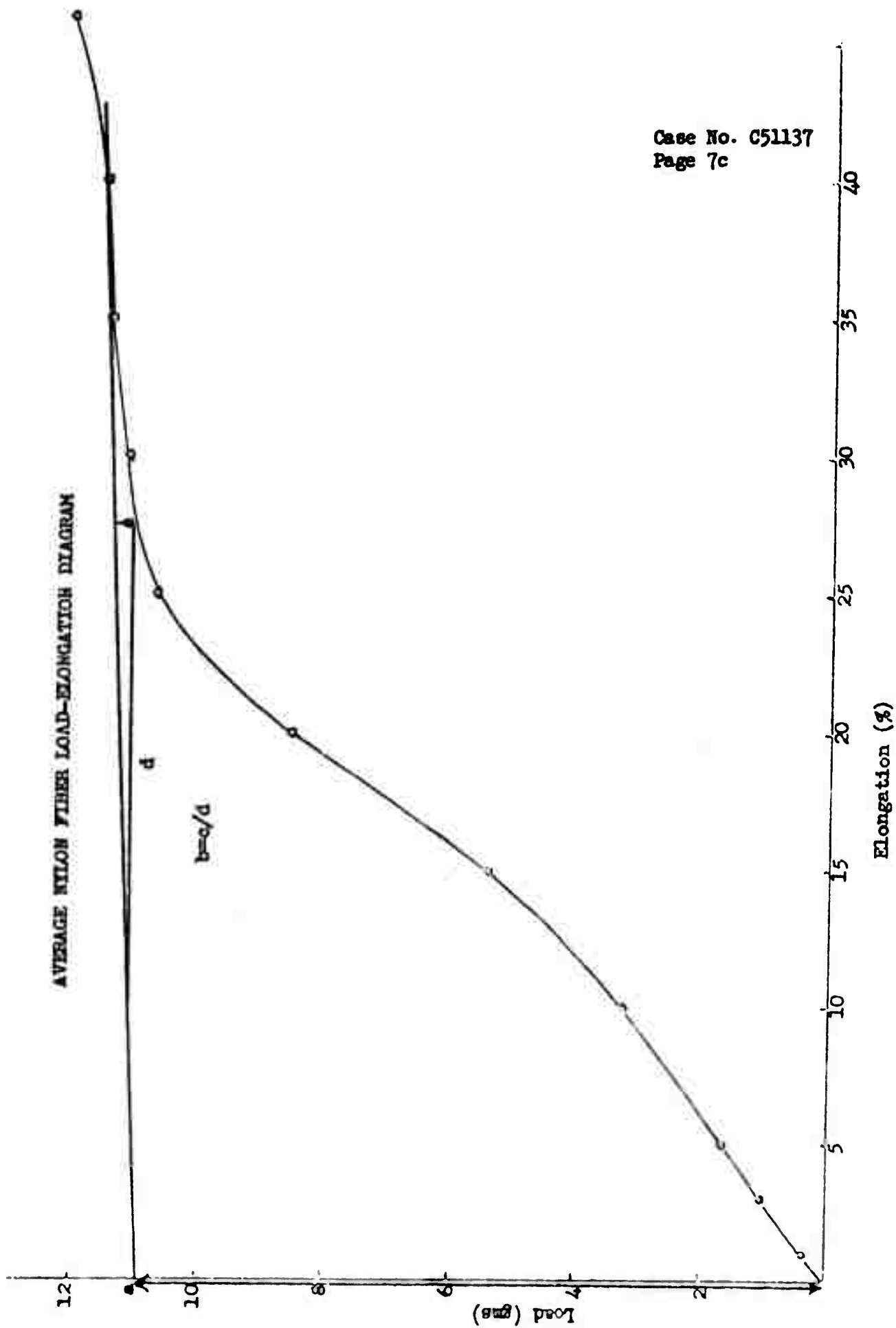
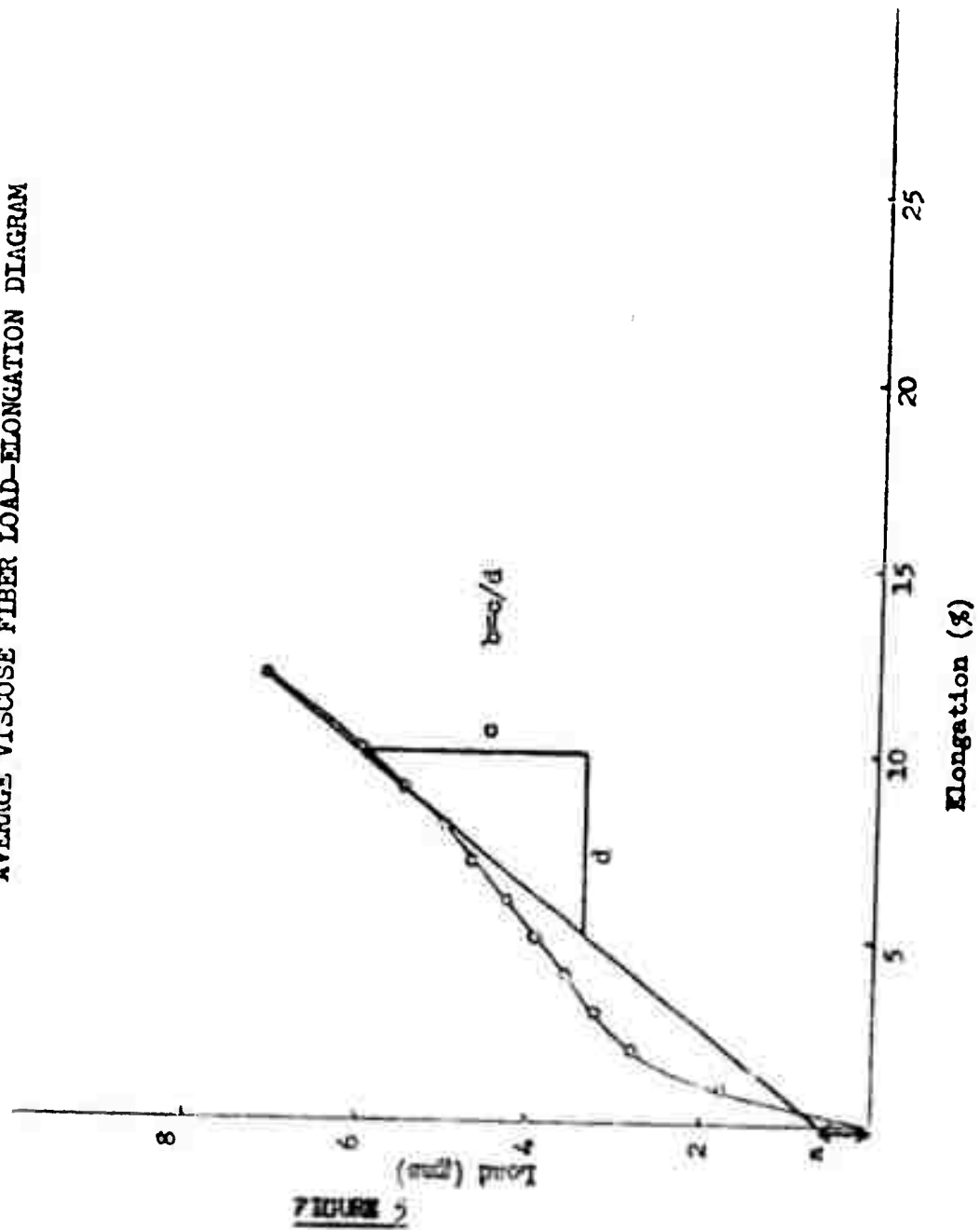


FIGURE 4

AVERAGE VISCOSE FIBER LOAD-ELONGATION DIAGRAM



4. Fiber Repeated-Strain Tests

Comment has been made on the importance of yarn repeated-strain and low-strain elasticity. It will be of considerable interest to relate the low-strain and elastic behavior of the several different fibers to the performance of the blended yarns.

A number of possible techniques may be applied to measure this type of performance. Each has its peculiar limitations and particular advantages. Moreover, each may provide information on elasticity either of a different sort or of different magnitude. The reasons for this are too involved to be easily explored here. However, the following simplification will suffice for present purposes.

Textile fibers, being visco-elastic, exhibit time-dependent as well as force-dependent deformations. On application of a given force the strain suffered by the fibers will be greater with greater time--creep occurs. Similarly, on unloading, the extent of restoration of original dimensions will depend on how long one waits to measure the specimen. There is always an "immediate elastic" response plus a "primary creep" and also frequently a "secondary creep" or permanent set. Thus, the time-scale of the experiment will in some measure influence the apparent elasticity of the material under test.

In the present work a rather short time-scale was employed. Hence the data on fiber elastic recovery appear to be lower than some data in the literature by Meredith (10) and Muding (13). The discrepancy is considered to be due mostly to the amount of primary creep that is included in the elastic recovery values. On the other hand, the present work was performed in a fashion differing in other details also, and the over-all difference between elastic recovery data reported here and that of other workers should be considered in that light.

Single fibers were tested as follows. A fiber was clamped in the upper jaw of the Instron and a weight of .02 gram suspended from its lower end. This was necessary to straighten out the gross crimp and permit uniform starting lengths and tensions. This tension by no means completely uncrimped the fibers (see below). Consider that for vibro-scoping 0.100 gram is customarily hung on the fibers, and that their yield loads were in the neighborhood of 2-4 gram; the .02 starting tension is considered insignificant. The fiber was then subjected to five cycles of tensioning up to a fixed extension and back to the starting load. The strain rate was 50% per minute.

On the sixth cycle fibers were brought up to rupture. The "elasticity" was measured as the amount of strain recovered between fifth cycle extension and starting load. This value was calculated as a percent of the maximum imposed strain level of the test and is expressed as "elastic recovery". For example, a 1" fiber was repeatedly strained between "zero load" (.02 grams starting tension) and a gross length of 1.05". At the end of five cycles, zero load was reached with the fiber at a length of 1.02". The elastic recovery would be $.03/.05 \times 100 = 60\%$.

Another item calculated was the change in stress between first and fifth cycles to achieve the specified strain level. This is a measure of the decay in load-supporting capacity of the fibers under repeated strain¹.g. Both the percent elastic recovery and percent decay in load capacity are given in Table III for fibers removed from extracted 4-1/2 t.p.i. yarns.

Finally, "percent crimp" was determined. The data are also given in Table III. This is purely arbitrary and a relative measure. The stress-strain curve of a crimped fiber has a short "toe" which signifies a certain amount of extension under low load up to the point where "Hookean" strain sets in and the curve sweeps upward. The two zones are not sharply separated, but by suitable extrapolation of the "Hookean slope", a measure of crimpiness can be made.

B. Yarn* Tensile Studies - One Cycle To Rupture

The measurement of yarn strength and elongation, as affected by twist and blend composition, accounted for a substantial portion of the work in this program. The establishment of a satisfactory routine test and handling procedure required considerable preliminary investigation. In large measure these efforts were instructive and worthy of comment. For clarity and consistency in reporting, however, many details will be omitted although the general nature of the different problems and their solution should be mentioned.

During spinning, the fiber stocks had been oiled in various degrees. One purpose of oiling is to aid the operation by reducing friction. Tests on yarn still containing the spinning oil indicated that the lubricant effected yarn properties. It was necessary, therefore, to remove it. This was accomplished by rewinding yarn from the original 2 lb. packages onto perforated tubes. The tube-wound yarn was then extracted in several changes of warm carbon tetrachloride.

*For description of yarns and processing details see Appendix II of (4).

TABLE III
PERCENT ELASTIC RECOVERY OF FIBERS AND
PERCENT LOAD DECAY IN FIVE CYCLES

	Strain Level <u>%</u>	Elastic Recovery <u>%</u>	Load Decay <u>%</u>	<u>%</u> <u>"Crimp"</u>
<u>Wool</u>	6	73	4.4	
	10	51	4.8	
	15	44	2.8	4.2
<u>Nylon</u>	5	73	8.1	
	10	63	6.0	
	15	62	7.5	2.1
<u>Viscose</u>	2	62	6.4	
	4	50	5.2	
	6	35	5.1	0.6

Samples of extracted yarn for testing were taken from the tubes, as needed, taking care not to disturb yarn twist while clamping specimens in the jaws. After each yarn tensile specimen had been broken it was cut away from the jaws flush with their facing edges. The specimens were individually weighed and the weight recorded along with other pertinent data. By this means individual specimen tenacities could be calculated.

It is known that testing speed and specimen lengths will influence strength results to some extent. A study of these variables was made on certain selected yarns in a series involving 10", 5", 2-1/2", and 1-1/4" specimens. The results are given in Table IV, A through E.

Consider first the rupture elongation data in these tables. Apparent elongation for all yarns was significantly higher at the 1-1/4" gage length than at all others. This may have been due to "jaw penetration", a factor which acquires some significance only when gage lengths become small. It results from the fact that the measured free length between jaws (i.e., the nominal gage length) is not the only portion of yarn undergoing extension.

For a short and indeterminate distance into the jaws there is tension on the yarn which contributes to the over-all stretch to rupture which is eventually recorded. If jaw penetration is, say, 1/8" at each jaw, that would represent a 20% discrepancy between the true gage length (1-1/4" + 1/4") and the nominal (1-1/4"). At 2-1/2" gage length the equivalent error is 10% and at 10" this error is only 2.5%. It should be noted that the net influence on calculated elongation to rupture in this case would not be 2.5 units of % E, but 1/40th of the calculated value of % E. For example, the 2.5% error at 10" gage length would give, for a yarn whose true elongation was 10%, a value of 10.25%, not 12.5%.

There may be other causes for a true increase in elongation to rupture at 1-1/4" gage length, which are related to the changed mode of yarn failure when a large number of fibers are gripped in both jaws. If such is the case, some manifestation of this change in the yarn rupture process ought to be apparent in the rupture strength values at 1-1/4" gage length. Indications of such an effect are detected in the lowest twist yarns other than 100% wool.

A rather detailed discussion of the yarn strength-gage length effect is given in Section III. For the present, therefore, it will simply be noted that there is a mild general upward trend of strength with decreasing gage length. Earlier comments about "weak spots" in fibers and their influence on apparent fiber strength with changes in test length

TABLE IV-A

EFFECT OF GAGE LENGTH ON TENSILE
PROPERTIES OF EXTRACTED 100% WOOL

<u>Twist</u>	<u>Rupture</u>		<u>Elongation</u>		<u>Denier</u>	<u>Tenacity</u> <u>Gms/Den.</u>
	<u>Strength</u> <u>#</u>	<u>St. Dev.</u> <u>#</u>	<u>%</u> <u>St. Dev.</u>			
1) Tests at 10" gage length, 5"/min. jaw speed						
4-1/2	0.95	0.09	22.2	2.74	999	0.43
7	1.00	0.09	27.0	3.89	947	0.50
9-1/2	1.21	0.12	31.2	5.26	897	0.61
12	1.15	0.12	32.2	3.57	897	0.58
14-1/2	1.25	0.15	31.8	6.72	982	0.58
2) Tests at 5" gage length, 2-1/2"/min. jaw speed						
4-1/2	0.96	0.11	23.1	3.55	985	0.44
7	1.12	0.12	28.4	3.32	1028	0.49
9-1/2	1.29	0.19	31.6	3.39	985	0.59
12	1.19	0.12	32.4	3.31	850	0.64
14-1/2	1.32	0.17	34.4	6.70	928	0.65
3) Tests at 2-1/2" gage length, 1-1/4"/min. jaw speed						
4-1/2	0.92	0.14	24.4	5.71	921	0.45
7	1.00	0.10	28.2	2.77	893	0.51
9-1/2	1.26	0.12	33.7	3.88	879	0.65
12	1.22	0.10	33.3	5.13	865	0.64
14-1/2	1.46	0.24	38.2	7.67	1077	0.62
4) Tests at 1-1/4" gage length, 3/4"/min. jaw speed						
4-1/2	0.76	0.12	25.0	5.15	850	0.41
7	0.88	0.15	30.4	6.11	907	0.44
9-1/2	1.34	0.14	38.6	2.80	935	0.65
12	1.39	0.10	41.0	2.20	907	0.70
14-1/2	1.45	0.14	43.2	4.40	964	0.68

TABLE IV-BEFFECT OF GAGE LENGTH ON TENSILE
PROPERTIES OF EXTRACTED 100% NYLON

<u>Twist</u>	<u>Rupture</u>		<u>Elongation</u>		<u>Denier</u>	<u>Tenacity Gms/Den.</u>
	<u>Strength #</u>	<u>St. Dev. #</u>	<u>%</u>	<u>St. Dev.</u>		
1) Tests at 10" gage length, 5"/min. jaw speed						
4-1/2	3.03	0.74	28.1	4.04	875	1.57
7	4.20	0.60	32.8	3.61	914	2.08
9-1/2	4.87	0.77	36.9	3.38	964	2.29
12	4.55	0.90	37.0	5.90	893	2.31
14-1/2	4.17	0.36	39.1	2.63	882	2.14
2) Tests at 5" gage length, 2-1/2"/min. jaw speed						
4-1/2	3.51	0.57	34.7	4.46	893	1.78
7	3.99	0.82	35.3	4.70	900	2.01
9-1/2	5.21	0.85	44.2	3.10	971	2.43
12	4.90	0.68	45.2	4.31	928	2.39
14-1/2	4.17	0.59	43.4	3.91	865	2.19
3) Tests at 2-1/2" gage length, 1-1/2"/min. jaw speed						
4-1/2	3.05	0.93	36.3	6.78	836	1.65
7	4.40	0.74	41.6	4.74	907	2.20
9-1/2	6.33	1.60	50.5	3.52	1106	2.60
12	5.48	0.88	51.7	5.23	978	2.54
14-1/2	4.42	0.40	50.7	5.38	836	2.40
4) Tests at 1-1/4" gage length, 3/4"/min. jaw speed						
4-1/2	3.98	0.59	47.3	5.99	935	1.93
7	4.62	0.65	49.0	6.37	935	2.24
9-1/2	6.51	0.97	62.8	5.92	1191	2.48
12	5.12	0.75	57.6	5.24	935	2.48
14-1/2	4.26	0.62	62.2	7.69	850	2.27

TABLE IV-C

EFFECT OF GAGE LENGTH ON TENSILE
PROPERTIES OF EXTRACTED 50% WOOL/50% NYLON

<u>Twist</u>	<u>Rupture</u>		<u>Elongation</u>		<u>Denier</u>	<u>Tenacity</u> <u>Gms/Den.</u>
	<u>Strength</u> <u>#</u>	<u>St. Dev.</u> <u>#</u>	<u>%</u>	<u>St. Dev.</u>		
1) Tests at 10" gage length, 5"/min. jaw speed						
4-1/2	1.30	0.34	22.0	3.41	829	0.71
7	2.53	0.23	30.6	2.48	928	1.24
9-1/2	2.44	0.30	31.4	2.29	822	1.35
12	2.79	0.28	33.9	2.66	943	1.34
14-1/2	2.77	0.23	35.4	2.20	925	1.36
2) Tests at 5" gage length, 2-1/2"/min. jaw speed						
4-1/2	2.37	0.58	28.6	3.20	1106	0.97
7	2.40	0.29	31.0	2.48	900	1.21
9-1/2	2.45	0.39	34.8	3.05	836	1.33
12	2.71	0.29	36.5	4.00	907	1.36
14-1/2	2.82	0.92	41.3	2.45	907	1.41
3) Tests at 2-1/2" gage length, 1-1/4"/min. jaw speed						
4-1/2	2.61	0.43	30.6	2.98	1049	1.12
7	2.66	0.30	34.0	3.42	950	1.27
9-1/2	2.51	0.38	39.0	2.87	765	1.49
12	2.94	0.37	39.5	4.45	978	1.36
14-1/2	3.00	0.37	44.5	3.79	978	1.39
4) Tests at 1-1/4" gage length, 3/4"/min. jaw speed						
4-1/2	2.10	0.33	34.7	3.35	907	1.05
7	2.77	0.34	39.5	2.93	1021	1.23
9-1/2	2.59	0.30	46.6	3.39	822	1.43
12	3.08	0.39	46.7	4.60	964	1.45
14-1/2	3.07	0.37	54.4	6.07	964	1.44

TABLE IV-DEFFECT OF GAGE LENGTH ON TENSILE
PROPERTIES OF EXTRACTED 100% RAYON

<u>Twist</u>	<u>Rupture</u>		<u>Elongation</u>		<u>Denier</u>	<u>Tenacity</u> <u>Gms./Den.</u>
	<u>Strength</u> <u>#</u>	<u>St. Dev.</u> <u>#</u>	<u>%</u>	<u>St. Dev.</u>		
1) Tests at 10" gage length, 5"/min. jaw speed						
4-1/2	1.43	0.36	11.0	2.08	771	0.84
7	2.44	0.25	13.8	0.61	964	1.15
9-1/2	2.41	0.26	13.7	0.66	952	1.15
12	1.87	0.40	10.7	1.70	793	1.07
14-1/2	2.04	0.28	12.7	1.25	888	1.10
2) Tests at 5" gage length, 2-1/2"/min. jaw speed						
4-1/2	1.42	0.14	11.5	1.00	730	0.88
7	2.43	0.22	14.3	0.50	921	1.20
9-1/2	2.56	0.25	15.1	1.00	935	1.24
12	1.90	0.44	12.1	2.08	723	1.19
14-1/2	2.06	0.25	13.3	1.56	843	1.11
3) Tests at 2-1/2" gage length, 1-1/4"/min. jaw speed						
4-1/2	1.66	0.32	14.4	1.64	765	0.99
7	2.60	0.43	17.5	0.87	921	1.28
9-1/2	2.64	0.27	13.0	0.75	879	1.36
12	2.47	0.32	11.6	1.09	921	1.22
14-1/2	2.40	0.35	12.4	1.09	893	1.22
4) Tests at 1-1/4" gage length, 3/4"/min. jaw speed						
4-1/2	1.65	0.30	13.8	1.20	680	1.10
7	2.57	0.41	16.1	1.03	879	1.33
9-1/2	2.68	0.25	16.8	0.83	879	1.38
12	2.66	0.45	15.8	1.54	964	1.25
14-1/2	2.37	0.39	16.8	1.09	879	1.22

TABLE IV-E

EFFECT OF GAGE LENGTH ON TENSILE
PROPERTIES OF EXTRACTED 50% WOOL/50% VISCOSE

Twist	Rupture		Elongation		Denier	Tenacity Gmc/Den.
	Strength #	St. Dev. #	% St. Dev.			
1) Tests at 10" gage length, 5"/min. jaw speed						
4-1/2	0.92	0.13	8.53	0.96	851	0.49
7	1.34	0.14	10.63	0.96	899	0.68
9-1/2	1.53	0.13	11.15	0.76	887	0.78
12	1.45	0.13	11.55	1.17	849	0.78
14-1/2	1.38	0.16	10.85	1.35	889	0.71
2) Tests at 5" gage length, 2-1/2"/min. jaw speed						
4-1/2	1.06	0.14	10.00	1.23	893	0.54
7	1.34	0.13	11.28	0.90	808	0.75
9-1/2	1.59	0.13	11.53	0.81	864	0.84
12	1.62	0.19	13.12	0.22	921	0.80
14-1/2	1.58	0.14	12.45	1.16	879	0.82
3) Tests at 2-1/2" gage length, 1-1/4"/min. jaw speed						
4-1/2	1.13	0.15	10.65	1.55	850	0.60
7	1.28	0.13	11.69	0.84	794	0.73
9-1/2	1.67	0.18	13.41	0.81	879	0.86
12	1.66	0.15	13.86	0.89	907	0.83
14-1/2	1.64	0.21	13.92	1.01	950	0.79
4) Tests at 1-1/4" gage length, 3/4"/min. jaw speed						
4-1/2	1.08	0.16	11.92	1.14	850	0.58
7	1.41	0.21	13.94	1.06	850	0.75
9-1/2	1.58	0.19	14.16	1.09	822	0.87
12	1.53	0.19	14.89	0.97	794	0.87
14-1/2	1.61	0.17	15.42	0.87	907	0.81

should be equally valid for staple yarns. However, yarn strength is a property dependent on several inter-acting factors which may operate to offset the anticipated "weak spot" effect. These factors are the subject of discussion later.

In any event, it was resolved that routine yarn testing for the evaluation of twist-blend effects would be performed at 10" gage length on solvent extracted yarn. The number of specimens necessary to provide data with sufficient statistical reliability had to be decided. A probable error the mean of $\pm 5\%$ was considered tolerable. To ascertain the number of specimens required to achieve this precision one uses a standard statistical test. It can be shown that a coefficient of variation of 10% in a sampling of 17 specimens will provide a mean with a probable error not over 5% at the 95% confidence level.

A statistical study of the data taken on the original series of tests on 100% wool yarns at 10" gage showed that 17 specimens would provide the required precision in nearly all cases. This, then, was accepted as the minimum number of specimens per yarn test. The specimens were selected at random from the extracted yarn sample at intervals of several yards. Thirty-inch lengths of yarn adjacent to each specimen were saved for the microscopical examinations described in Technical Report No. 1 (4). The basic data on the 55 yarns is given in Tables V, A and B.

Average stress-strain diagrams were calculated from the original load-elongation charts. These are given in Figures 6 - 15. Plots of tenacity vs. twist for the several different blends are given in Figures 16 and 17.

It will be quite apparent after examination of the tables and charts that both blend composition and twist influence yarn tensile behavior. There is nothing novel in this. Similar data for wool-nylon yarns, both woolen and worsted types, as well as for nylon/viscose and nylon cotton yarns, has appeared in the literature (2, 11, 12, 17, 18) to mention just a few. Comparison of some of the results of these workers with data from the present study is made in Section III.

C. Yarn Repeated-Strain Studies

Repeated-strain tests on yarns were performed under conditions generally conforming to those applied to fibers. Specimens were pretensioned with a 1 gram weight and clamped at 10.0" jaw separation. Five cycles to strain levels of 2, 4 and 6% for the viscose blends and 5, 10, and 15% for the nylon blends were applied. Strain recovery on the fifth cycle was determined and calculated as a percentage of the maximum imposed strain level for the test. Besides such data on recovery from deformation, the values of load required to achieve given strain levels

TABLE V-A
TENSILE PROPERTIES OF BLENDED
YARNS AT 10" GAGE LENGTH

Twist	Rupture		Elongation		Denier	Tenacity Gms/Den.
	Strength #	St. Dev. #	%	St. Dev.		
<u>100% Wool</u>						
4-1/2	0.95	0.09	22.2	2.74	999	0.43
7	1.05	0.09	27.0	3.89	946	0.50
9 1/2	1.21	0.12	31.2	5.26	897	0.61
12	1.15	0.12	32.2	3.57	896	0.58
14-1/2	1.25	0.15	31.8	6.72	982	0.58
<u>87.5% Wool/12.5% Nylon</u>						
4-1/2	0.94	0.17	21.5	4.02	971	0.44
7	1.21	0.12	25.6	2.41	907	0.61
9-1/2	1.40	0.12	30.3	1.88	932	0.68
12	1.58	0.20	31.4	2.66	939	0.76
14-1/2	1.43	0.14	30.8	3.80	889	0.73
<u>75% Wool/ 25% Nylon</u>						
4-1/2	0.98	0.30	20.8	4.42	918	0.48
7	1.44	0.18	24.3	6.52	858	0.76
9-1/2	1.86	0.18	31.5	2.44	971	0.87
12	1.88	0.26	30.6	4.04	935	0.91
14-1/2	1.76	0.19	33.3	3.84	939	0.85
<u>50% Wool/50% Nylon</u>						
4-1/2	1.30	0.34	22.0	3.41	829	0.71
7	2.53	0.23	30.6	2.48	928	1.24
9-1/2	2.44	0.30	31.4	2.29	822	1.35
12	2.79	0.28	33.9	2.66	943	1.34
14-1/2	2.77	0.23	35.4	2.20	925	1.36
<u>25% Wool/75% Nylon</u>						
4-1/2	1.98	0.45	24.7	2.73	819	1.10
7	3.48	0.33	32.3	2.00	882	1.79
9-1/2	3.81	0.39	34.6	3.16	971	1.78
12	3.88	0.46	36.9	3.16	928	1.90
14-1/2	3.53	0.62	35.9	3.91	960	1.67

TABLE V-A (CONTINUED)

TENSILE PROPERTIES OF BLENDED
YARNS AT 10" GAGE LENGTH

<u>Twist</u>	<u>Rupture</u>		<u>Elongation</u>		<u>Denier</u>	<u>Tenacity Gms/Den.</u>
	<u>Strength</u> <u>#</u>	<u>St. Dev.</u> <u>#</u>	<u>%</u>	<u>St. Dev.</u>		
<u>100% Nylon</u>						
4-1/2	3.03	0.74	28.1	4.04	875	1.57
7	4.20	0.60	32.8	3.61	914	2.08
9-1/2	4.87	0.77	36.9	3.38	964	2.29
12	4.55	0.90	37.0	5.90	893	2.31
14-1/2	4.17	0.36	39.1	2.63	882	2.14

TABLE V-B
TENSILE PROPERTIES OF BLENDED
YARNS AT 10" GAGE LENGTH

Twist	Rupture		Elongation		Denier	Tenacity Gms/Den
	Strength #	St. Dev. #	%	St. Dev.		
<u>100% Wool</u>						
4-1/2	0.95	0.09	22.2	2.74	999	0.43
7	1.05	0.09	27.0	3.89	946	0.50
9-1/2	1.21	0.12	31.2	5.26	897	0.61
12	1.15	0.12	32.2	3.57	896	0.58
14-1/2	1.25	0.15	31.8	6.72	982	0.58
<u>87.5% Wool</u>						
4-1/2	0.83	0.11	9.26	1.16	852	0.44
7	1.07	0.35	8.97	0.98	809	0.57
9-1/2	1.04	0.20	11.39	1.32	808	0.59
12	1.17	0.11	12.26	2.07	930	0.57
14-1/2	1.02	0.09	9.92	1.63	864	0.53
<u>75% Wool</u>						
4-1/2	0.91	0.12	9.59	0.96	898	0.46
7	0.93	0.31	10.86	1.74	862	0.49
9-1/2	1.22	0.09	10.30	0.76	899	0.62
12	1.11	0.12	8.73	1.43	865	0.56
14-1/2	1.02	0.15	10.50	1.59	865	0.54
<u>50% Wool</u>						
4-1/2	0.92	0.13	8.53	0.96	851	0.49
7	1.34	0.14	10.63	0.96	899	0.68
9-1/2	1.53	0.13	11.15	0.76	887	0.78
12	1.45	0.13	11.55	1.17	849	0.78
14-1/2	1.38	0.16	10.85	1.35	889	0.71
<u>25% Wool</u>						
4-1/2	1.56	0.22	11.3	1.06	965	0.73
7	1.98	0.17	13.0	0.79	942	1.01
9-1/2	1.94	0.22	13.4	1.44	919	0.96
12	1.91	0.19	14.0	0.87	902	0.96
14-1/2	1.87	0.27	12.2	1.28	1050	0.81

Case No. C51137

Page 11d

TABLE V-B (CONTINUED)

TENSILE PROPERTIES OF BLENDED
YARNS AT 10" GAGE LENGTH

<u>Twist</u>	<u>Rupture</u>		<u>Elongation</u>		<u>Denier</u>	<u>Tenacity Gms/Den.</u>
	<u>Strength #</u>	<u>St. Dev. #</u>	<u>% #</u>	<u>St. Dev.</u>		
<u>0% Wool</u>						
4-1/2	1.43	0.36	11.0	2.08	771	0.84
7	2.44	0.25	13.8	0.61	964	1.15
9-1/2	2.41	0.26	13.7	0.66	952	1.15
12	1.87	0.40	10.7	1.70	793	1.07
14-1/2	2.04	0.28	12.7	1.25	888	1.10

YARN STRESS-ELONGATION DIAGRAMS WOOL-NYLON SERIES 4.5 tpi

- 100% wool
- ◻ 12.5% nylon
- ▲ 25% nylon
- △ 50% nylon
- ◊ 75% nylon
- + 100% nylon

