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Shrinkage of Knitted Fabrics
Part 1: Wash & Tumble *vs.* Rinse & Tumble

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1. Introduction

One of the most important areas of IIC's research and development work is the effort towards providing a rational, scientific framework for the prediction of weight, dimensions and shrinkage of finished knitted fabrics.

A crucial objective in this work is the definition - and the experimental determination - of the so-called fully relaxed dimensions for a given sample of finished cloth.

The underlying assumption is that it is only the fully relaxed state which can be predicted reliably since, presumably, any other state is more or less unstable and therefore subject to larger experimental errors in its specification.

There is no universally agreed definition of the fully relaxed state or how it may be experimentally realised although it is generally supposed that a washing and tumble drying procedure is probably necessary.

So far, our own definition has been based upon a relaxation procedure involving five cycles of washing and tumble drying performed upon five replications per sample.

This procedure was selected after numerous preliminary trials which investigated the influence of several important variables and is considered to be sound. However, it has to be admitted that the range of fabric samples available to the preliminary trials was not as broad as could have been desired. Furthermore, we have very little insight into the detailed mechanism of shrinkage or its progress as a function of number of washing / drying cycles - especially beyond the fifth cycle. Finally, it should also be considered that the industry would find our relaxation procedure to be far too expensive in both time and materials.

Therefore, from several points of view, it seemed worthwhile to make a detailed investigation into the mechanism of shrinkage of knitted fabrics, as a function of fabric type and finishing as well as the method of relaxation used, in the hope of gaining a better understanding of the fully relaxed state.

As a spin-off from such an investigation, it was hoped to be able to make a recommendation to the industry for a much less expensive relaxation procedure which is nevertheless capable of returning reliable and relevant results.

This report presents the results of the first stage of the investigation which had the following objectives.

1. Following shrinkage over ten wash / tumble cycles for a good range of grey and finished fabrics.
2. Comparing the results returned by a standard wash / tumble procedure with those of an abbreviated method which uses a full wash on only the first cycle and uses only a rinse for all subsequent cycles.
3. Determining the expected precision of shrinkage testing results (confidence limits) to see whether the number of replications could safely be reduced.

2. Experimental

The investigation was carried out in modular form. Each module consisted of four fabrics in two pairs where the pairs were usually matched in every respect but one.

Each of the four fabrics was sampled in ten replications which were divided into two sets of five for the two separate relaxation procedures.

The first cycle of relaxation was identical for both sets and consisted of a standard 60°C wash in an automatic domestic washing machine (Hoover) followed by rinsing, spinning and tumble drying.

Subsequent cycles were identical to this for one set (Method 1A) but for the other set (Method 1C) the 60°C wash was omitted and the cycle began with a rinse.

For all replications length and width of a marked 50 cm square were measured in each of three places at the beginning of the experiment and after each cycle. After each cycle, average shrinkage and 95% confidence limits were calculated for each fabric over the five replications.

During the time available, five modules were completed making twenty fabrics in all. The details of the fabrics are given in *Table 1*.

3. Results

3.1. Comparison Between Methods

The average shrinkages are given in *Tables 2 and 3* for Method 1A (wash and tumble) and in *Tables 4 and 5* for Method 1C (rinse and tumble). The corresponding 95% confidence limits are given in *Tables 6/7 and 8/9* respectively.

Brief inspection of these tables suggests that:

1. Length shrinkage is generally progressive but seems to have levelled off before the tenth cycle.
2. Width shrinkage, on the other hand, shows very little change after the first cycle except for a few cases where there is a marked decrease with the number of cycles.
3. Results from the two methods seem to be rather similar.
4. There is apparently no pattern in the 95% confidence limits. Results from the first cycle are generally as reliable as any others.

Figure 1 shows a plot of all the shrinkage results comparing the two methods. Although there is a certain amount of scatter, it seems that the data are clustered more-or-less evenly around the Y = X line. This supports the idea that both methods return the same information. *Figures 2, 3 and 4* show the same data broken down according to fabric type. From these it would appear that the 1 x 1 rib fabrics are providing more scatter than the interlock or plain jersey.

Table 10 shows the data averaged over cycles, and these averages are shown plotted in *Figures 5 and 6*. *Table 10* also indicates the fabric type and the tightness factor ($\sqrt{Tex}/l$). The following conclusions may be drawn:

1. Apparently the two methods are returning (on the average) identical results.
2. There is no obvious pattern in the 95% confidence limits in relation to test method or shrinkage level or tightness factor.
3. However, the rib fabrics tend to have higher confidence limits, i.e. the results are less reliable.

4. Most of the time, the confidence limits are below 1.5 percentage points but for three fabrics (all 1 x 1 rib) values between 2 and 4% were found.
5. One gains the impression that in general, width shrinkage data are less reliable than length.

3.2. Confidence Limits and the Number of Replications

The average confidence limits are about 0.8 percentage points for the length and 1.1 points for width. These limits are based on measurements for five replications. If the number of replications were to be reduced (as would be desirable for cheaper industrial test methods) then the average confidence limits can be expected to increase as shown in *Table 11*, although individual fabrics (particularly 1 x 1 rib?) may give greater values.

Clearly if we need to estimate shrinkage to within ± 1 percentage point then, on the evidence of these trials, at least four, and preferably five, replications are required.

A single sample (as often used in industry) should not be contemplated and the result from two replications will, on average, be reliable to only ± 2½ percentage points. Even for an industrial test method, it seems that three replications should be specified.

3.3. Comparison Between Samples

If we allow that the two methods are returning essentially the same result, then averaging over methods will give a more accurate representation of the shrinkage behaviour and these averages can be used to make comparisons between fabrics.

Figures 7 to 26 show the results of plotting these averages as a function of number of cycles. The lines which are drawn upon these graphs were obtained by regression analysis using a model which will be described later.

Looking through *Figures 7 to 26*, three different types of behaviour can be noted as the number of cycles is increased.

1. Progressive Shrinkage
2. Little or no change
3. Regressive shrinkage (expansion) after the first cycle.

The data in *Table 12* make a comparison between the various fabrics of this aspect of shrinkage behaviour. In *Table 12*, shrinkages after one cycle and five cycles are compared with the "Total" shrinkage which is defined as the average of cycles 8, 9 and 10. The proportion of total shrinkage achieved after 1 and 5 cycles is shown as a percentage.

Looking at these proportions we may classify fabrics according to the proportion of total shrinkage achieved after 1 and 5 cycles, for example:

Progressive shrinkage (P) : Less than 90% of total after 1 cycle.

Little or no change (N) : 90% to 110% of total after 1 cycle.

Regressive shrinkage (R) : More than 110% of total after 1 cycle.

In addition, we would hope to find that all fabrics had achieved close to (90 - 110% of) the final shrinkage after five cycles.

According to these criteria, *Table 12* includes the classifications for the various fabrics and also indicates the fabric type and finish.

Out of the 40 possibilities, (20 length and 20 width) there are 17 examples of progressive shrinkage all of which are for the length direction. There are four examples of regressive shrinkage, all of which are in the width direction. There are 19 examples of little or no change, the majority of which (16) are in the width direction.

All of the samples which show regressive shrinkage have very low total shrinkages (less than 6%) and the fact that the shrinkage levels are so low means that the detailed behaviour is of little practical consequence. Therefore, for practical purposes (and even though regressive shrinkage behaviour is extremely interesting from an academic and theoretical point of view) we may perhaps be permitted to generalise as follows:

1. The length direction shows significant progressive shrinkage with number of cycles.
2. The width direction shows little or no further change after the first cycle.

In addition, we may note that:-

3. After five cycles practically all fabrics are within 90 - 110% of the final shrinkage.
4. Grey fabrics relax faster than finished ones.
5. With one exception, mercerised fabrics relax more slowly than unmercerised.

3.4. Normalised Shrinkage Behaviour

A more detailed comparison between fabrics and over cycles can be made if the shrinkage values are normalised by expressing the shrinkage after a given cycle as a ratio or a percentage of the total shrinkage as defined in the previous section. *Table 13* shows these data for the length direction and *Table 14* for the width. The corresponding plots are given in *Figures 27 and 28*.

Figure 27 shows clearly the progressive nature of length shrinkage and the relatively large differences between fabrics up to at least the fifth cycle.

Figure 28 confirms that, with the noted few exceptions (which are of small practical consequence), width shrinkage is essentially completed after the first cycle.

3.5. Regression Analysis and the Mechanism of Shrinkage

The divergence of behaviour between fabrics, and especially the phenomenon of regressive shrinkage, leads one to suspect that the mechanism of shrinkage may include (at least) two distinct relaxation processes which proceed simultaneously. The exact nature of these processes remains to be determined by more detailed investigation but for the present we may postulate two, namely:

1. Relaxation of strains
2. Consolidation of yarn structure

Relaxation of strain means the elimination of tensions imposed during manufacturing and processing and could be expected to be a rather rapid process for most fabrics. One might suppose that such relaxation might be the most rapid for grey fabrics which have suffered only relatively minor tensions and these only in the dry state. Conversely, the mercerised materials have suffered rather large tensions under conditions of drastic swelling and might be expected to require more than one wetting / drying cycle to relax the strains.

Consolidation of structure means any changes in the specific volume and the length of the yarns which might be caused by the washing and tumbling procedure itself and can perhaps be thought of as analogous to the felting of wool fabrics - although it would be expected to produce changes in cotton yarns of much smaller magnitude than those found in wool.

A third mechanism can also be postulated namely progressive loop relaxation by which is meant a change in the stiffness / elasticity of the yarns brought about by the washing and tumbling procedure and which could lead to a change in the shape of the loop (ratio of length to width to thickness) and might thus lead to further changes in fabric dimensions.

Without prejudging what the nature of the actual process may turn out to be, it was decided to run a regression analysis on the normalised data, averaged over the two methods, assuming two simultaneous shrinkage processes whose magnitudes both decrease exponentially with the number of cycles but at different rates.

Thus the model chosen was the following.

$$Y_n = Y(R)_n + Y(C)_n$$

where, Y_n is the shrinkage after n cycles

$Y(R)_n$ is the component due to relaxation

$Y(C)_n$ is the component due to consolidation

and

$$Y(R)_n = a \, . \, [\, 1 - Exp\,(-bn)\,]$$

$$Y(C)_n = p \, . \, [\, 1 - Exp\,(-qn)\,]$$

where, *a* and *p* are the maximum shrinkages due to relaxation and consolidation,

b and *q* are the “rate” constants.

At this stage it should perhaps be pointed out that the model is, in fact, strictly speaking untenable since it describes a uniform process whereas we are in fact measuring the consequences of several discrete steps. For example the model is theoretically capable of predicting the level of shrinkage after, say, 1.25 or 6.32 cycles which are clearly meaningless propositions.

Nevertheless the exercise was thought to be useful if it resulted in equations of practical value and if the disparate behaviours of the various samples could be unified thereby.

Tables 15 and 16 show the values of the regression coefficients which resulted from non-linear least squares regression analysis. The corresponding regression curves have already been shown in *Figures 7 to 26*.

These results must be viewed with rather mixed feelings. On the one hand, the plotted curves certainly give a good representation of the experimental data and the results of *Table 15* show excellent correlation coefficients with r^2 never below 0.93 for the length shrinkage equations.

On the other hand, the results in *Table 16* show that the shrinkage in width is much less reliably predicted by the chosen two-process model: only eight of the equations return values of r^2 greater than 0.8. For several of the fabrics there is a good deal of uncertainty in the given coefficients and the computer algorithm for minimising the squares of the differences had great difficulty in settling on optimum values. The reason for this probably lies in the narrow ranges of some of the data together with the relatively large scatter.

Nevertheless a few significant conclusions can be drawn, assuming the two-process model to be adequate.

1. The two processes proceed at vastly different rates.
2. The fast process, here attributed to *Relaxation* is essentially complete after one or two cycles with a rate constant whose average over all fabrics is about 2.7 for the length direction and 3.7 for the width.
3. On the average, the fast process accounts for about 80% of the ultimate (infinite number of cycles) shrinkage in length and 150% of the shrinkage in width.
4. The slow process, here attributed to *Consolidation* (although loop relaxation may also play a part) is much slower with a rate constant whose average over all fabrics is about 0.2 for the length direction and 0.29 for the width. This process is still incomplete after ten cycles but its effect is by then very small.
5. On the average, the slow process accounts for about 26% of the ultimate shrinkage in length and -58% in the width.
6. Thus, for length shrinkage, the two processes are complementary leading to progressive shrinkage. In the width direction they are opposite, leading to partial cancellation and a rather unpredictable behaviour which can range from mildly progressive to regressive.
7. For the range of samples examined there seem to be no consistent connections between the rate constants and the fabric type or finish.

Figures 29 and 30 illustrate how the model breaks the observed shrinkage down into the assumed two component processes. They refer to the grand averages of shrinkage for all samples and as such represent a mythical fabric but, nevertheless, one which could, presumably, be observed.

Incidentally, there is no obvious good reason why the rate constants for either of the two processes should be different for the length and width directions and perhaps this aspect could be borne in mind in future investigations. Due to the nature of the data (range and scatter) the rate constants for the length direction are much more secure than those for width. Perhaps the length constants could be used as (more-or-less) fixed inputs for a width regression analysis. Such a strategy would not improve the correlation coefficients for the width equations but it might remove some of the obviously erroneous constants and coefficients: for example, Fabrics 8 and 10 in *Table 16*.

4. Conclusions

1. The two methods of measuring shrinkage seem to return the same results, within experimental error and, since it is quicker and cheaper, the rinse / tumble technique is therefore to be preferred.
2. Length shrinkage, according to these methods, is progressive at least up to the tenth cycle

but the extent of further change after five cycles is rather small.

3. Width shrinkage is not progressive and a measurement after one cycle is probably adequate for practical purposes.
4. The confidence limits of shrinkage measurements are such that, for research purposes, a minimum of four, and preferably five replications must be recommended. For industrial purposes a minimum of two and preferably three replications is desirable.
5. For research purposes a minimum of five cycles must be recommended. For industrial purposes two cycles might be considered as a reasonable compromise for quality control purposes only.
6. A five-cycle / five-replication test will normally return results which are secure to within ± 1.5 percentage points and will give a good indication of "ultimate" shrinkage but occasional rogues will be encountered.
7. A one- or two-cycle / three-replication test will probably return results which are normally secure to within ± 3 percentage points but the found shrinkages will not necessarily be fully representative of the "ultimate" fabric shrinkage. Length shrinkage will be underestimated by up to five percentage points and width shrinkage may occasionally be over-estimated.
8. There is evidence that the mechanism of shrinkage, under the conditions of these tests, is not simple. At least two underlying mechanisms, proceeding at different rates, must be postulated to account for the observed data. Although there were certain analytical difficulties (due to the scatter in the width results) a two-process model seems capable of explaining both length and width shrinkage. Further experimental and analytical work will be needed to validate this approach and to elucidate the source of "consolidation" shrinkage.

