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DEVELOPMENT OF HIGH TENACITY-HEAT STABLE DACRON YARNS

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FOREWORD

This report was prepared by Fabric Research Laboratories, Inc., under USAF Contract Number AF 33(600)-24087. It is the second of two technical reports submitted under the subject contract, the first being WADC TR 55-135. This contract was initiated under Project Number 7320, "Air Force Textile Materials", Task Number 73201, "Textile Materials for Parachutes" and was administered under the direction of the Materials Laboratory, Directorate of Research, Wright Air Development Center, with Lt. Peter Y. Stanton acting as Project Engineer.

Acknowledgement is sincerely given to Messrs Myron J. Coplan, Ernest R. Kaswell, Henry M. Morgan and Dr. Milton M. Platt for their guidance and advice on this project.

Acknowledgement is also sincerely given to Miss Helen Rosolko, Miss Carol White and Miss Joan Crowe for their part in conducting the numerous laboratory experiments and in the evaluation of the results.

This report covers period of work from June 1954 to July 1955.

ABSTRACT

Dacron yarn, because of its superior resistance to thermal degradation when exposed to temperatures of 350-400°F. for prolonged periods, has been suggested as a replacement for nylon in deceleration parachutes. Dacron's strength retention after high temperature exposure is good, but a longitudinal shrinkage of the order of 20% takes place which presents problems of parachute component dimensional stability. Secondly, this 20% shrinkage is reflected in lower strength and energy to weight ratios, thus requiring proportionately heavier parachutes. Furthermore, the added elongation resulting from thermal shrinkage is composed primarily of secondary creep or permanent set. Upon deployment of the parachute the possibility exists that fabric components might deform at the time of stress application, but not recover upon stress removal unless and until the parachute or its components are again elevated to the 350°F level.

At the inception of this phase of the study there was available from The DuPont Company high tenacity (6.1 grams/denier), nominal rupture elongation (9.2%), high thermal shrinkage (20%) Dacron yarn. By free relaxation at an elevated temperature this yarn could be converted to medium tenacity (4.8 grams/denier), high elongation (36%), low shrinkage ($<$2%) yarn.

Preliminary experimentation showed that cyclical yarn stressing and relaxing processes at elevated temperatures would produce a yarn of the desired high tenacity, nominal rupture elongation and low shrinkage, provided that the yarn was allowed to relax completely after the last stressing cycle.

In an attempt to develop Dacron yarn of optimum properties, those factors which were found to have an influence on ultimate properties were thoroughly investigated. These included stretching temperatures, times, and amounts and sequences of stretching-relaxing systems.

The optimum process so far developed consists of three basic steps, namely:

1. 20% hot stretch at yarn temperatures of 340-390°F.
2. Fixed length at 430-450°F.
3. Free shrinkage at 350°F.

Yarn produced by such a process has a tenacity of 6.7-7.0 grams/denier, an elongation of 14-16% and a shrinkage of less than 2% at 350°F.

This process is an improvement over the multiple cycle methods originally studied. Furthermore, it is undoubtedly cheaper in terms of both equipment cost and production.

Concomitant with the research, a pilot processing machine was developed and some consideration was given to the commercial practicability of the process insofar as production speed was concerned.

It is recommended that this study be continued in order to further determine those factors which influence the development of an optimum yarn. Also, the ultimate design and construction of a commercial prototype machine is needed in order to produce yarn in sufficient quantities so that end items may be prepared and thoroughly evaluated.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

M. R. WHITMORE
Technical Director
Materials Laboratory
Directorate of Research

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I. INTRODUCTION:

As part of a program for the development of optimum deceleration parachutes, the Air Force is interested in the replacement of certain nylon end items with equivalent materials composed of Dacron. This is because the heat degradation resistance of nylon fails to meet Air Force temperature requirements. Nylon degrades severely when exposed to temperatures of 350°F. This degradation is measurable when the material, after such exposure, is returned to standard conditions before testing. In a previous Wright Air Development Center Study (AF 33(600)-22932) Coplan1/, has shown that Dacron exhibits relatively good heat resistance at 350°F for times up to 10 minutes, and only mild and apparently acceptable degradation when exposed for 24 hours.

In a previous technical report, Kaswell and Coplan2/ have discussed the development of heat stable Dacron ribbons, cloths, threads, braids, webbings and tapes. Pages 1 to 10 of that report show that while commercially produced Dacron exhibits high strength retention after prolonged heating, it shrinks significantly upon exposure to high temperatures. Table I shows the properties of Type 5500 normal tenacity, and Type 5100 high tenacity Dacron producer's yarns before and after exposure to temperatures of 350°F and 425°F for 10 minutes. It will be noted that the heat exposure causes shrinkages in the order of 20 to 25% with concomitant inincreases in denier and decreases in tenacity. Absolute strengths are reduced slightly. Furthermore, rupture elongations increase essentially proportionately to the percent shrinkage. Thus, rupture elongations are in the order of magnitude of 35 to 40% after heat stabilization via heat relaxation shrinkage. This may be compared with rupture elongations of about 20% in equivalent nylon items. Section III of Wright Air Development Center Technical Report 55-135 discusses in thorough detail, the relationships between heat shrinkage, rupture elongation and their effect on the repeated use of Dacron parachute materials2/.

At that time, it was recognized that high elongation-low shrinkage, or low elongation-high shrinkage Dacron yarn were alternates obtainable by conventional processing methods. Development of a high tenacity, nominal elongation, zero heat shrinkage Dacron yarn thus became the objective of this phase of the program. Such a yarn would most closely meet the current nylon end item specifications.

Preliminary experiments were conducted2/ wherein, via repeated stress procedures at high temperatures, a yarn of high tenacity, nominal elongation and very low shrinkage was obtained (Table II).