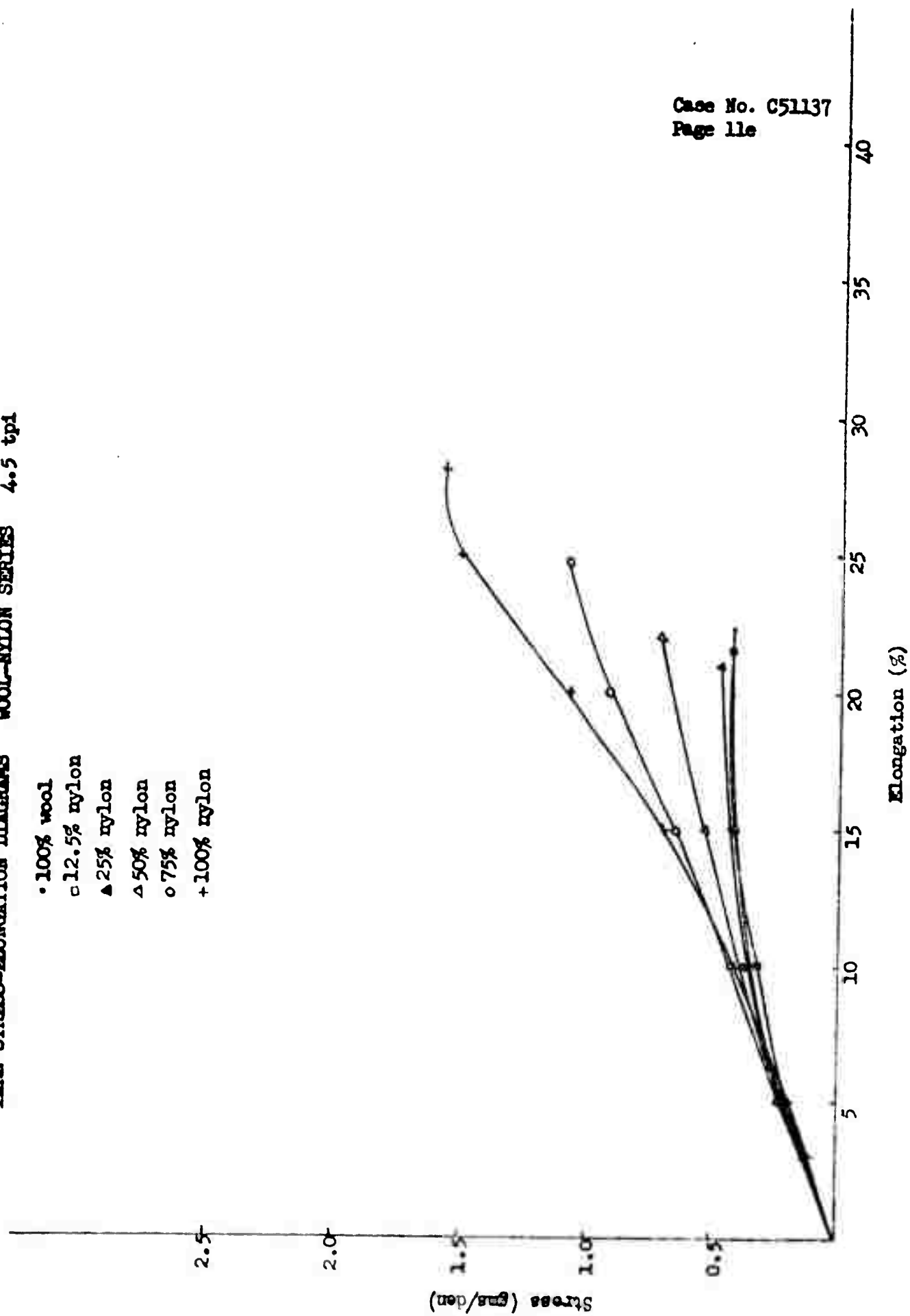


FIGURE 6

YARN STRESS-ELONGATION DIAGRAMS WOOL-NYLON SERIES 7 tpi

• pure wool
○ 12.5% nylon
△ 25% nylon
◊ 50% nylon
○ 75% nylon
+ 100% nylon

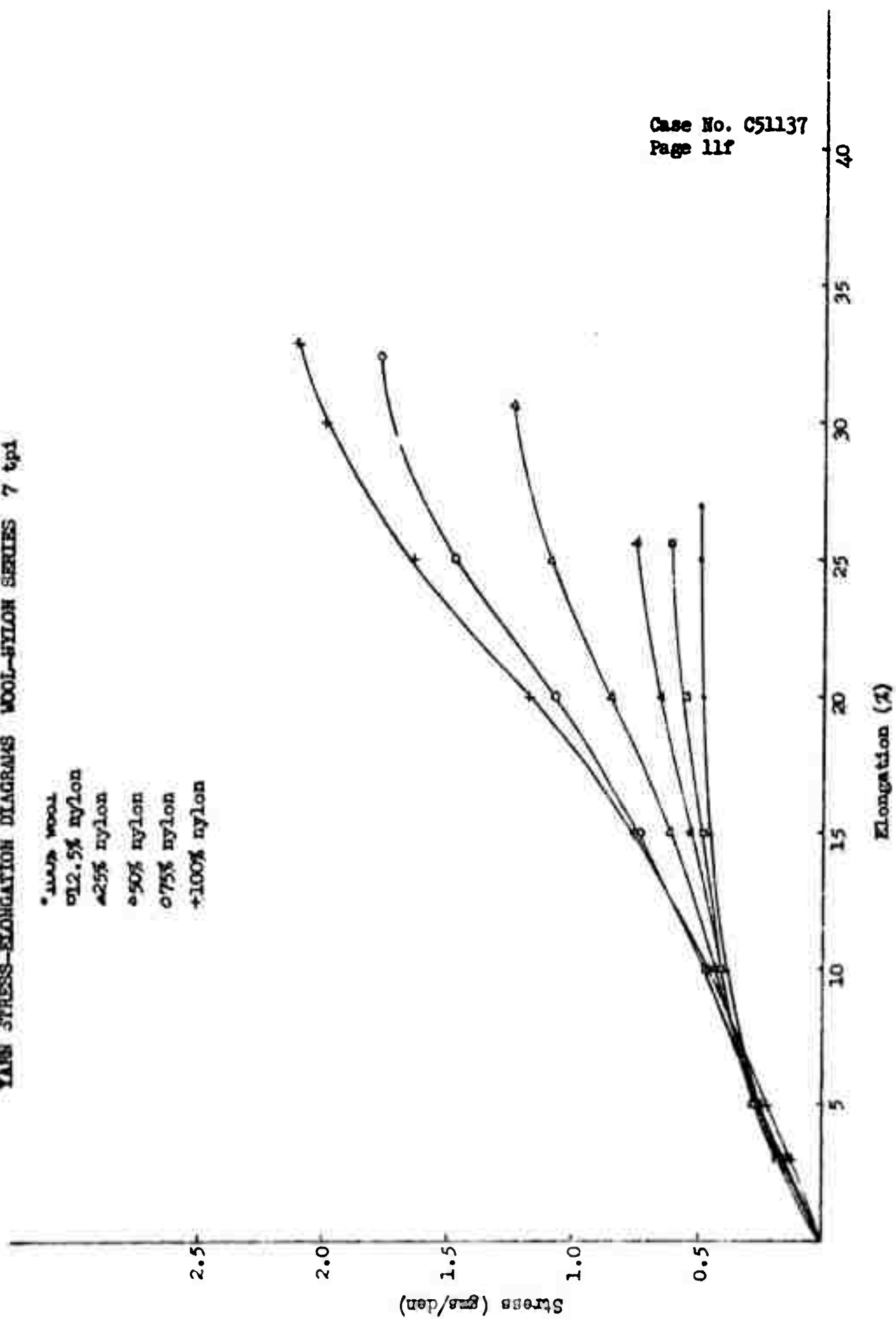


FIGURE 7

YARN STRESS-ELONGATION DIAGRAMS WOOL-NYLON SERIES 9.5 tpi

- 100% wool
- 12.5% nylon
- ▲ 25% nylon
- △ 50% nylon
- ◊ 75% nylon
- + 100% nylon

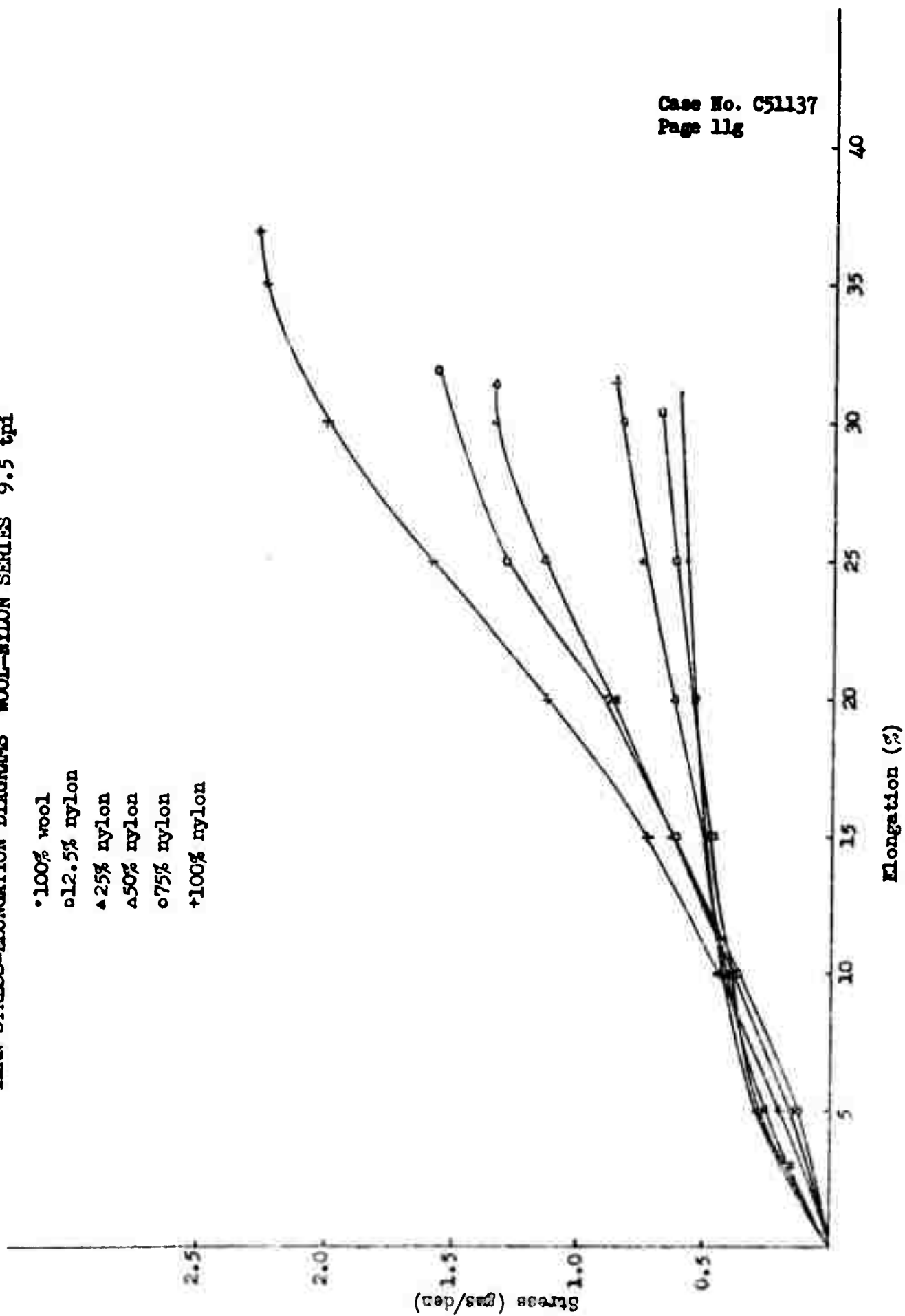


FIGURE 8

YARN STRESS-ELONGATION DIAGRAMS WOOL-NYLON SERIES 12 tp1

• 100% wool
□ 12.5% nylon
▲ 25% nylon
△ 50% nylon
○ 75% nylon
+ 100% nylon

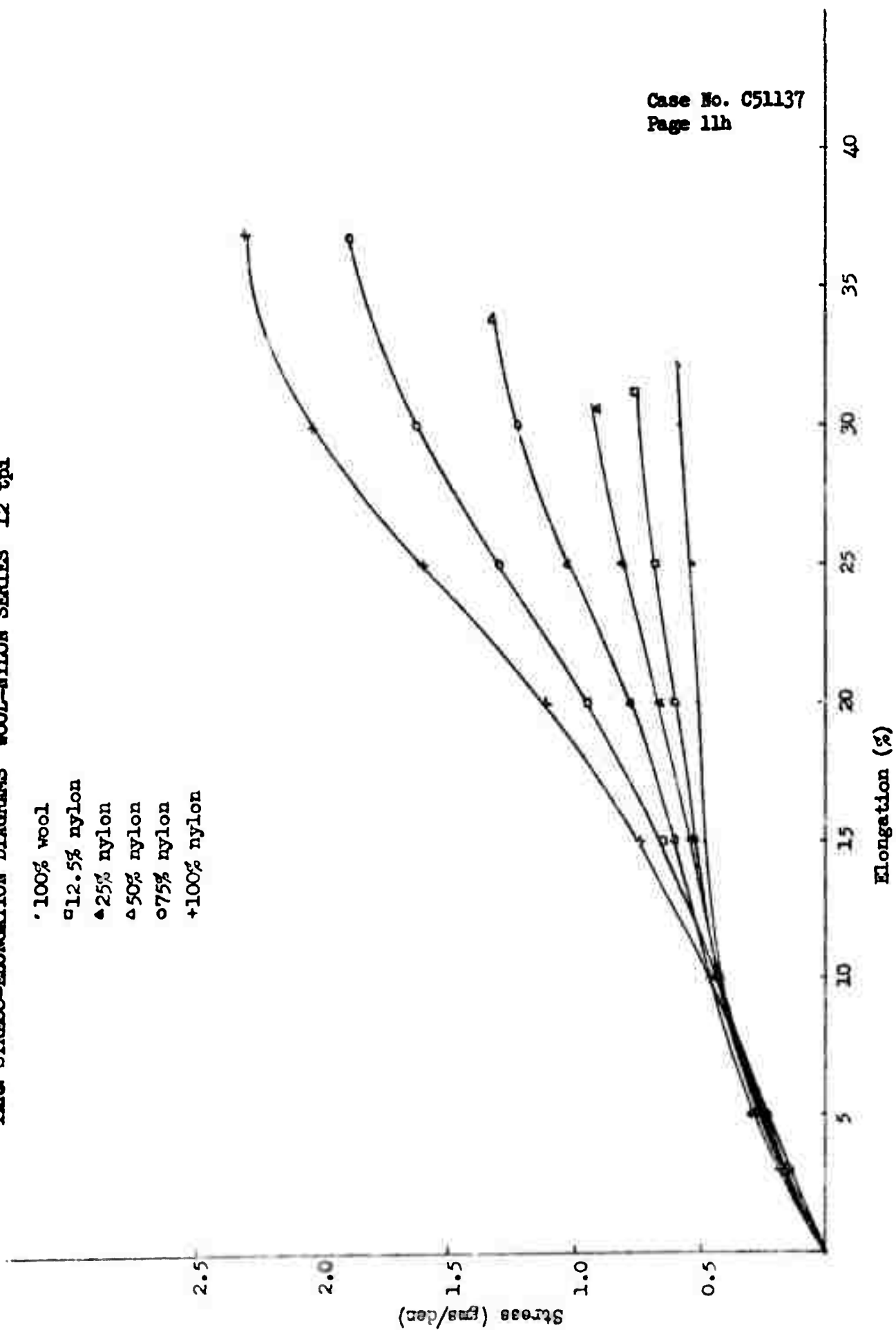
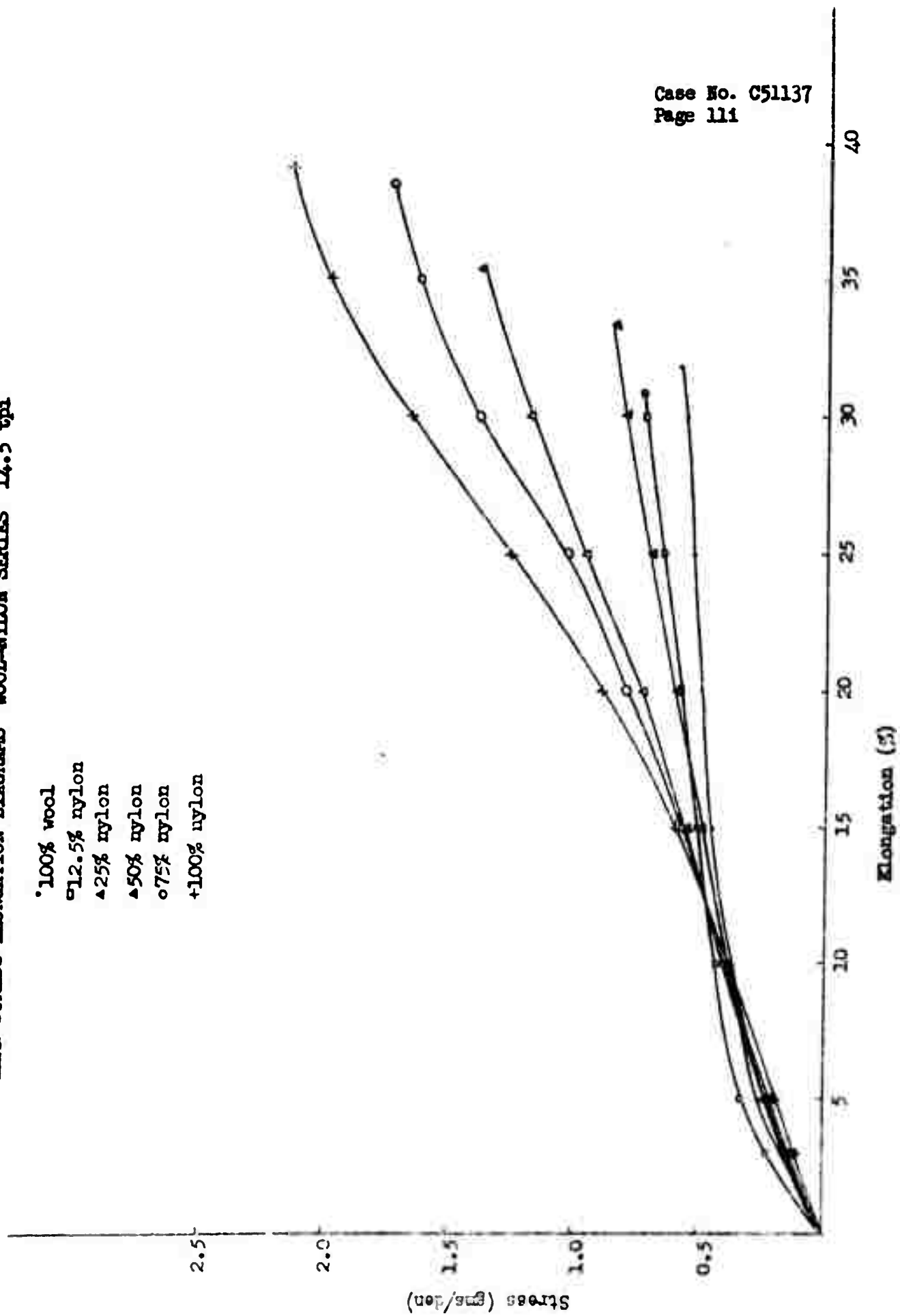


FIGURE 9

YARN STRESS-ELONGATION DIAGRAMS WOOL-NYLON SERIES 14.5 tp1

• 100% wool
 ○ 12.5% nylon
 ▲ 25% nylon
 △ 50% nylon
 ◊ 75% nylon
 + 100% nylon



Case No. C51137
Page 111

FIGURE 10

YARN STRESS-ELONGATION DIAGRAMS WOOL-VISCOSE SERIES 4.5 tpi

• 100% wool
 □ 12.5% viscose
 ▲ 25% viscose
 △ 50% viscose
 ○ 75% viscose
 + 100% viscose

Case No. C51137
 Page 11J

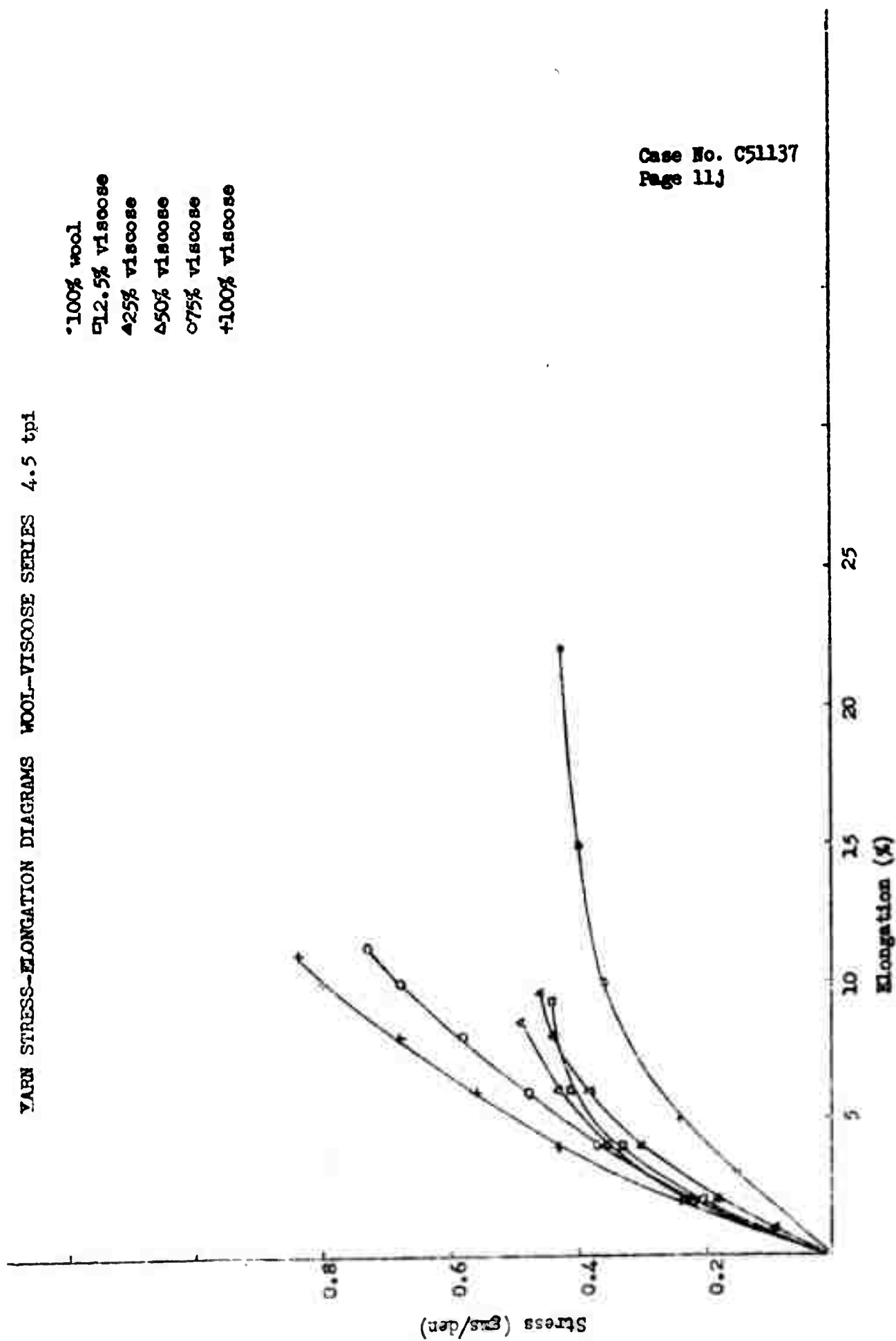


FIGURE 11

YARN STRESS-ELONGATION DIAGRAMS WOOL-VISCOSE SERIES 7 tp1

• 100% wool
□ 12.5% viscose
▲ 25% viscose
△ 50% viscose
○ 75% viscose
+ 100% viscose

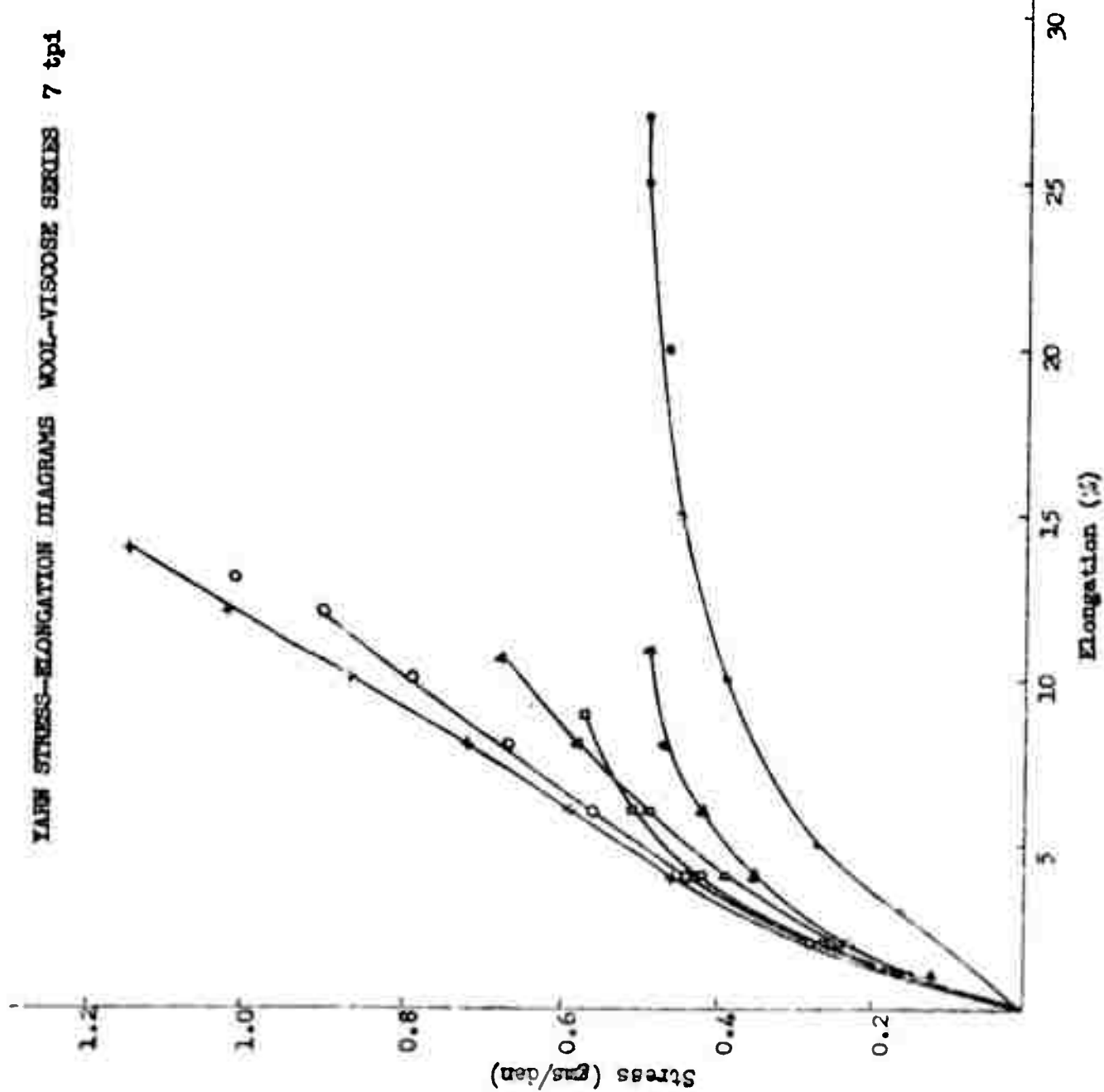


FIGURE 12

YARN STRESS-ELONGATION DIAGRAMS WOOL-VISCOSE SERIES 9.5 tp1

100% wool
 12.5% viscose
 25% viscose
 50% viscose
 75% viscose
 100% viscose

Case No. C51137
Page 11-1

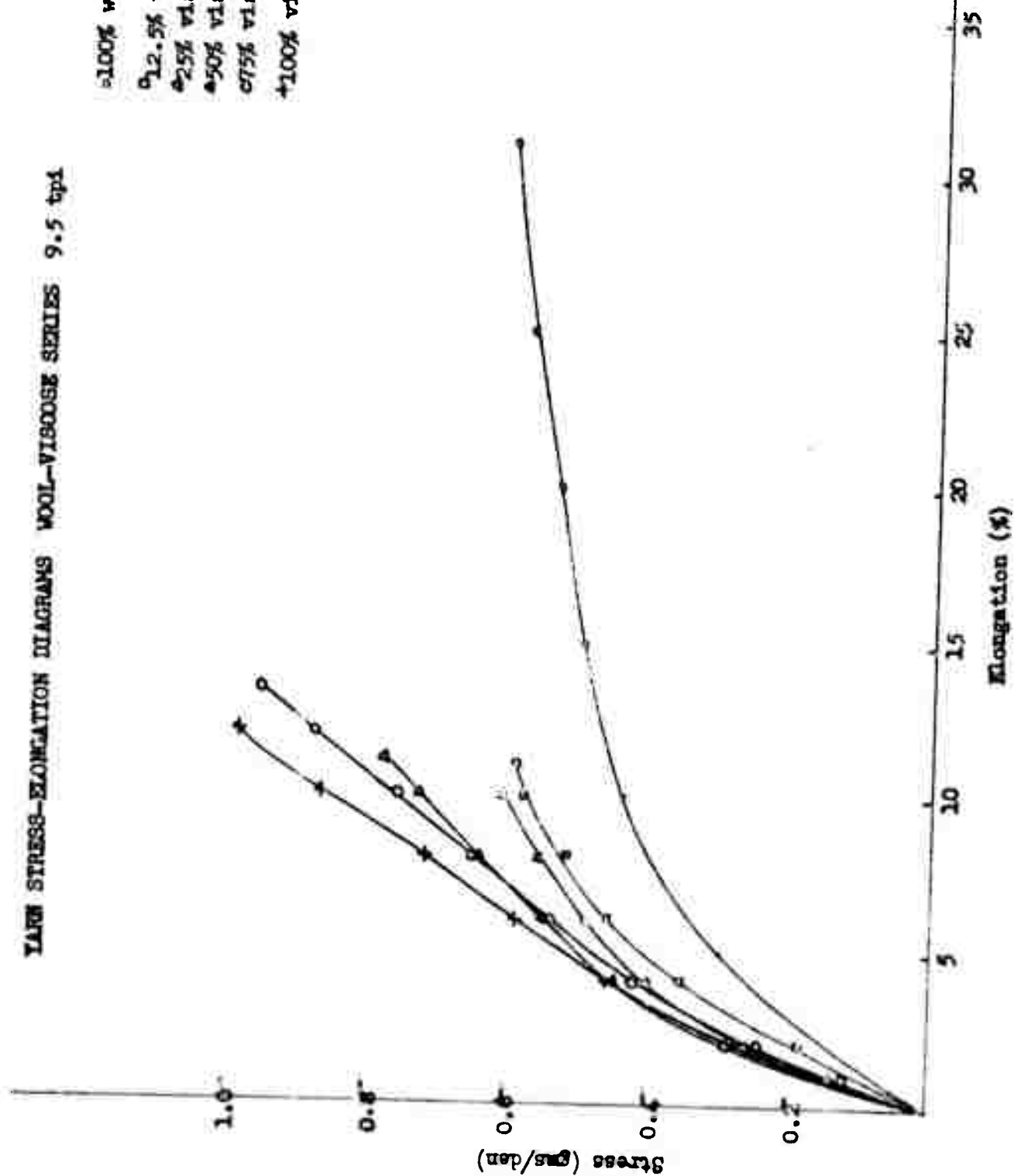


FIGURE 13

TAPE STRESS-ELONGATION DIAGRAMS WOOL-VISCOSE SERIES 12 tpi

- 100% wool
- 12.5% viscose
- △ 25% viscose
- ▲ 50% viscose
- 75% viscose
- + 100% viscose