Table 1

FABRICS USED IN THE SHRINKAGE/RELAXATION TRIAL

No.	Type	Nom. Yarn/St. Len.	Finishing
1	Interlock	34/340	Jet dye, compact
2	Interlock	34/340	Mercerise,Jet Dye, Compact
3	Rib	30/350	Jet dye/compact
4	Rib	30/350	Mercerise,Jet dye, compact
5	Plain Jersey	2-72/287	Grey
6	Plain Jersey	28/321	Grey
7	Interlock	38/340	Grey
8	Rib	30/285	Grey
9	Interlock	38/340	Mercerise, jet dye, Cross-link
10	Interlock	38/340	Jet dye, crosslink
11	Rib	30/285	Mercerise, jet dye, cross-link
12	Rib	30/285	Jet dye, crosslink
13	Interlock	34/324	Mercerise, jet dye, compact
14	Interlock	34/324	Jet dye, compact
15	Rib	26/267	Jet dye, compact
16	Rib	30/267	Mercerise, jet dye, compact
17	Plain jersey	28/306	Overflow dye
18	Plain jersey	2-56/306	Overflow dye
19	Plain jersey	2-56/306	Mercerise, overflow dye
20	Plain jersey	28/306	Mercerise, overflow dye

Table 2

LENGTH SHRINKAGE : Wash & Tumble

Cycle / Fabric	1	2	3	4	5	6	7	8	9	10
1.	13.5	15.4	16.1	17	17.4	18.2	18.4	19.4	18.8	19.4
2.	11.9	13.7	14.8	15.8	16.3	17.6	17.7	18.4	18.6	19.4
3.	14.6	17.1	18.7	18.1	18.7	19.4	19.3	19.3	19.7	19.7
4.	16.7	18.3	19.7	20.2	20.5	21.4	20.3	21.8	21.4	21.9
5.	18.5	19.7	20.8	20.7	20.6	20.6	20.7	20.9	21.2	21
6.	20.8	22	22.1	22.7	22.6	22.8	22.8	22.9	23.3	23.2
7.	21.2	23.1	23.6	24.3	24.4	25	24.9	24.5	25.2	25.3
8.	15	16.2	16.6	17	17	17.2	17.2	17	17.6	17.9
9.	7.6	8.1	9.2	9.3	9.8	10.5	11	10.3	11.2	10.9
10.	11.8	13.3	15.4	15	14.7	15.5	15.7	16.4	16.3	16.3
11.	9.1	10.1	10.7	11	11	12.1	11.6	11.8	12.1	11.8
12.	10.3	11.2	12	12.4	11.9	12.8	12.9	13.1	13	13.1
13.	12	14.3	16.1	16.5	17.2	17.8	17.7	18	18.8	18.6
14.	10.9	12.2	13.5	13.7	14.1	14.4	14.6	14.7	15.1	14.9
15.	8.9	10.1	10.7	10.8	11.3	11.4	12	11.8	12	11.8
16.	10	10.9	11.6	11.5	11.7	11.8	11.9	11.9	12	12
17.	11.7	12.8	13	13.4	13.2	13.8	13.5	13.7	14.1	14.2
18.	9.5	10.5	10.4	10.6	11.1	11	10.4	11.3	10.9	11.1
19.	3.3	5.6	5.5	6.4	6.5	6.2	6.1	7.3	6.9	7.3
20.	10.5	13.6	13.8	15.5	14.8	15.3	14.3	15.9	15.5	16.3

Table 3

WIDTH SHRINKAGE : Wash & Tumble

Cycle / Fabric	1	2	3	4	5	6	7	8	9	10
1.	7.1	7.2	6.9	6.4	6.1	6.2	5.8	6.2	5.4	6
2.	7.5	7.3	6.4	5.9	5.8	4.8	4.9	4.5	4.1	4.6
3.	10	7.9	6.4	5.2	4.7	4.3	4	4.3	3	3.5
4.	8.6	6.7	4.5	3.8	3.3	2.6	2.2	2	0.7	2
5.	15.6	16	16.3	16.4	15.9	16.2	16.2	16	16	16.2
6.	15.6	16.1	16.8	16.6	16.5	16.5	16.8	16.6	16.4	16.7
7.	11.9	12.1	12	11.6	11.1	10.5	10.3	10.2	11	9.9
8.	18.9	19.8	20.6	20.2	20.3	19.8	19.9	19.8	20.1	19.3
9.	10.7	10.6	10.4	10.3	10	10.3	9.6	9.7	9.6	9.4
10.	9.4	8.9	9.6	9.1	9.5	9.9	9.8	9	9.5	9.2
11.	11	10.7	10.3	10.2	9.9	10.2	9.8	9.8	9.6	9.4
12.	8.5	7.2	7.6	6.9	7.6	6.9	7	5.9	7	5.7
13.	5.8	5.6	4.9	4.9	4.2	3.6	4.3	3.7	3.5	2.8
14.	7.6	7.4	8	7.8	7.4	7.2	7	7.3	7.9	7.2
15.	5.9	5.8	5.7	5.9	5.5	5.4	4.6	5.4	5.6	5.9
16.	5.6	5.5	5.5	5.3	4.9	4.8	4.5	4.5	5	4
17.	10.6	10.8	10.5	10.8	11.2	10.7	10.8	11	11.2	11.1
18.	10.6	11.3	11.3	11.5	11.3	11.6	11.5	11.6	11.8	12
19.	21.5	21.5	21.3	21.7	20.7	21	20.6	20.6	21	20.8
20.	18.6	17.1	16.8	16.7	16.3	16.1	16	16.6	16.8	16.1

Table 4

LENGTH SHRINKAGE : Rinse & Tumble

Cycle / Fabric	1	2	3	4	5	6	7	8	9	10
1.	15.2	16	16.4	16.9	17.7	17.6	18.1	17.8	19.2	19.1
2.	12.2	14.1	15.9	17.1	18.8	19.4	19.6	20.3	21.6	22.1
3.	15.1	16	16.7	17	17.8	17.8	18.4	18.2	18.8	18.9
4.	16.8	19	19.9	21	21.6	22	22.5	22.3	23.2	23.2
5.	20	19.9	20.5	20.8	20.8	21.1	21.4	20.7	21.2	20.9
6.	22.2	22.7	23.1	23.1	23.1	23.2	23.5	23.5	23.6	23.6
7.	22.2	22.9	23.8	23.4	23.4	23.7	23.9	23.9	24.3	24
8.	14.9	15.6	16	16.2	16.3	16.5	16.7	16.3	16.9	16.7
9.	7	8.5	8.5	9.4	10.2	10.1	10	10.8	11.5	11.2
10.	12.6	13.6	13.7	14.3	14.6	15	15	15.5	16	15.8
11.	8.7	10.2	9.4	11	11.5	11.7	11.7	12	12.4	12.2
12.	9.8	10.1	9.8	10.7	10.9	11.1	11.3	11.7	12.1	11.5
13.	12	14.6	15.8	16.5	17.5	17.7	18.9	19.1	19.9	19.9
14.	10.3	11.8	12.5	12.8	13	12.7	13.3	13.3	14.1	13.4
15.	6.3	7.4	7.6	8	8	8	8.3	8.4	8.8	8.2
16.	10.2	11.5	12	12.3	12.3	12.6	12.8	12.7	13.3	13
17.	12.6	12.8	13.4	13.8	13.6	13.8	14	13.7	14.2	14.4
18.	10.6	10.1	10.8	11.1	11	11.2	11	11	11.2	11.5
19.	5.4	5.9	6.7	5.6	6.4	6.6	6.7	5.9	7	6.4
20.	13.1	14.8	15.5	15.7	16.2	17	16.3	16.4	16.9	16.7

Table 5

WIDTH SHRINKAGE : Rinse & Tumble

Cycle / Fabric	1	2	3	4	5	6	7	8	9	10
1.	7.1	7	7.3	7.4	7.8	7	7.3	7.1	7.5	7.3
2.	7.7	7.2	6.5	5.9	5.4	4.8	5.1	4.4	4.7	4.1
3.	10.7	10.8	10.2	9.2	10.1	9	8	7.4	8	7.9
4.	8.1	6.9	5.2	3.2	3.3	2.7	2.3	2.3	1.8	1
5.	14.1	15.5	15.6	15.6	15.2	15.3	15.5	15.8	16.3	16.1
6.	13.2	13.6	13.9	14	14.1	14.2	14.4	14.1	14.5	14.5
7.	12.3	12.3	12.6	12.6	12.6	12.4	12.7	11.8	12.6	11.9
8.	20.9	21.1	21.9	21.6	21.3	21.6	21.6	21.2	22	21.3
9.	10	9.8	9.3	9.3	9.3	9.1	9.4	8.9	8.8	8.9
10.	8.8	8.5	8.5	8.6	8.9	9.1	9.3	9.2	9.2	9.4
11.	11.2	10.5	10.8	11	11.3	10.7	10.9	10.8	10.8	11.1
12.	7.4	8.3	7.4	8.6	8.3	8.4	8	8.3	8.3	8.5
13.	5.9	5.4	5.3	4.9	4.4	4	3.6	3.6	3.9	3.1
14.	7.4	8.5	8.1	8.7	8.2	8.1	8.3	8.5	8.9	8.3
15.	9.9	10.4	10.1	10	10.1	9.6	10	10	10.4	10.1
16.	5.5	5.8	5.2	5.3	4.9	4.7	4.7	5.2	5.3	4.5
17.	10.8	10.8	10.7	10.6	11	11.6	11.1	11.3	11.8	11.2
18.	12.6	12.6	12.8	12.5	13	13.3	13.5	13.4	13.6	13.3
19.	21.8	21.4	21.1	20.9	21.1	20.8	21.3	21.2	21	21.1
20.	17.7	16.6	16.4	15.9	16	15.8	16.3	15.8	15.8	15.7

Table 6

95% c.l. on LENGTH SHRINKAGE : Wash & Tumble

Cycle / Fabric	1	2	3	4	5	6	7	8	9	10
1.	0.6	0.5	1	0.7	0.9	0.9	1.3	0.7	1	0.9
2.	0.9	1.3	1.2	1.1	1	0.7	0.7	0.9	0.8	1.2
3.	1.9	2.1	4	1.7	1.9	1.6	1.8	2.1	1.6	2
4.	0.8	1.7	1.2	1.1	1.5	1.5	1.4	0.9	1.5	0.9
5.	0.4	0.3	0.7	0.4	0.5	0.2	0.4	0.3	0.4	0.6
6.	0.8	0.6	0.7	0.6	0.9	0.7	0.6	0.7	0.4	1
7.	0.5	0.4	0.5	0.3	0.4	0.4	0.7	0.7	0.4	0.7
8.	0.4	0.3	0.3	0.2	0.5	0.4	0.7	0.5	0.4	0.6
9.	0.5	0.4	0.7	0.4	0.4	0.4	0.5	1.9	0.5	0.6
10.	0.6	2.2	2.3	1.6	0.9	0.6	0.9	1.1	1.1	0.3
11.	1	0.5	0.6	0.9	0.8	0.6	0.6	0.9	0.4	0.6
12.	0.6	0.5	0.7	0.7	0.8	0.6	0.7	0.8	0.4	0.7
13.	1	0.5	0.5	0.6	0.8	0.8	1.4	0.6	0.5	0.9
14.	0.2	0.7	0.8	0.8	0.7	0.4	0.6	0.5	0.6	0.8
15.	0.4	0.6	0.4	0.4	0.4	0.4	0.8	0.7	0.6	0.4
16.	1.3	1	1.2	1.2	0.7	1.3	1.1	1.1	1	1.1
17.	0.3	0.3	1	0.5	0.5	0.3	0.5	0.3	0.2	0.4
18.	0.6	0.3	0.6	0.7	1.3	0.7	0.6	0.9	1	0.4
19.	2	0.9	0.8	0.7	0.8	1	0.8	1	0.9	0.9
20.	0.8	0.7	0.8	1.5	1.1	0.7	1	0.6	0.7	1

Table 7

95% c.l. on WIDTH SHRINKAGE : Wash & Tumble

Cycle / Fabric	1	2	3	4	5	6	7	8	9	10
1.	0.5	0.4	0.8	0.5	0.3	0.5	0.6	0.6	0.6	0.7
2.	0.9	0.6	0.9	0.8	0.8	0.8	1	1.1	1.2	1.2
3.	2.1	3.3	4.9	3.1	3.1	3.6	3.4	3.9	3.4	3.5
4.	2.1	2.8	2.4	2.8	3.2	3.2	2.9	2.1	1.8	2.3
5.	0.8	0.3	0.8	0.5	0.6	0.5	0.5	0.5	0.6	0.5
6.	0.6	0.9	1	1.1	0.5	0.8	0.6	0.6	1	0.5
7.	0.3	0.5	0.5	0.8	0.7	1	0.9	0.5	1.1	0.3
8.	0.9	0.7	1.1	0.8	1.5	1.2	1.3	1	1.1	1
9.	0.6	0.6	0.9	0.5	0.8	0.5	0.5	1.3	0.8	1.2
10.	1.4	1.5	0.9	1.4	1.2	1.2	1	1.1	1.3	1.3
11.	1.5	0.6	0.5	1.4	1.2	0.7	1	1.1	1.5	1
12.	0.9	1.7	0.9	0.9	0.6	0.9	0.7	1.5	0.9	1.3
13.	0.8	1.3	0.8	0.7	1.2	0.7	0.8	0.6	0.9	1
14.	0.9	0.8	0.5	0.8	0.7	0.2	0.3	0.7	0.9	0.8
15.	0.6	0.9	0.4	0.7	0.5	0.8	1.4	0.5	0.5	2.3
16.	1.3	1.8	1.1	1.2	1.5	1.3	1.6	1.3	1.2	1.6
17.	0.8	0.9	0.6	0.5	0.3	0.7	0.7	1.1	0.6	0.6
18.	0.8	0.8	0.8	1.2	1	1	0.8	0.8	0.7	0.9
19.	0.5	0.9	1	0.7	1.1	1	0.9	1.3	0.9	0.6
20.	1.1	0.7	0.8	0.8	0.7	0.6	0.6	0.7	0.6	1.2

Table 8

95% c.l. on LENGTH SHRINKAGE : Rinse & Tumble

Cycle / Fabric	1	2	3	4	5	6	7	8	9	10
1.	1.2	0.9	1.1	1.1	1.1	1.2	1	0.9	1.1	1.1
2.	0.6	0.6	0.7	0.5	0.5	0.8	0.5	0.6	0.7	0.4
3.	2.6	1.8	1.8	1.6	1.7	1.6	1.7	1.6	1.7	1.8
4.	0.6	0.7	0.6	0.3	1	0.4	0.3	0.5	0.8	0.9
5.	0.8	0.7	1.6	0.3	0.6	0.7	0.5	0.7	0.3	0.9
6.	0.9	0.8	0.8	0.8	0.7	0.8	0.6	0.8	1.2	0.9
7.	0.2	0.5	0.1	0.5	0.3	0.4	0.4	0.3	0.3	0.5
8.	0.3	0.3	0.3	0.4	0.6	0.3	0.4	0.3	0.4	0.3
9.	1	0.7	0.8	0.4	0.6	0.5	0.7	0.4	0.4	0.4
10.	0.7	0.7	0.6	1.4	0.6	0.6	1	0.6	0.5	0.4
11.	0.4	0.3	1.1	0.2	0.1	0.5	0.4	0.3	0.4	0.4
12.	0.8	0.4	0.4	1.3	0.8	0.6	0.5	0.6	0.6	0.9
13.	0.2	0.3	0.3	1.8	0.6	0.8	0.7	1.1	0.6	0.5
14.	0.9	1	0.6	0.2	0.3	0.3	0.5	0.6	0.7	0.5
15.	2	2.1	2.1	2.1	1.8	2.1	1.9	2.1	2	2.3
16.	1	0.7	0.9	0.9	1	0.9	0.9	1.1	0.8	0.9
17.	0.3	0.5	0.5	0.4	0.4	0.3	0.4	0.3	0.4	0.4
18.	0.5	0.7	0.5	0.6	0.4	0.7	1.2	1	0.7	0.3
19.	1.4	0.6	1	1	0.8	1.2	1.2	0.9	1.1	0.7
20.	1.8	0.9	1.1	0.6	1.2	1	0.9	1	1.1	0.6