1/ Coplan, M. J., "A Study of the Effect of Temperature on Textile Materials". WADC Technical Report 53-21

2/ Kaswell, E. R. and Coplan, M. J., "Development of Dacron Parachute Materials". WADC Technical Report 55-135

TABLE I

Comparison of 250 Denier Type 5500 and 220 Denier Type 5100 Dacron Producer's Yarn

	250 Denier Type 5500 Regular Tenacity	220 Denier Type 5100 High Tenacity
Original Properties		
Breaking Strength (lbs.)	2.4	2.9
Denier	255	214
Tenacity (g.p.d.)	4.3	6.2
Elongation (%)	12.8	10.8
Shrinkage at 350°F. - 10 min. (%)	22.4	20.4
Shrinkage at 425°F. - 10 min. (%)	25.0	23.5
Properties After Exposure at 350°F. for 10 min.		
Breaking Strength (lbs.)	2.4	2.7
Denier	327	272
Tenacity (g.p.d.)	3.3	4.6
Elongation (%)	46.4	39.1
Shrinkage at 350°F. - 10 min. (%)	0	0
Properties After Exposure at 425°F. for 10 min.		
Breaking Strength (lbs.)	2.5	2.7
Denier	336	287
Tenacity (g.p.d.)	3.4	4.3
Elongation (%)	50.2	44.4
Shrinkage at 350°F. - 10 min. (%)	0	0

TABLE II

Properties of High Tenacity-Heat Stable Type 5500 Dacron Yarn

	Original	After Treatment at 350°F. (Experiment #1)	After Treatment at 350°F. (Experiment #2)
Strength, lbs. at 70°F., 65% R.H.	2.4	3.1	2.7
Denier	255	239	240
Tenacity, g.p.d.	4.3	5.8	5.2
Elongation, %	12.8	20.7	19.0
Shrinkage, % after 10 min. at 350°F.	22.4	0.6	----

At this point the program was expanded to permit concentrated effort in the development of such a heat stable high tenacity yarn. This report discusses in detail the theory, experimental procedures and results appertaining to this development.

II. OUTLINE OF RESEARCH PROGRAM:

At the outset, the project was classified into four separate but chronological phases, briefly reviewed as follows:

2.1 Literature Survey

Information on the art of hot stretching and relaxing thermoplastic yarns may be found in various technical journals and the patent literature. The object of this phase of the program was to assimilate and coordinate as much of this information as possible in order to provide sufficient background for proper execution of the program. A study of the mechanical as well as the physico-chemical aspects of the program was conducted for possible utilization in the latter phases of the research, namely, the design of a pilot yarn processing unit.

2.2 Establishment of Yarn Processing Conditions

Excluding speed of operation, three variables were thoroughly investigated relative to the development of an optimum yarn, viz:

Processing Temperatures
Amount of Stretch
Sequences of Stretching and Relaxation

Each of these factors, as well as their interaction, was thoroughly studied in order to arrive at optimum process conditions. Original work was confined to the treatment of discreet lengths of yarn (e.g., 6 inches in length).

2.3 Development of a Continuous Yarn Processing Method

Having established the operating conditions on a non-continuous basis it then became necessary to make the process a continuous one. Untreated, Dacron producer's yarn was introduced at the start of the operation and the high strength-heat stable yarn delivered after passing through the various stages of the process. The speed of operation or rate of production of finished yarn was not considered during this phase, the main objective being continuity.

2.4 Construction and Operation of Pilot Unit

Having arrived at a given set of hot stretching-heat relaxing conditions, a commercial prototype machine was constructed which embodied all of the processing principles established during the research and development phases. It is felt that the Yarn Processing machine so constructed, is fully adaptable to full scale production.

III. DISCUSSION OF RESULTS:

3.1 Literature Survey

The hot stretching of polymeric Dacron and like filamentous materials is discussed chiefly in United States Patent Numbers 2,578,889; 2,556,295; 2,604,689; 2,604,667; 2,541,149; all of which are issued to E. I. duPont deNemours & Company. The basic theory is well known. Briefly, there are considered to be two structural changes involved in the hot stretching operation. The first is orientation of the long chain molecules, and the second is crystallization of the molecules into favorable positions. From the general review of published information, it was felt that the stretching process should be performed in such a way as to utilize both the orientation and crystallization steps. A study of both phases was conducted. The literature survey, while not producing any one definite operational technique, did provide a certain amount of background information which aided considerably in the latter phases of the program.

3.2 Establishment of Yarn Processing Conditions

At the commencement of this program, 220 denier, Type 5100, high tenacity Dacron was unavailable. Therefore, the decision was made to investigate 250 denier, Type 5500, medium tenacity Dacron fully, since this yarn was in commercial production at the time. Part way through the program, however, it was learned that Type 5100 was again available and therefore more time was devoted to its study in the latter phases of the program. In general, it has been found that almost all of the information gained using Type 5500 can be applied equally well to Type 5100.

Figure 1 shows tenacity-elongation curves for Types 5100 and 5500 Dacron when tested at standard conditions of 70°F., and 65% R.H. Figure 2 illustrates the same behavior of the yarns at 350°F.

3.2.1 Initial Stretching - Stabilizing Experiments

Changes in the ultimate breaking strength of Type 5500 Dacron yarn were initially effected in a group of preliminary experiments using a standard laboratory oven which could be thermostatically controlled at various temperatures. Two skeins of yarn were placed in the oven at a given temperature. One group was allowed to "freely shrink" (F.S.), while the other was held at its "original length" (O.L.) during exposure. Combinations of the two techniques were also employed. Both exposure temperature and exposure time were varied. Results are shown in Table III.

The results of Table III show that strength improvements can be obtained by merely holding a yarn at fixed length at temperatures of 350°-425°F. for various lengths of time. This is essentially, however, an application of stretch since the yarn has a potential shrinkage of approximately 22%