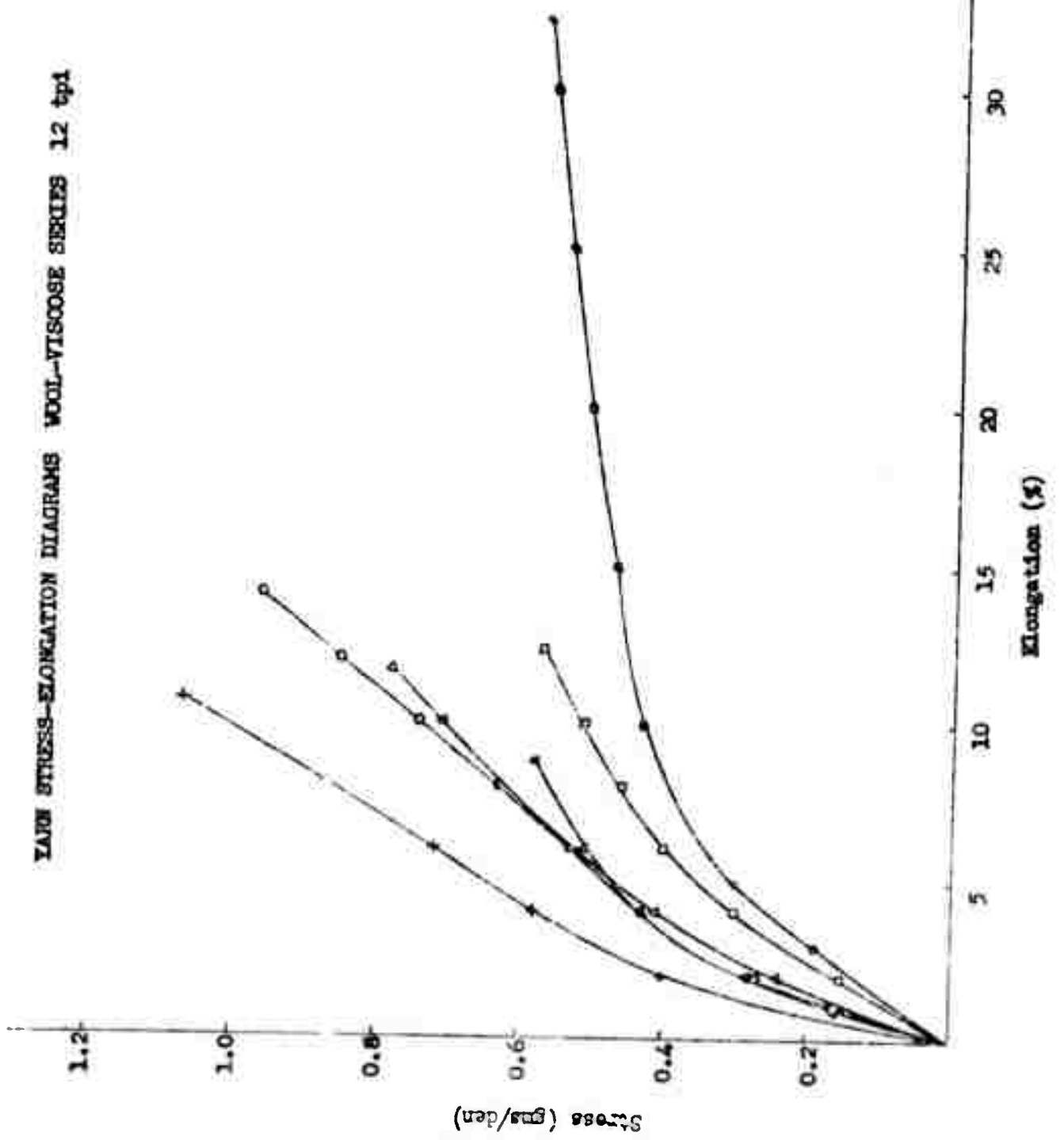


FIGURE 1a

YARN STRESS-ELONGATION DIAGRAMS WOOL-VISCOSE SERIES 14.5 tpi

100% wool
 92.5% viscose
 82.5% viscose
 70% viscose
 50% viscose
 25% viscose
 100% viscose

Case No. C51137
Page 11n

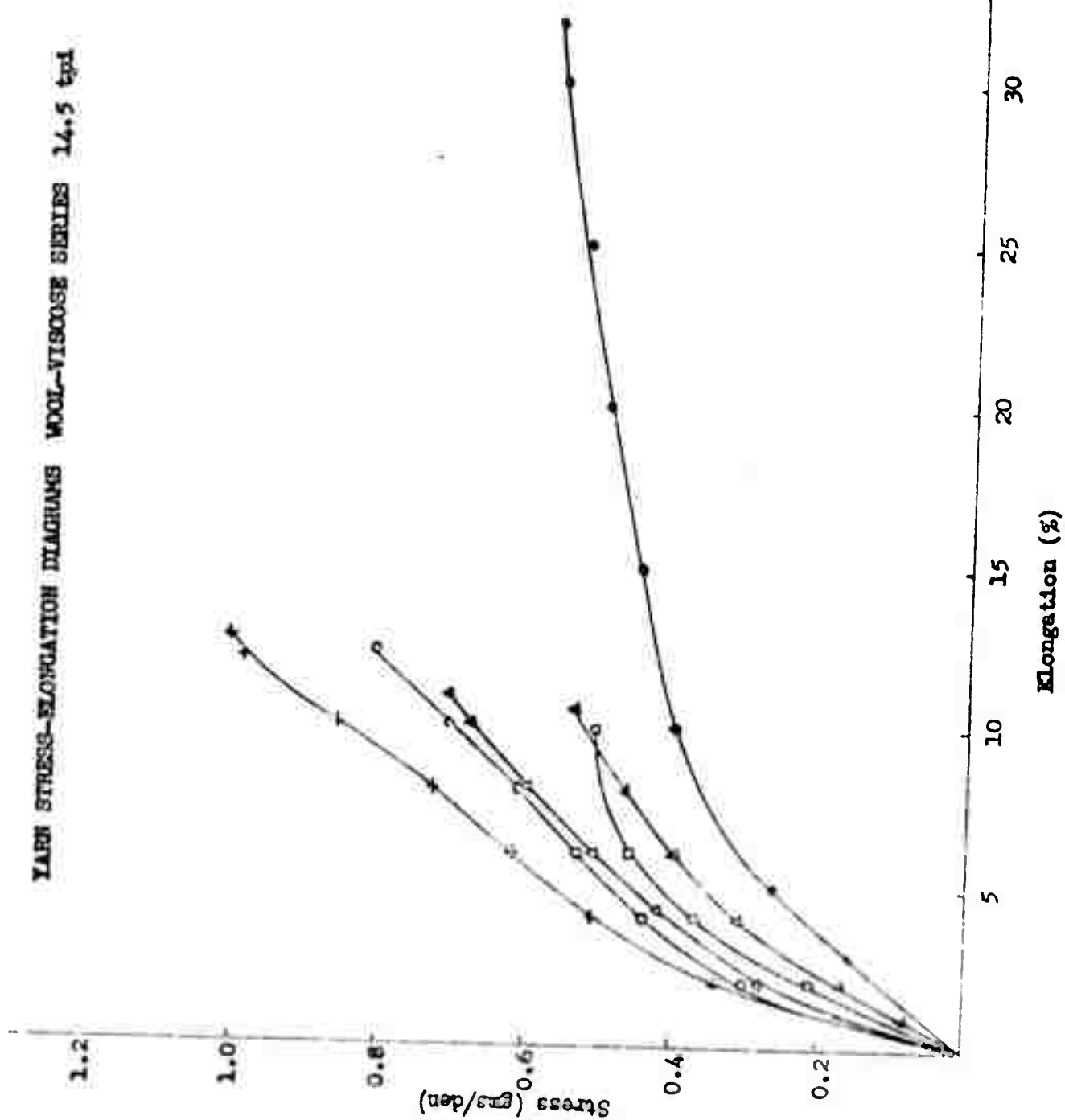


FIGURE 15

EFFECT OF TWIST ON RUPTURE STRESS WOOL-NYLON SERIES

100% wool
x 12.5% nylon
■ 25% nylon
△ 50% nylon
○ 75% nylon
○ 100% nylon

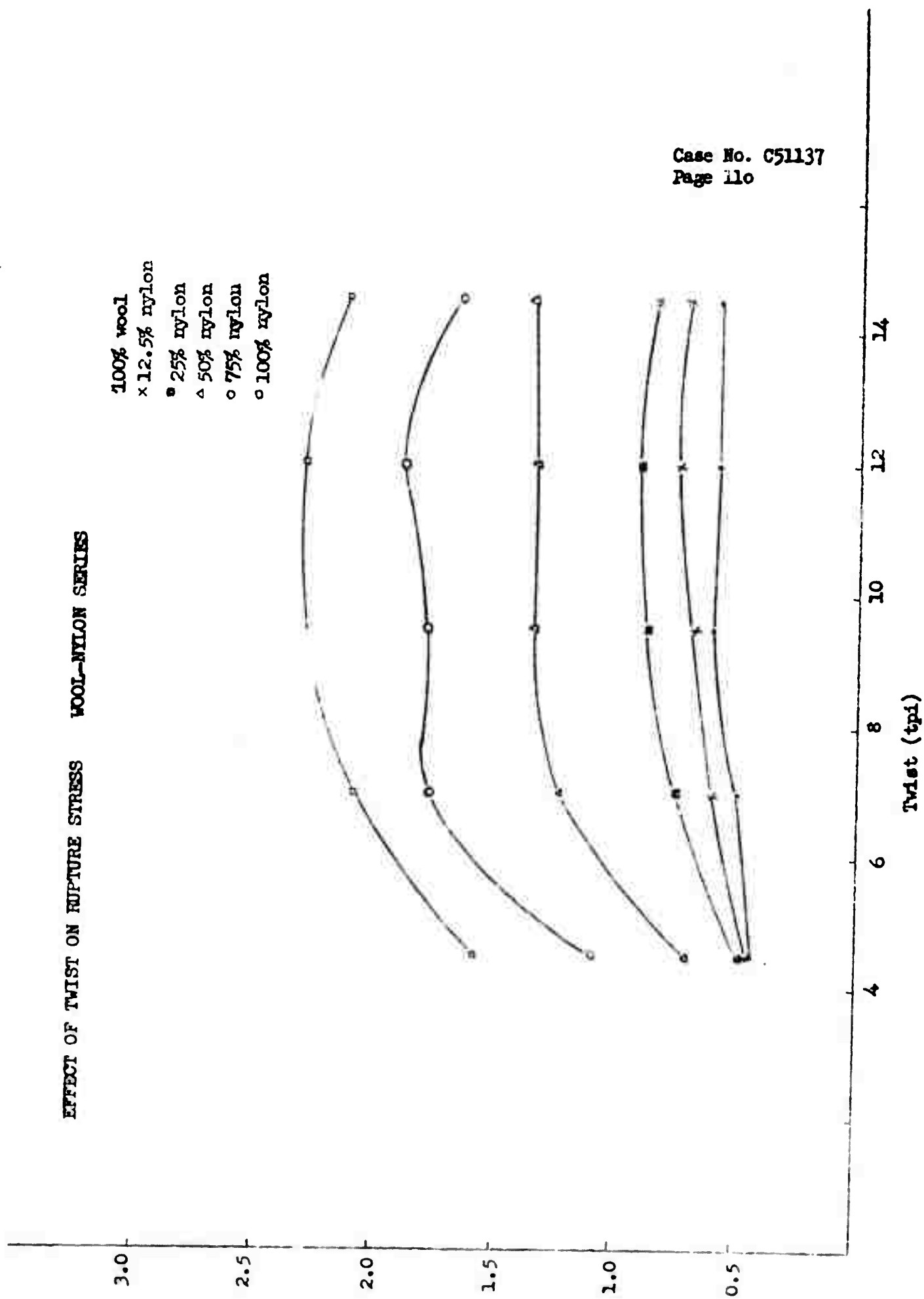


FIGURE 16

EFFECT OF TWIST ON RUPTURE STRESS WOOL-VISCOSE SERIES

• 100% wool
 x 12.5% viscose
 □ 25% viscose
 Δ 50% viscose
 ○ 75% viscose
 ▽ 100% viscose

Case No. C51137
 Page 11p

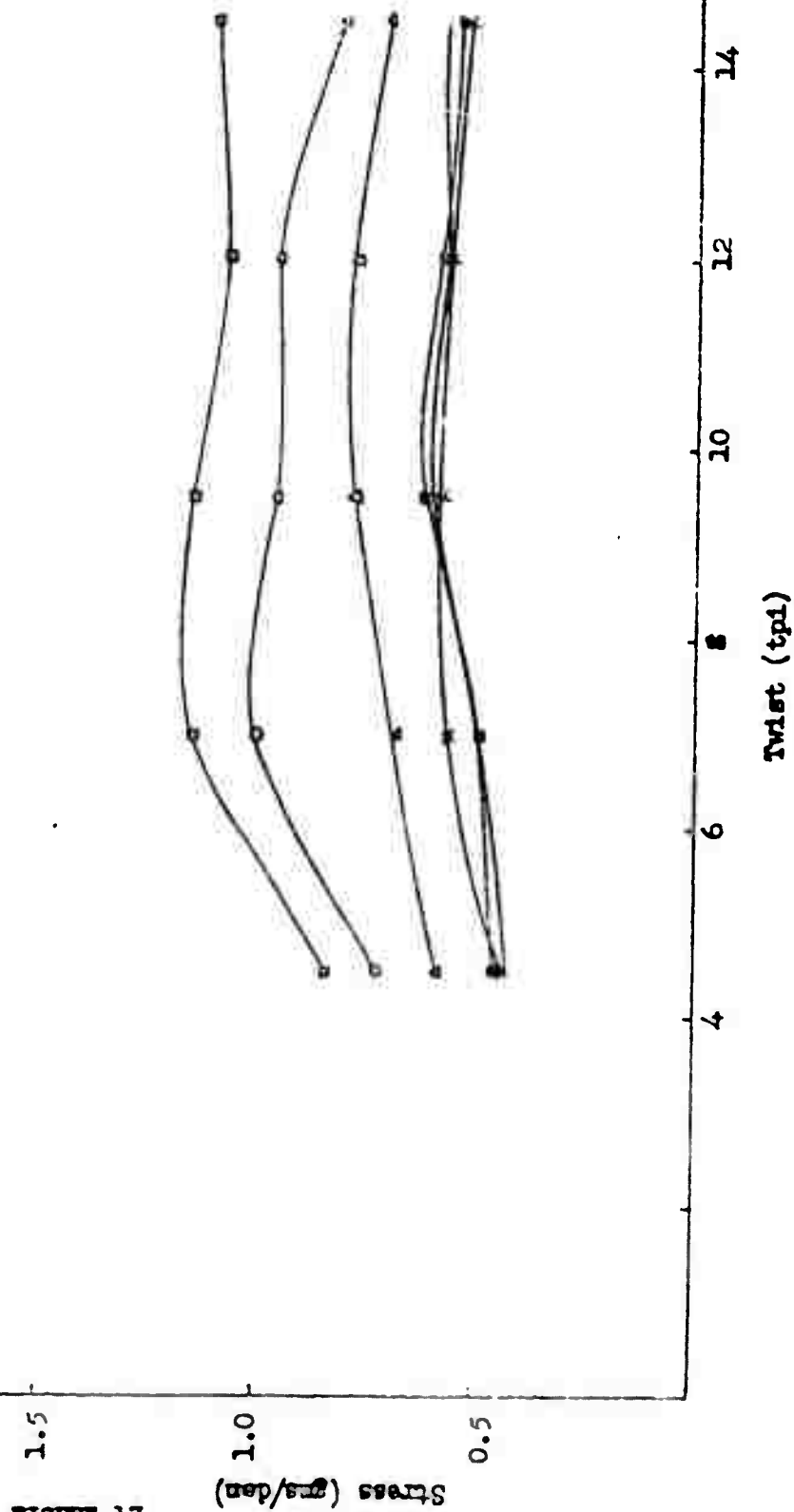


FIGURE 17

during repeated-straining were also determined. Crimp determinations were made on a limited number of yarns in a fashion similar to that described for fibers.

In the present report interest is focused on both the ability of blended yarns to recover dimensionally from repeated straining and their load-supporting capacity in such treatment. It is hoped, by evaluation of these factors, to illuminate in some measure the mechanisms of stress transfer among the fibers in the yarn and how this is modified by blend composition and twist. Other data, such as resilience--a measure of recoverable energy--will be covered in conjunction with a subsequent study on yarn bending behavior.

As for the current study, Figures 18 and 19 show the effects of blend composition on elastic recovery of yarns (as here defined). Two important items are discernible. First, it will be noted that for all blends and strain levels there is practically no discrimination among the five yarn twists. This is indicated by the rather random cross-overs of the lines in each group of plots. Second, there is a pronounced trend of recovery vs. blend for the viscose series, and a minor one at high strain levels for the nylon series. This will be discussed in Section III.

To illustrate the indifferent, or minor, effect of twist on yarn recovery, Figures 20 and 21 were plotted with twist being the independent variable. In these graphs the elastic recovery values were averaged for the 2, 4 and 6% strain level in the viscose series, and the 5, 10 and 15% level in the nylon series. It will be seen that for every blend, with the possible exception of 100% viscose, there is no consistent trend or notable effect of twist on elastic recovery. This is somewhat surprising and is the subject of further discussion in Section III. Evidently, in the yarns currently under study, any given blend over a wide range of twists was equally recoverable from repeated straining to levels from 1/8 to 1/2 of rupture elongation.

The influence of twist is felt, however, when one examines the load decay accompanying the repeated-straining to particular levels of strain. Figures 22 and 23 illustrate the pronounced decrease in percent load change between the first and fifth cycles with increasing twist in all cases except the 2% strain level in the viscose series.

Now, on the other hand, the influence of blend composition is not clear and consistent. The effect of blend is illustrated in Figures 24 and 25. Here it will be seen that the blend composition has a negligible or erratic bearing on load decay except at the higher strains and lower twists. The probable significance of this information is to be discussed shortly but the evidence seems to indicate that load decay is influenced by fiber-controlled yarn geometry while elastic recovery is influenced by intrinsic fiber elastic properties.

EFFECT OF BLEND ON ELASTIC RECOVERY WOOL-NYLON SERIES

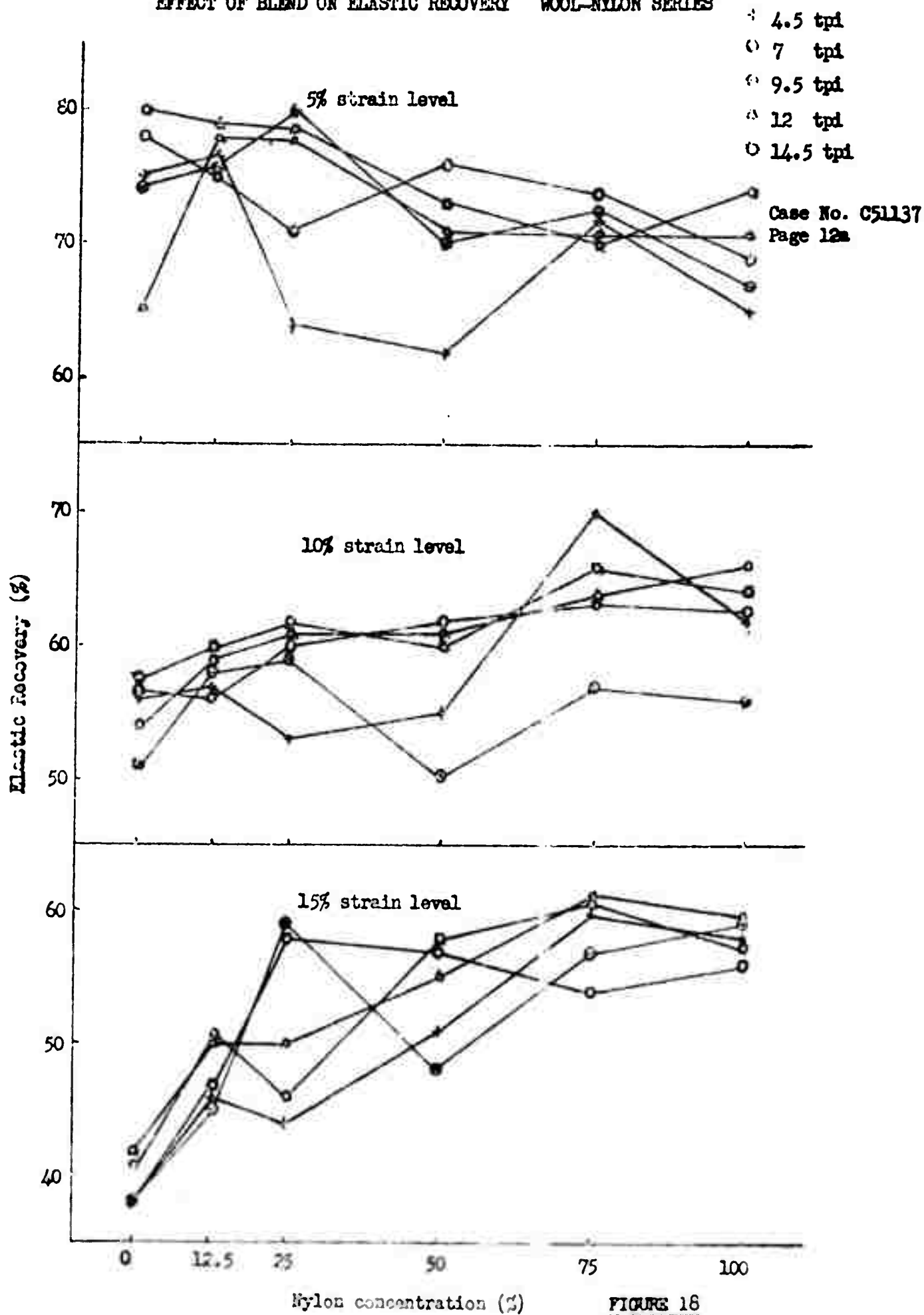


FIGURE 16

EFFECT OF BLEND ON ELASTIC RECOVERY WOOL-VISCOSE SERIES

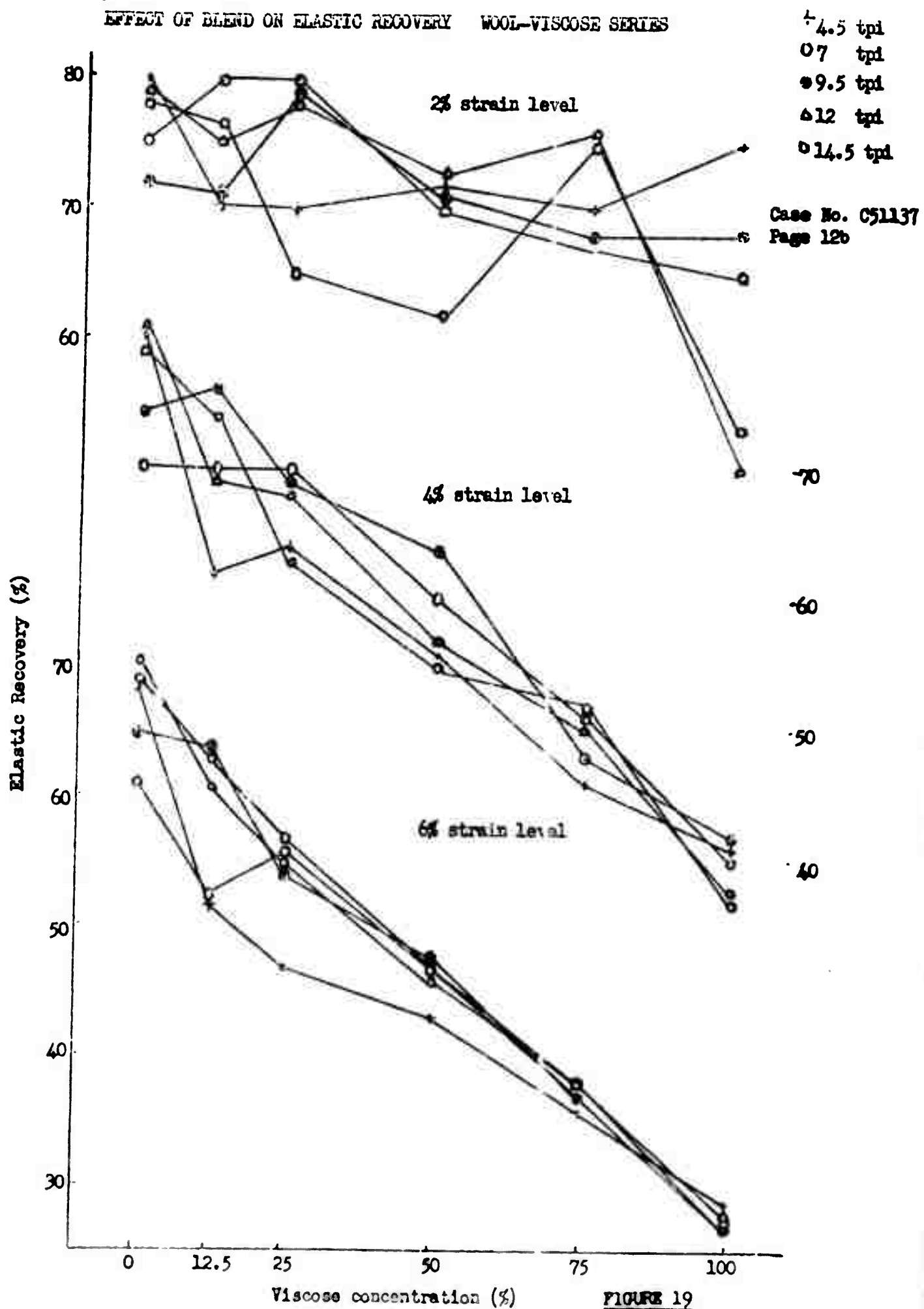


FIGURE 19

EFFECT OF TWIST ON ELASTIC RECOVERY WOOL-NYLON SERIES

(Average of three strain levels)

Case No. C51137
Page 12c

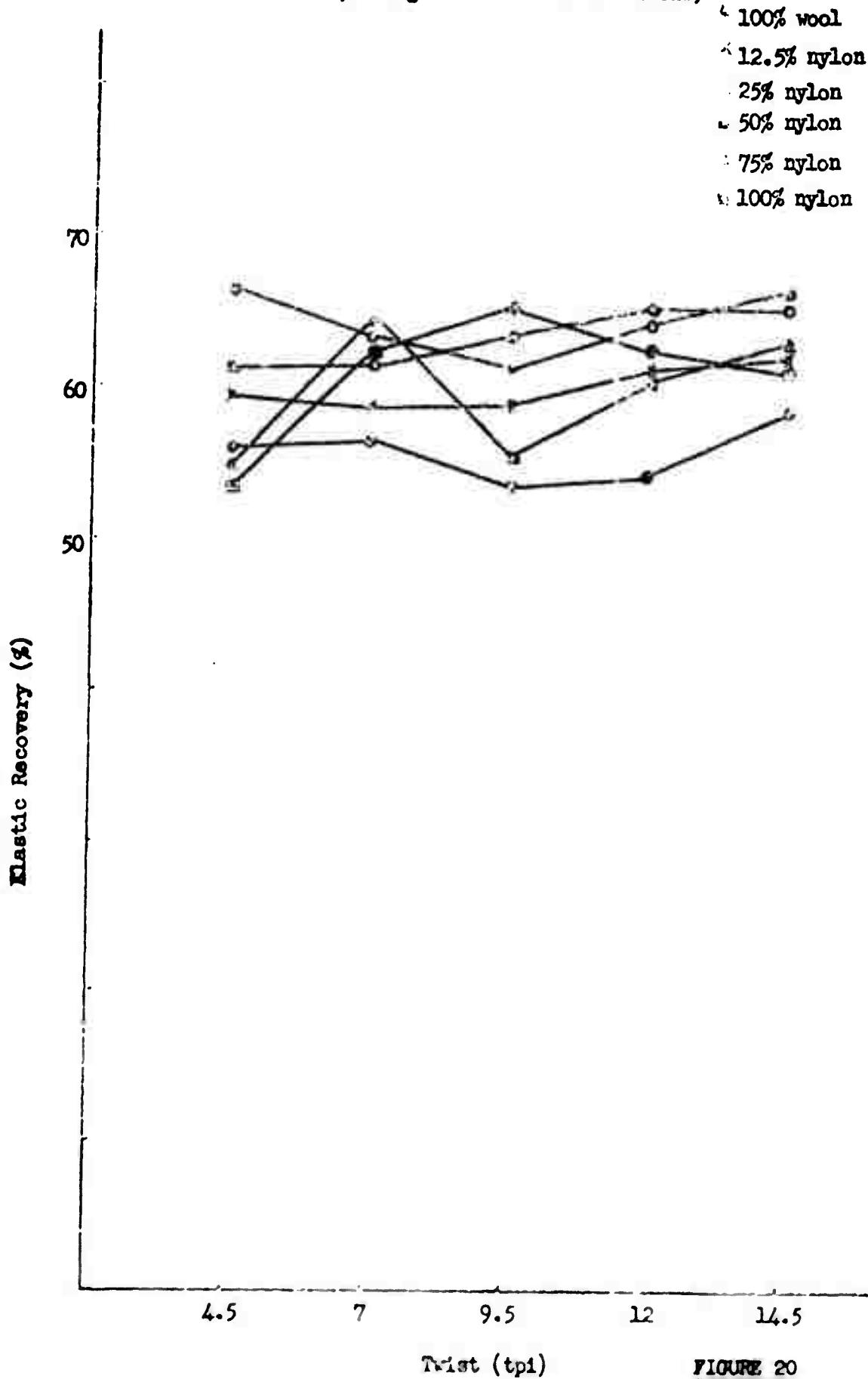


FIGURE 20

EFFECT OF TWIST ON ELASTIC RECOVERY WOOL-VISCOSE SERIES

Case No. C51137
Page 12d

(Average of three strain levels)