Table 9

95% c.l. on WIDTH SHRINKAGE : Rinse & Tumble

Cycle / Fabric	1	2	3	4	5	6	7	8	9	10
1.	1.1	0.5	0.8	0.8	0.6	1.1	1.3	1.1	0.8	1
2.	0.7	0.7	0.6	0.7	0.6	0.3	0.5	0.7	0.5	0.8
3.	2.9	3.3	4	3.1	3.5	3.9	5.5	2.8	4.3	5
4.	1.3	3.5	1.5	1.2	1	1.3	1.4	1.3	1.4	1.2
5.	1.1	1.2	1.1	0.8	0.7	1	0.7	0.9	0.7	0.8
6.	0.7	0.3	1	0.5	0.4	0.5	0.4	0.6	0.7	0.6
7.	0.3	0.4	0.8	0.5	0.8	0.9	0.3	0.5	0.6	0.3
8.	1.2	0.4	0.9	0.9	0.9	0.8	1	0.9	1.3	1
9.	1.6	1.1	2.2	1.6	1.1	0.8	1.2	1	1.6	1.3
10.	0.4	1.4	0.6	1.4	0.5	0.8	0.7	0.7	0.6	0.8
11.	0.2	0.6	2.1	0.7	0.5	0.6	0.6	1.1	0.5	0.5
12.	1	1.3	1.7	1.3	1.3	0.9	1.5	1.3	1.3	1.7
13.	1.6	1.1	0.9	1.3	0.9	1.4	1.4	1.2	1	1
14.	0.6	0.6	0.4	0.4	0.5	0.9	0.5	0.4	0.9	0.4
15.	3.2	3.4	3.7	3.6	3.6	3.2	3.7	3.1	3.7	3.9
16.	0.4	0.4	0.6	0.6	0.4	0.5	0.7	1	0.5	0.8
17.	0.6	0.7	0.6	0.8	0.6	0.7	1.3	0.6	0.4	0.8
18.	0.4	0.8	0.9	0.9	0.9	0.8	1	0.5	0.8	0.6
19.	2	1.1	1.1	1.4	1.2	1.5	1.2	1.4	1.4	1.3
20.	1.6	1.1	1	0.9	0.9	1.1	1	1.1	1	0.6

Table 10

RESULTS AVERAGED OVER CYCLES

FABRIC			% SHRINKAGE				95% CONFIDENCE LIMITS			
			LENGTH		WIDTH		LENGTH		WIDTH	
No.	Type	T.F.	1A	1C	1A	1C	1A	1C	1A	1C
1	I	12.2	17.4	17.4	6.3	7.3	0.85	1.08	0.56	0.91
2	I	13.8	16.4	18.1	5.6	5.6	0.99	0.60	0.93	0.59
3	R	12.6	18.5	17.5	5.3	9.2	2.09	1.78	3.43	3.83
4	R	13.8	20.2	21.2	3.6	3.7	1.27	0.62	2.56	1.50
5	PJ	14.2	20.5	20.7	16.1	15.5	0.41	0.71	0.56	0.90
6	PJ	14.3	22.5	23.2	16.5	14.1	0.69	0.83	0.77	0.57
7	I	11.6	24.2	23.6	11.1	12.4	0.51	0.36	0.67	0.53
8	R	15.3	16.9	16.2	19.9	21.4	0.43	0.38	1.05	0.93
9	I	12.9	9.8	9.7	10.1	9.3	0.63	0.59	0.77	1.34
10	I	11.7	15.1	14.6	9.4	9.0	1.17	0.72	1.24	0.79
11	R	17.2	11.1	11.1	10.1	10.9	0.69	0.41	1.04	0.75
12	R	15.5	12.3	10.9	7.0	8.2	0.65	0.70	1.03	1.34
13	I	13.9	16.7	17.2	4.3	4.4	0.77	0.69	0.88	1.19
14	I	12.9	13.8	12.7	7.5	8.3	0.61	0.55	0.66	0.56
15	R	17.6	11.1	7.9	5.6	10.1	0.51	2.06	0.86	3.50
16	R	18.0	11.5	12.3	5.0	5.1	1.11	0.92	1.38	0.58
17	PJ	15.9	13.4	13.6	10.9	11.1	0.43	0.39	0.68	0.70
18	PJ	15.0	10.7	11.0	11.5	13.1	0.71	0.66	0.90	0.78
19	PJ	16.7	6.1	6.3	21.1	21.2	0.99	0.99	0.89	1.34
20	PJ	15.9	14.6	15.9	16.7	16.2	0.89	1.02	0.77	1.04
Mean			15.1	15.1	10.2	10.8	0.82	0.80	1.08	1.18
s.d.			4.6	4.9	5.3	5.0	0.39	0.44	0.70	0.90

Table 11

EXPECTED* 95% CONFIDENCE LIMITS FOR REDUCED NUMBERS OF REPLICATIONS

REPLICATIONS	95% CONFIDENCE LIMIT	
	LENGTH	WIDTH
5	0.8	1.1
4	1.0	1.3
3	1.3	1.8
2	~2.1	~2.9

* from c.l. = $\frac{t\sigma}{\sqrt{n}}$

where, n = number of replications

σ = estimated population standard deviation

t = students T for n degrees of freedom

Table 12

COMPARISONS OF SHRINKAGE BEHAVIOUR BETWEEN FABRICS

FABRIC AND FINISH	LENGTH Total	LENGTH 1/T%	LENGTH 5/T%	LENGTH Class.	WIDTH Total	WIDTH 1/T%	WIDTH 5/T%	WIDTH Class
1 I34/340 JDH	19.0	75.3	92.6	P	6.6	107.7	105.4	N
2 I34/340 MJDH	20.1	60.2	87.6	P	4.4	171.7	127.2	R
3 R30/350 JDH	19.1	78.0	95.7	P	5.7	181.7	129.6	R
4 R30/350 MJDH	22.3	74.9	94.5	P	1.6	510.7	200.0	R
5 PJ2-72/287 GREY	21.0	91.4	98.8	N	16.1	92.5	96.9	N
6 PJ28/321 GREY	23.4	91.9	97.9	N	15.5	93.1	99.0	N
7 I38/340 GREY	24.5	88.3	97.5	P	11.2	107.6	105.7	N
8 R30/285 GREY	17.1	87.7	97.3	P	20.6	96.5	100.8	N
9 I38/340 MJDX2	11.0	66.4	90.9	P	9.2	112.0	105.2	N
10 I38/340 JDX2	16.1	76.1	91.4	P	9.3	98.3	99.7	N
11 R30/285 MJDX2	12.1	73.8	93.8	P	10.3	108.0	103.2	N
12 R30/285 JDX2	12.4	80.8	91.9	P	7.3	109.4	109.8	N
13 I34/324 MJDH	19.0	63.2	91.0	P	3.4	170.5	126.6	R
14 I34/324 JDH	14.2	74.2	95.3	P	8.0	93.7	97.6	N
15 R26/267 JDH	10.2	74.7	94.9	P	7.9	100.4	98.6	N
16 R30/267 MJDH	12.5	80.9	96.3	P	4.7	117.9	103.5	N
17 PJ28/306 BRAZ	14.1	86.6	95.5	P	11.3	95.0	98.7	N
18 PJ2-56/306 BRAZ	11.2	90.1	98.8	N	12.6	92.3	96.6	N
19 PJ2-56/306 MBRAZ	6.8	63.5	94.3	P	21.0	103.2	100.0	N
20 PJ28/306 MBRAZ	16.3	72.5	95.2	P	16.1	112.5	100.1	N

I = INTERLOCK
R = RIB
PJ = PLAIN JERSEY

JD = JET DYED
M = MERCERISED
X2 = CROSSLINKED
BRAZ = OVERFLOW DYED

Table 13

NORMALISED LENGTH SHRINKAGE : AVE OF BOTH METHODS

	Percent of Total shrinkage									
Cycle	1	2	3	4	5	6	7	8	9	10
Fabric										
1.	75.6	82.7	85.6	89.4	92.6	94.4	96.2	98.1	100.3	101.6
2.	60.2	69.3	76.4	82	87.5	92.3	93.1	96.4	100.2	103.4
3.	77.9	86.8	92.7	92.1	95.7	97.5	98.7	98.1	100.6	101.2
4.	75	83.8	88.9	92.4	94.4	97.3	96	98.9	99.9	101.2
5.	91.7	94.5	98.6	98.9	98.8	99.4	100.4	99.2	101	99.7
6.	91.9	95.8	96.9	98.1	97.9	98.7	99	99.4	100.4	100.2
7.	88.3	93.8	96.6	97.3	97.5	99.2	99.3	98.7	100.8	100.4
8.	87.7	93.3	95.6	97.3	97.3	98.9	99.3	97.7	101.1	101.1
9.	66.4	75.5	80.7	85.6	91.2	94.4	95.7	96	103.3	100.7
10.	76.1	84.1	90.6	91.4	91.4	95	95.7	99.3	100.6	100.1
11.	73.8	84.4	83.6	91.4	93.8	98.9	96.8	98.9	101.5	99.6
12.	80.8	85.4	87.8	93.1	91.9	96.4	97.4	99.8	101	99.1
13.	63.2	75.8	83.7	86.6	91	93.2	96.3	97.4	101.6	101
14.	74.2	84.3	91.3	92.9	95.3	95.1	97.7	98.3	102.5	99.3
15.	74.7	86.1	90.1	92.4	94.9	95.5	100	99.2	102.1	98.7
16.	80.9	89.8	94.6	95.3	96.3	97.6	99	98.7	101.4	99.8
17.	86.6	90.9	93.9	96.8	95.5	98.2	98	97.7	100.6	101.7
18.	90.1	92.4	94.6	96.8	98.8	99.4	95.8	99.8	98.9	101.2
19.	63.5	84.1	89.6	88.4	94.3	94.2	94.3	97	101.9	101.1
20.	72.5	87.2	90	95.8	95.2	99.2	94	99.2	99.5	101.3

Table 14

NORMALISED WIDTH SHRINKAKE : AVE OF BOTH METHODS

	Percent of Total Shrinkage									
Cycle	1	2	3	4	5	6	7	8	9	10
Fabric										
1.	107.7	108	108.3	105.1	105.4	100.3	99.8	101.1	98	100.9
2.	171.7	164	147	133.7	127.2	108.6	113.9	101.3	99.7	.98.9
3.	181.7	163.5	146.3	126.7	129.6	117.1	105.5	103.3	96.8	99.9
4.	510.1	415.3	296.6	213.1	200	164.5	137.9	131.8	77.4	90.8
5.	92.4	98	99.2	99.5	96.9	98	98.6	98.9	100.6	100.5
6.	93.1	95.9	99.3	99	99	99.3	100.7	99.2	99.9	100.9
7.	107.6	108.2	109.5	107.8	105.7	101.7	102.2	97.9	105.1	97
8.	96.5	99.2	103.1	101.4	100.8	100.4	100.7	99.4	102.2	98.4
9.	112	110.7	106.9	105.8	105.2	105	103	101.2	99.6	99.2
10.	98.3	94	98.2	95.7	99.7	102.9	103.5	98.5	101	100.5
11.	108	103.3	102.9	102.9	103.2	101.7	100.9	100.5	99.4	100.1
12.	109.3	106.2	103	106.5	109.8	105	103.7	97.7	104.7	97.6
13.	170.5	161.1	147.4	143.7	126.5	112	114.5	105.9	107.6	86.5
14.	93.7	99.1	100.4	103	97.6	95.5	95.9	98.5	104.9	96.5
15.	100.4	102.5	99.6	100.8	98.5	95.2	92.5	97.7	100.8	101.5
16.	117.8	118.8	113.4	112.2	103.5	99.7	96.9	101.8	108.6	89.6
17.	95	96.1	93.8	95.4	98.7	99	96.7	99	102.1	98.9
18.	92.3	94.7	95.1	95.1	96.6	99	99	99.1	100.7	100.1
19.	103.2	102.3	101.3	101.7	100	99.6	100.1	99.9	100.2	99.8
20.	112.5	104.4	102.9	101	100.1	98.9	100.1	100.4	101	98.5

Table 15

REGRESSION ANALYSIS OF LENGTH SHRINKAGE

FABRIC	RELAXATION a	RELAXATION b	CONSOLIDATION p	CONSOLIDATION q	CORREL. COEFF. r^2
1	14.1	3.21	7.3	0.13	0.999
2	10.6	3.44	12.6	0.16	0.996
3	15.3	2.48	4.9	0.21	0.984
4	15.9	2.96	7.0	0.27	0.992
5	18.6	4.18	2.5	0.46	0.930
6	22.1	3.33	2.0	0.12	0.989
7	22.1	3.06	2.8	0.24	0.977
8	15.5	2.96	2.2	0.17	0.955
9	6.5	3.71	5.5	0.20	0.985
10	12.9	2.37	5.4	0.10	0.976
11	8.2	3.41	4.3	0.26	0.958
12	9.3	5.93	3.6	0.21	0.969
13	12.2	2.03	8.6	0.18	0.996
14	10.7	2.31	3.9	0.25	0.976
15	7.7	2.38	2.8	0.25	0.976
16	10.6	2.44	2.2	0.24	0.985
17	12.4	3.25	2.5	0.13	0.952
18	9.7	4.96	1.6	0.28	0.964
19	5.6	1.38	2.2	0.07	0.975
20	12.3	2.01	4.3	0.32	0.987

Table 16

REGRESSION ANALYSIS OF WIDTH SHRINKAGE

FABRIC	RELAXATION a	RELAXATION b	CONSOLIDATION p	CONSOLIDATION q	CORREL. COEFF. r^2
1	7.6	3.20	-1.3	0.21	0.861
2	9.6	2.55	-5.8	0.26	0.986
3	12.1	4.39	-7.1	0.25	0.984
4	12.7	2.71	-11.3	0.39	0.993
5	16.9	2.71	-0.9	2.73	0.778
6	18.7	3.23	-3.3	3.97	0.690
7	12.7	3.32	-3.7	0.06	0.709
8	21.0	2.94	-22.8	0.002	0.541
9	10.5	8.87	-2.4	0.08	0.969
10	9.3	3.30	-0.03	1.02	(~0.3)
11	10.9	4.51	-1.0	0.10	0.681
12	8.0	6.11	-2.2	0.03	0.464
13	6.4	3.90	-4.9	0.11	0.966
14	8.4	2.50	-0.5	0.54	0.274
15	8.7	3.21	-1.0	0.58	0.198
16	6.7	2.51	-2.2	0.31	0.738
17	12.6	3.17	-1.6	1.56	0.07
18	13.9	3.27	-1.6	4.05	0.392
19	22.3	5.02	-1.4	0.45	0.875
20	19.3	6.12	-3.2	0.65	0.945