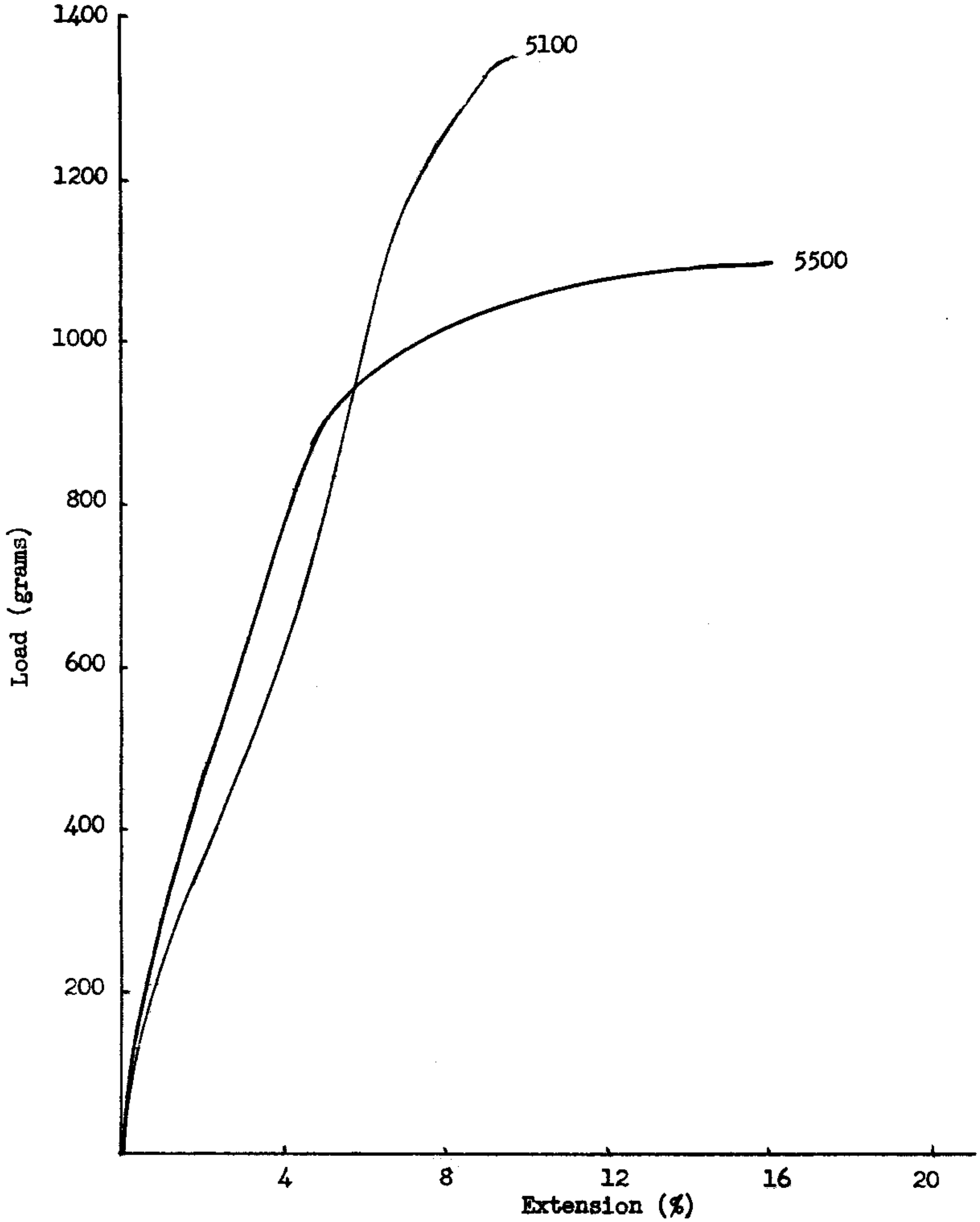

Figure 1. Load-Extension Curves for 250 denier, Type 5500 Dacron and 220 denier, Type 5100 Dacron at 70°F. and 65% R.H.

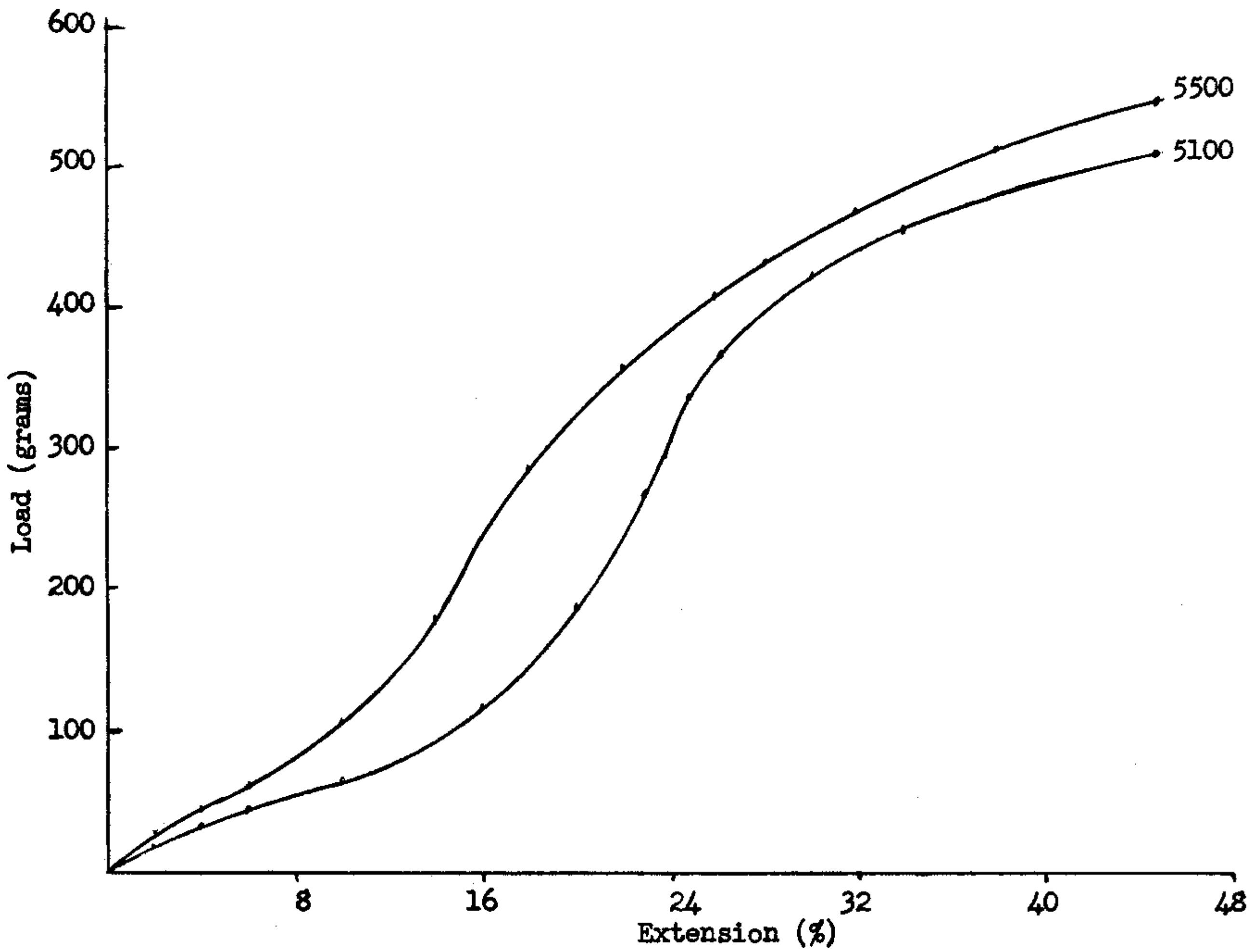

Figure 2. Load-Extension Curves for 250 denier, Type 5500 Dacron and 220 denier, Type 5100 Dacron Yarns at 350°F.