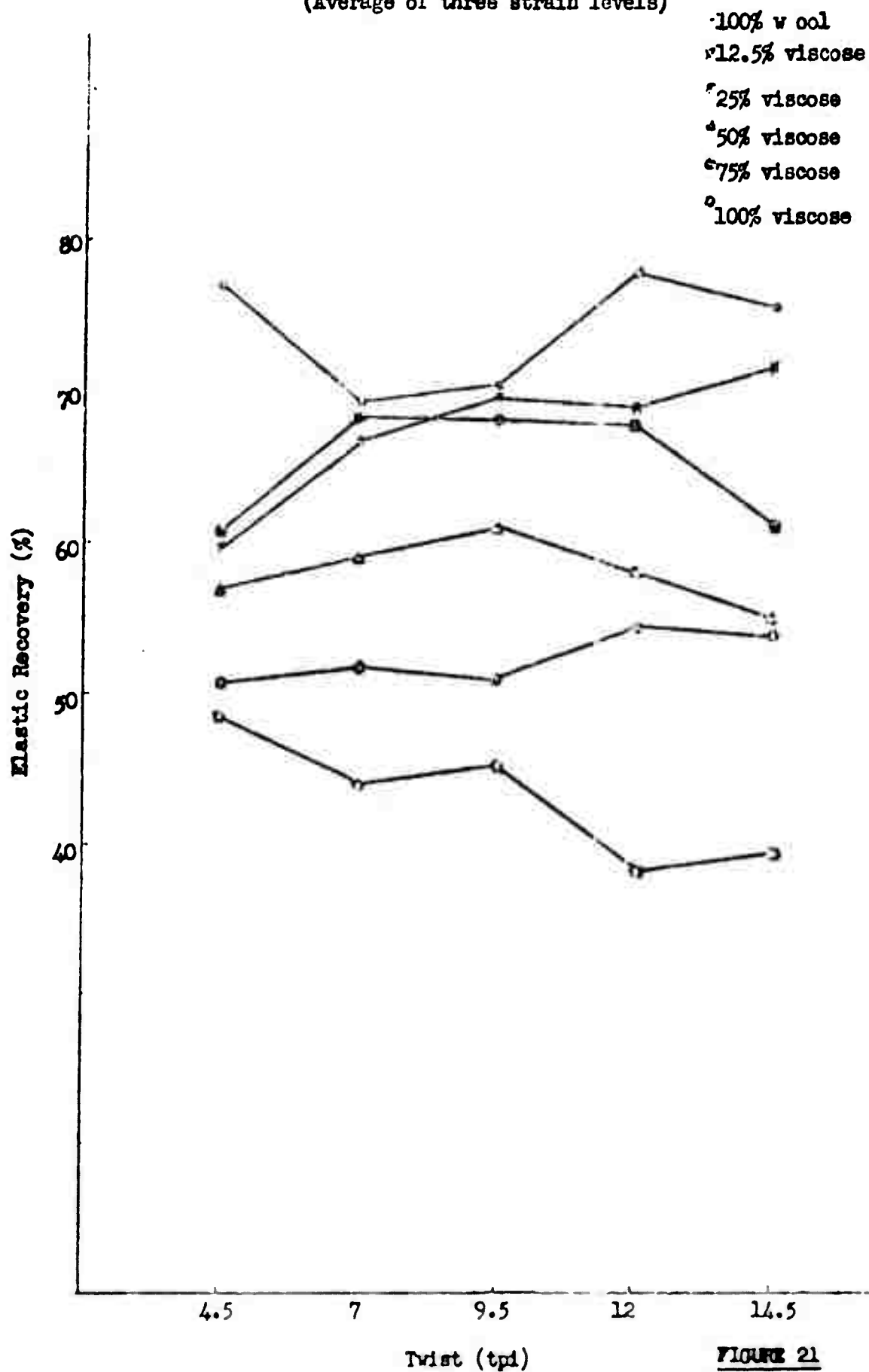
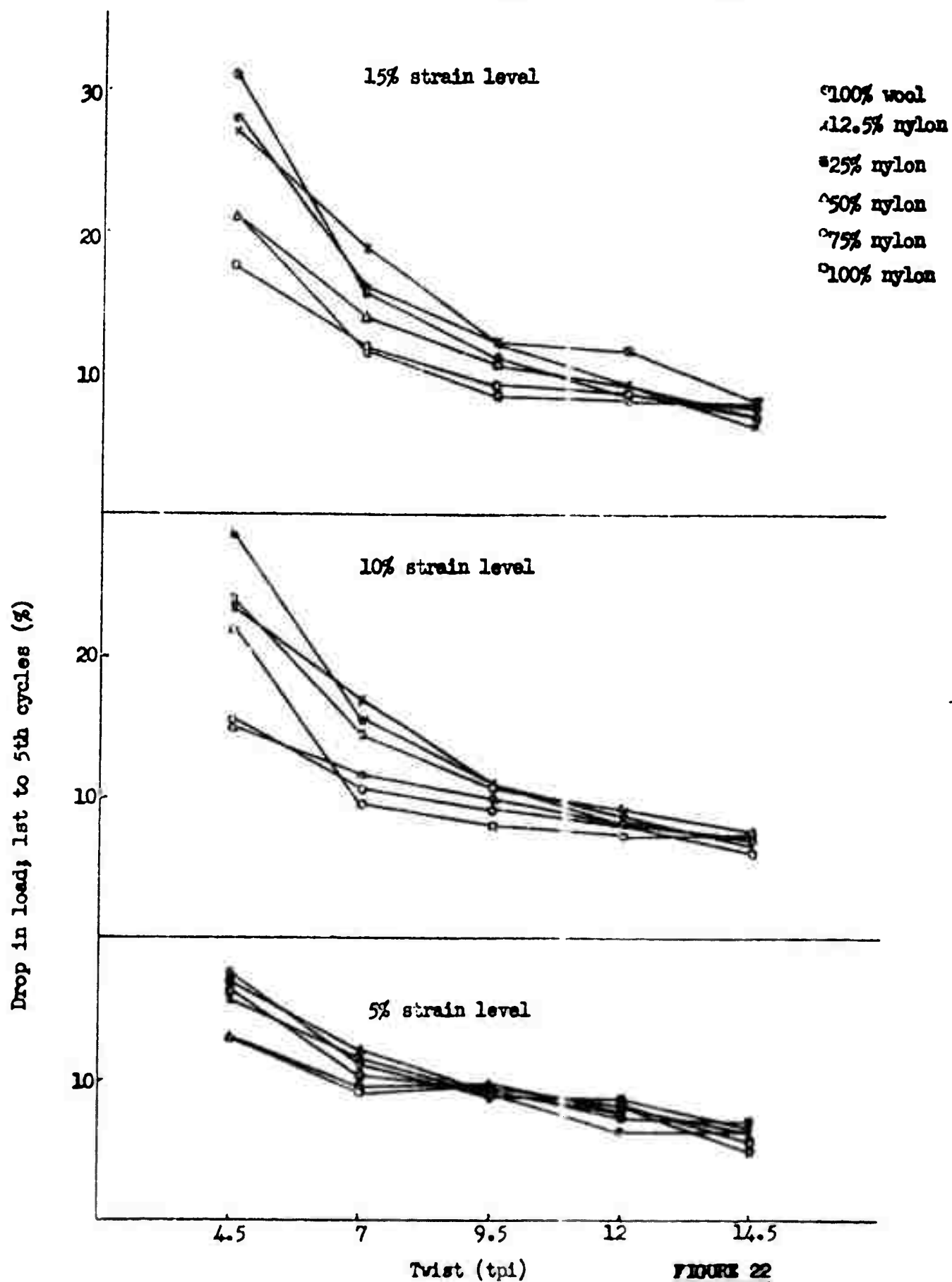
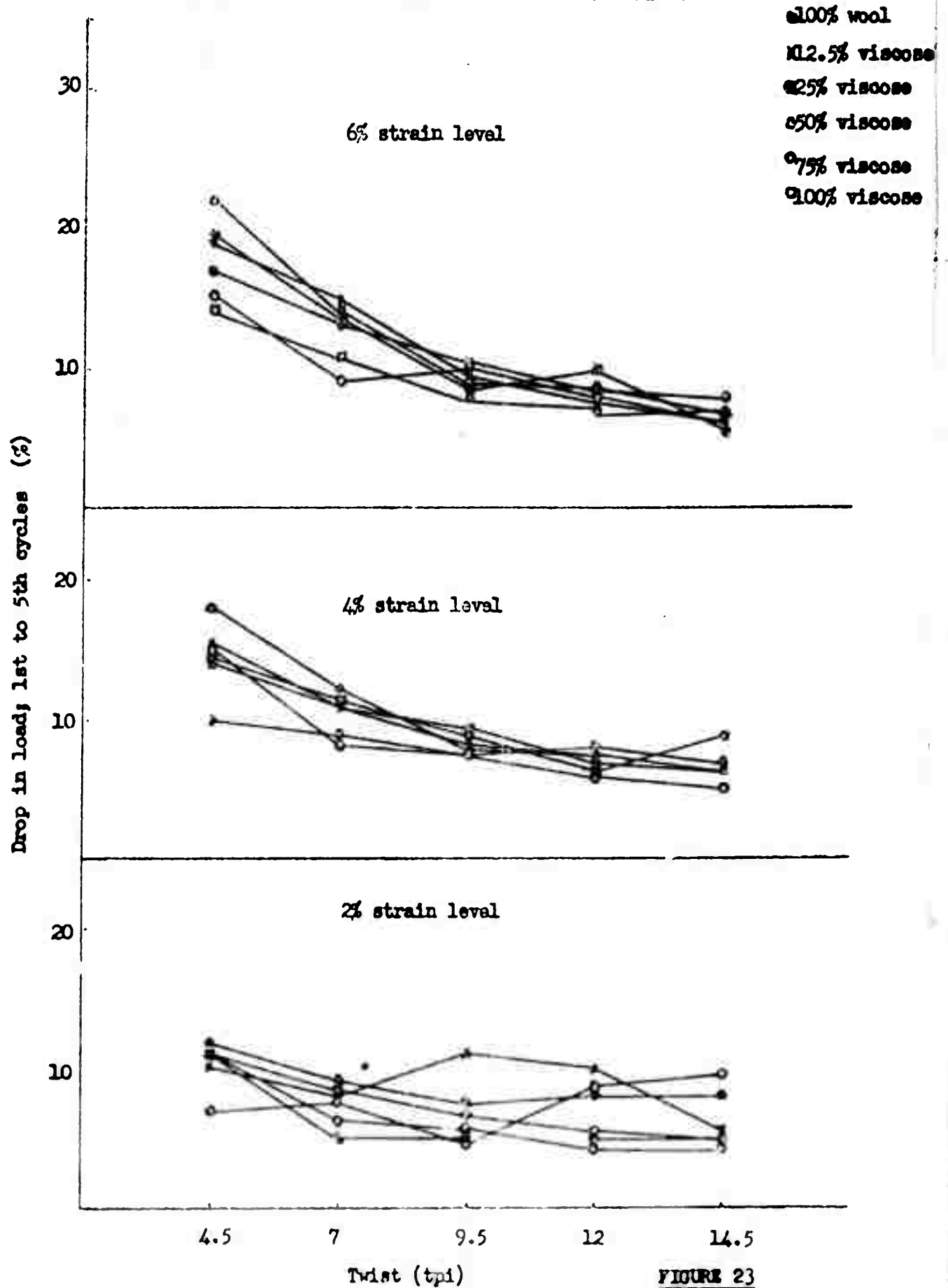


FIGURE 21

EFFECT OF TWIST ON LOAD DECAY WOOL-NYLON SERIES



EFFECT OF TWIST ON LOAD DECAY WOOL-VISCOSE SERIES



EFFECT OF BLEND ON LOAD DECAY WOOL-NYLON SERIES

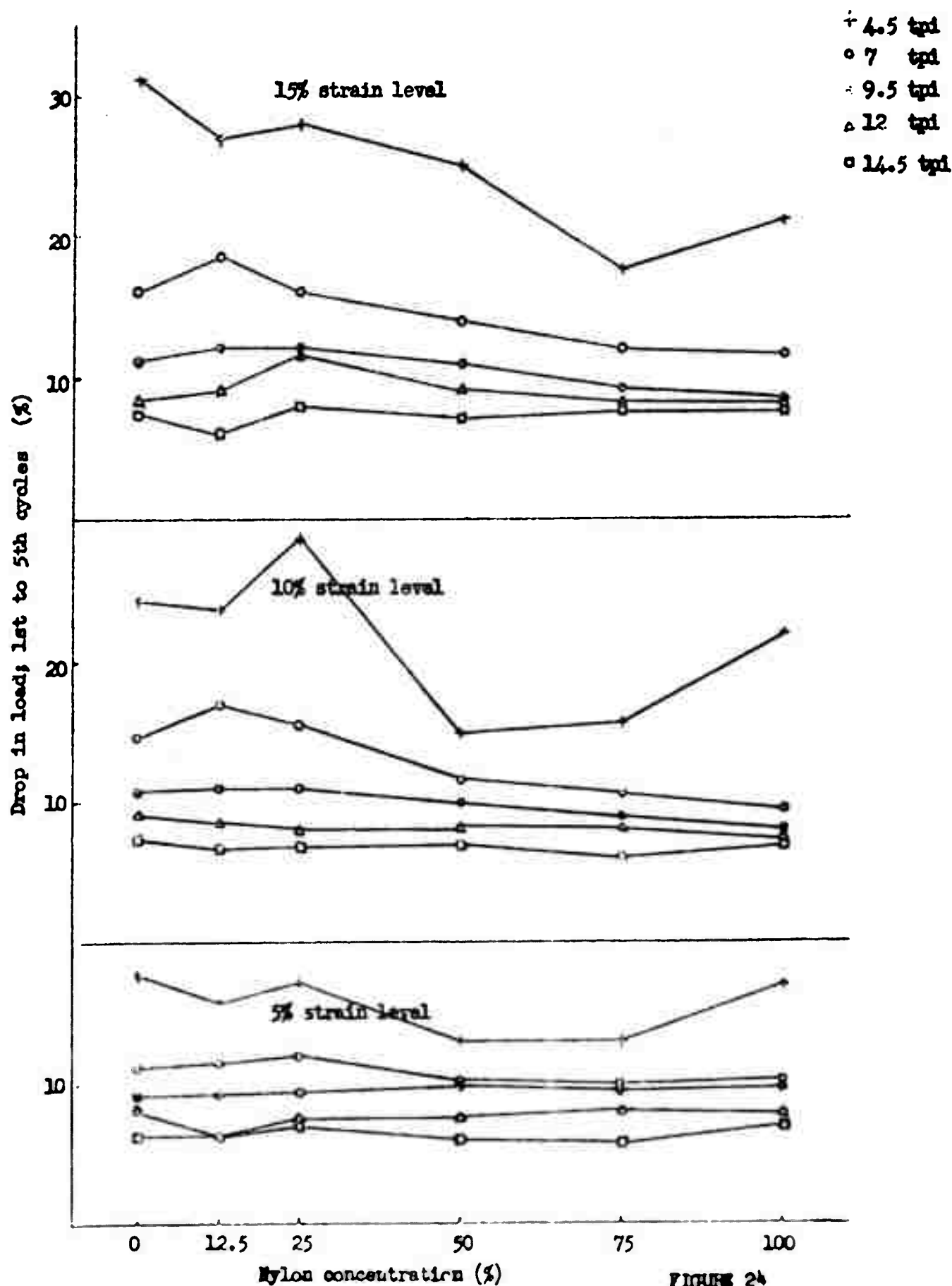


FIGURE 24

EFFECT OF BLEND ON LOAD DECAY WOOL-VISCOSE SERIES

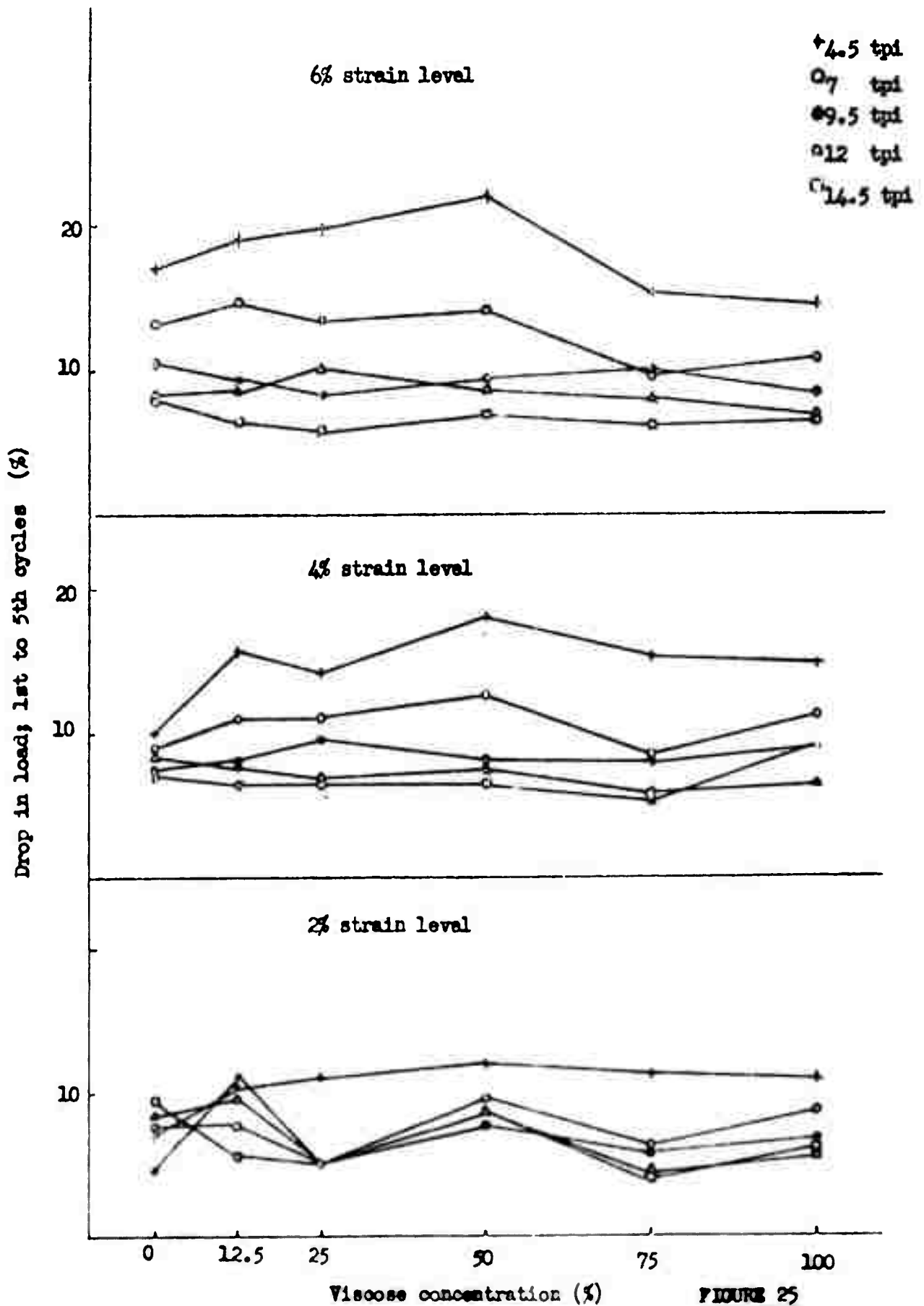


FIGURE 25

Another item of some note was considered in connection with repeated-strain tests. It was desired to determine if, and to what extent, low to moderate repeated-straining changed the rupture properties of the yarns. Figures 26 and 27 summarize the rupture tenacity information. In all plots the line drawn is a smoothed twist vs. tenacity curve corresponding to the one-time rupture loading end-point. The points shown are rupture tenacities after repeated-straining to particular strain levels. It will be seen that the 100% wool yarn at the three lowest twists shows a consistent drop in tenacity after pre-cycling to strains from 2% to 15% (See both Figures 26 and 27). At the highest twists, however, there is no effect of cycling at any strain level on the tenacity of the 100% wool yarns.

The 100% nylon yarn exhibits a similar effect in the two lowest twists. It is also noted that the points fall further away from the curve with increasing strain level. For the most part, all other points fall close enough to the curves to be considered within reasonable bounds of consistency. In a few cases there appears to be some increase in tenacity with mechanical conditioning.

Figures 28 and 29 illustrate the effect of pre-cycling on rupture elongation. Elongation was calculated from the total extension from original length prior to cycling and includes the "set" due to repeated straining. Except for the 100% wool yarn which shows an erratic scatter of points around the curve, and the 100% nylon yarn which exhibits reasonable consistency, it will be seen that pre-straining the yarns generally increases total rupture elongation slightly for all blends examined.

III. DISCUSSION

A. General

In attempting to relate the performance of a blended yarn to the performance of the constituent fibers many factors must be considered. Some of these will eventually be relegated to positions of minor significance while others emerge as dominating. There is one basic principle, however, that seems paramount in the analysis of any spun staple yarn, regardless of fiber content.

It is simply this. The "average" properties of a staple yarn are governed not only by average fiber properties and average yarn geometry but also by a multitude of variabilities, irregularities, and non-uniformities. Combining in the same yarn two different fiber types simply complicates the picture to another degree. That a blended yarn frequently exhibits "anomalous" properties should be no more surprising than those instances when behavior follows rules of simple proportionality. Consider

EFFECT OF REPEATED STRAINING ON YARN TENACITY WOOL-VISCOSE SERIES

Case No. C51137
Page 13b

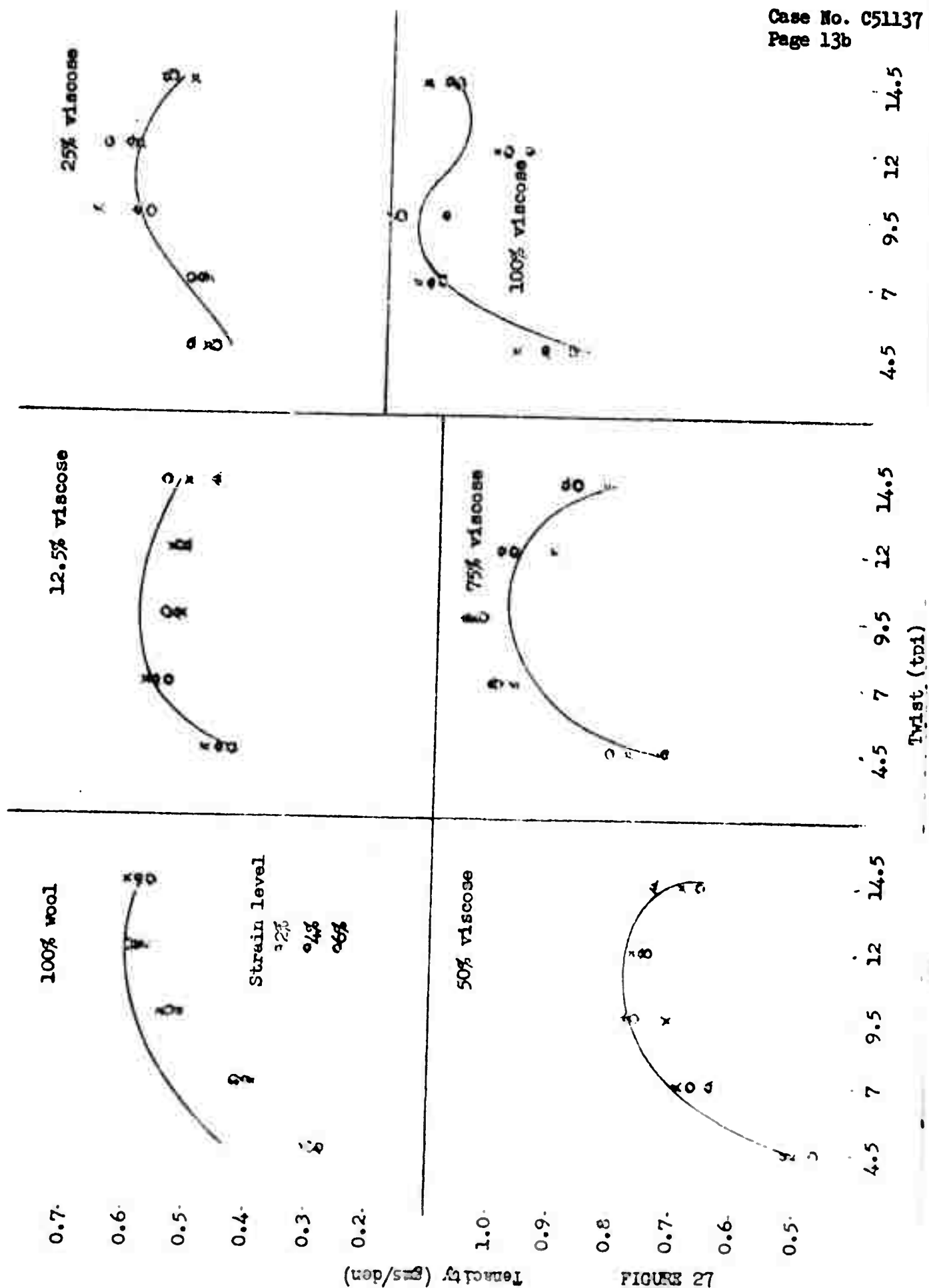


FIGURE 27

EFFECT OF REPEATED STRAINING ON YARN RUPTURE ELONGATION WOOL-NYLON SERIES

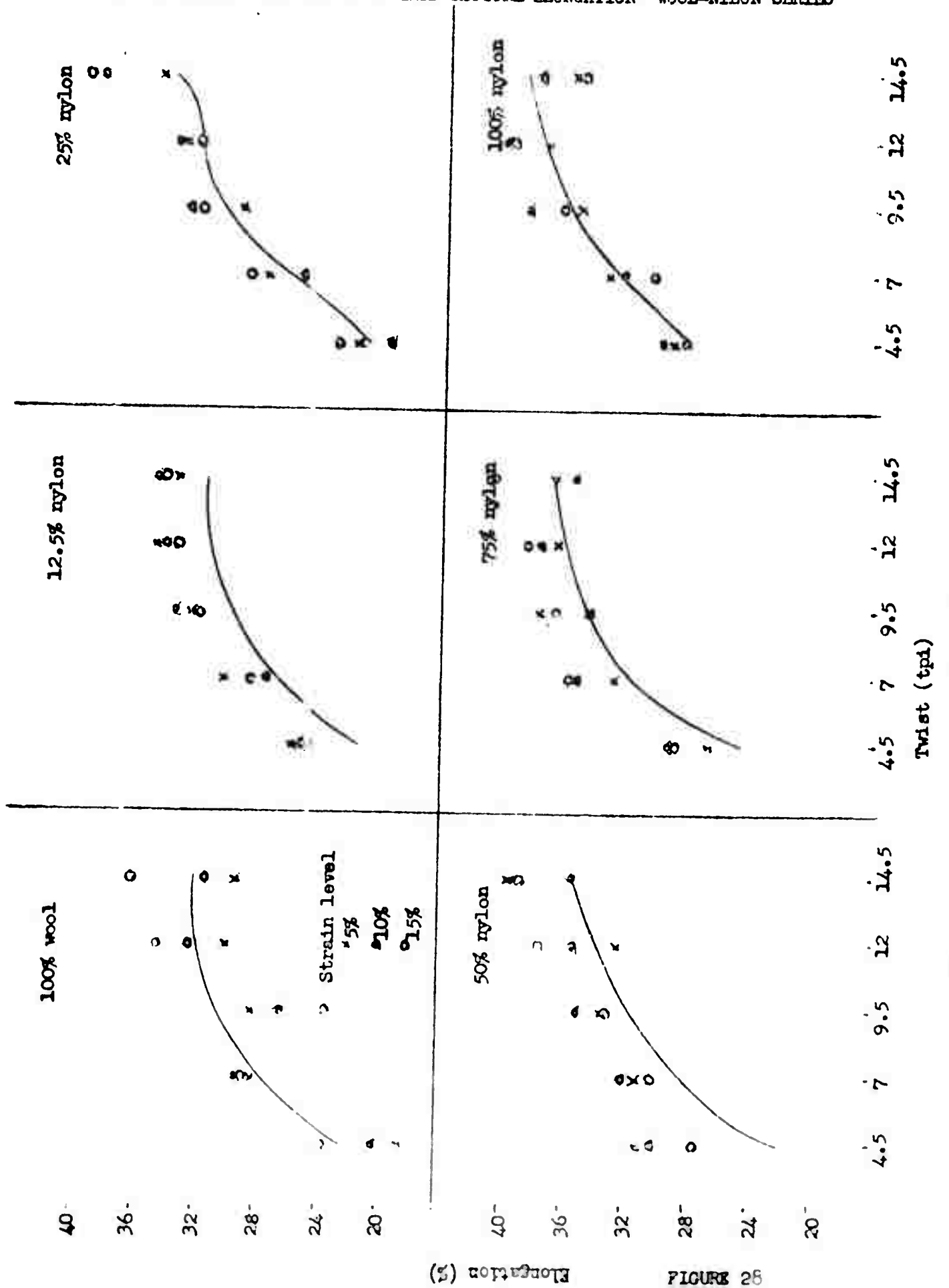


FIGURE 26

EFFECT OF REPEATED STRAINING ON YARN RUPTURE ELONGATION WOOL-VISCOSE SERIES

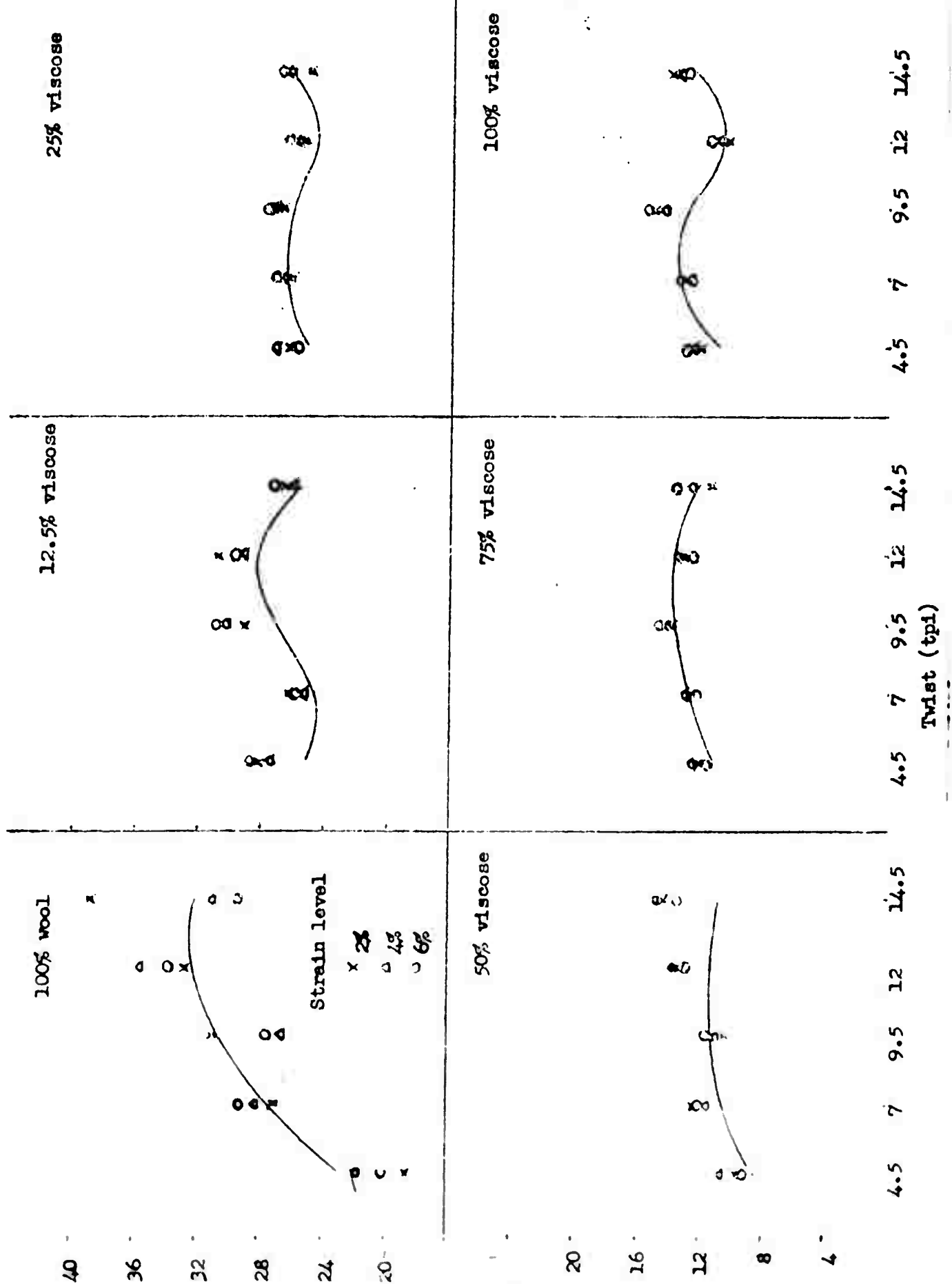


FIGURE 29

(x) 100% wool

some of the several variabilities which contribute to the problem of defining fiber properties, for example.

One customarily describes two dimensions of a fiber: length and cross-sectional area (or diameter if the fiber has a regular cross-sectional shape). But generally neither one of these dimensions is truly definable as a constant even for a single particular fiber. How, for instance, does one measure the true untensioned length of a crimped fiber? By the distance between its ends, or by estimating the gross path length of the fiber in space? Neither of these "lengths" may be the true length of fiber as it would be measured in a yarn. In an "untensioned" yarn, the fiber may have been partly uncrimped, is subject to lateral forces, is in a spiral path, etc. In practice, fiber length and crimp must be measured outside the yarn according to some standard practice and is then defined in terms of that measuring method. [See for example (5)].

Take cross-sectional area. Very often, at least for natural fibers, the cross-sectional area of a fiber varies along its length. If one is reasonably successful in determining the "average" diameter of the fiber, he has yet to evaluate the variability of this dimension.

The importance of the elusiveness of these two physical dimensions of a fiber can be readily illustrated. Suppose one is interested in ascertaining the rupture stress and strain of a highly crimped fiber having first, no diameter variation along its length. Assume that the crimped "length" between fiber ends at zero load is 1 inch, and that the overall path length of the fiber is 1.2 inches. That is, the fiber has 16.7% crimp ($0.2/1.2 \times 100$). Assume, also, that the fiber will rupture at a length of 1.6 inches. Is its rupture elongation 60% ($.6/1.0$), or 33% ($.4/1.2$)?

In the yarn it will not rupture until the distance between its ends is increased to 1.6 inches. Yet it may lie in the yarn with all or any part of its original crimp. In the yarn, therefore, it may rupture at a net stretch of anywhere from 33-60%.

Now consider a fiber which is not crimped, but exhibits only diameter variation. Assume, as is reasonable for most fibers, that the intrinsic material strength is constant at all cross-sections, and therefore the section of smallest diameter will determine the rupture tension. But the tension that causes failure at the thinnest section represents something less than rupture stress at all other sections. Except for the rupture "zone", all other regions are at less than their rupture strain at the time the fiber fails. The net effect will be an apparent over-all fiber rupture strain--and stress--lower than the true value of any zone including the thinnest one.

This has been very nicely demonstrated by a recent note in the literature of Bankey and Glen (1). They tested 25 mm. long wool fibers marked at intervals of 5 mm. The average diameter of each 5 mm.

interval was measured, and the extension of each such segment was also measured while the whole fiber was being strained to rupture. Table VI is taken from their article.

This data reveals that when the fiber as a whole had been strained 5%, some segments had been strained 2% or less, while others had been strained 10% or more. At the rupture there was as much as 9.5% difference in elongation between two segments. Undoubtedly, the ultimate strength of the heaviest part of the fiber had yet to be achieved. What are the "true" rupture properties of such a wool fiber as it lies in a yarn?

In a yarn, the fiber is not gripped at each end with the middle free to extend as between jaws. The existence of an aggregation of fibers twisted together results in the development of a system of mutual gripping along the length of the fiber by friction that reduces the "free gage length" of any one fiber considerably. But to what extent is not known. Thus, the properties of a fiber as measured externally to a yarn may be different from those developed within the yarn, but the appropriate conditions for testing are not specified. As a matter of fact, they are probably not unique, but depend on the yarn twist, it being altogether conceivable that increased twist results in a reduction of effective gage length. Such an effect was amply demonstrated in the referenced study of cordage yarns (15).

It should be noted that the two effects (crimp and variation of cross-sectional area) have been discussed thus far only as they occur within a single fiber. The problems attendant would be those if all the fibers in a yarn had similar crimp and area effects. But on top of this, there are also differences among fibers in regard to their average crimpiness, average cross-sectional area and the "within fiber" variabilities of these two items.

Earlier, some of the difficulties encountered in testing fibers were discussed and a standard single-fiber test procedure was described. It must be recognized that fiber properties derived by this procedure may not be accurately representative of the real properties of the fibers as they operate in a yarn. Having no better choice, however, these are the properties that are to be employed for analysis of yarn performance.

Now, consider the irregularities encountered in the yarn. In the most common idealizations, the yarn is conceived as a uniformly twisted bundle of parallel cylinders. A uniform packing from interior to exterior shells is often assumed, along with rotational symmetry. The geometry of all cross-sections is considered similar.

TABLE VI*

**PARTIAL AND TOTAL ELONGATION OF A WOOL FIBER AT
DIFFERENT LEVELS OF EXTENSION AS RELATED TO THE
MEAN DIAMETERS OF THE SEGMENTS**

<u>Segment</u>	<u>Mean Diam. (μ)</u>	<u>Levels of Total Extension</u>			
		<u>Elongation (%)</u>			
		<u>5.2%</u>	<u>15.5%</u>	<u>24.2%</u>	<u>32.9%</u>
1	30.0	2.0	6.0	20.0	28.0
2	29.9	0.0	5.9	19.6	29.4
3	28.0	3.9	21.6	27.4	35.3
4	28.0	9.6	21.2	25.0	34.6
5	26.6	10.4	22.9	29.2	37.5
1-5	28.5	5.2			32.9

*Bankey and Glen - Tex. Res. J. (April 1955)

Stress distribution of the fibers in such an assembly upon yarn straining can be calculated. With the knowledge of fiber properties, the tensile behavior of the yarn can be predicted.