Figure 1

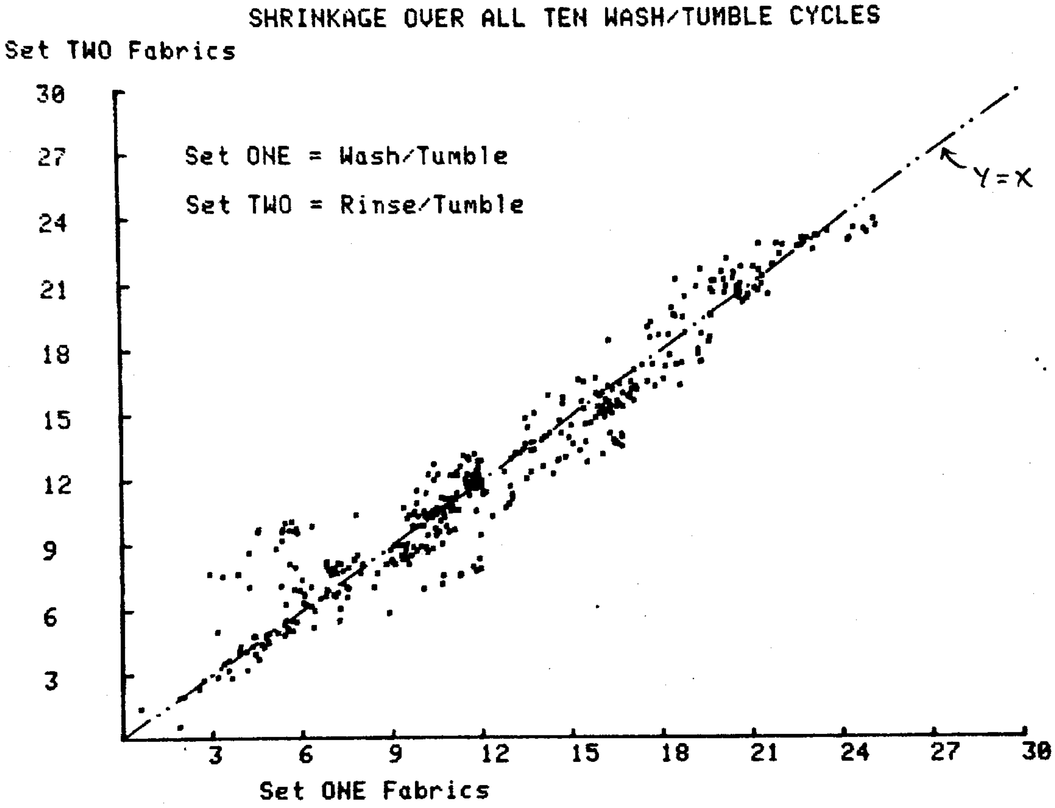


Figure 2

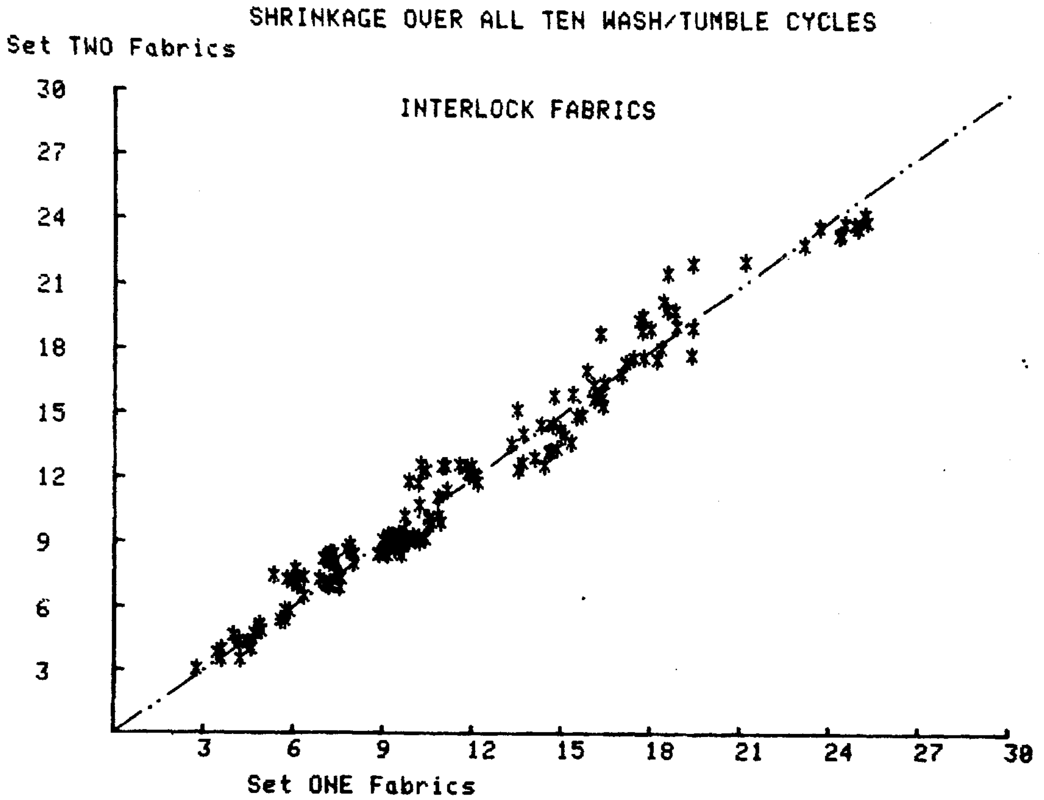


Figure 3

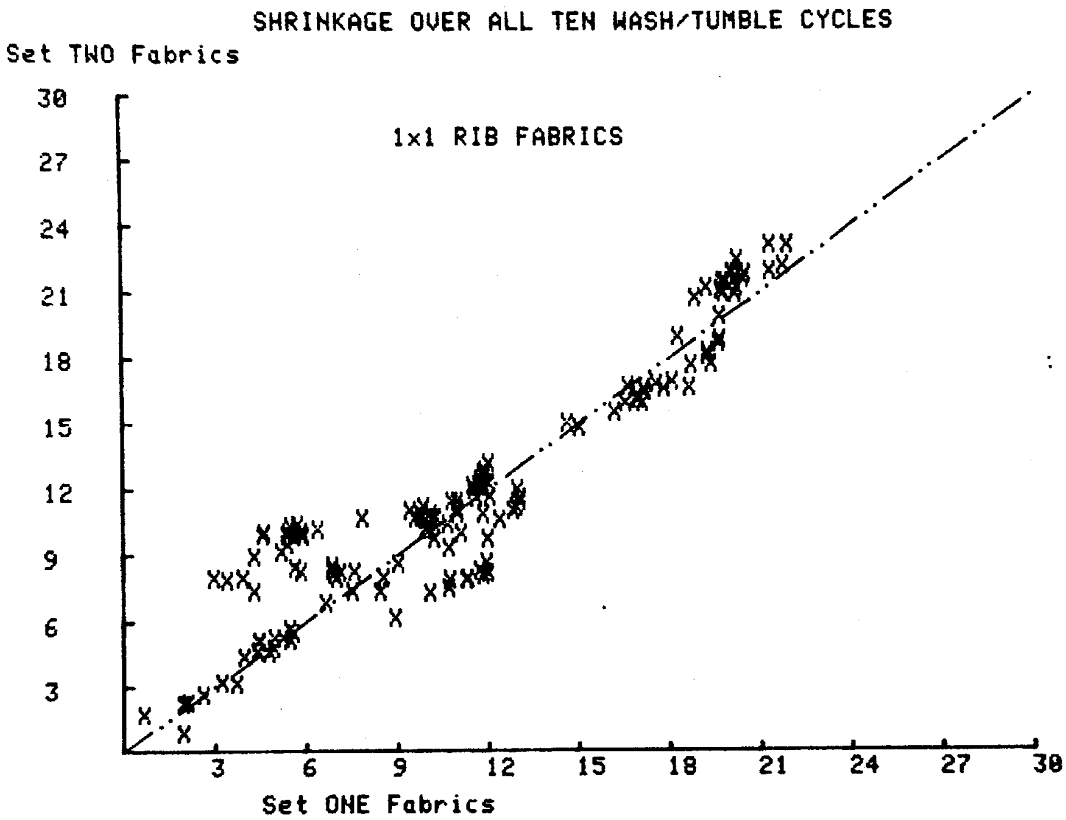


Figure 4

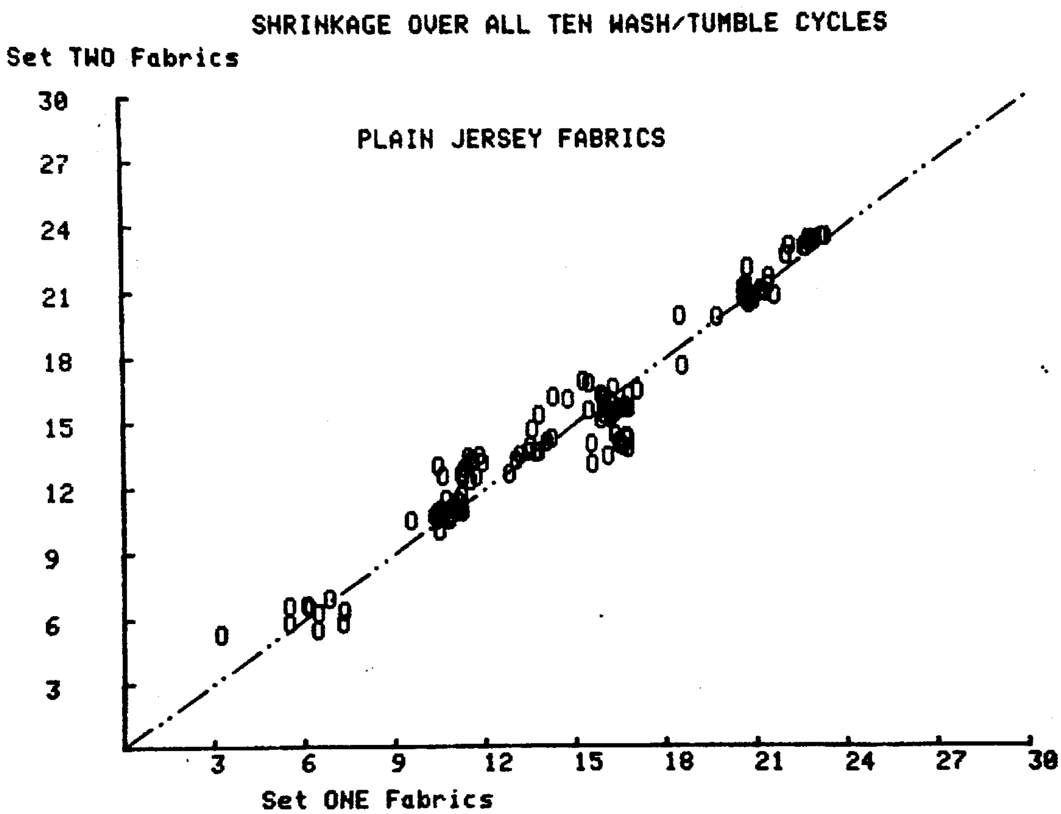
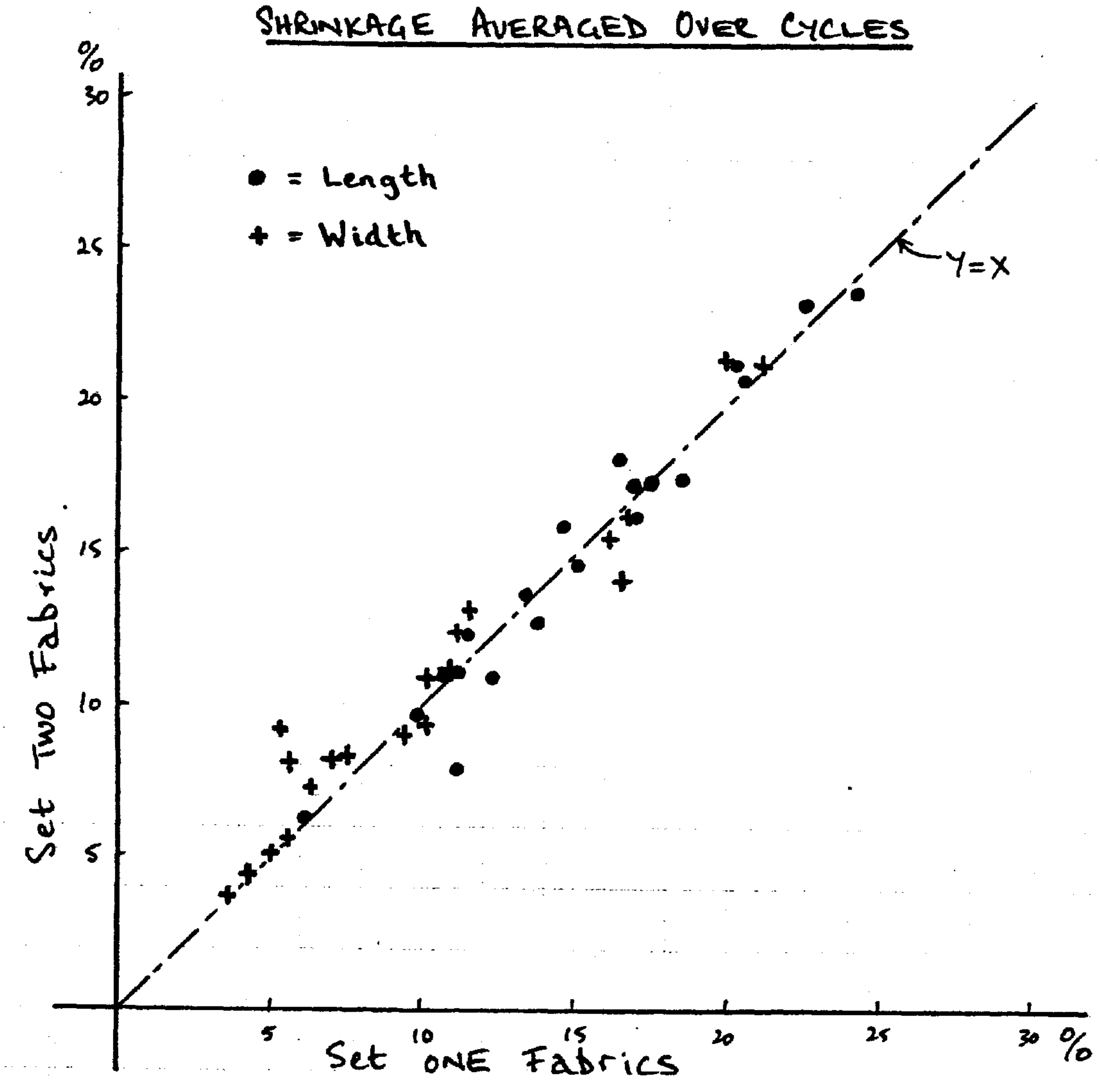
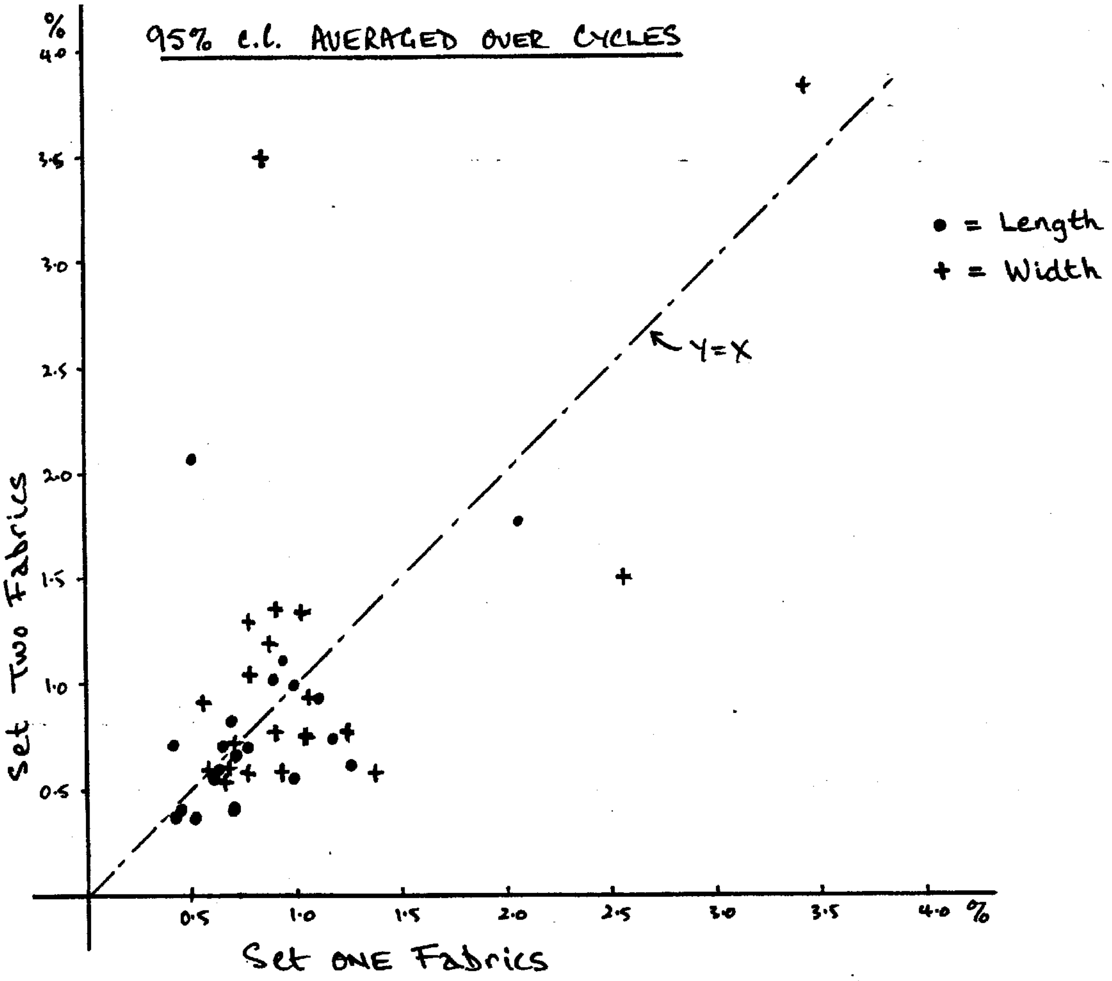