TABLE III

Effect of Exposure Time on Breaking Strength of 250 Denier, Type 5500 Dacron Yarn Held at Original Length and/or Freely Shrunk at Various Temperatures

Exposure Conditions	Breaking Strength (Grams) at 70°F., 65% R.H. Five Minutes	Ten Minutes	Twenty Minutes
Control - No Exposure	1120		
O.L. at 350°F.	1255	1233	1244
O.L. at 375°F.	1280	1292	1312
O.L. at 400°F.	1233	1317	1280
O.L. at 425°F.	1303	1280	1275
F.S. at 350°F.	1180	1107	1188
F.S. at 375°F.	1133	1135	1148
F.S. at 400°F.	1143	1100	1105
F.S. at 425°F.	1047	1030	925
O.L. at 375°F. - Cooled to Room Temperature, then F.S. at 350°F.	1280	1265	1313
O.L. at 400°F. - Cooled to Room Temperature, then F.S. at 350°F.	1213	1310	1312
O.L. at 425°F. - Cooled to Room Temperature, then F.S. at 350°F.	1323	1272	1240

F.S. = Free Shrinkage
O.L. = Original Length

Note: All tests were made on an Instron Tensile Tester of 2000 grams full scale capacity, jaw speed one inch per minute.

at these temperatures and therefore a load must be applied to maintain the original yarn length and thus prevent shrinkage. A further indication of the advantages of this type of treatment may be found in Table IV. It can be seen that the length change of yarns given some form of stretching (holding at original length) before free shrinking is much less than those which are allowed to shrink freely at any given temperature.

It can be seen therefore from Tables III and IV that controlled heating and relaxing techniques can provide an improved, heat stable, Type 5500 Dacron yarn. Of particular note is the last item of Table IV which pertains to a yarn simply held at fixed length at 425°F. This exhibits a slight increase in length if subsequently exposed unrestrained at 350°F. This increase results in a lowering of the yarn denier which, in turn, results in a still greater tenacity (grams/denier) as compared with the freely shrunk samples. Furthermore, both the "freely shrunk" and "original length" yarns are stabilized to the 350°F. temperature. In other words, a higher strength thermally stable yarn can be obtained by a procedure as outlined in the last item of Table IV.

3.2.2 Detailed Study of "Original Length" Step

A more thorough investigation of the effect of holding at "original length" on a Type 5500 hot stretched yarn has been made. Here the time as well as the temperature of treatment was varied. The object was to define further the "original length" condition when the initial hot stretch and the subsequent free shrinking conditions were held constant. Results are shown in Table V.

The data as shown in Table V are somewhat variable. In general, it seems that "original length" temperature of 435-455°F. is required to produce a higher strength Type 5500 Dacron yarn. However, the differences found in yarn strength over the entire time-temperature range studied are not considered to be too significant. The variability in strength of the producer's yarn as received from the duPont Company is of the same order as the overall spread in the test results. In fact, the rupture tenacity, which is the breaking strength on a unit weight basis, of all of the above yarn samples lies between 5.9 and 6.1 grams per denier.

3.2.3 Initial Study of Stretching-Stabilizing Variables

After having acquired a certain amount of background information on the principles involved in hot stretching, it was possible to set up a detailed series of experiments designed to provide information concerning the three major stretching variables, namely:

a. Processing Temperatures
b. Amount of Stretch
c. Sequences of Stretching and Relaxation

TABLE IV

Percent Length Change of 250 Denier, Type 5500 Dacron During Exposure to Various Temperatures and by Various Means for Five Minutes

Treatment	Percent Change in Length During Treatment
O.L. at 350°F.	Nil
O.L. at 375°F.	Nil
O.L. at 400°F.	Nil
O.L. at 425°F.	Nil
F.S. at 350°F.	-17.6
F.S. at 375°F.	-19.9
F.S. at 400°F.	-24.2
F.S. at 425°F.	-22.3
O.L. at 375°F. - Cooled to Room Temperature F.S. at 350°F.	-11.6
O.L. at 400°F. - Cooled to Room Temperature F.S. at 350°F.	-7.8
O.L. at 425°F. - Cooled to Room Temperature F.S. at 350°F.	+1.2[a]

[a] Plus sign indicates sample growth.

TABLE V

Effect of "Original Length" Time and Temperature on Tensile Strength of Hot-Stretched, Type 5500 Dacron Yarn. Samples were then Freely Shrunk at 350°F. for Five Minutes

Temperature (°F.)	Breaking Strength (grams) at 70°F., 65% R.H. "Fixed Length" Time (Minutes)					
	5	4	3	2	1	1/2
H.S. Control Yarn	1441	-	-	-	-	-
405	1383	1407	1410	1392	1420	1380
415	1388	1405	1416	1370	1392	1407
425	1386	1389	1391	1388	1364	1380
435	1418	1407	1438	1441	1460	1411
445	1432	1437	1418	1434	1419	1426
455	1452	1403	1391	1422	1410	1406

These experiments were conducted on a non-continuous or "batch" process in a large heated air chamber. The size of the unit was such that it could be used in conjunction with an Instron Tensile Tester. The heating and recording controls associated with the chamber enabled temperatures up to 430°F. to be employed and maintained to within ± 1°F. Two hooks, the upper fastened to the load cell and the lower to the cross head of the Instron, were designed so that continuous lengths of yarn in skein form could be treated under pre-determined conditions. The skein was inserted into the chamber and allowed to shrink freely before each test in order to facilitate the operation. The subsequently applied stretch, therefore, includes that portion required to remove the originally obtained 22% shrinkage. If 22% is subtracted from each applied stretch, the true stretch on the non-shrunk yarn is essentially attained.