This has been done with considerable success for filamentous yarns and cordage structures (13), where the real yarn geometry is reasonably approximated by the ideal. The woolen type yarns in the present study differ in that the real geometry departs markedly from the ideal in the following respects:

1. The fibers in the real yarn are not parallel cylinders. Most are crimped. They do not lie for their entire length at a given radius from the yarn axis, but "dart" and even go through 180° reverses.
2. There is a decided gradient of packing from "inside" to "outside" of the yarn (4).
3. There is a considerable variation in number of fibers from cross-section to cross-section (4).
4. There is a disparity in actual twist from cross-section to cross-section (Figure 1b, Technical Report No. 1 - 4)

Finally, as regards the blended yarns:

5. There is a considerable variation in blend composition from cross-section to cross-section (4), and
6. Within cross-sections there is a tendency for excess wool to appear at yarn surfaces (4).

Each of these factors influence the observed behavior of the yarns. When they are accounted for, however, the tensile properties of the blended yarns can be explained and even predicted with gratifying precision.

The effect of fiber properties, even as these are measured under arbitrary conditions, is pronounced and falls into two categories.

First, the intrinsic mechanical properties of the fibers--strength, elongation, elastic recovery--are directly reflected in the equivalent behavior of yarns. Second, the geometry of the fibers markedly influences the geometry of the yarns. In turn, such differences in yarn twist, regularity, density, etc., as are due to fiber geometry are also felt in the measurement of yarn properties.

B. Low-Strain Extensibility

In order to measure low strain extensibility of yarns or fibers, a true zero-load length must be established for the specimen. The problems in this connection have already been noted. In this work certain arbitrary conditions were adopted. Yarns were pretensioned under a 1 gram load and then subjected to repeated strain. Fibers were pretensioned with .02 grams load. The so-called uncrimping portions of the several stress-strain curves were found. The absolute values of crimp so determined may be questioned but the relative "tensile softness" under extremely low loads is well revealed.

Figure 30 summarizes the general effect of both twist and blend on yarn crimpiness. It also indicates the levels of average single-fiber crimp. It is obvious that increased twist reduces the amount of low-strain extension that occurs prior to the "Hookean slope" for wool, nylon and their blends. There is no such effect in viscose and the 50/50 wool viscose blend.

The reasons for this seem fairly obvious. The viscose fibers, as removed from yarn, had very little residual crimp. In both 100% viscose and 50% viscose yarns at any twist, the essentially crimpless viscose fibers are subjected almost immediately to material straining, and the yarn stress-strain curve starts up rather steeply. In both the wool and nylon yarns at the lower twists, much of the original fiber crimp is free to be straightened during the earliest period of loading. At lowest twist the yarns actually exhibit about as much as or more "crimp" than the fibers.

It should be noted, however, that the pretensioning load for fibers (.02 grams) was roughly four times higher than the average per fiber load employed for the yarns. (There were about 200 fibers per cross-section in the yarns and the load of 1 gram represents roughly .005 grams per fiber.) This might account for the apparently greater crimp shown in the 100% nylon yarn than was found for single nylon fibers, since the higher pretensioning load would have removed more crimp prior to measuring in the latter case.

It is interesting to observe how nearly linear the fall in crimp is for the 100% wool yarns with increase in twist as compared with the early sharp drop exhibited by the 100% nylon and nylon blends. In Technical Report No. 1 it was shown that blending nylon (and viscose) with wool markedly increased the packing of the core of the yarns. It would seem that a related phenomenon may be involved here.

Twisting a bundle of crimped fibers evidently reduces their freedom to unbend either by "locking" them together or by directly

FIBER CRIMP AND EFFECT OF TWIST ON YARN CRIMP

Case No. C51137
Page 17a

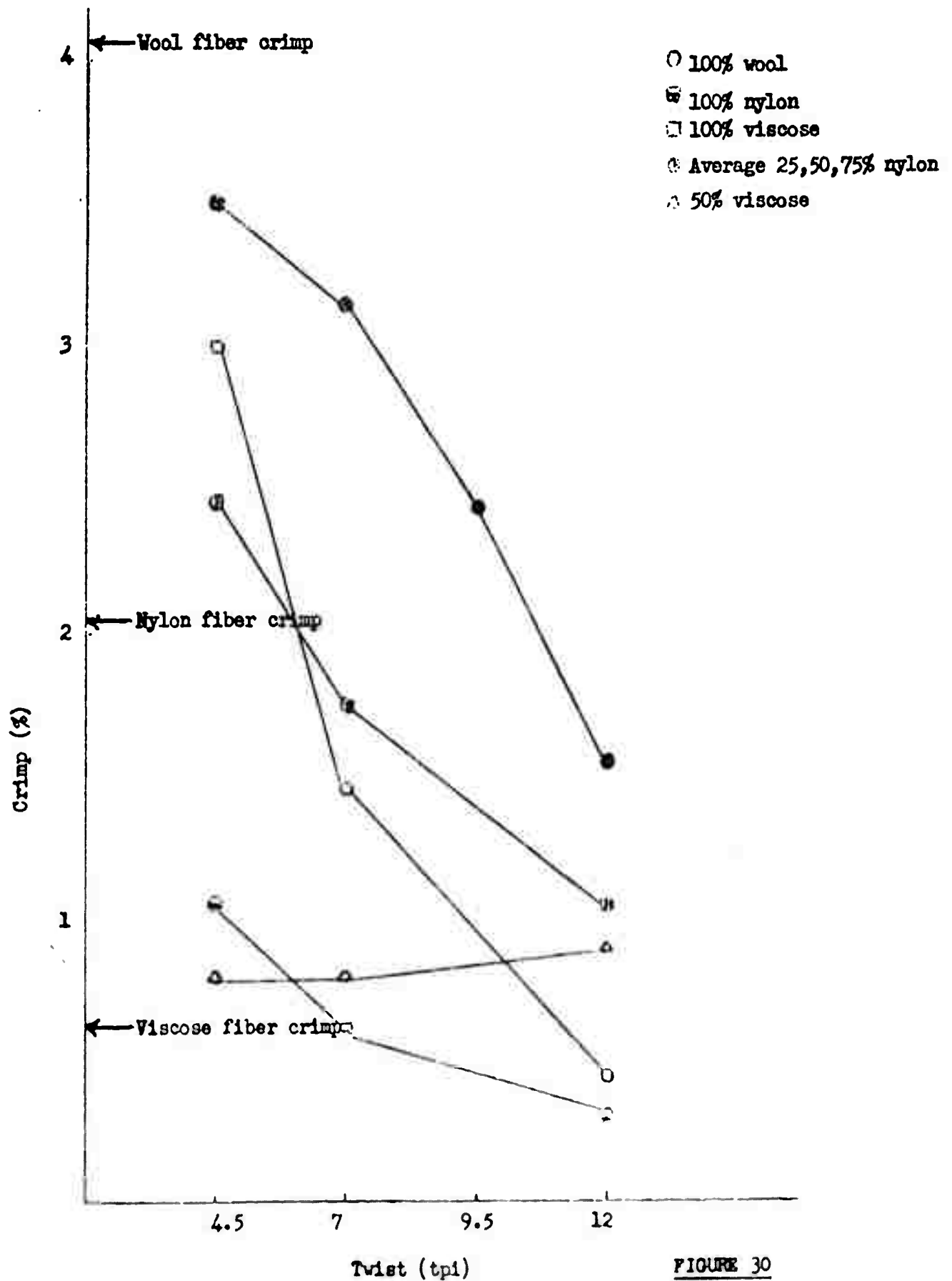


FIGURE 30

absorbing the excess fiber length in the helical paths required of the fibers. The greater susceptibility of nylon to packing and its influence on the packing of the wool-nylon blends may also be responsible for the somewhat greater reduction of yarn crimpiness with twist that is evidenced by these yarns.

In any event, the low-strain softness of yarns, as manifested by uncrimping under tension, is in general consistent with the same property of the fibers. Wool shows the greatest, nylon nearly as much, and viscose very little. The viscose fibers, having been essentially decrimped during yarn processing, mask the wool fiber crimpiness in the 50/50 blend. The wool-nylon blends fall about intermediate between 100% wool and 100% nylon. Twist has a dominating influence except where the fibers have already been decrimped as in the viscose and viscose blend. It would appear that the crimpiness of a yarn is one of those properties dependent on the geometry of the fibers and their ability to retain that geometry under the forces due to twist and in spinning.

C. Repeated-Strain Elasticity

In Section II-B, 2 it was shown that twist had, at most, a small and erratic effect on the ability of the yarns to recover from repeated strain up to five cycles. On the other hand, there seemed to be a definite dependence on blend composition. If the elastic recovery values of the five twists for each blend are averaged together, the dependence of this property on blend is indicated by Figure 31.

At the 4% and 6% strain level (above the "yield" of viscose) the apparent elasticity of the wool-viscose blends shows a remarkably linear decrease with viscose concentration. At 2% strain, there is also a general trend downward with increasing viscose concentration which is nearly linear.

The elastic recovery is not as nicely linear with concentration for the wool-nylon blends however. Besides, there is a trend downward in elastic recovery with nylon concentration at the 5% strain level, and trends upward at 10% and 15%.

The question is, how much of the yarn inelasticity is due to geometric rearrangement of the yarn structure, e.g., drafting of fibers, and how much is due to fiber permanent set? Do the intrinsic elastic properties of the fibers account for the behavior of the yarns?

In Figures 32 and 33 are several plots taken from the literature showing either elastic recovery or elastic deformation vs. strain for the three fiber types with which this study is concerned. Each of these other workers employed different techniques and different

SUMMARIZED EFFECT OF BLEND ON YARN ELSTIC RECOVERY
(Averaging three twists)

Case No. C51137
Page 18a

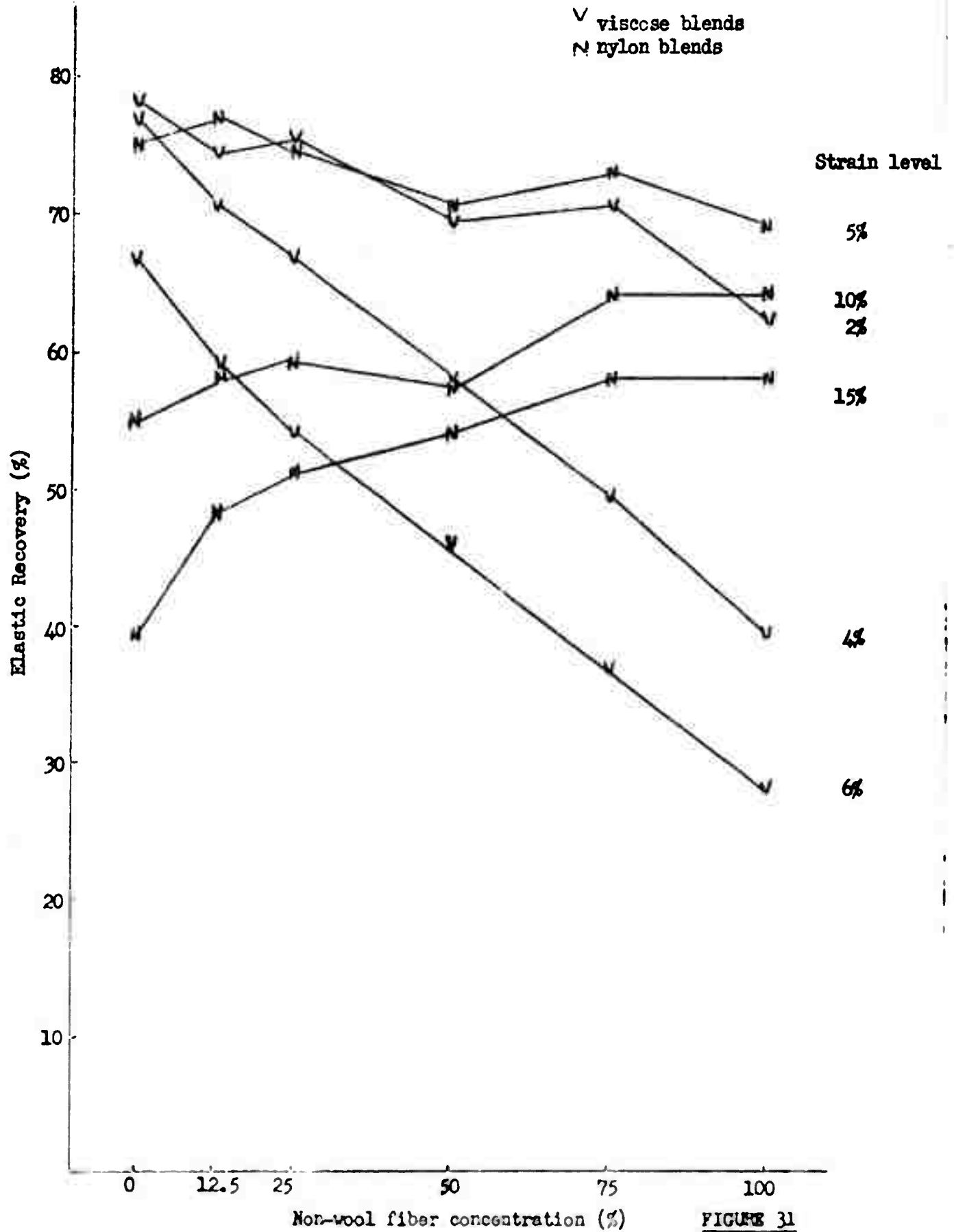


FIGURE 31

EFFECT OF STRAIN ON ELASTIC RESPONSE OF WOOL, NYLON, AND VISCOSE

A). Single fiber elastic recovery; Meredith (10)

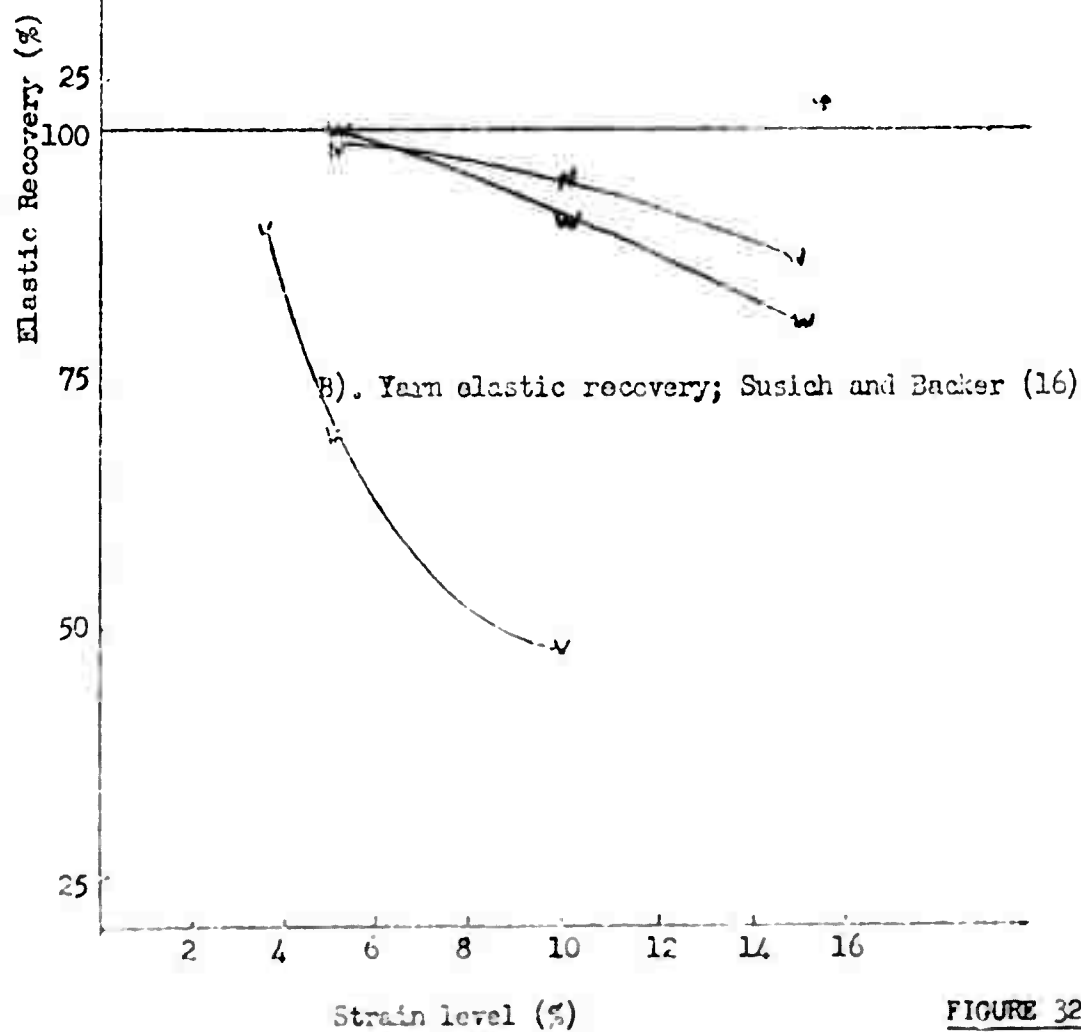
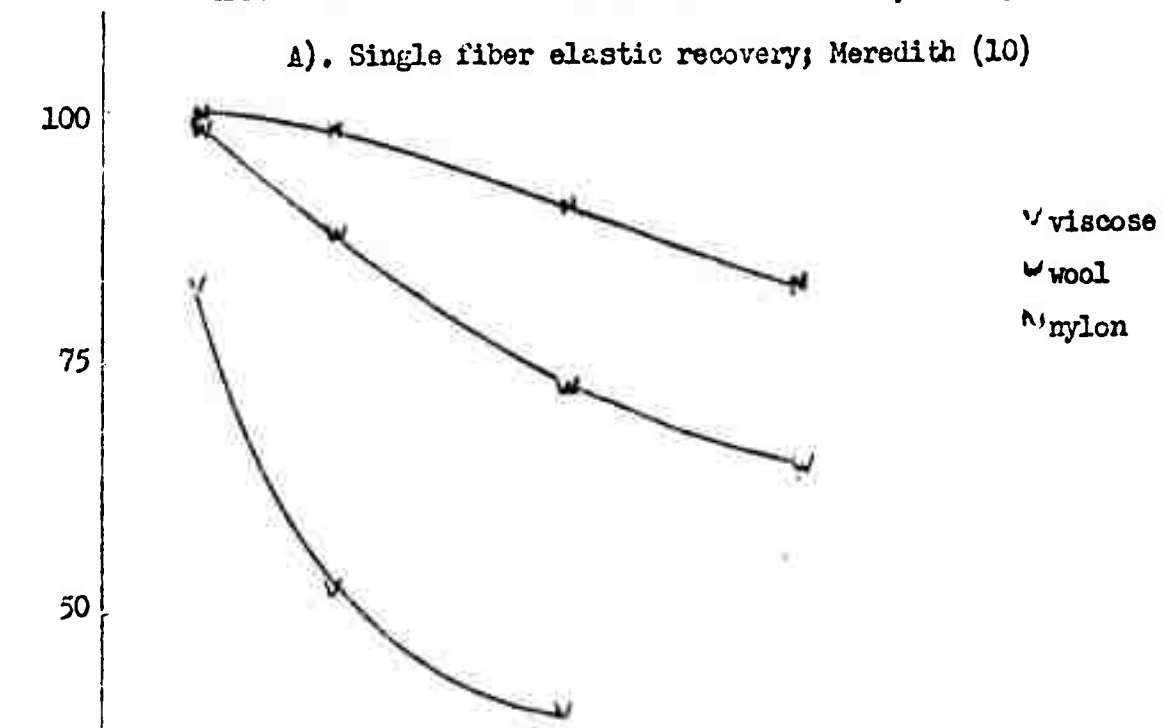


FIGURE 32

EFFECT OF STRAIN ON ELASTIC RESPONSE OF WOOL, NYLON, AND VISCOSE

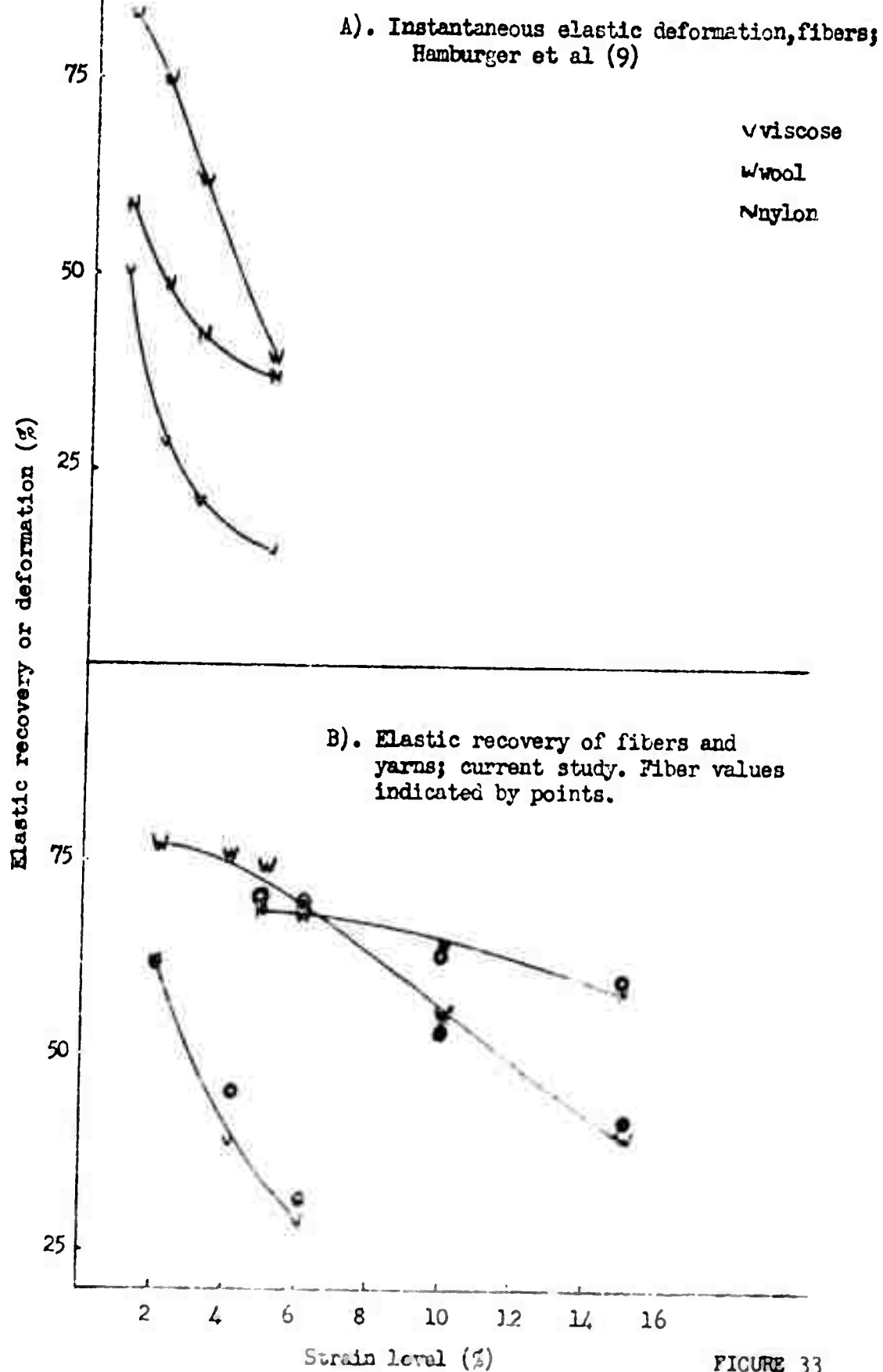


FIGURE 33

fiber stocks. Meredith (10) worked with single fibers using essentially slow rates of loading and long periods of recovery. Hamburger (9) employed sonic methods to measure "instantaneous elastic deformation". Susich and Backer (16) used yarns (filament nylon, worsted wool, and staple viscose). The absolute values of elastic recovery for these workers cannot be expected to coincide with those in Figure 33b.

What is of interest in comparing the several separate plots in Figures 32 and 33 is the great similarity in shape of curves and the relative positions of the wool, nylon and viscose plots. The cross-over of the wool and nylon curves at about 3-6% strain is important. In Figure 31 it was shown that at 5% strain, elastic recovery decreased slightly with increasing nylon while at 10% and 15% the elastic recovery improves. This is understandable now in view of the superior elastic recovery of wool below 3-6% strain, and its poorer than nylon performance above that level.

In the case of wool and viscose, wool is superior at all strain levels tested, and this is reflected in the performance of the blends. At 2% strain level the superiority of wool fiber over viscose is less than at 4 and 6%, and this effect is also apparent in Figure 31 where the slopes of the 4% and 6% elastic recovery vs. blend lines are rather steeper than at the 2% level.

Finally, in Figure 33b, the elastic recovery of single fibers taken from the low-twist yarns of the present study are plotted as points. They fall remarkably close to the curves for the 100% yarns. It would seem from all this that the elastic recovery of yarns is directly controlled by the equivalent property of the fibers. Also, the effect of this seems to be that in a blended yarn the elastic response of the component fibers average together in nearly proportion to their concentrations. Why this should be so is not immediately clear and two possible explanations will be developed shortly.

Although the extent of recovery of original dimension on repeated-straining seems to be unaffected by twist, it was shown in Figures 23 and 24 that the load decay during this operation was affected by twist.

Low twist yarns showed a high decay and increasing twist rapidly dropped this to values near that shown by the fibers. This is recapitulated for the 100% yarns in Table VII.

This table provides a rather interesting clue to one of the important functions of twist in the tensile behavior of yarns. If

TABLE VIICOMPARISON OF LOAD DECAY OF 100% YARNS
WITH RESPECTIVE FIBERS

<u>Strain Level, %</u>	<u>Content</u>	<u>Fiber</u>	<u>% Load Decay, Five Cycles</u>				
			<u>Yarn at Twist (T.P.I.)</u>				
			<u>4.5</u>	<u>7</u>	<u>9.5</u>	<u>12</u>	<u>14.5</u>
6	Wool	4.4	17	13	11	9	8
10	Wool	4.8	24	15	11	9	7
15	Wool	2.8	31	16	11	9	8
5	Nylon	8.1	17	10	10	8	7
10	Nylon	6.0	22	10	8	7	7
15	Nylon	7.5	21	12	9	8	8
2	Viscose	6.4	11	9	7	6	5
4	Viscose	5.2	15	11	9	7	9
6	Viscose	5.1	14	11	8	7	7
2	Wool		7	8	5	8	9
4	Wool		10	9	8	8	7
5	Wool		18	11	9	9	7

the dimensional recovery of repeatedly strained yarn is virtually unaffected by twist and almost identical with the dimensional recovery of the component fibers, how can it be that load decay of the yarns is quite sensitive to twist? Moreover, why does it drop with increasing twist almost asymptotically to the level of the single-fiber load decay?

Imagine that a yarn consists of two concentric regions. The interior, or "heart", of the yarn is packed to high enough twist-density so that the fibers occupying this zone are able to bear the loads induced by straining the yarn without slipping over one another. In yarn tension then, these fibers are subject to material straining almost exactly to the same degree as the measured yarn strain. In respect to repeated-strain elasticity, the fibers in the high density heart of the yarn should behave as they do when tested as single fibers, and this zone of the yarn will then stretch and recover in accordance with the intrinsic fiber elasticity.

Now, surrounding the heart of the yarn is a layer of "fringe" fibers. In this angular zone the fibers are not packed together tightly enough to prevent some kind of slippage when the yarn is tensioned. Whether the slippage is strictly translation parallel to fiber axes, or uncrimping with lateral displacement and relocation of short elements of fiber length is immaterial. The point is that the fibers in this low-density zone are not strained to the same extent as those in the heart of the yarn, but they do require some force to move them. Part of this force is completely dissipated in overcoming the slippage friction.

Upon straining the whole yarn, these fibers find new locations with respect to one another--i.e., longitudinal translation, or lateral repositioning of crimps--and therefore on releasing the yarn they will exert a restoring force in tension much lower than that generated by the "heart" fibers. In fact, tension in many of the fringe fibers may well drop to zero before the heart fibers have recovered elastically to their ultimate ability. The heart fibers continue to retract, however, and in so doing develop compressive strain in the fringe zone. The compressive resistance of the fringe is extremely low, however, since these fibers are easily buckled, and therefore the heart fibers are hardly at all restrained from recovering to the degree that they desire.

The mechanism described here may be depicted diagrammatically as in Figure 34. The main spring represents the heart fiber assemblage, which stretches and recovers with the same elastic properties as the single fibers would. The fringe fibers at low enough yarn strain (b) may simply readjust spatially without slippage, but with increasing yarn strain (c) they will be strained to the point where they start to slip over each other.

DIAGRAMMATIC VERSION OF THE HEART-FRINGE EFFECT

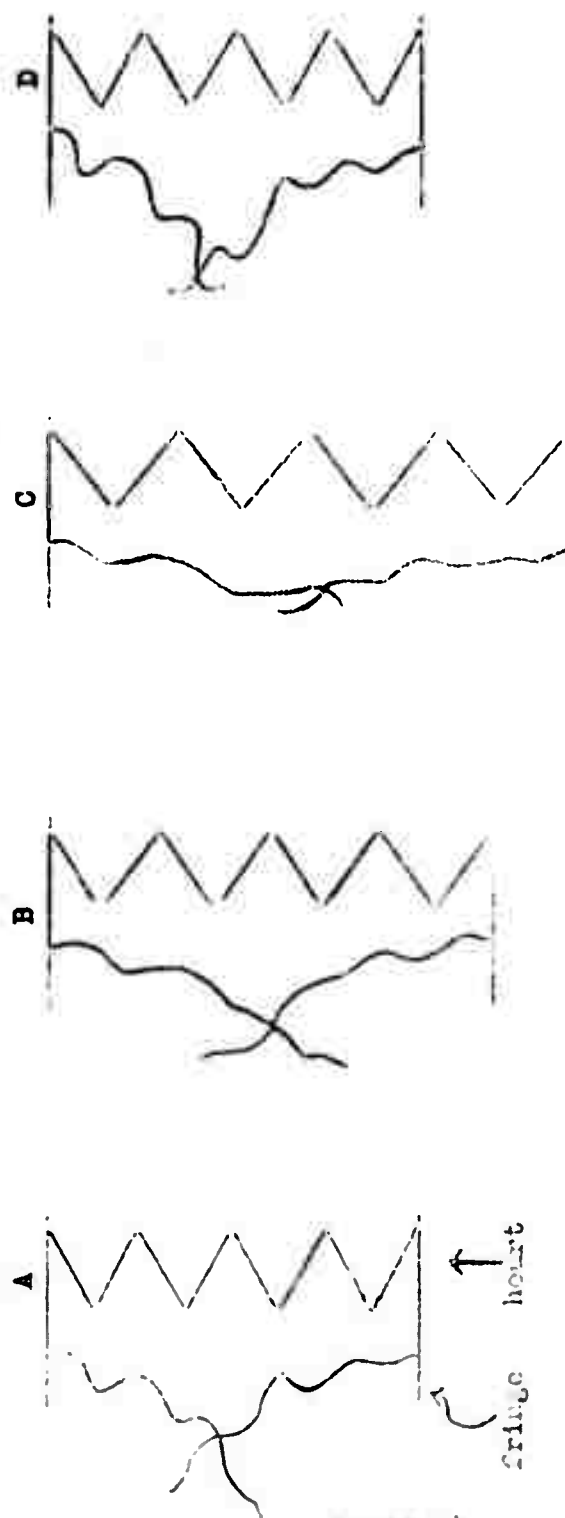


FIGURE 34

Case No. C51137
Page 20a

Progressive stretching of whole form represented by A through C; D represents retracted form only; A vs. D.

If elastic recovery is then allowed to occur (d), the heart fibers retract to their limit and the fringe fibers are either pushed back or are free to buckle into some new configuration.

It can thus be seen that the dimensional recovery of the yarn will be equivalent to that of the heart fibers. But the force to re-extend the yarn to condition c from condition d will be less than that originally required to go from a to c. This difference is the total load decay experienced in straining the yarn. Part of the load decay is due to the inelasticity of the main spring itself; the rest can be ascribed to non-recovered slippage friction force. The heavier the main spring relative to the friction of the tangled fringe points, the less will be the load decay on repeated straining.

Now, increasing twist has the effect of increasing the proportion of high density heart fibers in the yarn. It does so at the expense of the volume of material constituting the fringe. In the lowest twists, where heart fraction is low, adding twist has its greatest proportional effect on the change in heart to fringe ratio. Hence, there should be initially a fairly rapid drop in load decay with increasing twist which levels out and ultimately approaches the value that can be expected from single fiber performance when nearly all the fibers in a cross-section are, by virtue of high twist, part of the heart of the yarn.