Figure 5



SHRINKAGE AVERAGED OVER CYCLES
%
30
25
20
15
10
5
● = Length
+ = Width
Y=X
Set TWO Fabrics
5
10
15
20
25
30 %
Set ONE Fabrics

Figure 6



95% c.l. AVERAGED OVER CYCLES
%
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
Set Two Fabrics
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
%
Set ONE Fabrics
Y=X
• = Length
+ = Width

Figure 7

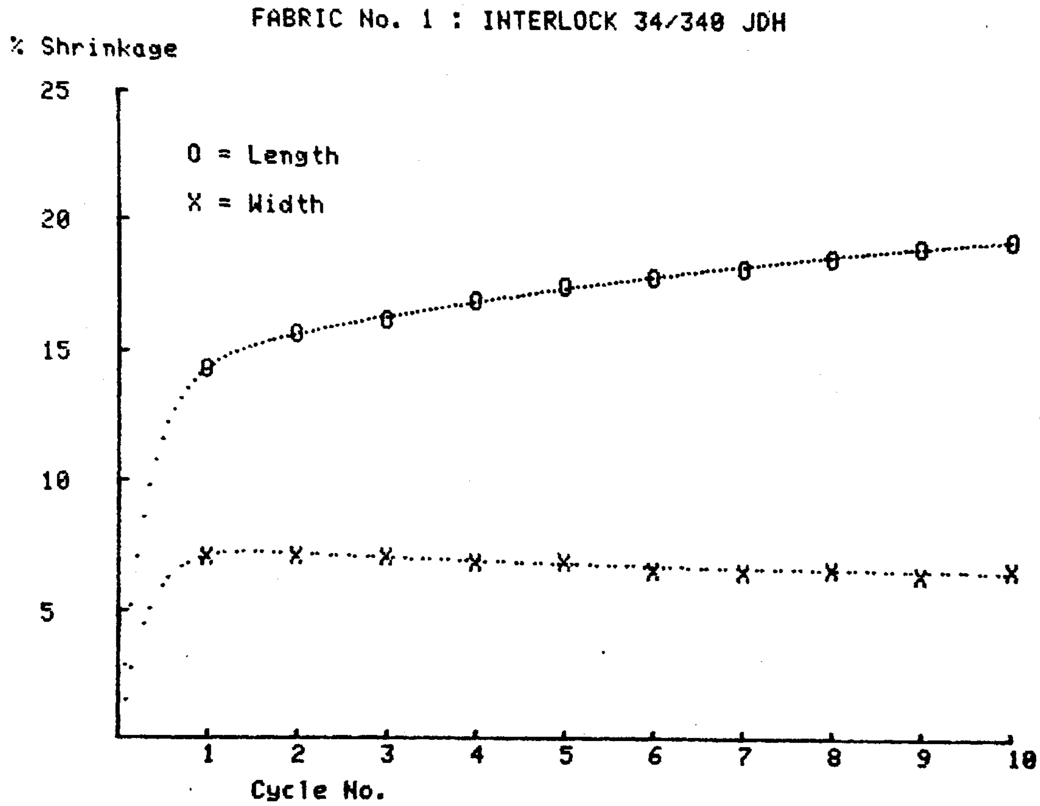
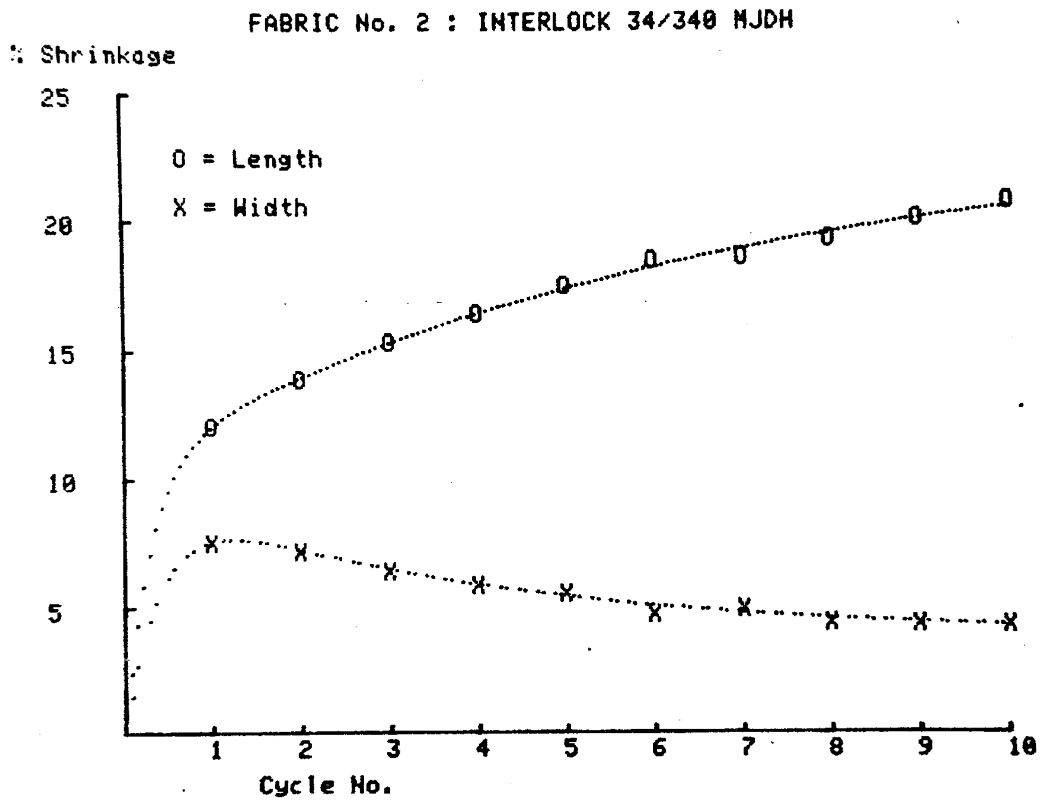


Figure 8



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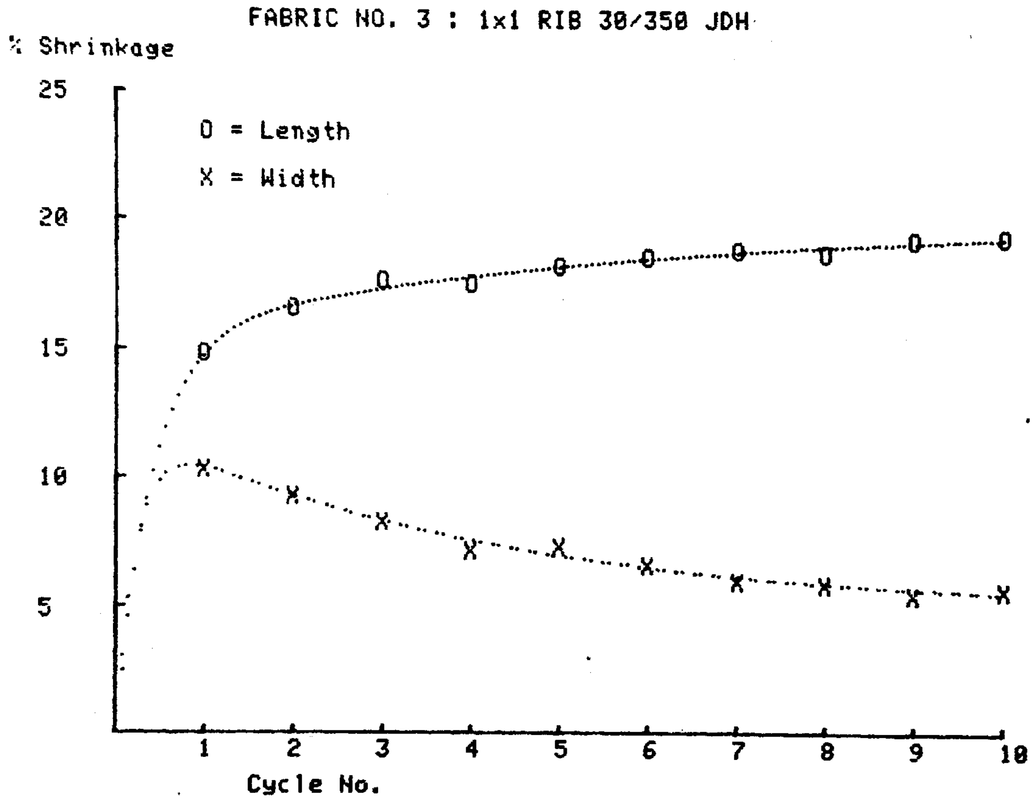

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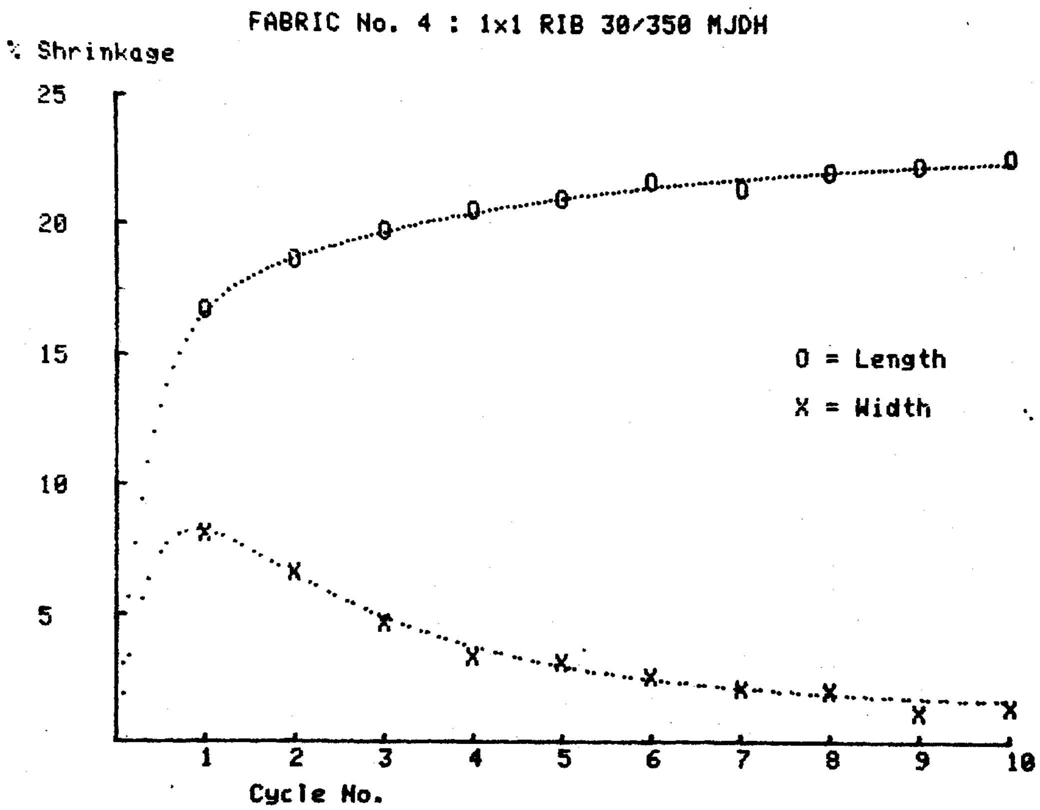

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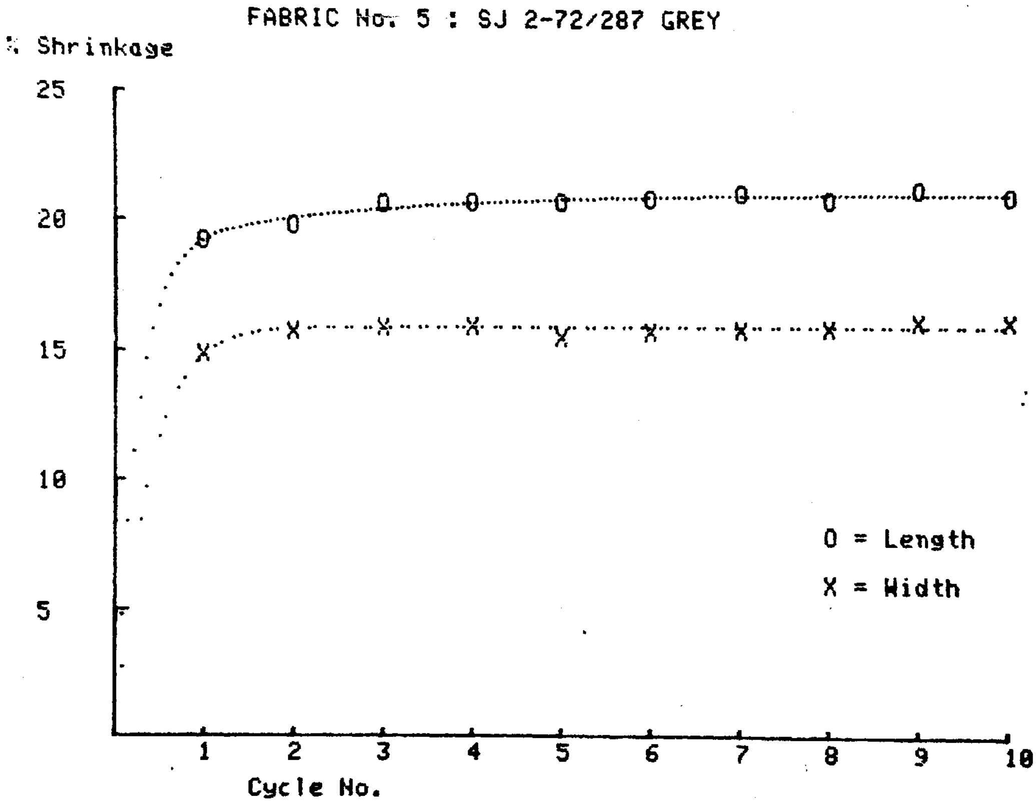