The three variables noted above were investigated and their effects on the tensile strength of Type 5500 Dacron yarn are shown in Figure 3. The time for each test was considerably longer than would normally be required for merely heating the yarn, each test consuming about five minutes of operating time. Nevertheless, a great deal of information was gained from this study. Considering each variable separately and then as part of the complete study, it can be seen that:

a. The breaking strength of the hot stretched-heat relaxed yarn varies inversely with the stretching-relaxing temperature. It will be shown later that of the two, relaxing temperature is the more critical. The amount of allowable stretch at the different temperatures increases with temperature. If, however, a selected stretch level common to several temperatures, (say 38% based on pre-shrunk length) is considered, it can be seen that as the temperature of the stretching-relaxing operation is decreased, yarn tensile strength increases.

b. The higher the amount of stretch imparted in the normal working range of up to 390°F., the higher the strength of the yarn produced.

c. Multiple stretch-relax cycling appears to be of some slight advantage in obtaining maximum strength yarn, perhaps because it minimizes filament damage. It is possible to produce a somewhat improved yarn at a lower initial degree of stretch by using the multi-cycling technique rather than by using only one cycle of stretching of larger magnitude and then relaxing.

In general, therefore, the data assembled during this non-continuous operational phase of the program indicate that a high degree of stretch, preferably for several cycles with some relaxation time between each cycle, can produce a high tenacity-thermally stable Dacron yarn. Stretching temperatures of 300-340°F. are required for efficient operation if the stretching and

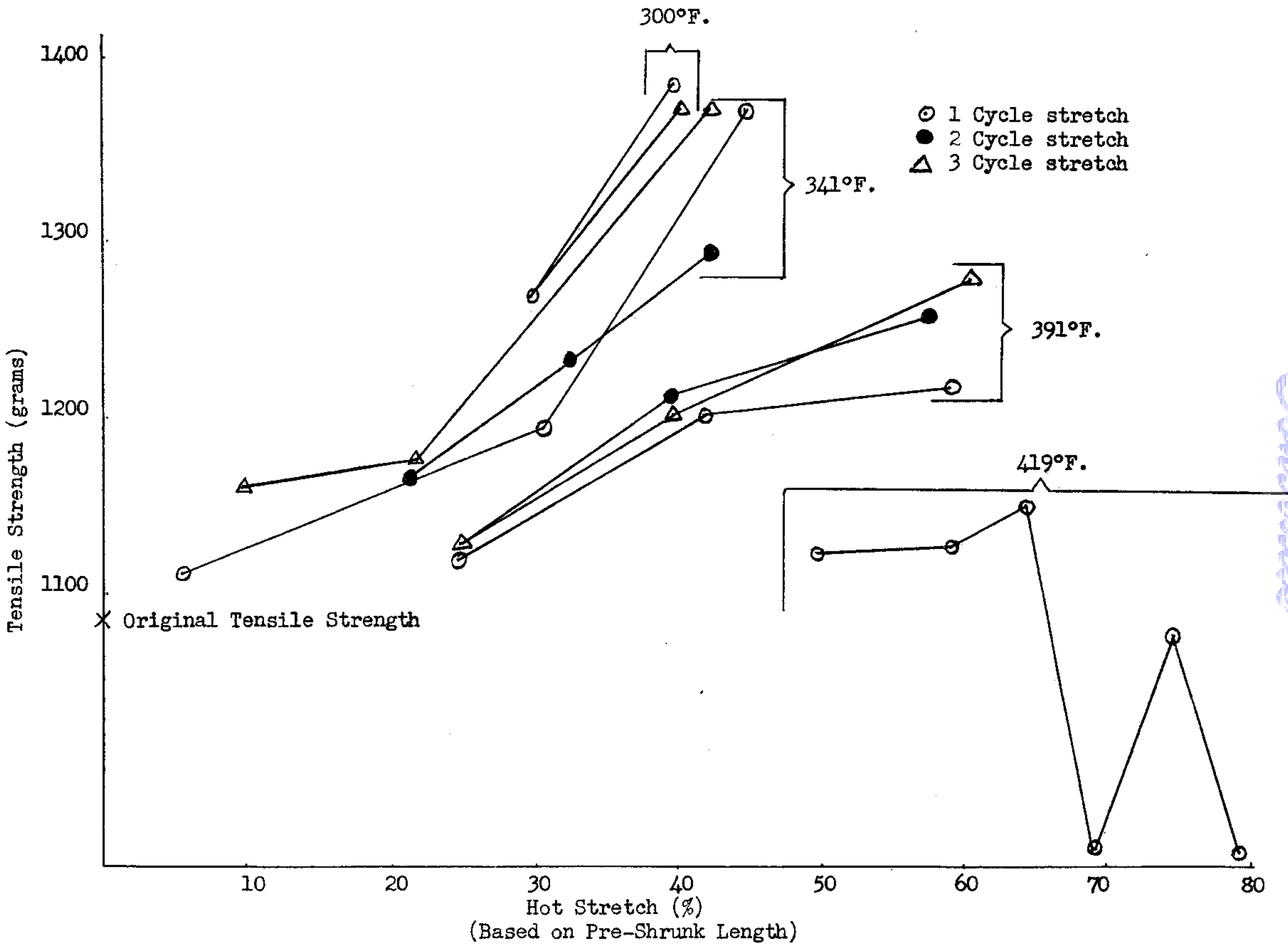

Figure 3. Effect of Degree of Hot Stretching and Relaxing 250 denier, Type 5500 Dacron Yarn at Various Temperatures on Tensile Strength at Standard Conditions

relaxing are to be accomplished in one chamber and by a batch process. Relaxation temperatures in excess of 350°F. are necessary if the yarn is then to be stable at 350°F. Figures 4 and 5 illustrate the change that can be induced upon either type of producer's Dacron yarn.

3.3 Development of a Continuous Yarn Processing Method

Having completed the above series of experiments on a non-continuous basis, a continuous hot stretching apparatus was designed and built so that a larger quantity of yarn could be produced for study. The heated chamber was still employed. However, two rolls of equal diameter were introduced for feed and take-up purposes so that yarn could be fed continuously (although extremely slow) through the hot air space. Figure 6 illustrates the apparatus employed. The system consists of the two aforementioned rolls connected together and driven manually by a chain drive. A speed differential is maintained through the use of sprockets of different size. The yarn is fed from the package to the slower turning feed roll, through the heated chamber (not shown in the photograph), thence to the faster turning roll and onto the take-up package. The draft is imparted between the two chain driven rolls. The amount of stretch can be varied and controlled through the use of different sized sprockets. Using this arrangement, the process is semi-continuous. The stretched yarn must be passed through the chamber a second time with overfeeding to allow the relaxation to occur.