This mechanism seems to be very well borne out by the data in Table VII and in Figures 22 and 23, both as to the shape of the curves and the ultimate load decay level achieved.

It should be expected that the effect of increasing twist on load decay will only be felt if the yarn strain level is high enough to cause slippage in the fringe. If the crimpiness of the fibers is great enough, and frictional resistance to slippage high enough, the fringe fibers may simply uncrimp on yarn straining at low enough levels. No force may be dissipated in slippage friction and in this case increasing twist should have little or no influence on load decay.

This seems to be confirmed by the data on wool fibers at the 2% and 4% strain levels shown in Table VII. Evidently, up to about 4% yarn tensile strain, the wool fiber fringe is capable of uncrimping without slippage. Hence the load decay is unaffected by twist and the repeated-strain cycle is comparable to going between a and b and a in Figure 34. This hypothesis is in close accord with the work of Burte (Tex. Res. J. - 1953 - 469) on the elastic properties of worsted top and roving. In this work evidence is given that even in the extremely low density fiber assemblies such as top, up to about 3 - 4% strain is achievable without significant slippage but mainly by deformation of fiber crimp.

Another aspect of the twist-slippage situation is illustrated in Figures 35 and 36. Here load decay is plotted against strain level for all twists and blends. It will be seen that as twist increases there is a gradually diminished slope of load decay with twist. At the highest twists there is essentially no change in percent load decay from strains between 2% and 6% for the viscose series and between 5% and 15% for the nylon series. Evidently at highest twist essentially the entire relaxation of the yarn is fiber relaxation, and if this is constant over the strain levels, then yarn relaxation is also constant over those strain levels.

The foregoing analysis of the function of twist in yarns in reducing fiber slippage during yarn tensioning amplifies somewhat the customary viewpoint. It is often inferred that yarns of low twist contain regions distributed along the fiber axis having insufficient frictional cohesion to develop the tensile strength of any of the fibers before such a zone slips apart. Additional twist is presumed to serve mainly the function of upgrading cohesion at these series-connected regions of low density until they eventually are made to stretch without slippage.

The current hypothesis does not abandon the notion that slippage zones are connected in series with non-slippage zones for extremely low twist yarns. But, for the yarns in the series under study--except for a few cases at 4 1/2 t.p.i.--the slippage of fibers is considered to be almost exclusively a parallel-connected effect. Namely, the fringe fibers in all cross-sections of the yarn slip in parallel with the true straining of the heart fibers. Additional twist serves mainly to increase the ratio of heart to fringe fibers in all cross-sections. This hypothesis is of considerable significance in connection both with the low-strain elastic properties of the blended yarns and the tenacity problem to be considered shortly.

Of course, it must be understood that the heart and fringe are not two distinct regions. In reality there is a gradient of packing density from the interior to the exterior of the yarns (4). Moreover, any given fiber may, for some part of its length, be bound into a region of high density where no slippage is possible, and then wander into some other region where it is not so tightly bound. Nevertheless, the general concept developed here is still applicable, namely, that twisting condenses more and more fibers into a zone which is entirely without slippage.

With some rational interpretation here as to the influence of twist on low-strain elasticity, the effect of blend remains to be resolved. Figure 31 indicated a decided influence of blend composition on elastic recovery, while other information has revealed that the elastic

EFFECT OF STRAIN LEVEL ON LOAD DECAY WOOL-NYLON SERIES

Case No. C51137
Page 22a

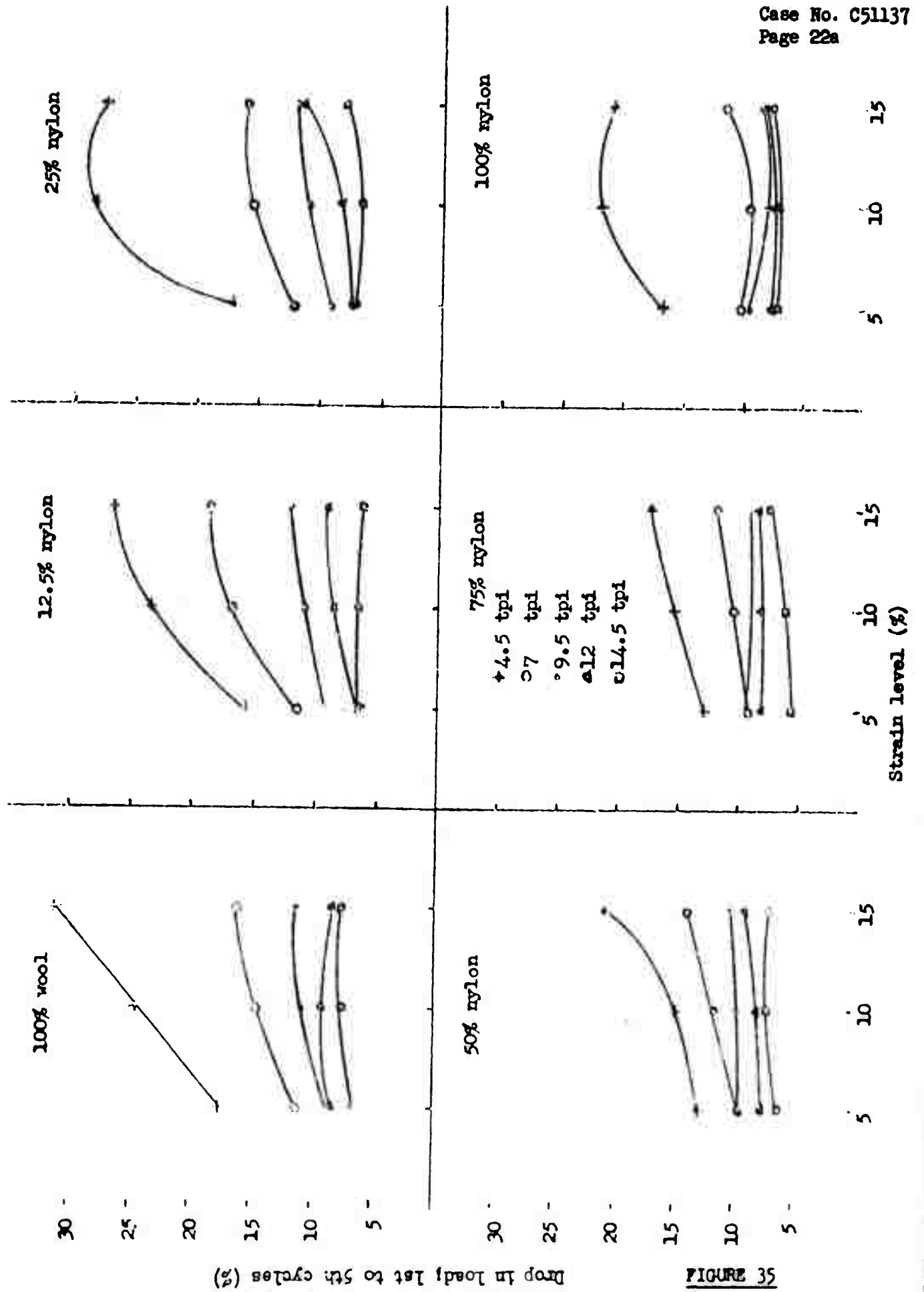


FIGURE 35

EFFECT OF STRAIN LEVEL ON LOAD DECAY WOOL-VISCOSE SERIES

Case No. C51137
Page 22b

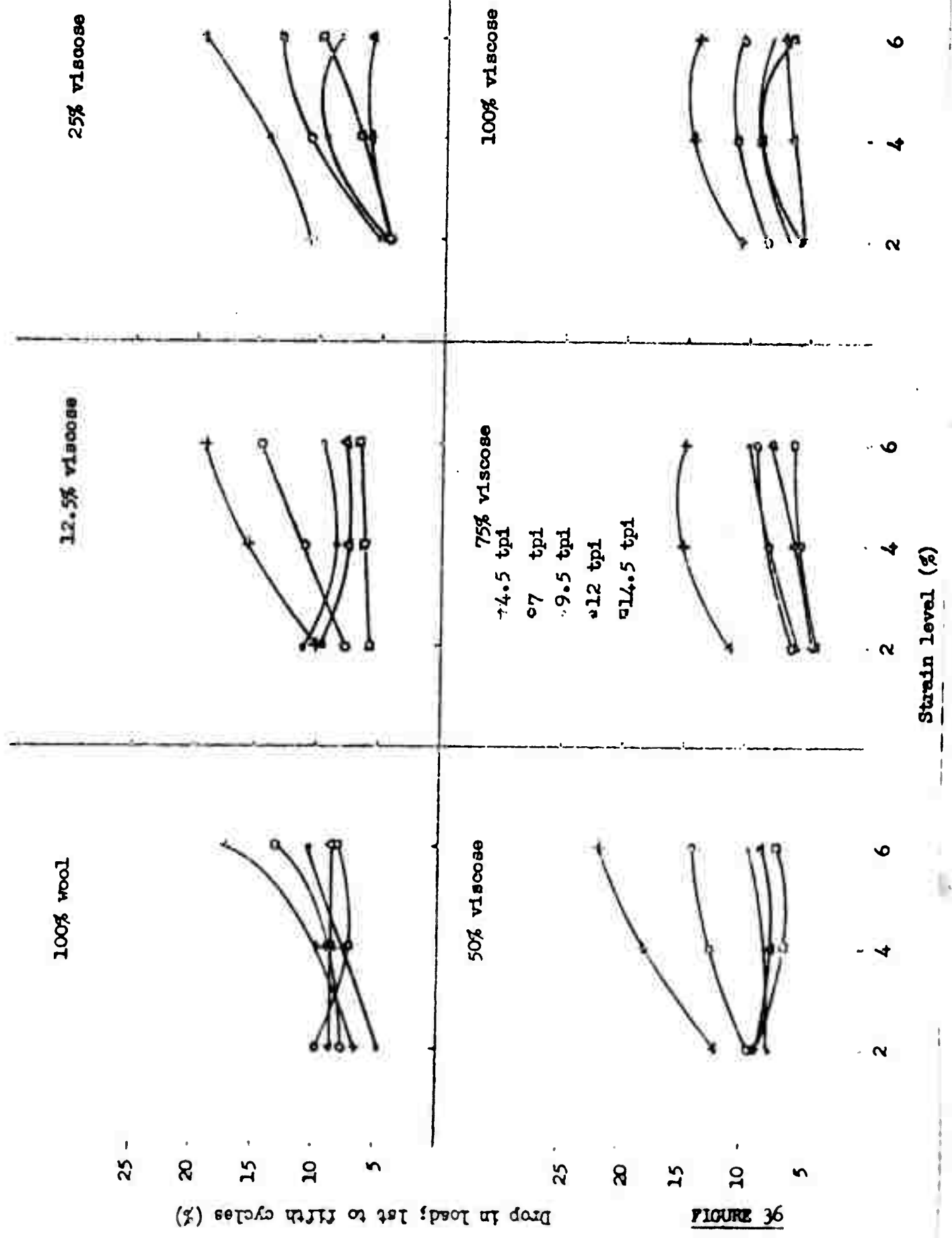


FIGURE 36

recovery of 100% wool, 100% nylon, and 100% viscose yarns was directly and almost perfectly dependent on the equivalent property of the fibers. It might therefore seem at first altogether reasonable that a 50/50 wool-viscose yarn should show an elastic recovery value halfway between that of 100% wool and 100% viscose. Remembering that the fringe fibers are supposed not to effect extent of recovery, consider only the heart fibers in a blended yarn.

Take two such fibers, one a wool, and one a viscose bound tightly together parallel to one another. Stretch the pair from 1" to 1.05" and let them retract. Suppose that the wool fiber--if unrestrained--would retract to 1.01", but the viscose fiber under its own influence would return only to 1.02". As the joined pair retract to 1.02" the viscose fiber no longer exerts a restoring force--it is "at rest". But the wool fiber still desires to retract to 1.01". It therefore exerts a compressive force on the viscose fiber and continues to retract. This compressive force in the viscose fiber increases and the residual tension in the wool fiber decreases as retraction beyond 1.02" progresses. Eventually these two forces are equal and the joined pair arrive at a balanced "rest" length somewhere between 1.01" and 1.02".

The question is, why is this equilibrium length half way between 1.01" and 1.02" for a 50-50 blend, 1/4 way between for a 75-25 blend, etc? There are several possible explanations. One of these depends on the assumption that the compressive modulus of viscose and the retraction tensile modulus of wool should be in close balance over quite a range in the low strain region. Other explanations are rather more elaborate entailing assumptions regarding limited freedom of motion among heart fibers on retraction of the yarn, without such freedom during tensioning.

No specific evidence is at hand to corroborate either hypothesis. It must be noted, however, that whatever explanation is correct for the strict proportionality of elastic recovery to blend composition for viscose blends, the identical circumstances do not prevail in the nylon blends. In the 50-50 wool-nylon, the elastic recovery is not half-way between that of 100% wool and 100% nylon, etc. Here, as for the viscose blends, the results can be explained either in terms of the state of balance between the compressive modulus of wool and the retractive tensile modulus of nylon, or by postulating some other condition of limited freedom of motion among the wool-nylon heart fibers on yarn retraction.

What is really the most important observation here is simply this. There are no good a priori grounds for assuming that elastic recovery of any blended yarn is going to be a strictly proportional function

of blend composition, even though mono-blends (one fiber type only) show that yarn elastic recovery is directly functional with fiber elasticity. What can be said, however, is that the elastic recovery of a blend will be somewhere between the elastic recovery of the respective fibers in the blend. It can be presumed, further, that higher concentrations of the more recoverable fiber will reflect in improved yarn recovery properties but the effect is not necessarily going to be in proportion to the change in concentration.

It so happens, that for the case of wool-viscose blends, there is a proportional drop in elasticity with increased concentration of viscose. For the nylon blends, there is a small general decrease in elastic recovery with increasing nylon at lowest strains, but enhanced recovery with increasing nylon at strains over 5%. The effect is non-proportional, there being an initial rapid improvement on first adding nylon, and a much less effect above 25-50% nylon in the blend.

As for the effect of blend on load decay, two fiber characteristics seem to function and their relative influence is dependent on yarn twist. Relaxation, or load decay, in the "main spring" of the yarn should reflect directly the relaxation properties of the individual fibers. Load decay due to fringe slippage will depend in great measure on the fiber surfaces, shape, degree of entanglement, and bending rigidity. The relative contribution of the heart will be least at lowest twist and in such cases the intrinsic relaxation properties of the constituent fibers may well be masked. At high enough twist, the fringe-friction becomes a negligible contribution to load decay and in these cases the principal effect should be due to fiber relaxation.

One would expect, therefore, from the fiber load decay of Table VII, that at some high twist the 100% wool yarn would exhibit lower relaxation than comparable nylon or viscose yarns. This is not evidenced even at 14 1/2 t.p.i. However, the principal assumption of nil fringe-friction effects may not be valid for the wool yarns even at 14 1/2 t.p.i. Nor would it be expected in any blend containing say more than 25% wool even at this high twist.

Technical Report No. 1 showed that even the 14 1/2 t.p.i. yarns still contained a low-density peripheral fringe in which some of the currently postulated force-dissipating friction may occur. Furthermore, all the blends exhibited a super-concentration of wool fiber on the yarn periphery. Both these factors being operative, there is therefore some reason to anticipate that wool-bearing blended yarns will generally suffer higher repeated-strain tensile load-decay for even the highest twist than that simply due to fiber relaxation alone.

D. Yarn Rupture Properties

1. Theoretical Maximum Translation Efficiency

The perfect textile yarn, from the point of view of fiber strength utilization, would be a twistless monofilament of infinite length having all cross-sections identical. The tenacity (rupture stress) of any sample of such a "structure" would always be exactly equal to the tenacity of the fiber substance (an obviously apodictic relationship). Fiber strength translation efficiency would therefore be 100%.

In practically every real textile structure translation efficiency is less than 100%. Perhaps the closest approach is achieved in certain very low twist filament yarns where the between-fiber variation in properties is low and the fiber stress-strain diagram is nearly flat near the rupture point. In such an assemblage all of the fibers will have been brought up to the level of their rupture stress before any of them begin to break. The rupture load of such a yarn will be pretty nearly the sum of the rupture loads of all the fibers in a cross-section.

However, as the same yarn is twisted up, the fibers are oriented in helixes and the yarn tensile strength will diminish because only a part of the tension in the angulated fibers is effective in the direction of the yarn axis. This is a so-called "component effect", and is predictable by simple geometric analysis of the twisted yarn.

Suppose, now, that in the original assembly the filaments differed among themselves in breaking elongation. As this array is tensioned some fibers will break before others have arrived at their full load carrying capacity. Some fibers having already been broken by the time the majority are brought up to maximum tension, the net effect is that the maximum measured strength of the yarn does not approximate the sum of the strengths of the fibers. This depressing influence constitutes one part of the so-called "serigraph effect". The severity of its influence depends on the slope of the average fiber stress-strain diagram and on the variability of rupture elongation among the fibers.

Twisting a group of filaments together combines this part of the serigraph effect with the component effect. But, twist also introduces another situation. There is a gradient of angulation of fibers from the outside of the yarn, where the angle is highest, to zero for the central fibers which are supposed to be simply twisted on their own axes. By virtue of this gradient, when the yarn is stretched the net strain in each of the fibers depends on its own particular helix angle, the highest strain being in the straightest fibers. This strain distribution will lead to earlier rupture of some fibers before others even if they were

otherwise identical in their tensile behavior. This has the same general depressing influence on yarn strength as the variation in fiber elongation and can be lumped together with it in the serigraph effect.

A considerable study has been made under another O.N.R. Contract (#N7 ONR 4211) in the area of translation efficiency of fiber strength in hard-fiber yarns and cordage structures. During this work a basic theory was evolved to combine the effects just described. A rather successful method of predicting the strength of such mono-blend (single fiber species) yarn was developed. The prediction equation required essentially knowledge of:

1. The average fiber stress-strain curve
2. Variability of fiber elongation to rupture.
3. Geometry of the yarn.

The present report will make no attempt to re-derive the general prediction equation and expound on its various ramifications, as this work has already been published (15). It states, however:

$$P_y = 2\pi \int_0^R b \left(\frac{a}{b} + e_y \cos^2 \theta \right) \cos^2 \theta \frac{N_u}{100} r dr \quad (1)$$

where

P_y = the load on the yarn for any strain e_y .

a = intercept on the load or stress axis of a line drawn tangent to the terminal slope of the average fiber stress-strain curve.

b = the terminal slope of the average fiber stress-strain curve.

θ = the helix angle of fibers at a distance r from the yarn center.

R = the yarn radius.

N_u = a cumulative distribution function expressing the number of fibers remaining intact at specified levels of strain.

From the information required, use of the equation permits one to draw the theoretical stress-strain diagram of a yarn for any twist

beyond which fiber slippage no longer occurs, (i.e., series slippage).

By suitable manipulation, the maximum value of P_y can be found, and from this the predicted yarn tenacity. Predicted yarn tenacity as a percentage of average fiber tenacity is the theoretical maximum yarn efficiency.

This theory of fiber strength translation is applicable to continuous filament yarns at any twist. For spun staple yarns, however, its usefulness is limited to yarn twists at and above "optimum". The meaning of "optimum twist" will be understood from the following.

An entirely twistless drafted assembly of staple fibers is incapable of sustaining any more tension than that necessary to cause the fibers to slip past one another. As this structure is twisted, the inter-fiber bearing forces increase and consequently so does the force of slippage friction. As noted in the previous discussion on low strain behavior at some fairly low twist the bearing friction in some relatively dense region of the yarn attains a point such that the fibers in this region no longer can slip past each other, but must break under tension. Additional twist expands this region and brings more and more of the fringe fibers into the zone of fiber rupture-without-slippage.

The amount of angulation induced by the twist necessary to bring a relatively large proportion of the fibers in a cross-section into the heart zone is not very great. Since the adverse geometric effects of twist increase with decreasing cosine of the helix angle, the unfavorable influence of angulation is hardly felt during the earlier stages of twisting. Hence, yarn strength gradually increases as the first twist is added and increasing numbers of fibers per section are made to bear load without slippage.

Eventually, however, with increasing twist the rate of increase of the heart fiber fraction is overtaken by the gradually more rapid decrease in the cosine of the angle. Yarn strength no longer rises with increasing twist, but passes through a plateau of strength vs. twist and then falls off. The optimum twist is that which generates highest yarn strength. Figures 16 and 17 illustrate the effect of twist on strength.

It should be noted, however, that at the optimum twist there is still a partition within yarn cross-sections between fringe fibers and heart fibers. It is presumably to the latter fibers only that strength efficiency calculations mentioned at the beginning of this section can be applied.

The fringe fibers add their weight to the yarn while contributing a very disproportionately low fraction of their strength. Therefore, the strength of the yarn even at optimum twist is not only less than the sum of the strengths of the heart fibers due to serigraph and component effects, but is even further depressed below average fiber strength because of this "non-loading" of fringe fibers.

In a spun staple yarn there is also a decided non-uniformity along the length of the yarns in number of fibers per cross-section. Technical Report No. 1 indicated that many sections had as much as 20% fewer fibers per section than the average. Moreover, the irregularities were dispersed in such a way that even yarn lengths as short as the nominal staple length of the fibers could contain both thick and thin cross-sections.

Now, in attempting to apply the theory of fiber strength translation to woolen-type spun staple yarns, at least these considerations must be taken into account. First, the theory applies to optimum twist and beyond. Second, comparison of calculated efficiency with found efficiency must allow for the essentially weight-without-strength factor of fringe fibers and must also take cognizance of the prevalence of thin spots which occur within the tested length of yarn.

Beyond these, there are other factors of perhaps lesser significance. It is known that besides weight irregularities along the yarn there are also twist irregularities. The twist tends to run to regions of least resistance, and these generally are the thinnest spots. Therefore, these not only contain fewer fibers but may also be twisted to a higher-than-average helix angle.

Besides this, there is the problem of fiber ends occurring in the rupture zone of the yarn. Obviously, sometimes there will be among the heart fibers of that particular longitudinal zone which is to rupture some fibers which add their weight without carrying load across this region simply because they terminate in it. Sometimes, therefore, a weak spot will occur just because of a "concentration of fiber ends".

Peculiar erratic distortion, or entanglements, are also quite common among groups of fibers, and these too can create unusual weakness. On the other hand, a certain amount of residual crimpiness in the heart fibers may tend to offset strain-distribution effects and provide for a somewhat stronger than anticipated combination of fibers at some cross-sections.

All of these foregoing comments represent limitations on the possible accuracy of predictions of strength translation efficiency of any spun staple yarn. But the present problem, as it applies to blended yarns, is at least one degree more complex.

In the blended yarns under consideration there are, of course, two species of fibers acting together. Each has its average properties and variability. Each will respond in a given geometric situation accordingly, and perhaps quite differently from the other. In spite of this, the strength-translation efficiency theories were felt to be adaptable to the blended yarns.

For a yarn composed of two different kinds of fiber there were two alternative general methods of adapting the calculation of translation efficiency. In the first method, a hypothetical "average fiber type" could be assumed to exist. The two different fibers in a blend would be lumped together into a single population. For each blend concentration, the population would be corrected accordingly, and for each such population the appropriate parameters would be calculated.

In the second method the desired parameters are calculated for each fiber type separately. The behavior of the yarn is assumed to reflect the behavior of each of these fiber species acting in parallel, taking due account of the relative proportions of each in the yarn.

This latter method was adopted for a number of reasons. First, once having characterized the wool fiber population, the viscose, and the nylon, there is no longer any necessity for performing repeated new calculations for each blend concentration. Second, the prediction of behavior of some arithmetically synthesized wool-viscose fiber, for example, smacked unduely of artificiality. The problem of blended yarn strength is a practical one, and although employment of a "synthesized fiber" might serve for prediction purposes, the consistent use of real fiber properties seemed to be recommended. The general procedure therefore is as follows.

The average fiber stress-strain diagrams of each of the fiber types is drawn. The slope of pre-rupture region and the intercept of this slope on the tenacity axis are found. The coefficient of variation of rupture elongation is calculated for each fiber type. From these, employing suitable corrections for non-continuous pre-rupture slope, the strength efficiency of untwisted fiber bundles was calculated for each of the fiber types alone. Similar calculations for twisted bundle efficiency were made taking account of helix angle influence on the stress-distributions in the twisted sections.

The properties of the three different fiber species necessary to these calculations and employed therein are given in Table VIII. It is recognized, as was noted earlier, that these data are by no means

entirely without fault. Fiber tests had to be run at a gage length of 1". The actual yarn "internal" gage length at which the fibers act may be much shorter, and at this length several factors may be different. Effective tenacity should be higher; average rupture elongation should be higher; but variability of rupture elongation may also be higher. It is not known whether the net effect would be in the direction of better or poorer bundle efficiency than that which was calculated from the data of Table VIII.

The translation efficiency of blends was not taken as the weighted average efficiency of each of the fiber types taken alone. It was necessary to determine first, by graphical analysis, the effect of twist on the theoretical stress-strain behavior of each of the fiber types taken alone. Then the stress-strain curve for any blend was developed by compositing those of the two fibers in the blend. The method used was similar to one described by Hamburger (8).

For any strain level each of the two fiber species in a twisted bundle was assumed to be responding according to its own predicted curve. The total stress borne by the blend at each strain level was calculated by summing after appropriately weighting the loads found on the two separate curves in proportion to the average blend composition. The maximum summative load sustainable by the two species acting in parallel was thus found. This was done for each of the blend proportions and for several twists.

Figure 37 illustrates the method. In the lower half are shown theoretical stress-elongation diagrams for the wool fraction and the nylon fraction developed by means of the equation given earlier. In the upper half of the figure are shown two composited stress-strain diagrams, one for a 50-50 blend of wool and nylon, the other for a 75% wool, 25% nylon. To develop the former, equal parts of each of the wool and nylon curves were averaged together. For example, the load level C is 0.5A plus 0.5B. To develop the 75/25 curve, the level F is 0.25E plus 0.75D.

The maximum loads achieved by the composited curves are marked by arrows. It is this value that is taken as a fraction of the weighted average tenacities of the two single fiber species in order to calculate theoretical maximum translation efficiency.

The curves in the upper half of Figure 37 also illustrate another point. Reference to Figures 6 through 10 will show that the real wool-nylon yarns actually gave stress-strain curves having cross-over points in the vicinity of 8-12% elongation. The two theoretical curves illustrated in Figure 37 do likewise exhibit a cross-over near 8%. Besides this, of course, the shapes of the stress-strain curves are well reproduced in the theoretical curves, both for the nylon blends and viscose blends.

TABLE VIII

FIBER PARAMETERS EMPLOYED IN EFFICIENCY CALCULATIONS

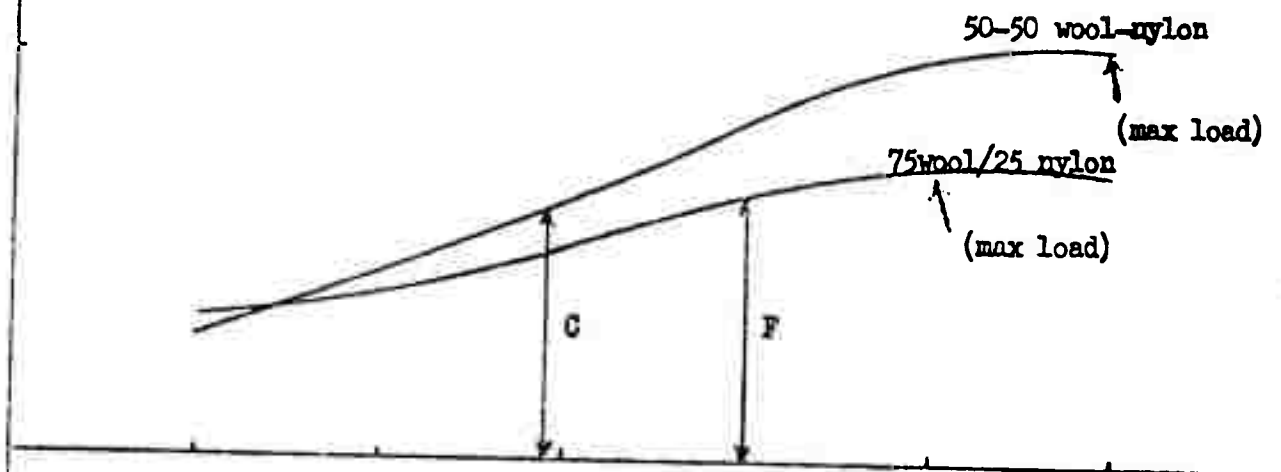
<u>Fiber</u>	<u>a/b*</u>	<u>% Em.</u>	<u>C.V. of % E</u>	<u>Tenacity Gms/Den.</u>
Wool	48	30.5	31	1.22
Nylon	520	44.9	19	3.77
Viscose	1.33	12.3	21	2.25

*Units are % E.

GRAPHICAL METHOD OF COMPOSITING TWO FIBER SPECIES

Case No. C51137
Page 30b

A). Compositing stress-strain diagrams



B). Individual fiber species stress-strain diagrams

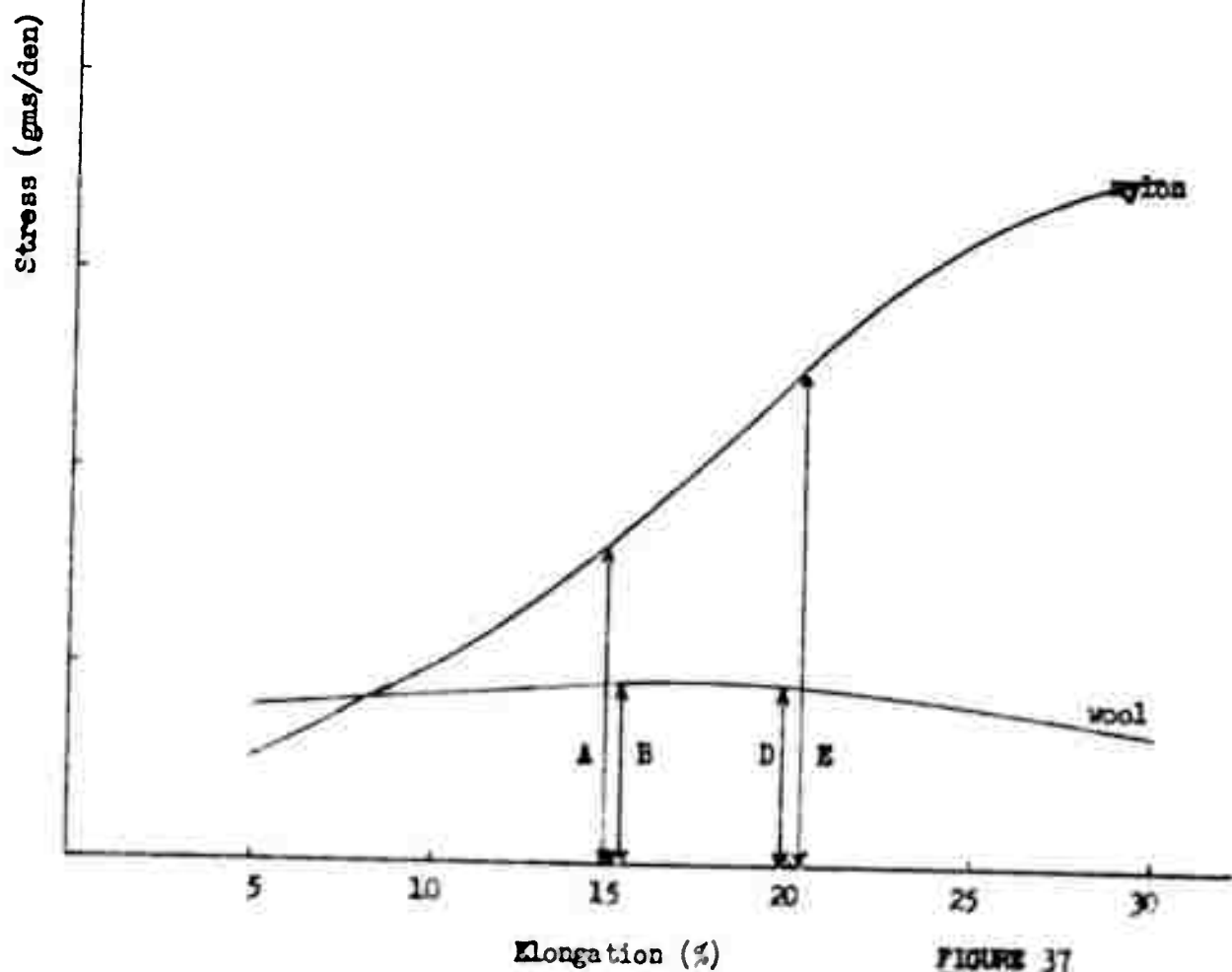


FIGURE 37

However, we are concerned here with the utility of the technique for predicting yarn strength. For this purpose, plots of theoretical efficiency, η , vs. twist are given in Figure 38 for several of the yarns.