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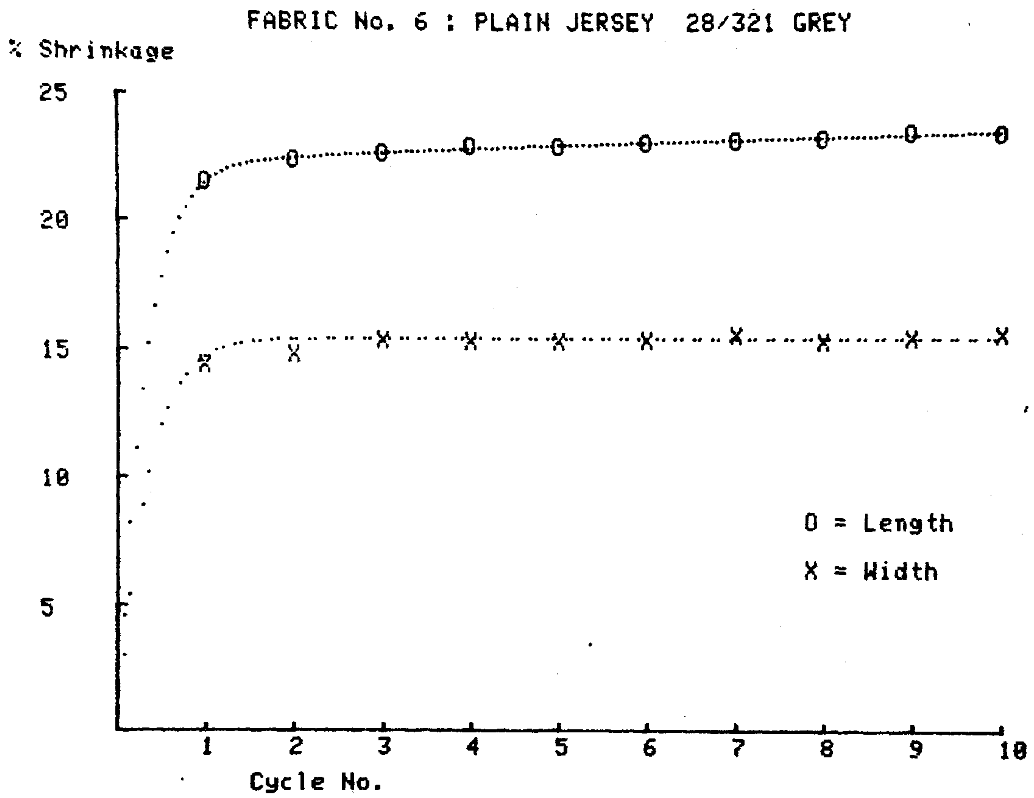


Figure 13

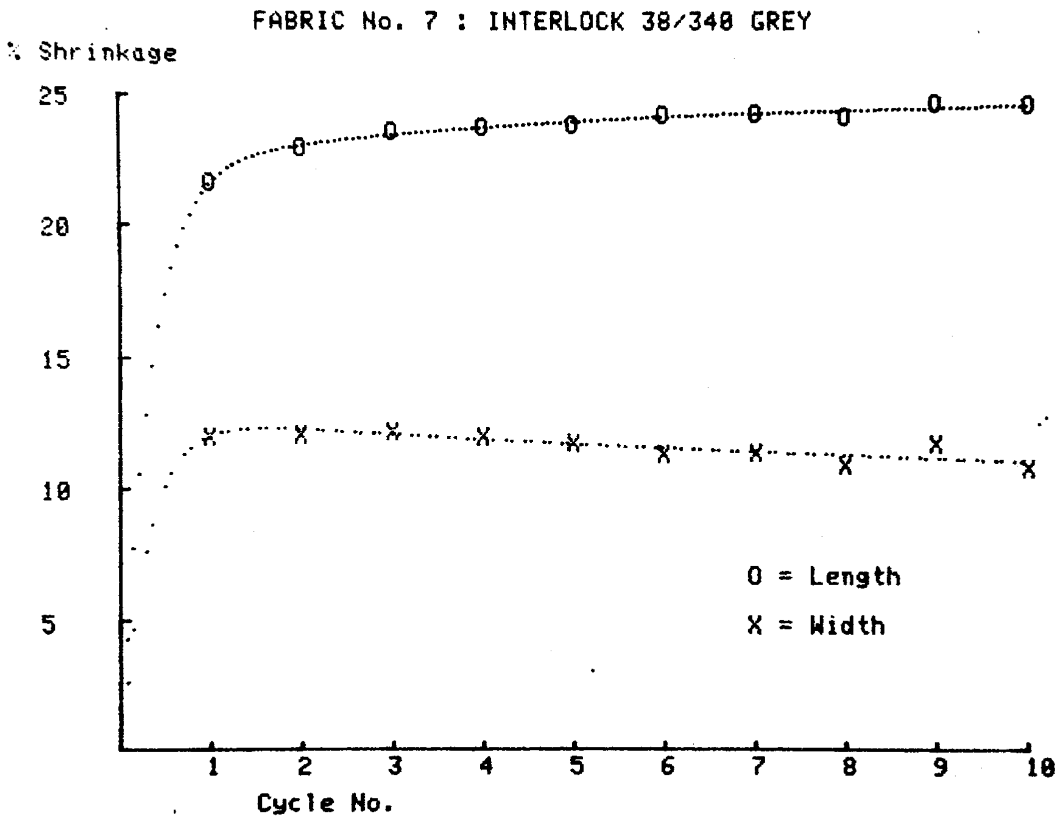


Figure 14

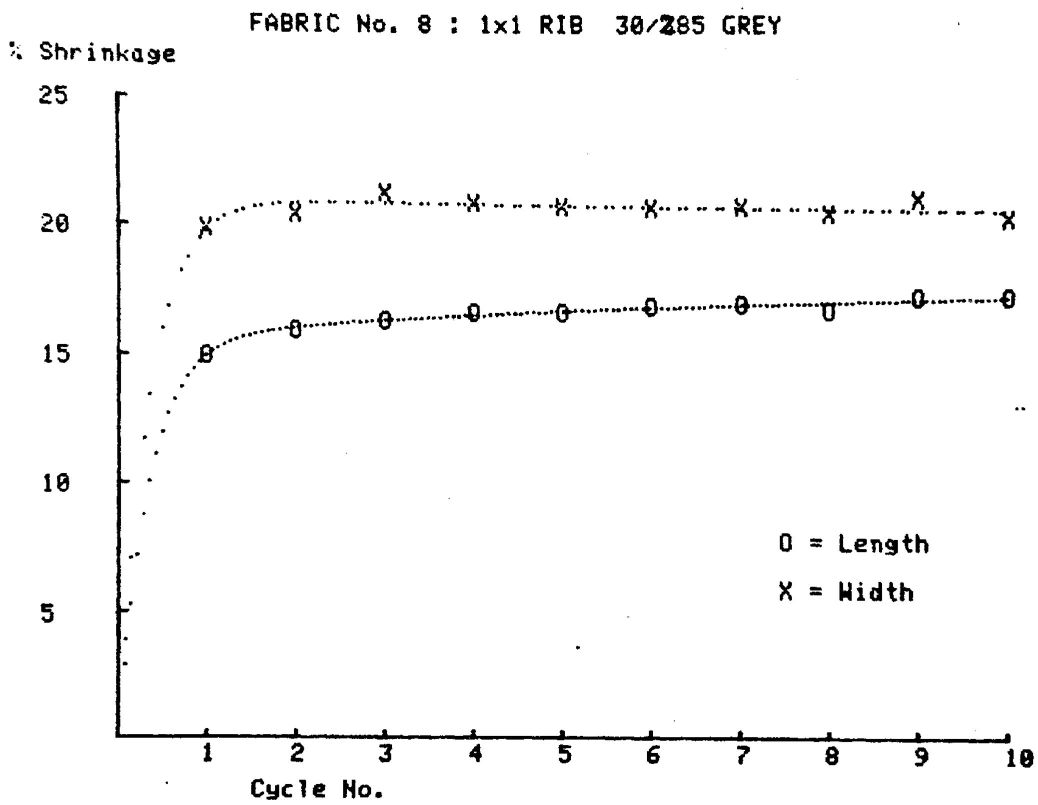
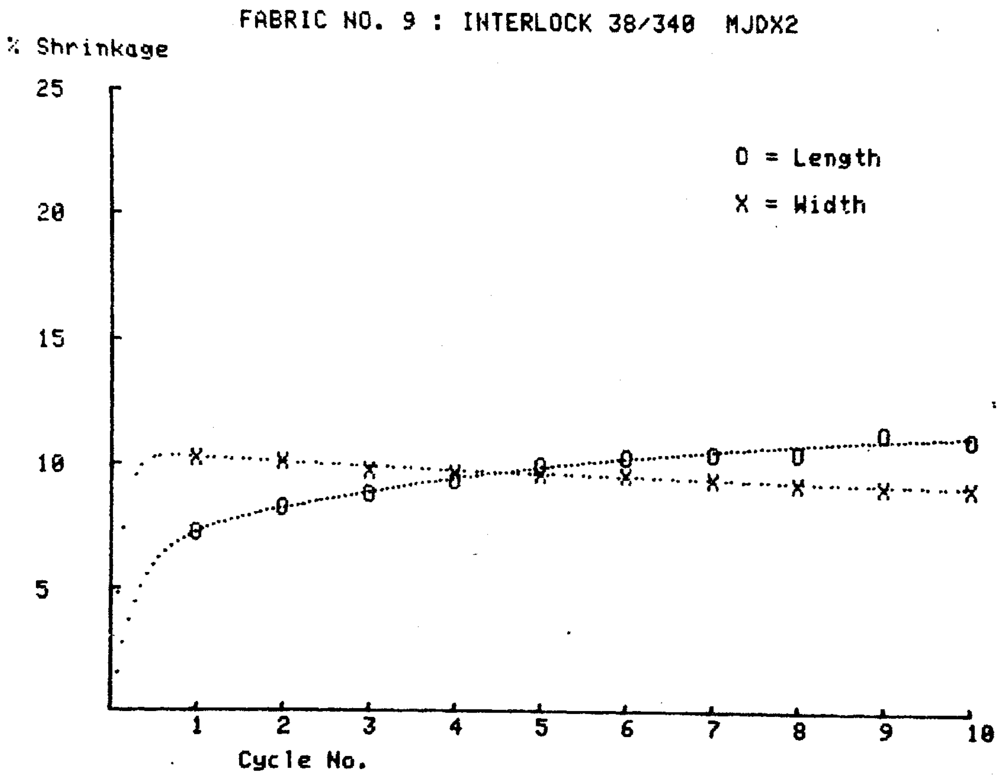


Figure 15



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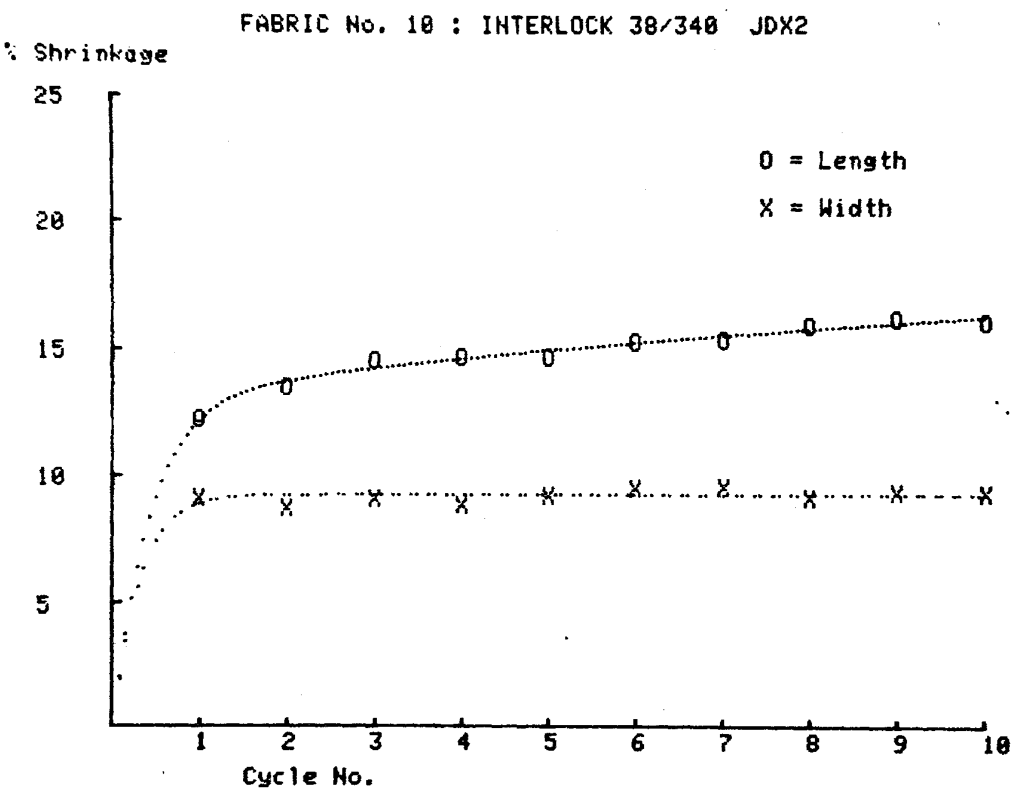

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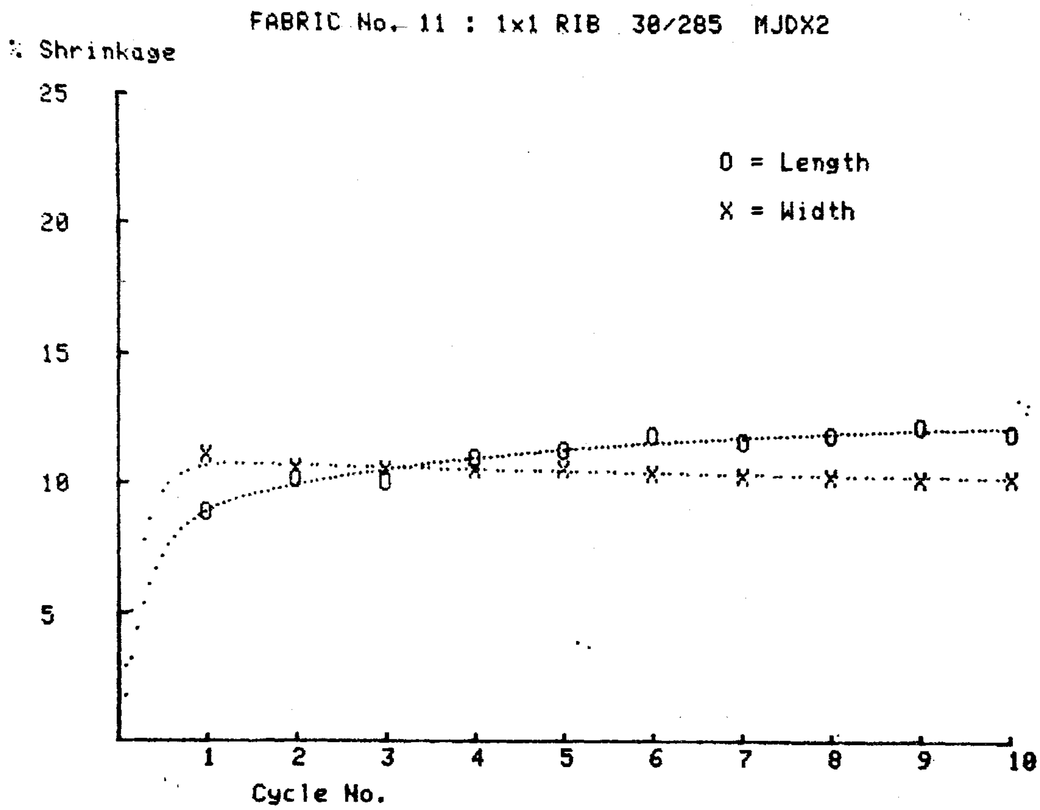