3.3.1 Study of Various Heat Stabilizing Treatments

An attempt was made to determine the effect of various heat stabilizing treatments on the tensile strength of hot stretched Type 5500 Dacron yarn. For one series of experiments a length of yarn was passed through the heated chamber and allowed to shrink freely before attempting any stretching. Such yarn is identified as being "preshrunk" in Table VI. After shrinking, part of the yarn was passed through a second time during which a pre-determined stretch was imparted. Part of the above yarn was given a third pass through the chamber, this time untensioned for the heat relaxing stage (Post-Relaxation). The remainder of the stretched yarn was reserved for testing without undergoing relaxation. Various combinations of the above two techniques provided the results of the series of experiments shown in Table VI.

The data as shown in Table VI indicate that:

1. The higher the stretch imparted, the higher the strength of the yarn produced.

2. The heat stabilizing or relaxing operation produces a denier increase rather than an absolute strength loss which in turn results in a lowering of yarn tenacity. Further study of methods by which the lowered denier obtained by hot stretching can be maintained during thermal stabilization was conducted and the results of these studies are given in Section 3.4.2.2 of this report.

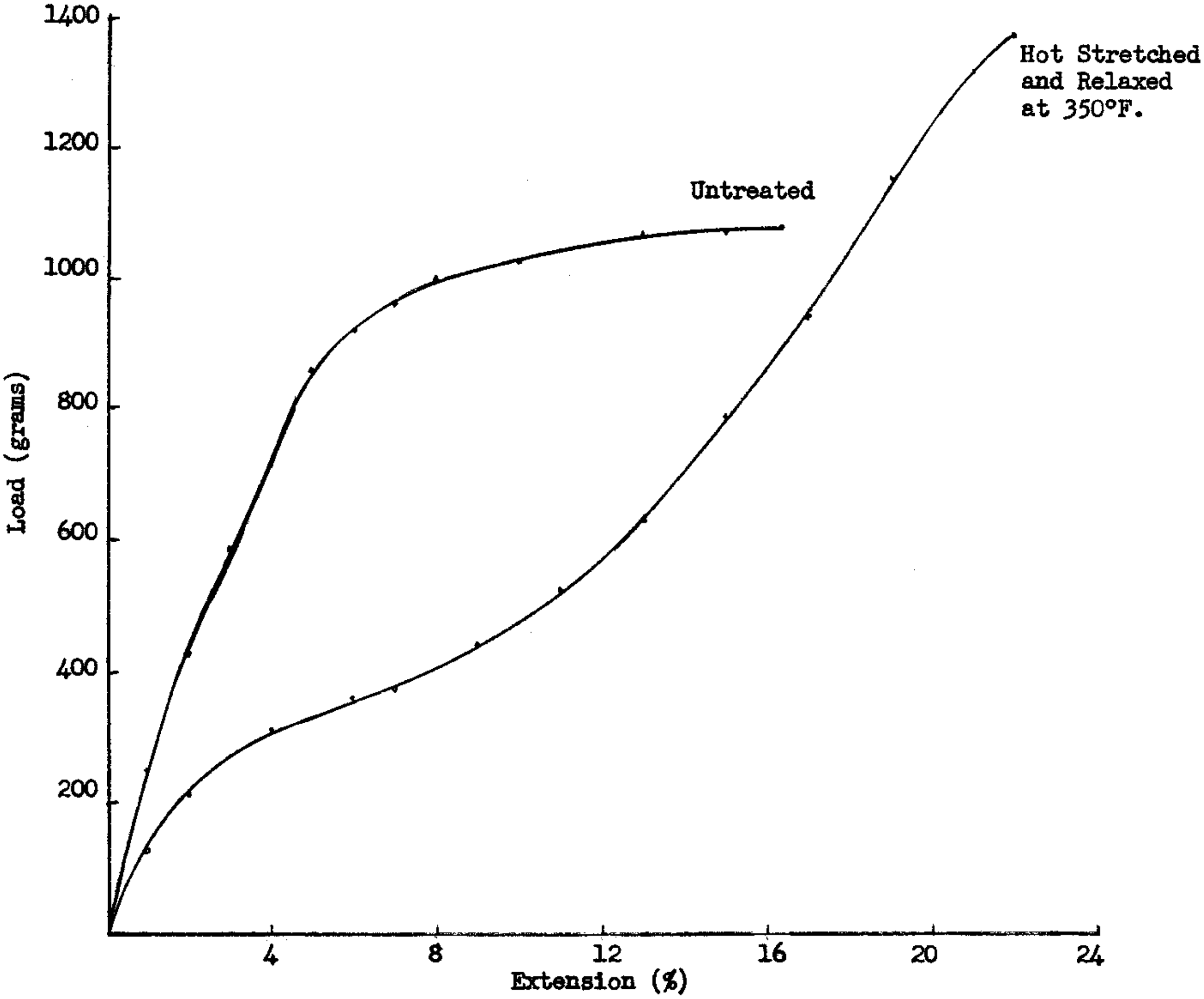

Figure 4. Tensile Properties of 250 denier, Type 5500 Dacron Tested Before and After Hot Stretching - Heat Stabilizing