These curves are drawn as they would be for a filament yarn where failure occurs with no fiber slippage. In actual fact the phenomenon of fringe fiber slippage is undoubtedly occurring to a great extent in the lower twists, say up to a helix angle of 20° , which for the present yarns would be up to about 9-1/2 turns per inch. Beyond that it is believed that slippage is still occurring in the low density periphery of the yarns, but the effect is less pronounced. In any event, the theoretical efficiencies for angles below 20° in Figure 38 are considered of little significance, and only the values at or above that level are worth checking against the experimentally determined yarn behavior.

2. Actual Yarn Efficiencies vs. Theoretical

Table IX provides a basis for the comparison of actual yarn efficiency with theoretical efficiency, the next subject for discussion. The actual yarn tenacities shown are the maximum strengths found from Tables V-A and V-B for each of the blends. The twists at which these strengths occurred are also shown in the fourth column. It will be seen that these are principally at 9-1/2 and 12 t.p.i. From the information of Technical Report No. 1 (See particularly Figures 38 - 41) on yarn diameters and by means of the equation:

$$\cos^2 \theta = \frac{1}{1 + 4\pi^2 r^2 n^2} \quad (2)$$

where

r = yarn radius

n = turns per unit length (in the same units as radius)

it can be shown, as has been mentioned, that 9-1/2 t.p.i. represents an external helix angle of $20-25^\circ$ for that radius of the yarn which bounds the region of highest density. The 12 t.p.i. yarns, by the same calculation, would have an external helix angle of between 25° and 30° at the outer boundary of the "heart" of the yarn.

It should be remembered, however, that these are the starting helix angles. At an elongation of 30% (rupture) the 9-1/2 t.p.i. will have been reduced to 7.3 t.p.i. and the 12 t.p.i. to 9.5. Therefore, the angulation at rupture will generally be about $20^\circ-25^\circ$ for most of the yarns.

TABLE IXEXPERIMENTALLY DETERMINED YARN EFFICIENCIES*

<u>Blend</u>	<u>Weighted Average Fiber Tenacity Gms/Den.</u>	<u>Exptl. Max. Yarn Tenacity Gms/Den.</u>	<u>Twist t.p.i.</u>	<u>Helix Angle of Heart (θ) Boundary °</u>	<u>Actual Efficiency %</u>
100% Wool	1.22	0.61	9-1/2	20-25	50
12.5% Nylon	1.54	0.76	12	25-30	49.3
25% Nylon	1.86	0.91	12	25-30	49.0
50% Nylon	2.50	1.35	9-1/2	20-25	54.0
75% Nylon	3.12	1.90	12	25-30	61.0
100% Nylon	3.77	2.31	12	25-30	61.1
12.5% Viscose	1.35	0.59	9-1/2	20-25	43.7
25% Viscose	1.48	0.62	9-1/2	20-25	42.0
50% Viscose	1.73	0.78	9-1/2	20-25	45.0
75% Viscose	1.99	1.01	7	<20	50.7
100% Viscose	2.25	1.15	9-1/2	20-25	51.0

* 10" long specimens

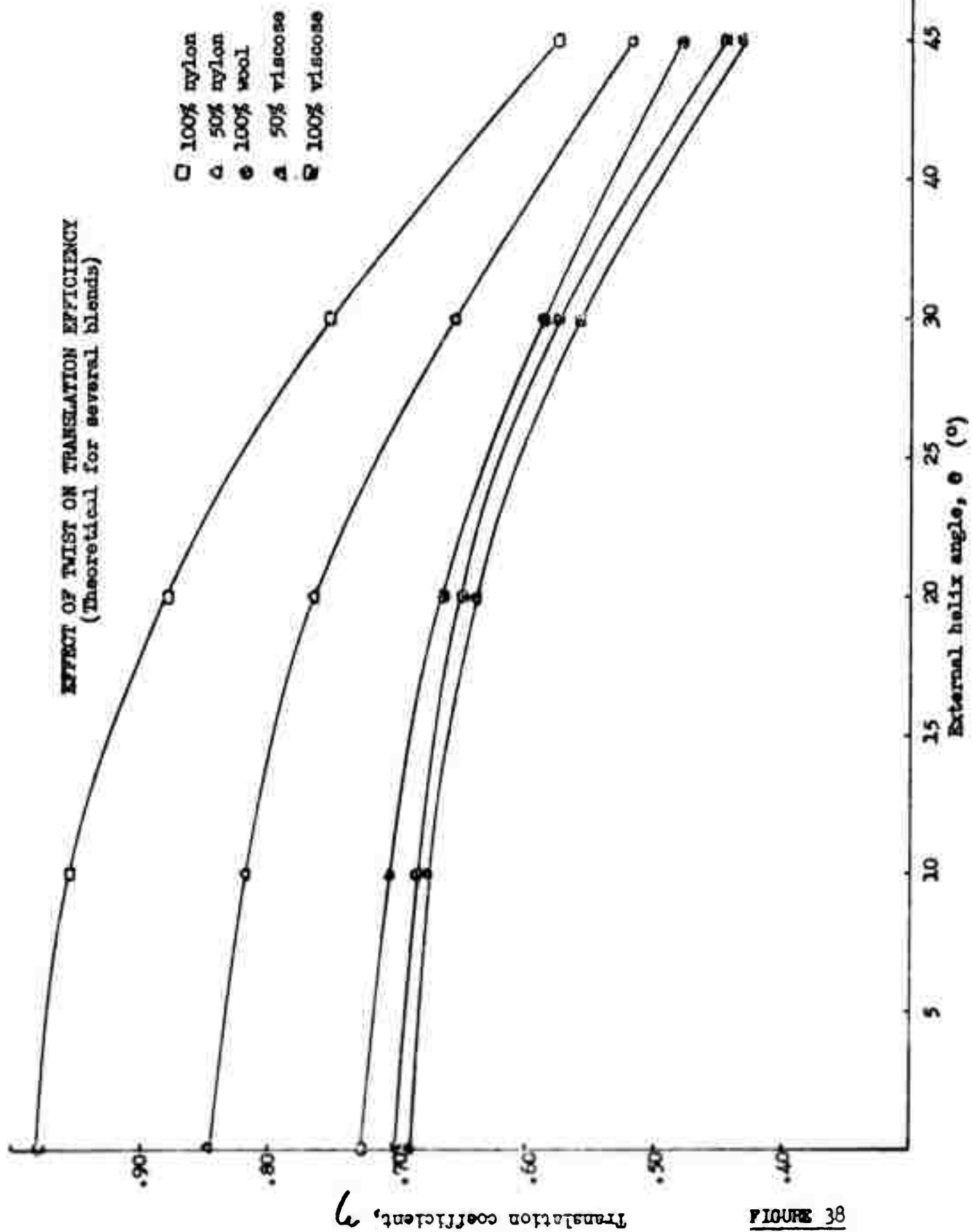


FIGURE 38

Theoretical translation efficiencies are plotted vs. blend for helix angles of 20, 30 and 40° in Figures 39 and 40. In Table X the actual efficiencies of the yarns are compared with theoretical efficiencies at three different external helix angles.

The significance of this table may be brought out by an example. Consider the first line. The actual maximum tenacity achieved in a 100% wool yarn was only 50% of the average tenacity of the fibers that compose it. According to theoretical calculations which take account of serigraph and component effects in an ideal twisted bundle of fibers, the strength yield should have been 67% at a helix angle of 20°, or 64% at an external helix angle of 25°. The factors contemplated in the theoretical prediction, therefore, can account for about 35 parts in 50 of the observed difference between the weighted average tenacity of the fibers and the actual tenacity developed in the yarn.

Some additional effects must therefore be operative to depress the yield of net fiber strength in yarn strength. The ratios tabulated in the last three columns indicate the general magnitude of these other depressing influences lumped into factor "X". This follows if:

$$\bar{S}_f \cdot X \cdot \eta = S_y \quad (3)$$

where

$\bar{S}_f$ = Wtd. average tenacity of fibers

S_y = Average yarn tenacity

η = Serigraph-component efficiency factor

X = Lumped factor for other depressing effects

$\frac{S_y}{\bar{S}_f}$ = The actual found yarn efficiency

and the ratios in the last three columns are simply found by dividing η into $\frac{S_y}{\bar{S}_f}$

It will be seen therefore that this "X factor" is about .70-.80 for most of the yarns. In other words, about 20%-30% of the potential fiber strength is in some way dissipated by factors other than those contemplated in translation efficiency considerations.

There are several possible causes, two general ones being

TABLE XCOMPARISON OF ACTUAL AND THEORETICAL EFFICIENCIES*

<u>Blend</u>	<u>Actual Efficiency %</u>	<u>θ</u>	<u>Predicted Eff. (%) at θ of</u>			<u>Ratio "X" (Found/Predicted)</u>		
			<u>20°</u>	<u>25°</u>	<u>30°</u>	<u>20°</u>	<u>25°</u>	<u>30°</u>
100% Wool	50	20-25	67	64	59	.75	.78	.85
12.5% Nylon	49.5	25-30	66	63	58	.74	.78	.85
25% Nylon	49	25-30	68	66	60	.72	.75	.82
50% Nylon	54	20-25	77	72	66	.70	.75	.82
75% Nylon	61	25-30	84	78	70	.73	.78	.87
100% Nylon	61	25-30	88	83	75	.70	.73	.81
12.5% Viscose	44	20-25	64	60	56	.69	.73	.79
25% Viscose	42	20-25	63	60	56	.67	.70	.75
50% Viscose	45	20-25	63	60	56	.72	.75	.80
75% Viscose	51	<20	63	60	57	.81	.85	.90
100% Viscose	51	20-25	64	61	58	.80	.84	.88

* 10" long yarn specimens

EFFECT OF BLEND ON TRANSLATION EFFICIENCY NYLON SERIES
(Theoretical for several twists)

Case No. C51137
Page 32b

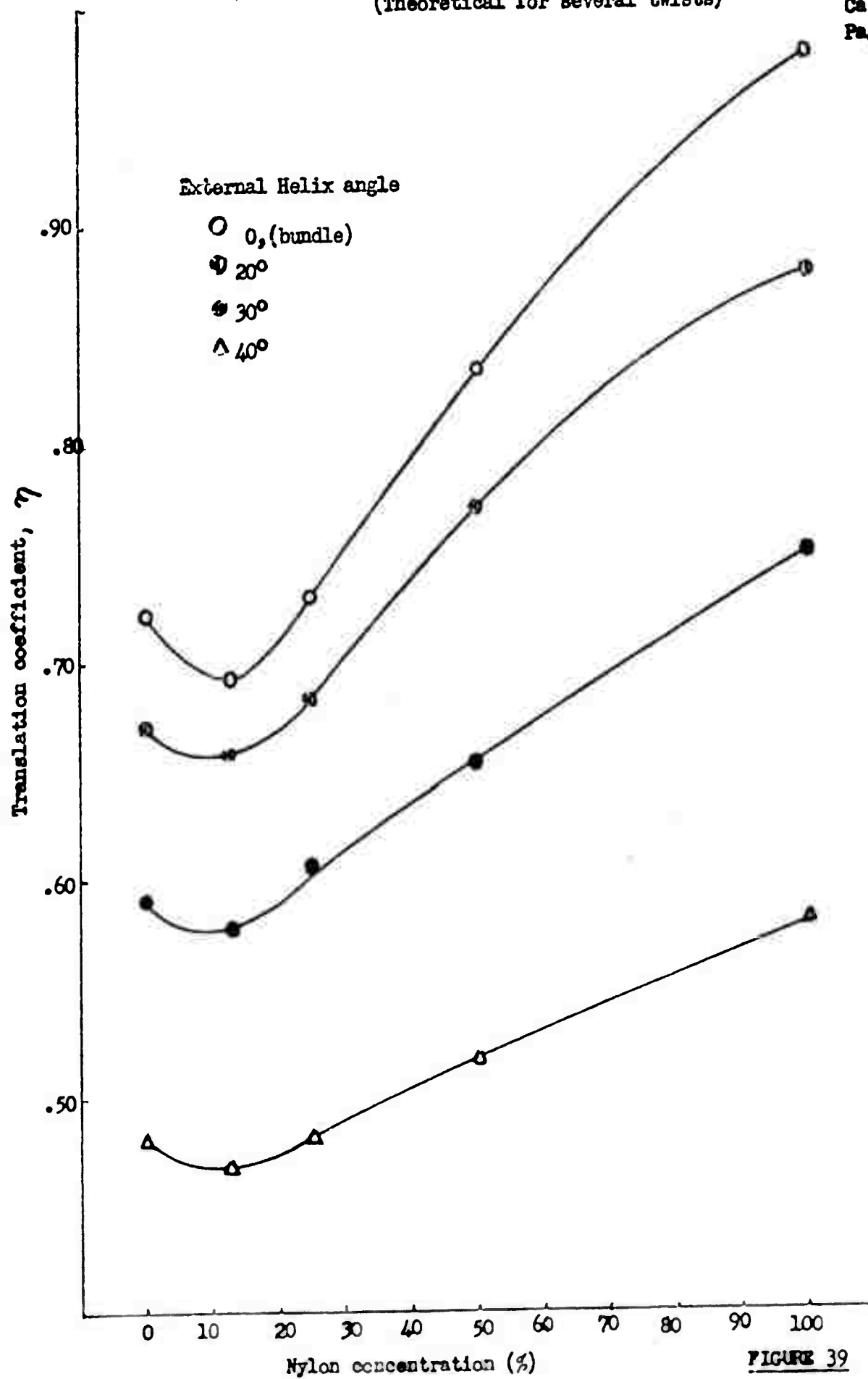


FIGURE 39

EFFECT OF BLEND ON TRANSLATION EFFICIENCY
 VISCOSE SERIES
 (Theoretical for several twists)

Case No. C51137
 Page 32c

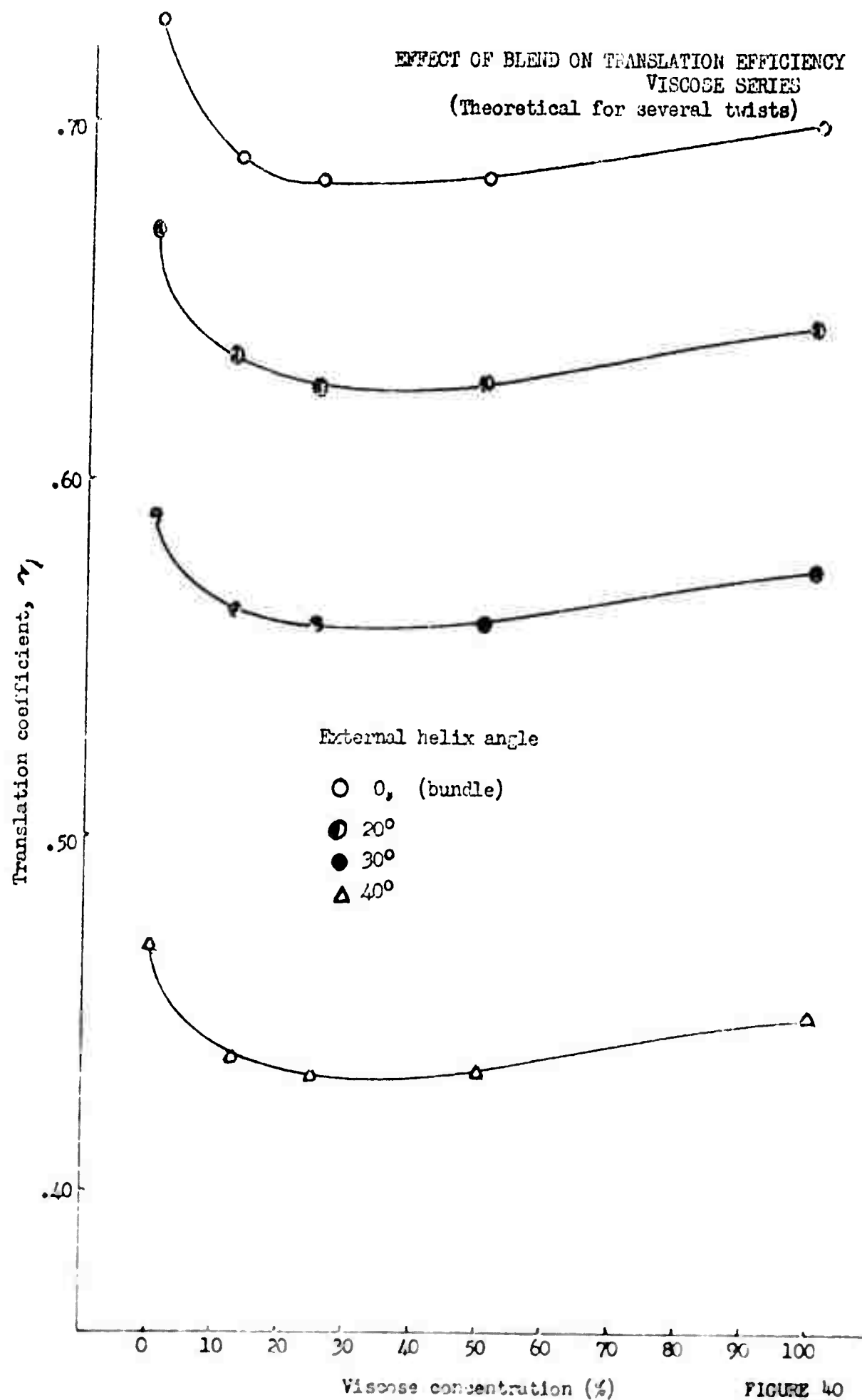


FIGURE 40

most important. The first is simply that the low-density peripheral fringe of fibers may be substantially non load-bearing at yarn rupture. Both Ewald and Landstreet (6) and Gregory (7) postulate a similar fringe-slippage situation in interpreting the strength of cotton yarns. Fibers in the outermost shell of the yarn are considered to add their weight but not much of their strength to the yarn. It is doubtful, however, if in the present case as much as 20% or 30% of the fibers are that ineffectual. Perhaps about half that amount belong in this category, for the present yarns.

This can be circumstantially verified again from the information of Technical Report No. 1, Figures 38-41. From these figures it can be shown that between 100 and 150 denier (out of an average of about 900 denier total yarn weight) falls outside a radius of 200 μ . This was the radius used earlier as defining the approximate boundary of the heart of the yarn. Beyond this radius the yarn density drops rapidly from about one-third of the mean density exhibited in the heart of the yarn. The average packing density of this outer 15% of the total yarn weight is actually about one-sixth of the interior density. If this disparity persists up to the point of yarn rupture it must be expected that, on the average, the outer 10-15% of the fibers in the yarn generally slip without rupturing. It is, of course, recognized that the fringe fibers contribute a load of some sort at rupture. However, if the interpretation given earlier for the influence of fringe friction on load decay in repeated stress is correct, then the actual load contribution of the fringe on one cycle to rupture runs to about .01-.02 Gms/Den. and is essentially insignificant compared with total yarn tenacities of .60 to 2.0 Gms/Den. This condition, then, may account for as much as half of the lumped "X" factor influence on yarn strength.

The second major contributor to the "X" factor has already been alluded to. It partakes of many facets, but may in general terms be described as the longitudinal variations in a spun staple yarn. These variations consist of point-to-point differences in twist, in weight, in fiber-end concentration, in degree of entanglement, and (for the present problem) differences in actual local blend concentration.

Technical Report No. 1 provided some quantitative information on the variability of denier and blend within 10" yarn lengths at distances of 2.0-2.5". It was seen that the denier at particular points could be as much as 20% lower than the average denier of a given 10" specimen of yarn. Similarly, blend concentration could easily vary from 38% to 54% nylon, for example, in a nominal 50-50 wool/nylon yarn, within a given 10" specimen.

The influence of longitudinal variations can be assessed by testing yarn strength at shorter and shorter gage lengths. Obviously, in

any length the weakest spot determines the sample strength. As sample length is reduced, the average strength should go up because stronger regions have a greater opportunity to govern measured sample strength.

This effect was actually observed. Figure 41 gives plots of average tenacity vs. gage length for several of the yarns at all twists. The general trend is obviously upward with decreasing gage length from 10" down to 1.25". Evidence for the existence of weak spots is therefrom adduced. This, of course, is as it should be.

Another effect observed in these plots which is as well noted here as elsewhere, is the more than occasional slight drop in strength going from 2.5" gage length to 1.25". At 2.5" very few fibers in the yarn are gripped in both jaws of the tester. At 1.25" this is no longer true, since a substantial fraction of the fibers were at least that long and longer. It is presumed that because of this, once the 1.25" gage length samples are clamped in jaws and tension applied, there is very little opportunity for readjustment of the positions of the fibers. At 2.5" gage length it is presumed that such spatial readjustment is still possible, and this may permit better strength realization than at 1.25".

In any event, both the existence of weak spots and the prevalence of weight irregularity along the length of the yarns has been experimentally established. It remains to determine whether the lower denier regions are actually the weaker regions, or whether some other causes must be sought.

In Figures 42-45 are plotted specimen strength vs. specimen weight for several of the 9-1/2 t.p.i. yarns at 10, 5, 2.5, and 1.25 inch gage lengths. It will be seen that for the most part there is a decided correlation between strength and weight. The dependence is least erratic at the 2.5 and 5.0 gage lengths, and the poorest showing seems to be among samples tested at 10" gage length. This situation is exactly as it should be if the apparent strength of 10" specimens is determined by the strength of low-denier regions about 2" long. It would be very interesting, therefore, to compare the actual efficiencies of the 2.5 and 10.0" long specimens to examine the possible magnitude of its contribution to factor "X".

Table XI-A gives the actual efficiencies at the two gage lengths. In part B of the Table is given the ratios of found efficiency to predicted efficiency. These are comparable to the three columns at the right of Table X, and have exactly the same significance as was discussed in connection with that table. It will be seen that the 10" strengths and efficiencies run about 10-15% lower than those for 2.5" gage length. This effect is in very close agreement with what can be predicted from the "weakest link" theory as it was applied in Technical Report No. 7 of Contract No. N7 ONR 4211. Earlier, in Tables IV A - E, the variation in strength of the 2.5" specimens was given. Using that

TABLE XIA. EFFECT OF GAGE LENGTH VS. FOUND EFFICIENCY
AT 9-1/2 T.P.I.

<u>Blend</u>	<u>Weighted Ave. Fiber Tenacity</u>	<u>Yarn Tenacity at</u>		<u>Efficiency at</u>	
		<u>10"</u>	<u>2.5"</u>	<u>10"</u>	<u>2.5"</u>
		Gms/Den.		%	
100% Wool	1.22	.61	.65	50	53
50-50 Wool/nylon	2.50	1.35	1.49	54	60
100% nylon	3.77	2.29	2.60	61	69
50-50 Wool/Viscose	1.73	.78	.86	45	50
100% Viscose	2.25	1.15	1.36	51	60

B. RATIO "X" AT 2.5 GAGE LENGTH, 9-1/2 T.P.I. At:

	<u>20°</u>	<u>25°</u>	<u>30°</u>
100% Wool	.80	.83	.90
50-50 Wool/nylon	.78	.83	.91
100% Nylon	.78	.83	.92
50-50 Wool/Viscose	.79	.83	.89
100% Viscose	.93	.98	1.03

EFFECT OF GAGE LENGTH ON YARN TENACITY

Case No. C51137
Page 34b

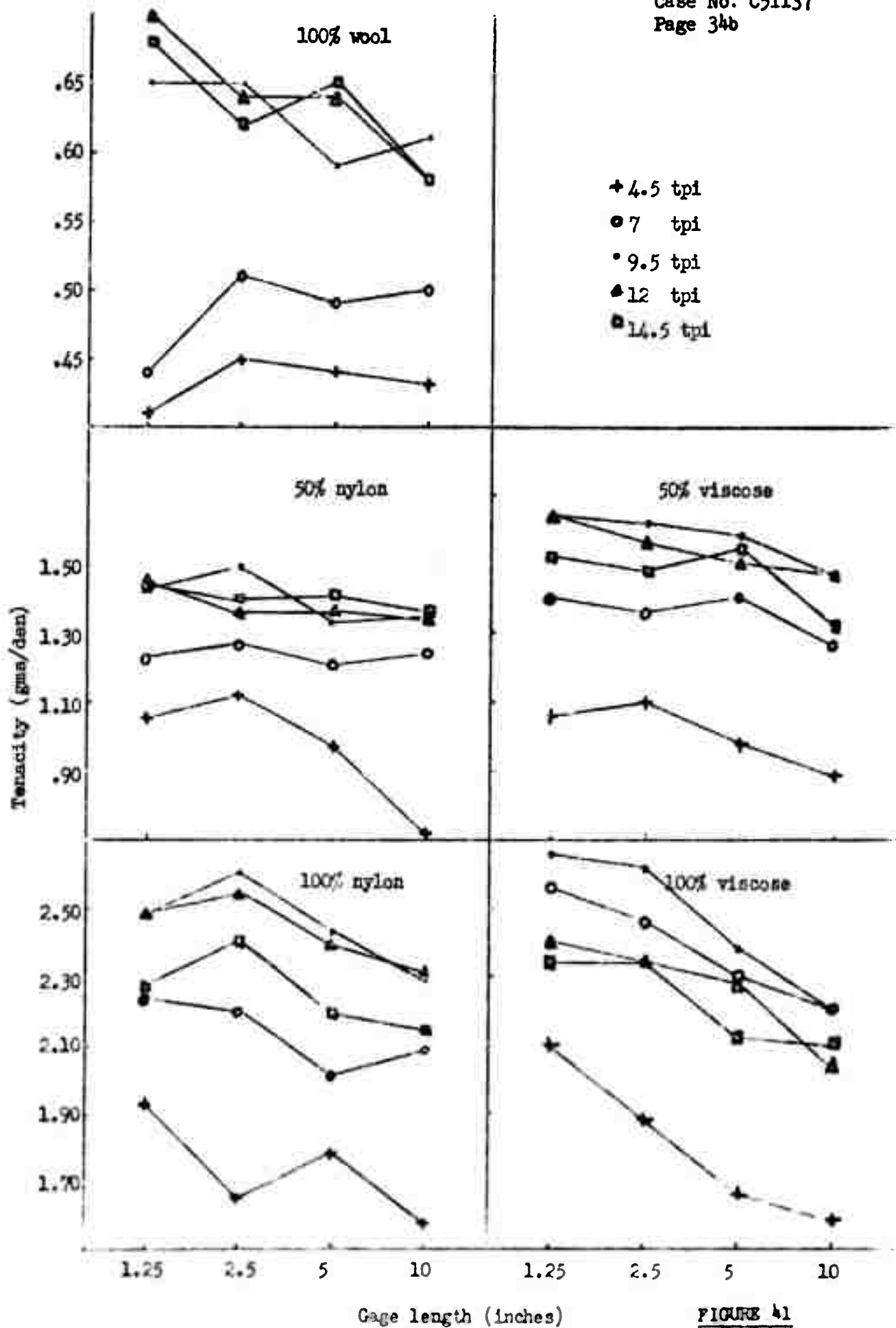


FIGURE 41

DEPENDENCE OF STRENGTH ON YARN WEIGHT AT DIFFERENT GAGE LENGTHS NYLON SERIES 9.5 t.p.i.

100% nylon

50% nylon

100% wool

1.25"
g.l.

2.50"
g.l.

Specimen strength (lbs)

Specimen denier

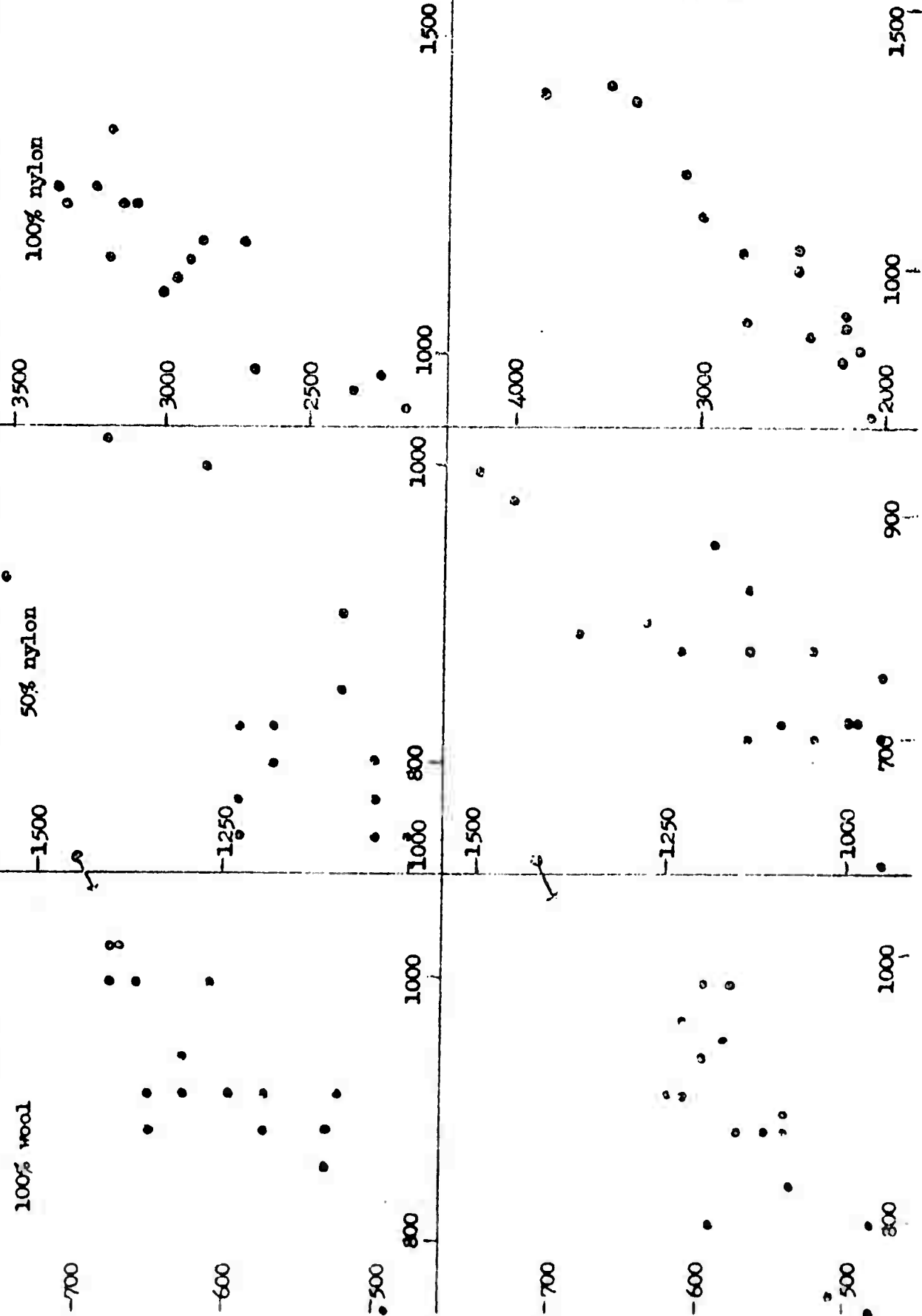
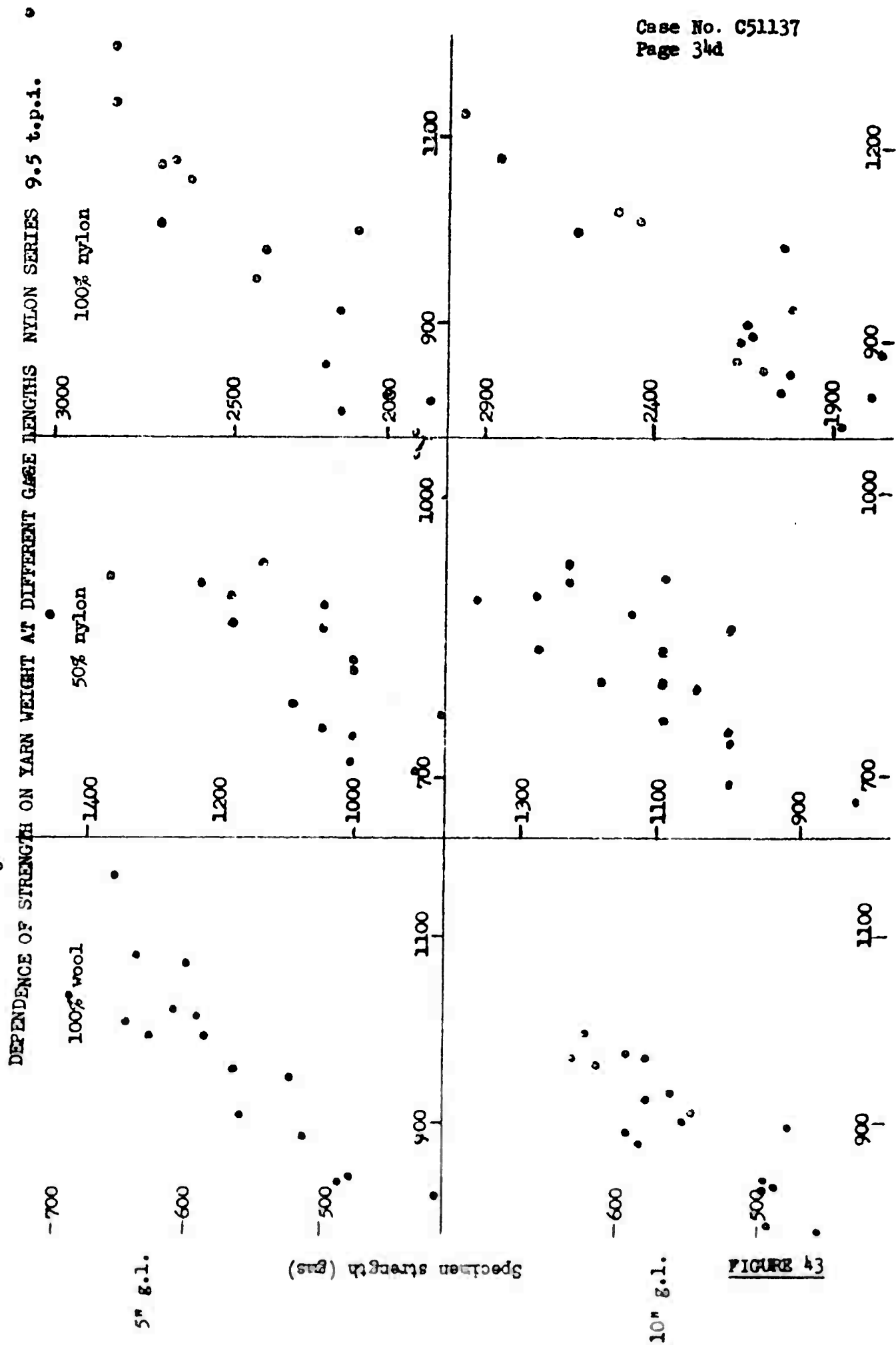
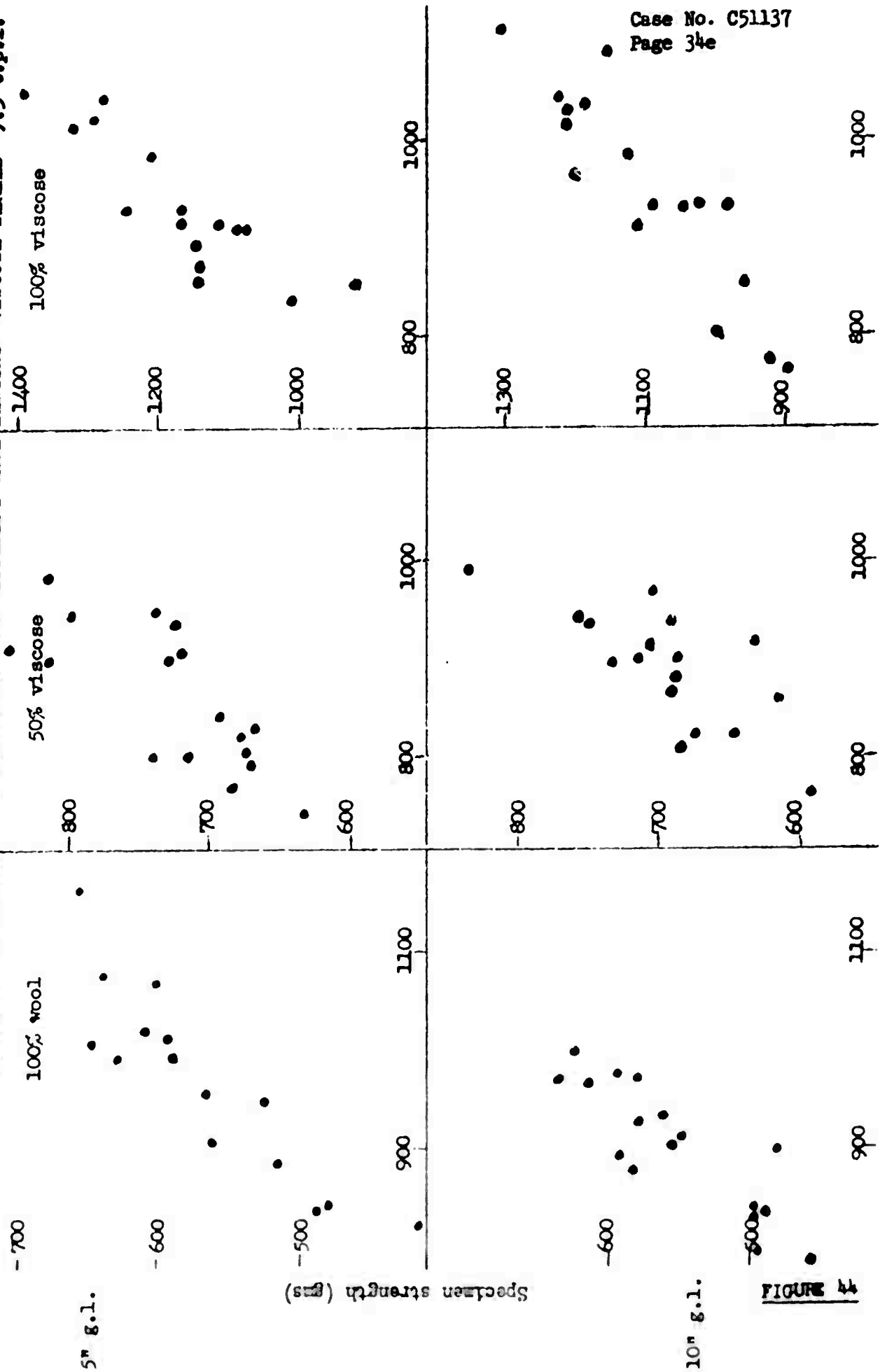