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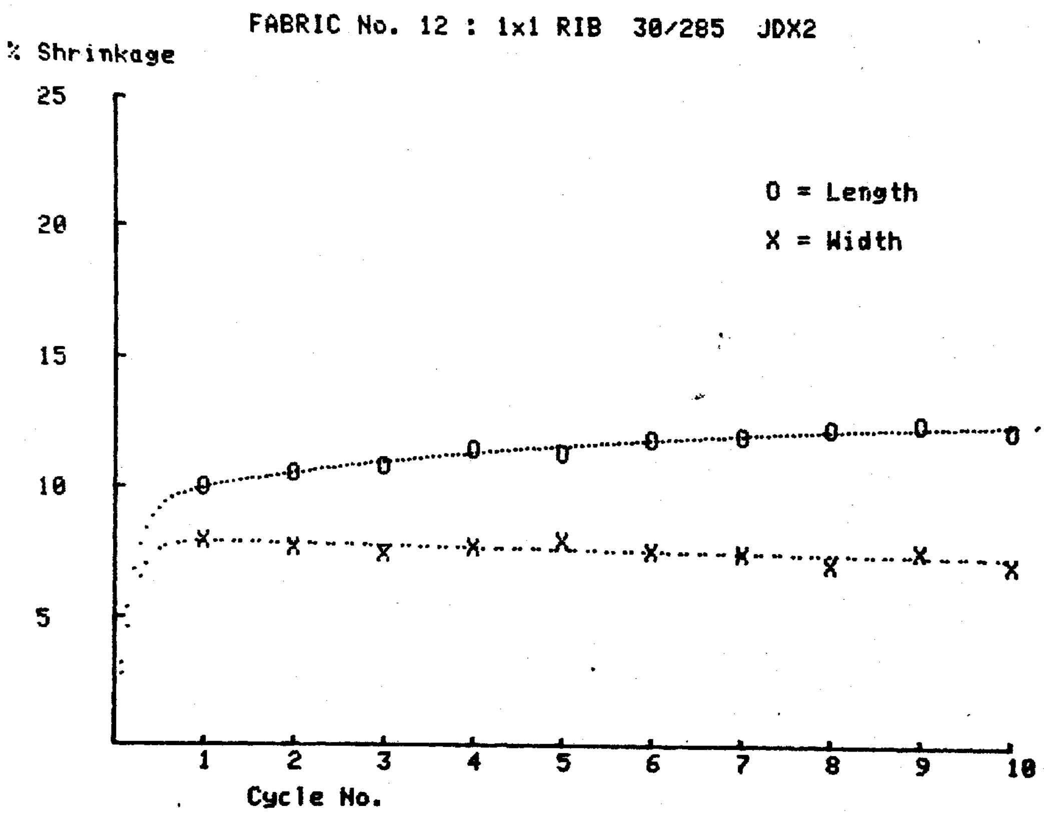

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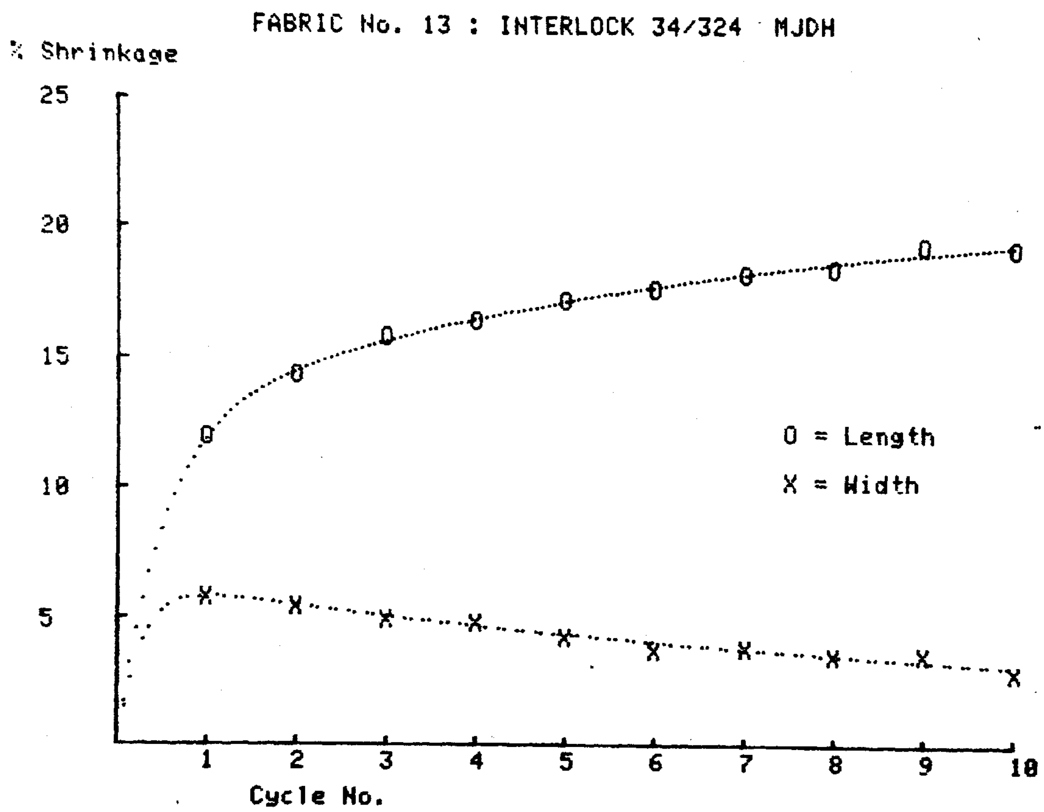
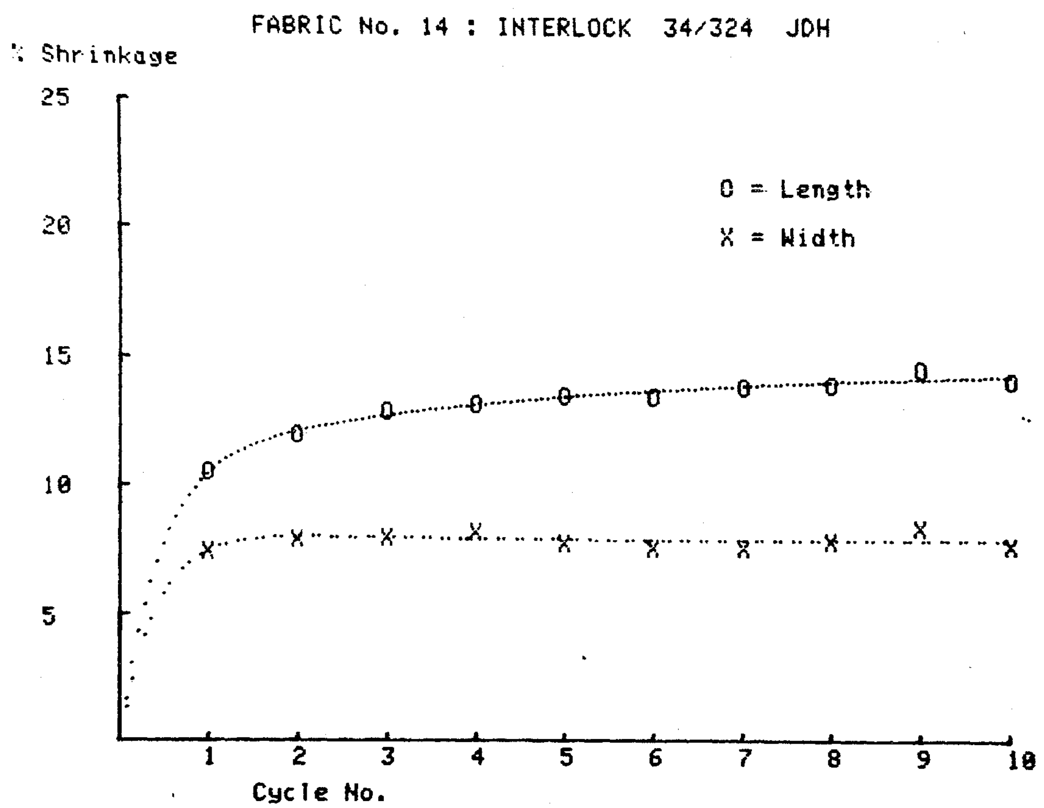


Figure 20



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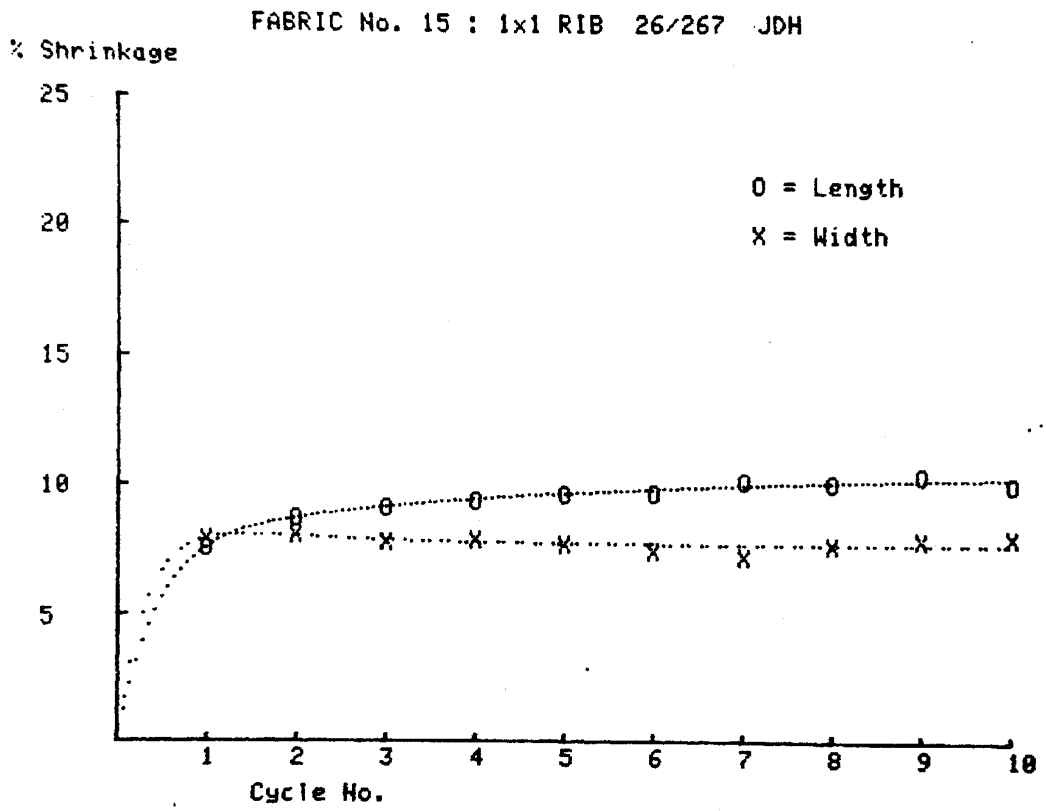

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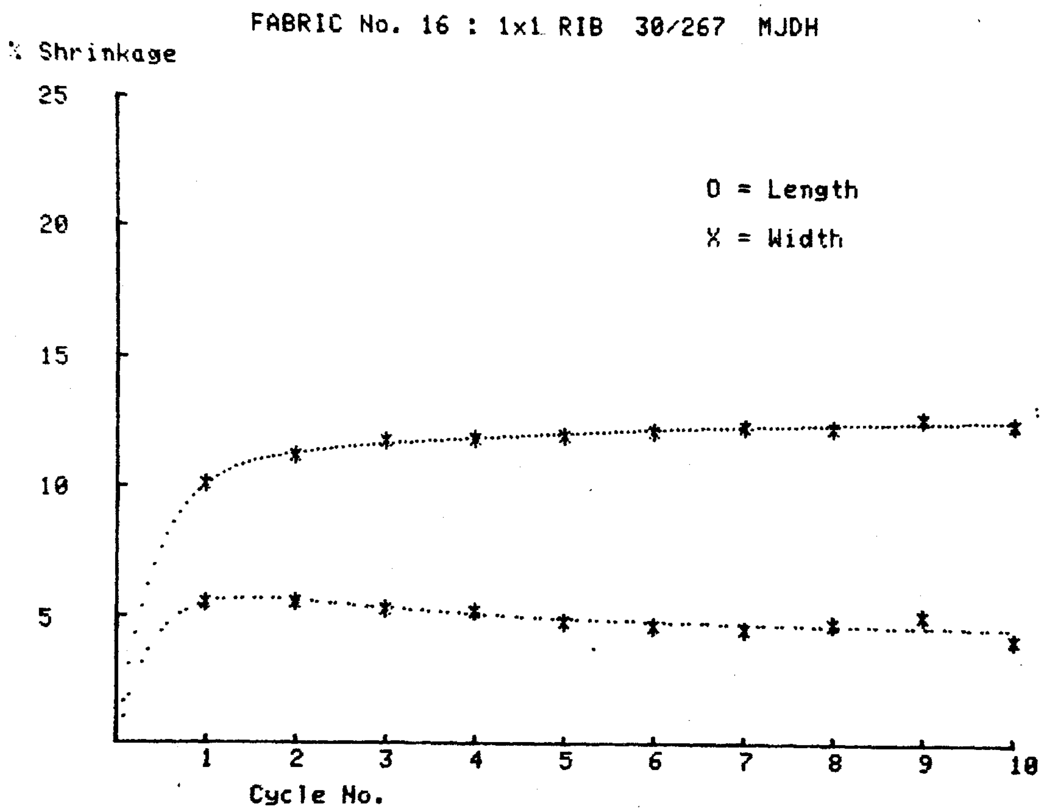

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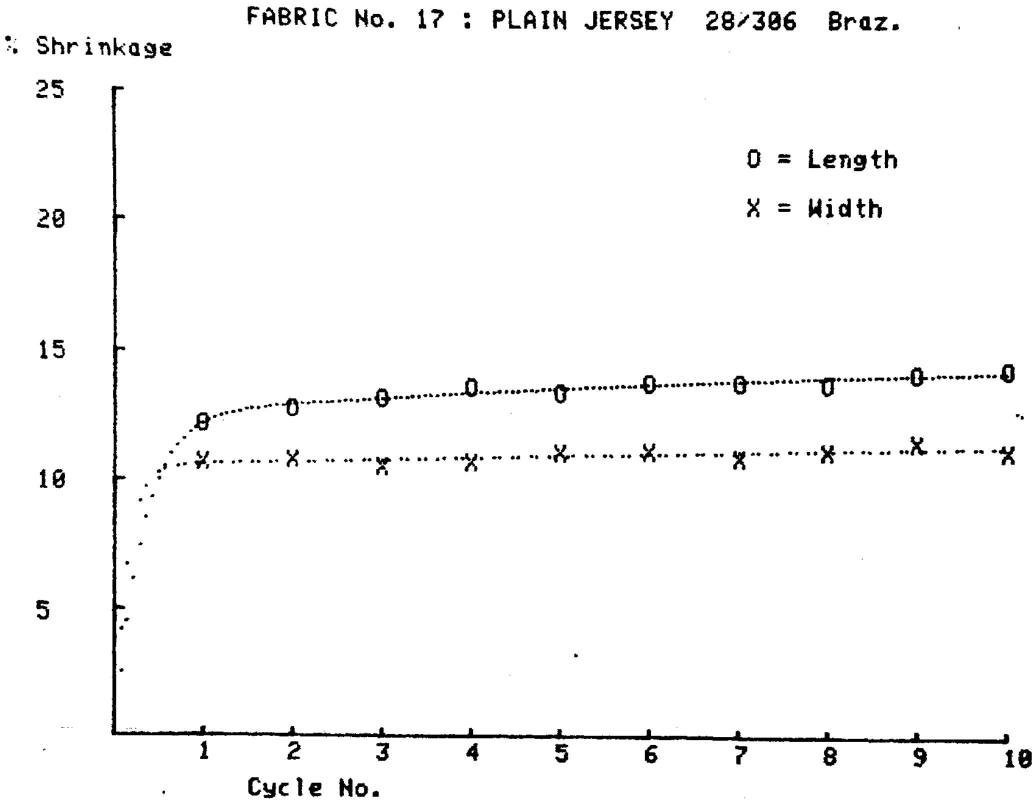