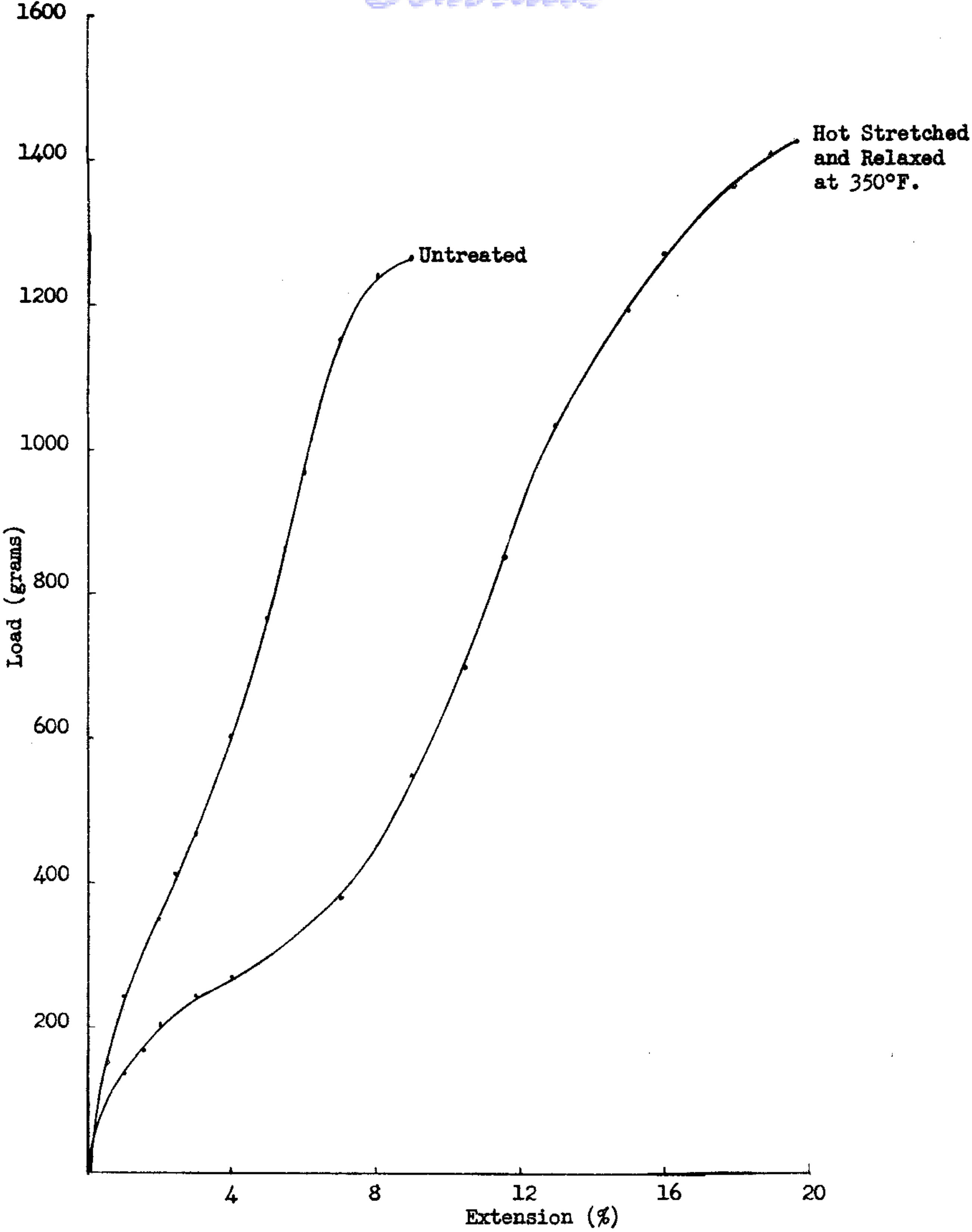

Figure 5. Tensile Properties of 220 denier, Type 5100 Dacron Tested Before and After Hot Stretching - Heat Stabilizing

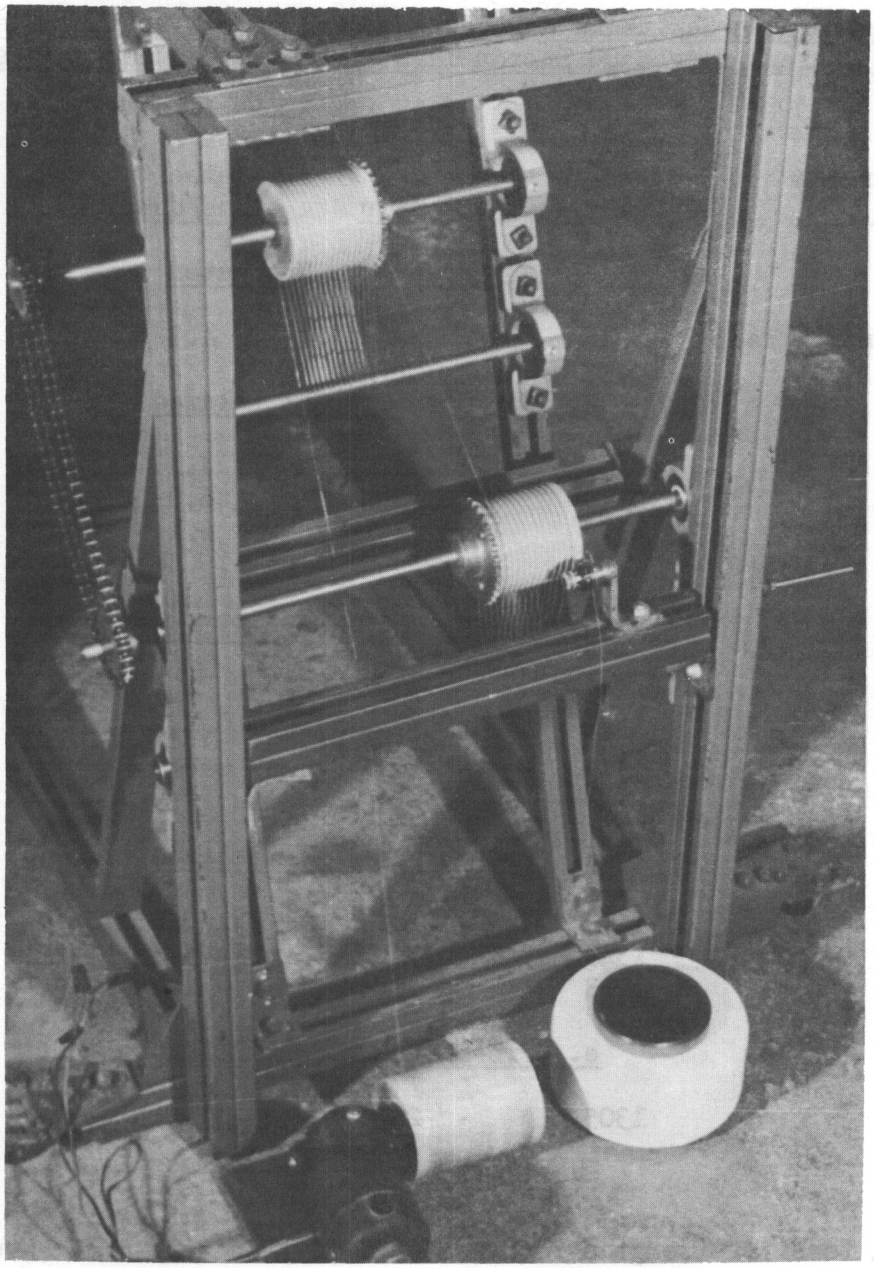

Figure 6. Photograph of Hot Stretching Equipment Used During Semi-Continuous Operation

TABLE VI

Effect of Pre-Shrinking and Post Relaxation on Tensile Strength[1] of 250 denier, Type 5500 Dacron Yarn Stretched Continuously at 340°F.