FIGURE 42

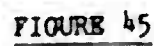


DEPENDENCE OF STRENGTH ON YARN WEIGHT AT DIFFERENT GAGE LENGTHS VISCOSE SERIES 9.5 t.p.i.



Case No. C51137
Page 34e

FIGURE 4



data, considering that there are four 2.5" "links" in a 10" specimen, that the C.V. of strength of these links was 10-15%, the average strength of four such units in series would then be about 10% lower than that of the average unit strength.

Now, if at 2.5" gage length, allowance is made as before for the fact that about 10-15% of the fibers in the average yarn cross-section are not bearing a fair share of the tensile load at optimum twist, then practically the entire content of factor "X" in 10" long specimens is accounted for. Indeed, for the 100% viscose yarn at 9-1/2 t.p.i., as little as 7% of the fibers need be assigned to the "non-working fringe" in order to complete the picture. As a matter of fact, this particular yarn did show the least amount of "fringe" (Figure 41, Technical Report No. 1).

Recapitulating the foregoing arguments leads to this. In order to apply the fiber strength translation theory developed for cordage yarns to blended woolen type yarns, two situations must be acknowledged. First, even at optimum twist, allowance must be made for the fact that only about 85-90% of all the fibers in an average cross-section are "workers". Second, the occurrence of thin spots due to the inevitable weight irregularities present in spun staple yarns, suggests that the yarn strength should be determined at a gage length approximating that of the fiber length. At longer lengths the average measured yarn strength must be expected to fall off. At 10" gage length, the yarn strength is determined by elements averaging 10-15% lighter than the nominal yarn weight. When compensation is made for these conditions, the behavior of the blended yarns conforms very nicely with predictions based on the helical geometry of the yarn and fiber properties composited properly by use of equation (1).

Other influences may not be entirely lacking, however, and deserve some comment. A condition that has been mentioned is the variability in blend from section to section along the yarn. In any particular test, however, this may have either a favorable or unfavorable influence on measured specimen strength. It was shown in Technical Report No. 1 that there was a longitudinal random distribution of blend operating independently of the longitudinal variation in weight. Hence the thin spots would as often contain an excess of one or the other of the two fibers. In the aggregate, therefore, the average strength of the rupture zone can be presumed to have been determined by the average blend composition.

A second condition also revealed in Technical Report No. 1 was the general hyper-concentration of wool in the yarn fringes. The effect of this would be primarily that the inner 85-90% of the yarn is slightly higher in concentration of the non-wool fiber. By and large this would mean that the weighted average tenacity of the strength-yielding fibers of the heart fraction of the yarn is slightly higher than that used in the calculations.

The effect of fiber ends occurring in the rupture zone is a third factor not quantitatively ascertained. The occurrence of non-through going fibers would have a negative effect on strength.

Variation in twist along the yarn is a fourth unaccounted for situation. In general, however, at the "optimum" twist for the yarn as a whole, the variation in twist from spot to spot is thought not to influence average strength too greatly. If it is true that twist tends to run to thin spots, then there might seem to be a double effect of weight irregularity on average yarn strength. However, a thin spot may have higher twist in turns per inch than the nominal average for the yarn and still not exceed the average helix angle. See Equation (3) where n and r are cosmultipliers.

If n , (turns), goes up in proportion to the decrease in r , (radius), θ is unchanged. Increased twist in the thin spots, rather than depressing their strength may to some measure tend to increase it by bringing more fringe fibers into the heart.

Finally, the possibility exists that the average fiber properties as measured at 1" gage length outside the yarn are not identical with the properties developed in situ under yarn tensioning. For example, if the effective gage length in yarn is, say, $1/16$ ", then average fiber strength should go up. But variability in elongation may also go up. The net effect may be either favorable or unfavorable insofar as translation efficiency is concerned.

Just to see how nearly satisfactory the basic assumptions are, however, in regard to the prediction of blended yarn strength, consider Figures 46 and 47. In the figures, the uppermost straight line is the plot of weighted average denier of the fibers vs. blend. The next lowest line is simply 85% of the top line and represents the correction for non-load bearing fringe fibers. It should be understood, of course, that 85% is an average effect and is used arbitrarily for all blends.

The third line down is 90% of the second line and is again an average arbitrary, although an altogether rational, correction for the average effect of thin spots in all of the 10" gage length test specimens of yarn. The last curved line drawn is the product of the third line and the values of η for 20° taken from Figures 39 and 40. The points that fall around this last line are the actual experimental points.

The agreement shown here is remarkably good and leaves very little room for any added corrections that may be called for. As a matter of fact, most of the corrections can be made within the framework of the factors η and "X". For example, the 100% viscose yarn was just shown to

COMPARISON OF PREDICTED AND EXPERIMENTAL YARN STRENGTHS
NYLON SERIES

Case No. C51137
Page 36a

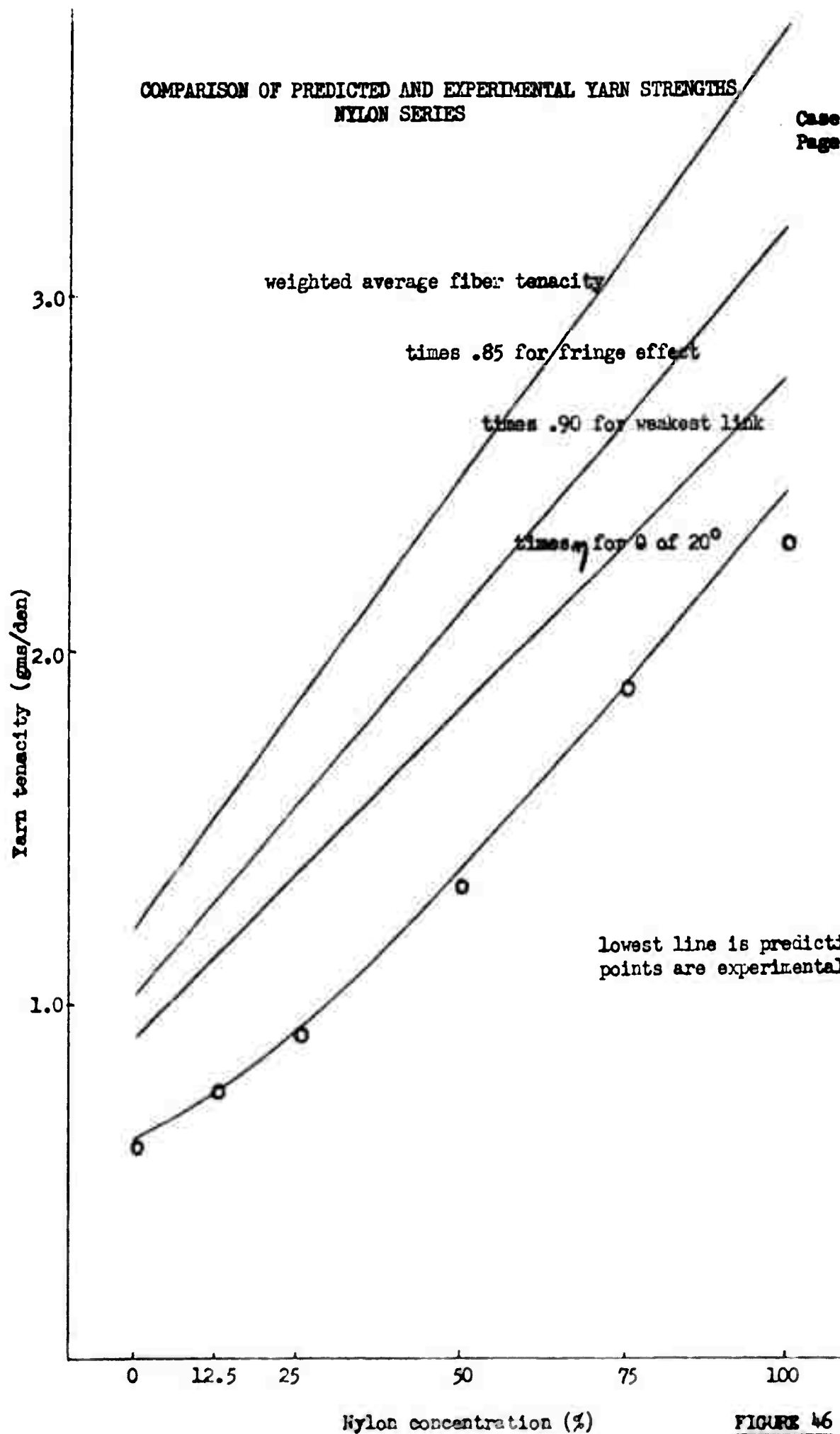


FIGURE 46

COMPARISON OF PREDICTED AND EXPERIMENTAL YARN STRENGTHS VISCOSE SERIES

Case No. C51137
Page 36b

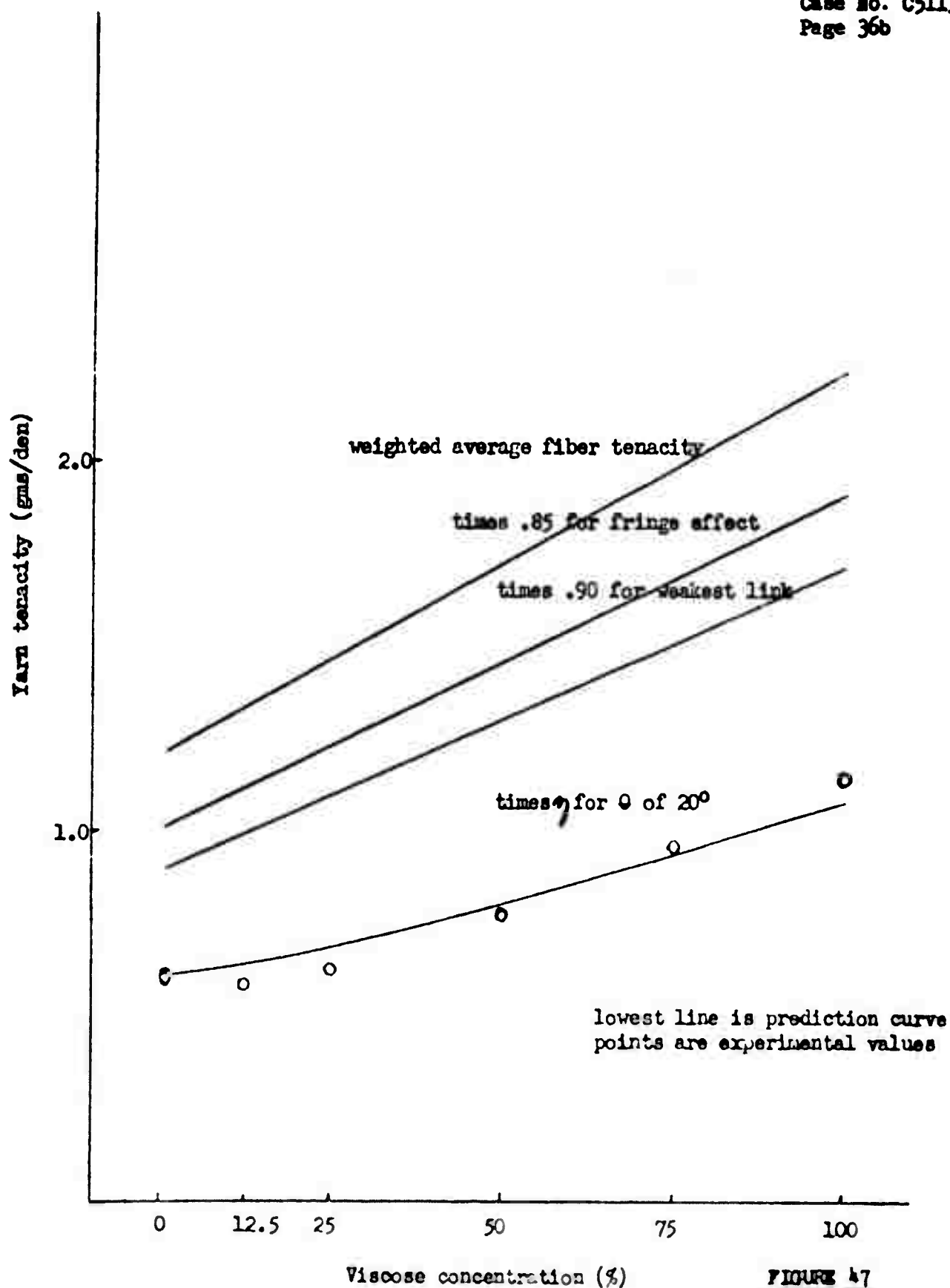


FIGURE 47

have less than the average 15% fringe of non-working fibers. If the original fringe correction--.85 of average fiber strength--had been taken as .93, then the 100% viscose yarn falls on the predicted line. The 100% nylon yarn was observed during spinning to run rather poorly, and the weight irregularity of this yarn was rather higher than the average. At the same time, because of its lower specific gravity, the yarn will have a greater diameter and consequently a somewhat higher θ . If both these effects are corrected, the predicted value of 100% nylon will be lower and the found value is almost perfectly in concord with it.

From all this, it is concluded that the basic method of calculating the translation efficiencies of hard fibers in cordage yarns is completely applicable to spun staple blended yarns provided the real geometry of these latter yarns is known. The structure of the woolen-type yarns departs from the ideal geometry to a greater extent than do the cordage yarns, both laterally (fringe) and longitudinally (thin spots). Corrections for these are estimated to account for 40% of the total strength loss going from fiber tenacity to yarn tenacity. The component and serigraph effects included in the factor η account for the remaining 60% of the net strength loss.

That the method is applicable to the blended yarns is even better borne out by the fact that the actual shape of the strength vs. blend curves conform with the practical situation. For example, Millard and Thornton (12) specifically comment on the shape of the strength vs. blend curve at low nylon concentrations. They seem to have found consistently that addition of small amounts of nylon does not give a proportional increase in yarn strength. This is explainable, now, in view of the fact that there is a sharp decrease in the combined efficiency of wool-nylon at low concentrations, (see Figure 39). The theoretical prediction plot of Figure 46 illustrates the low-concentration curvilinear effect on strength.

It is certainly worth noting, too, that a number of other workers have examined the strength of wool-nylon blends in both woolen and worsted structures, using various fiber lengths and fiber diameters. The general applicability of the basic methods encompassed in this report is illustrated in Figure 48.

This figure plots on the same scale (tenacity in gms/den.) data taken from the literature for six wool-nylon blend series, along with the data on our own wool-nylon yarns. Among these other yarns are:

- a) 800 denier, 64's - 70's broken Cape wool about 1-1/2" staple blended with 1-1/2 denier, 1-1/2" nylon; 10 t.p.i.; woolen system.
- b) 250 denier; 70's 3" wool blended with 3 denier 3" nylon; 30's worsted yarn; 20 t.p.i.

TENACITY VS. BLEND FOR SIX DIFFERENT WOOL-NYLON SERIES
 COMPARED WITH YARNS OF PRESENT STUDY
 (reference)

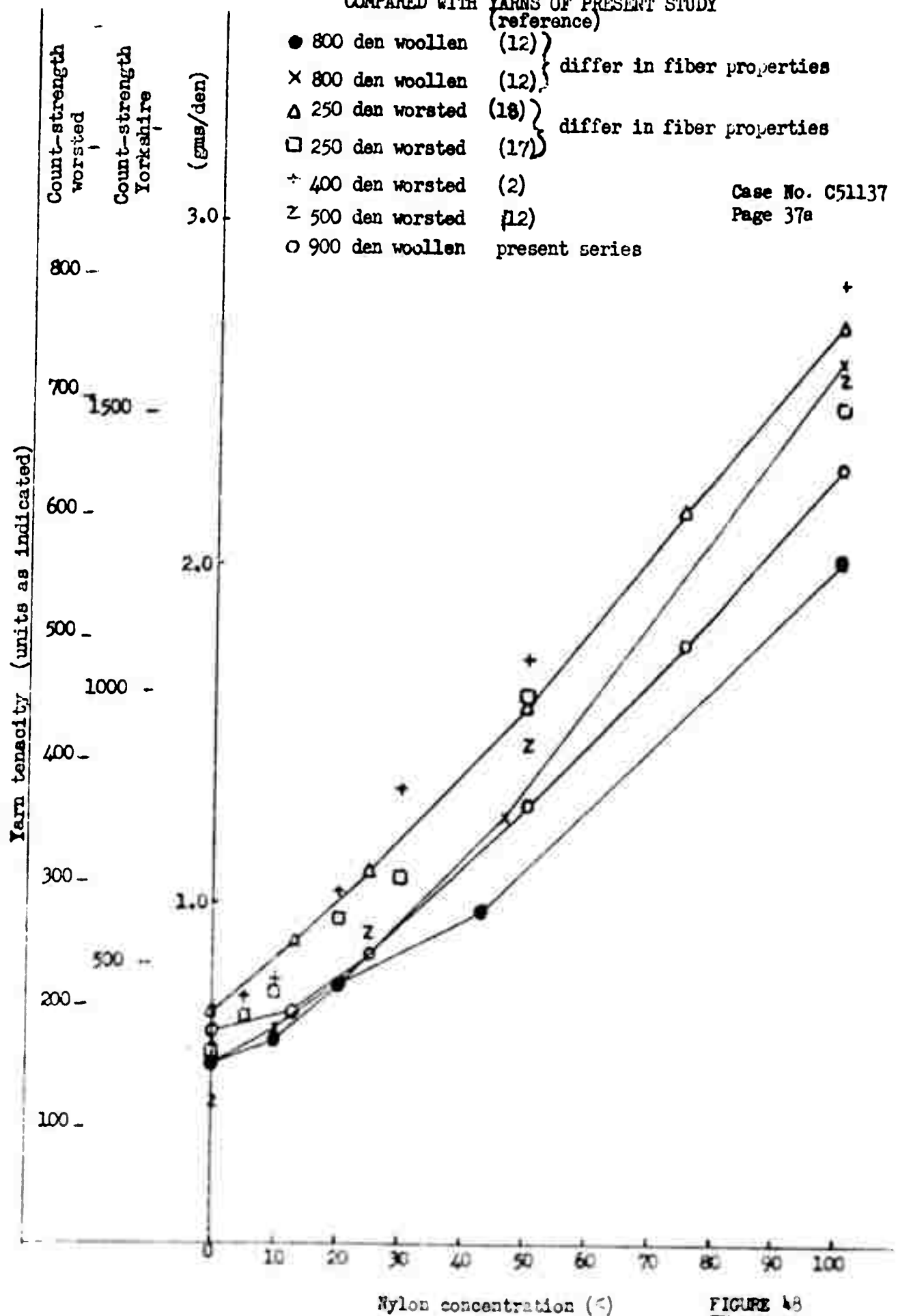


FIGURE 48

- c) 250 denier; 64's wool blended with 3 denier 4" nylon; 30's worsted; 20 t.p.i.
- d) 400 denier; 50's wool blended with 6 denier 6" nylon; 20's worsted; 14 t.p.i.
- e) 500 denier; 64's wool blended with 3 denier 4" nylon; 15's worsted; 10 t.p.i.

That there is a spread among these is not the least bit surprising. No data was given on the basic properties of the fibers and it is certainly likely that the different wools and nylons will have differed in average tenacity, elongation, and variability. Moreover, the group includes quite a gamut of fiber lengths and diameters, a reasonable variation in twist (although they are all approximately the same helix angle), a spread from 250 to 900 denier in the yarn, and finally, both woolen and worsted yarns. Besides, the yarns were tested at different gage lengths, different speeds and on different kinds of machines.

Yet, with all these, the correspondence among the several sets of data is not too bad and they follow quite faithfully the general pattern of strength vs. blend set up by the predicted curve of Figure 46. With the proper data on fiber properties and yarn structure, it is felt that the behavior of each of these series of yarns could have been predicted with the same accuracy as was done for the woolen yarns studied in the present program.

IV. CONCLUSIONS

A. Low-Strain And Repeated Stress Behavior

1. Low strain (1 - 2%) ease of extensibility or "softness" of the blended yarn is functional with the ability of the fibers as they lie in the yarn to uncrimp. First, of course, the fibers must have been crimped originally. Second, the process of yarn manufacture must not have decrimped them. Third, the yarn geometry must be such as to permit crimp unbending at low loads.

Fibers removed from low twist yarns exhibited crimpiness as follows: wool, 4%; nylon, 2%; viscose, 0.6%. Both of the latter two fibers had been artificially crimped. Evidently, however, processing had so modified the viscose fibers that they had been essentially decrimped by the time they arrived in yarn.

The 100% wool, 100% nylon and 100% viscose yarns at 4.5 t.p.i. (lowest twist) exhibited crimpiness magnitudes of the same order as that

of their component fibers, viscose showing essentially none. The 50-50 wool-viscose blend, however, does not reflect a proportional effect of both fibers. Rather, the essentially crimpless viscose acting in parallel with the crimped wool operates as a stiffening matrix and the apparent crimp of the wool-viscose mixture is as low as viscose alone. The nylon-wool blends showed crimpiness equivalent to that of nylon.

The effect of increasing twist is to diminish the apparent low-strain softness of the wool, nylon, and wool-nylon blends. The crimp is evidently absorbed in helical paths, and the freedom of fiber uncrimping hindered. The effect of twist is greater on the nylon and wool-nylon blends than on wool, there being a more rapid effect in the earlier up-twisting, and eventually a lower level of yarn crimpiness achieved at the higher twists. The effect of twist on viscose and the wool-viscose 50-50 blends is nil, since these yarns act as though they had no crimp in the first place.

In essence, wool, a high crimp fiber, promoted a "soft" yarn at low twists, which softness gradually diminished with increasing twist. Viscose fibers, having been decrimped, not only resulted in a "hard" low twist yarn, but also the blending with wool masked its crimpiness at any twist. The nylon fibers, with less crimp than the wool, provided yarn less "soft" than 100% wool. On twisting, this softness was more rapidly lost than it was for the wool. Blending nylon with wool tended to reduce yarn "softness" somewhat, bringing it down to approximately the level of nylon working alone.

2. Elastic recovery of yarns from repeated straining is functional with the equivalent property of the constituent fibers. In mono-blend yarns (one fiber species only) the yarn recovery and fiber recovery properties are essentially identical. In the wool-viscose blended yarns recovery was almost perfectly proportional with blend composition. There is no easy explanation and the result, while it is perhaps comforting, was not to be anticipated. The behavior of the nylon blend series is non-proportional with composition, and as indicated, there was no good reason to expect that it would be.

The poorest recovery behavior was exhibited by the viscose yarn, in accordance with the same deficiency of viscose fibers relative to wool and nylon. The nylon and wool fibers are more recoverable, but they reverse positions between themselves at about 6% strain. Below that, the wool fiber is more recoverable. Above that strain, nylon is superior. Both the mono-blend yarn and the wool-nylon blended series exhibit exactly the same trend. Increasing nylon content in a blend depresses recovery from repeated straining up to 5%, while it enhances recovery from repeated straining to 10% and 15%.

The effect of twist on elastic dimensional recovery is small or negligible. On the other hand, twist has a decided influence

on the load decay that accompanies the repeated straining. At highest twist, the load decay is in the same order as that exhibited by the fibers. As twist is reduced, load decay increases slowly at first, and then quite rapidly as the lowest twist is approached.

The two results--no effect of twist on recovery, pronounced effect on load decay--has been interpreted in the light of previous evidence given of the existence of two radial zones in the yarns. The inner "heart" contains fibers tightly twisted together. Here they are strained without slippage when the yarn is tensioned. Surrounding this zone is a fringe of fibers free to exert frictional drag during yarn extension, but not strained to any great degree.

Uptwisting draws more fiber from the fringe zone into the heart zone. In this connection, therefore, the effect of increasing twist is to reduce load decay on repeated straining. However, above some nominally low twist (4.5 for the present yarns) there is a sufficiently cohesive heart zone so that the yarn, under straining, is made to recover dimensionally in direct relationship to the recoverability of the fibers comprising this region. The fringe fibers are believed to offer little or no resistance to retraction, buckling, or otherwise easily deforming under axial compression when the heart fibers retract in accordance with their particular recovery properties.

B. Yarn Strength Considerations

The strength of the blended yarns can be entirely explained and predicted. The basic strength translation theory developed in connection with filament yarns and cordage structures is adaptable to solution of the problem of blended spun staple yarns when certain specific aspects of their structure are taken into account.

First, of course, the fact that the blended yarns are composed of two fiber species each having its own properties, must be taken into consideration. The method applied here assumed that the two fiber types acted individually but in parallel, and that each was similarly disposed within yarn cross-sections. From the predicted behavior of each species a composited picture of the binary fiber population was developed.

Secondly, an essentially non-load bearing fringe of fibers surrounding the heart of the yarn was allowed for. The existence of such a situation was soundly inferred from the microscopic examination of the subject yarns reported in Technical Report No. 1 (4).

Thirdly, weight non-uniformity along the yarn required reconciliation. It was known from the microscopic examination and other tests that weight varied along the yarn. It was also learned in the present study that strength and weight were well correlated at short gage lengths of testing. It was therefore concluded that the weight irregularity along the length of a 10" specimen resulted in "weak spots". The average strength of 10" specimens would thus be the average strength of their thinnest regions. The question of what length should be assigned to the thinnest region was resolved by assuming it to be roughly in the order of the average fiber length--about 2". From this assumption the strength correction for weak spots was determined.

The actual tenacity of the yarns varied from about 40% to 60% of the weighted average fiber tenacities. This left about half of the fiber strength to be accounted for. Allowances were made as follows:

- a) About 15% of fibers in the yarn cross-section at optimum twist were considered to be in the non-working fringe.
- b) Within 10" lengths of yarn the weak zone was taken as about 10% lighter per unit length than the gross weight per unit length of the entire test specimen.
- c) The working strength of this weak zone was assumed to be governed by the serigraph and component effects contemplated by the translation coefficient as determined for the composite fiber population.

The factors included under a) and b) constitute a factor "X"; the coefficient referred to in c) is η . When these are applied to the weighted average tenacity of the nominal blend, a prediction curve of strength vs. blend can be drawn. The actual strengths of the blended yarns fall remarkably well on this curve.

It was shown that in the wool-nylon series the factor η falls to a minimum at about 12.5% nylon. This accounts for the results shown herein and observed by other workers that strength improvement in nylon blends is not felt until above 10% nylon is added to the wool.

Beyond 12.5% nylon there is a roughly linear rise in translation efficiency with nylon content. Hence, with both increasing weighted average fiber tenacity, as well as increasing efficiency, blends above 12.5% nylon show a rise in strength with increasing nylon content.

For the wool-viscose series, the value of η falls away rather sharply from the level for 100% wool out to about 25% viscose;

after that it passes through a shallow trough and then rises only slowly toward 100% viscose. The net effect on yarn strength is simply that despite the increased average tenacity of the fibers, increasing viscose concentration accomplishes first, at low concentration, no improvement in yarn strength followed by relatively small improvement until upwards of 50% viscose is in the mixture.

A number of factors other than those included in "X" and η , which may affect yarn strength were mentioned. However, some of these could have either a favorable or unfavorable influence and depended on unknown and probably indeterminable features of the yarn and fibers. In view of the experimental evidence corroborating the items in "X" and η and the practical accuracy of the results, it was felt that other items are of secondary importance. That is not to say that in very poorly spun yarns or with the use of fiber stocks of much shorter fiber lengths than those employed in the present work, factors other than "X" and η might not have to be taken into account.

On the other hand, a comparison was made in this report among strength vs. blend curves of six different wool-nylon series including those of this work. The other workers employed yarns of different denier, twist, fiber length, fiber denier, and spun on both woolen and worsted equipment. Despite these disparities and the probability that basic fiber properties were also different, there is good correspondence among all six series. It is concluded that, for practical purposes, the postulations employed herein to explain blended yarn strength have quite broad general applicability.

11

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1

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