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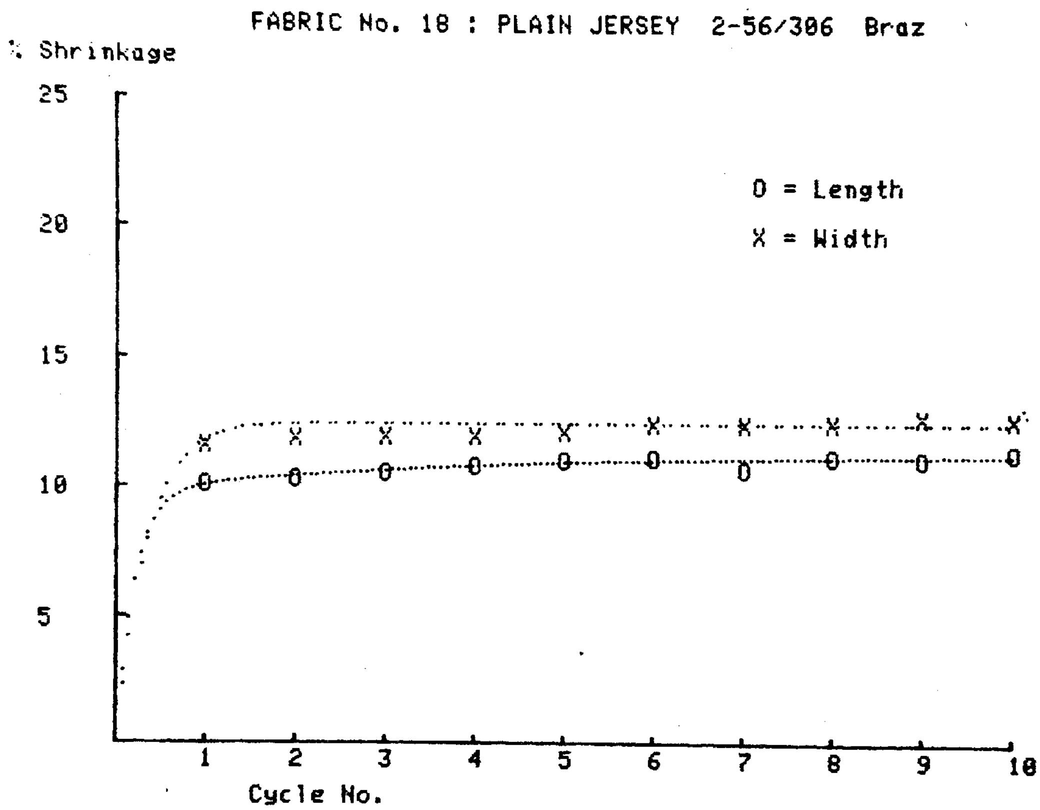

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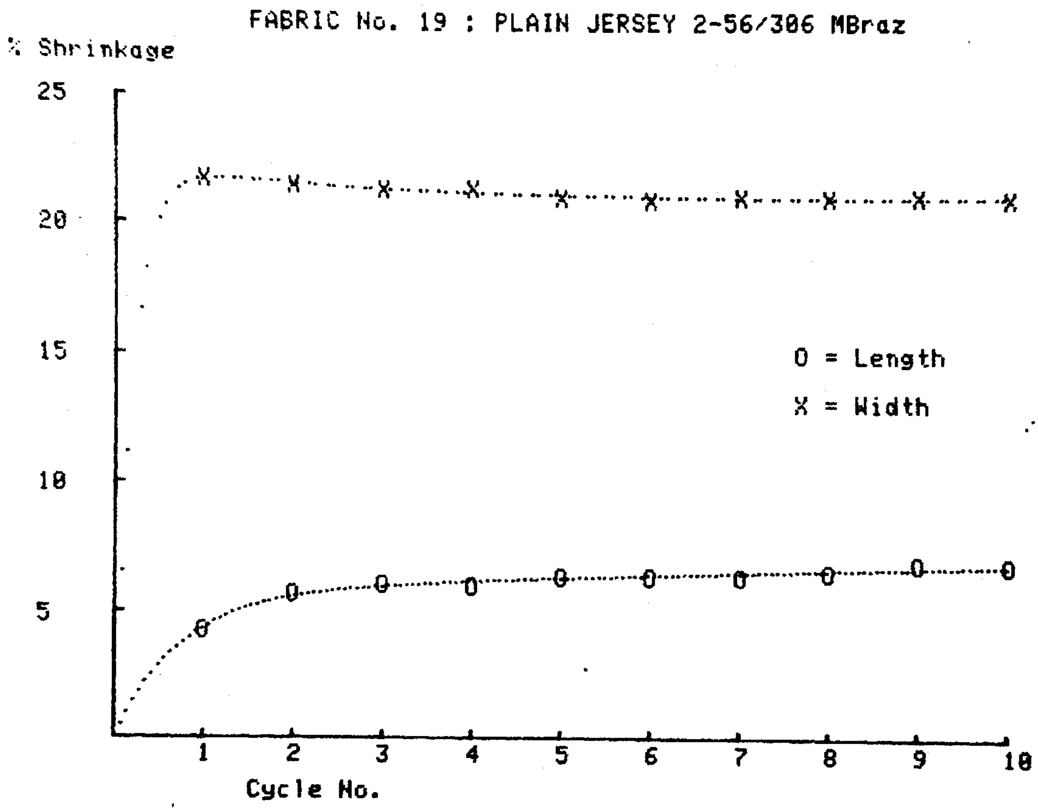

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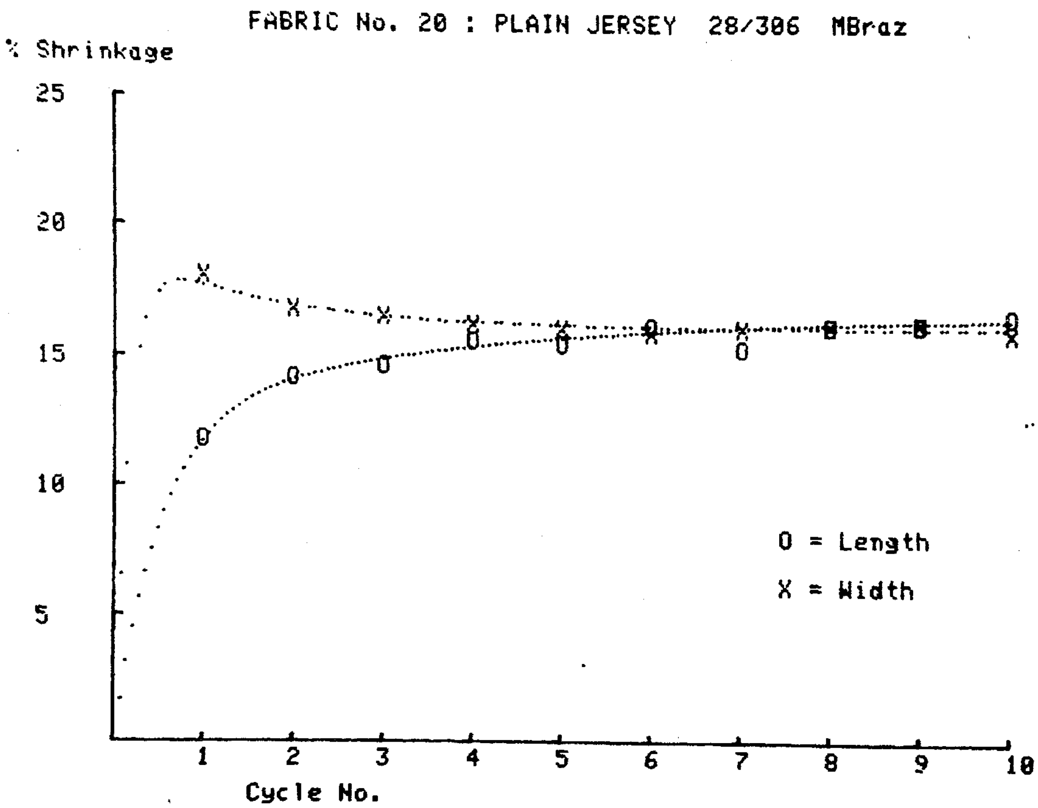

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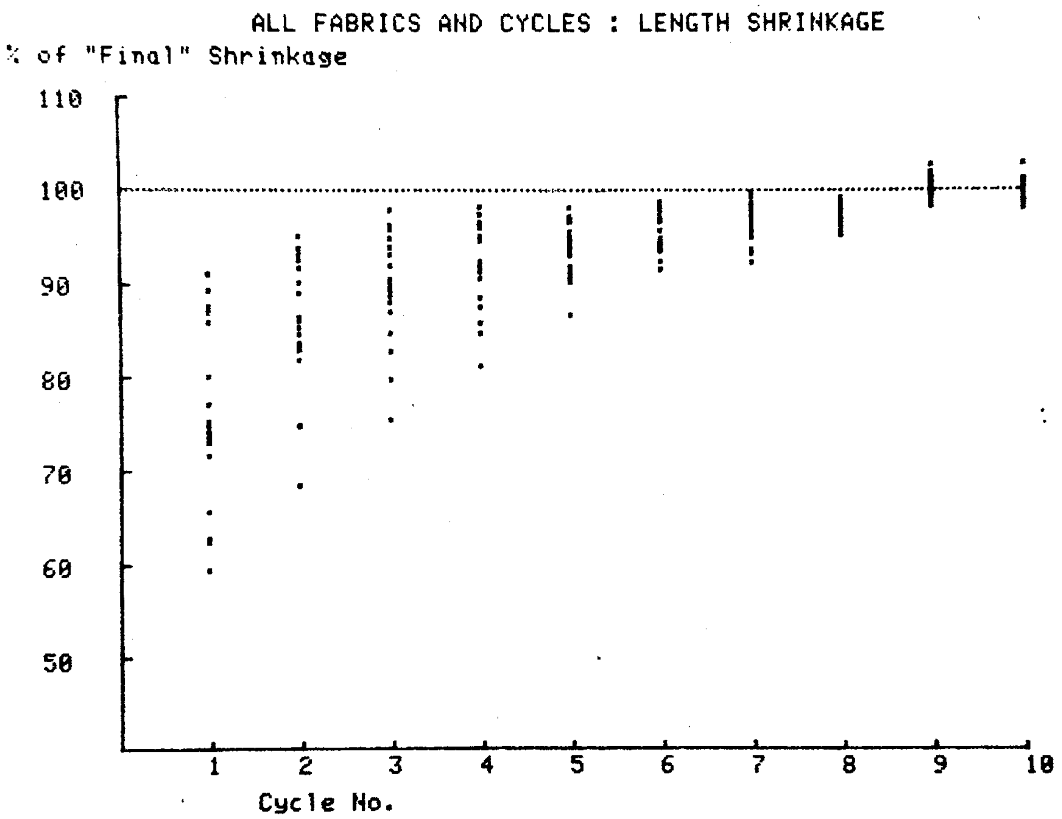

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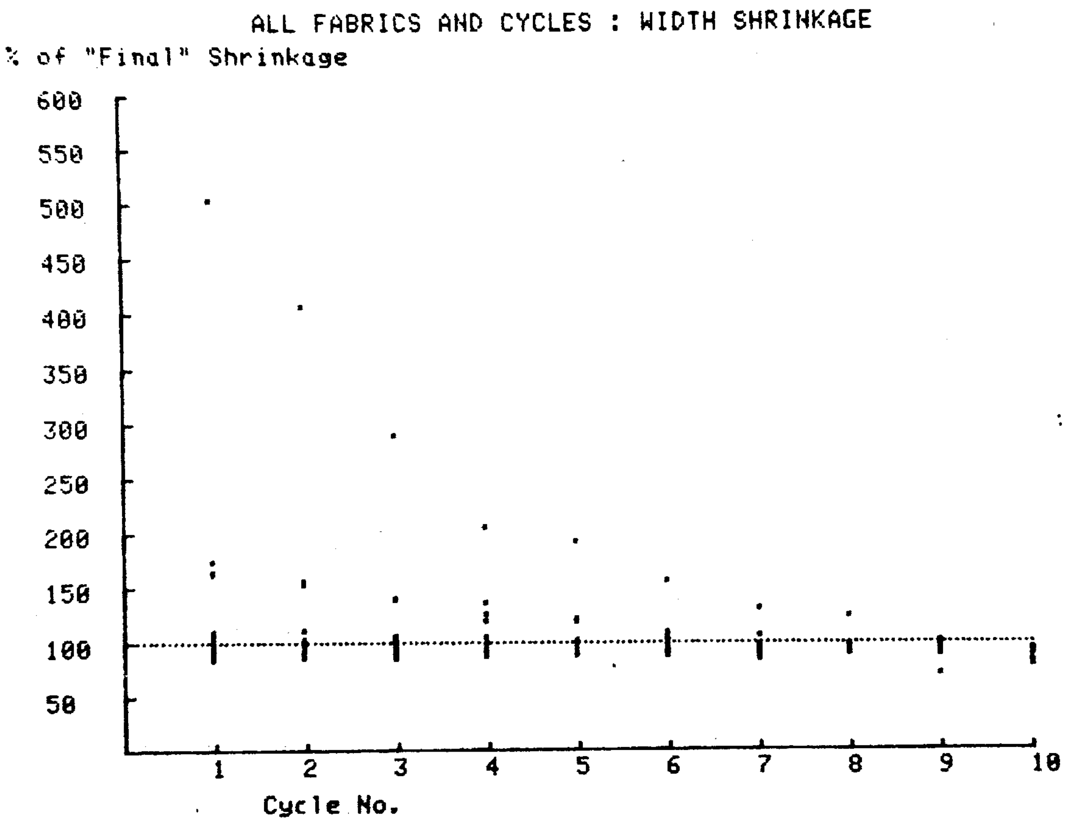

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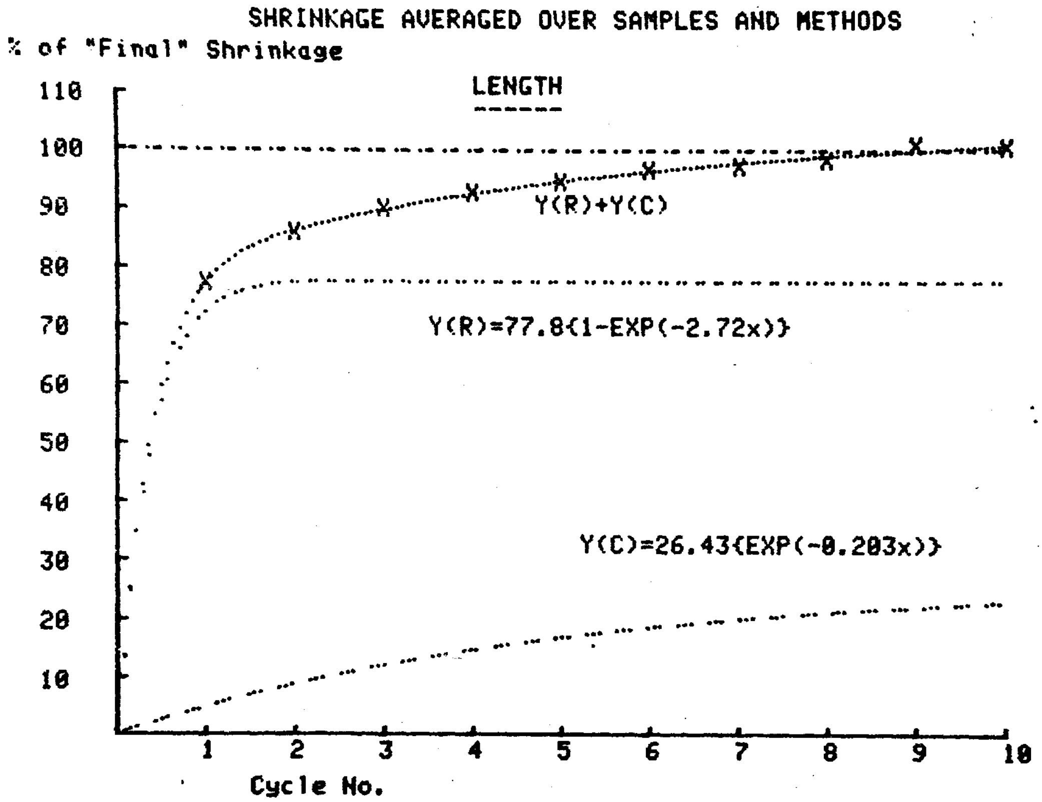

Figure 30