Hot Stretch (%)	Breaking Strength (grams)	denier	Tenacity (gms/den.)	Rupture Extension (%)
		a. Control - Untreated		
0 - Control Yarn	1086	252	4.3	16.2
		b. Non-Shrunk - Non Relaxed		
22	1469	205	7.1	7.5
17	1385	222	6.3	8.1
15	1375	226	6.1	7.8
10	1275	239	5.3	10.7
		c. Non-Shrunk - Post Relaxed		
22	1338	228	5.9	18.9
17	1346	251	5.3	22.0
15	1271	264	4.8	22.0
10	1230	267	4.6	23.5
		d. Pre-Shrunk - Non-Relaxed		
41[a]	1429	218	6.6	7.5
35[a]	1349	231	5.8	8.3
28[a]	1203	258	4.7	14.5
		e. Pre-Shrunk - Post Relaxed		
41[a]	1305	242	5.4	21.5

[1] All tensile strengths recorded at 70°F., and 65% R.H. (Average of approximately 10 breaks).

[a] Based on shrunken length.

3.3.2 Mechanization of Stretching - Stabilizing Process

For the next study the feed and take-up rolls were motorized in order to develop a more uniform stretching rate than is possible to attain manually. Also, at this point in the program, Type 5100 Dacron became available so that it too was included in further experiments. Here the research was divided into four segments, each studying the influence of certain processes on physical properties of Dacron yarn.

1. Study of continuous hot stretching rates at various temperatures. (Type 5500 Dacron).

2. Study of semi-continuous, multiple-cycle hot stretching. (Type 5500 Dacron).

3. Study of various relaxation techniques. (Type 5500 Dacron).

4. Study of continuous processing of Type 5100 Dacron.

3.3.2.1 Study of Continuous Hot Stretching Rates

As has been previously stated, the hot stretching-heat relaxing process is considered to consist of at least two steps, namely: (A) application of a certain amount of stretch to a yarn, and (B) complete removal of load at the desired temperature in order to allow the stretched yarn to shrink freely and completely. Step (A) is discussed below; step (B) will be discussed shortly.

The effect on tensile strength of the amount of hot stretch imparted to groups of yarns on a non-continuous basis has already been shown in Figure 3. Briefly, it has been found that within a fixed yarn temperature range of 330°F. to 390°F., a stretch of 20% above that required to compensate for the initial free shrinkage occuring in the test will produce a high strength Type 5500 Dacron yarn.

Those optimum conditions arrived at from the non-continuous phase were selected for the continuous process preliminary experiments. A variable speed motor enabled yarn production of from 10 to 35 yards/minute to be attained. Continuous sample lengths of fifty to one hundred yards, depending upon the operating speed, were stretched at various temperatures over the speed range noted. The results of this study are shown in Figure 7.

It can be seen from Figure 7 that over the range of temperatures and speeds selected, there is a measurable although not very significant difference in the tensile strength of the Type 5500 hot stretched Dacron yarn. In this initial experimental work on continuous processing certain apparatus limitations precluded studies at higher operating speeds. Subsequently the construction and use of a pilot unit permitted such higher speeds which approximated the commercial range. These results are discussed in Section 3.4.2.4 and show that proper stretching speed can be established by proper choice of heating conditions. It is important to point out that the yarn produced in the above study was not heat relaxed, once again due to the operational characteristics of the test unit in use. Some relaxation checks were made by placing certain of the above yarns in an oven at 350°F. and allowing them to relax. This produced a slight lowering of the absolute breaking strength of all samples tested after a five minute exposure. However, the relative differences between the various groups of samples did not change due to stabilization.

3.3.2.2 Study of Semi-Continuous Multiple-Cycle Heat Stretching

On the basis of early results which indicated some advantages to multi-cycle stretching, a second study involving semi-continuous multi-cycle stretching was conducted. Using the same unit described in Figure 6, a length of untreated Type 5500 Dacron yarn was passed continuously from the feed to the take-up roll, the selected amount of stretch being imparted. This sample was then replaced on the feed side for a second stretching treatment, not necessarily at the same draft employed on the first pass. In some cases the sample was given a third stretch, again at a selected draft. Since the samples were actually moved from the take-up to the feed side of the unit between successive stretchings, this process as described is considered to be semi-continuous. The yarn produced was not heat relaxed and therefore not heat stabilized. This latter step will be considered shortly. The results of the multiple-stretching study conducted by the above procedure are shown in Table VII.

At this point in the research, there still appeared to be some advantage to employing multiple-stretching. The results in Table VII indicate that improvements equal to, and in some cases greater than, those made by one cycle of 20% stretch can be obtained. Since 20% stretch is very close to the breaking elongation at these temperatures, it would be wiser to employ several cycles of lower stretch to obtain the desired yarn strength. A more uniform product would probably result with less chance of filament damage and subsequent yarn failure. Multiple-cycling has been investigated further with the pilot stretching unit, discussed in Section 3.4.2.3.

3.3.2.3 Study of Heat Stabilizing Treatments

One of the prime requisites of the research is that the resulting high strength Dacron yarn be thermally stable to a temperature of 350°F. By this is meant that shrinkage of the processed yarn must not exceed 2% after 24 hours exposure to the above noted temperature. It has been found that producer's Type 5500 Dacron shrinks 21.8% when exposed to 350°F. for from five minutes to twenty four hours. Once a sample has been exposed to this elevated temperature, however, there will be no further shrinkage upon subsequent exposure. As a matter of fact, probably 99% of the total shrinkage which is going to occur does so within five seconds. It is obvious, then, that one method of heat stabilizing a hot stretched yarn is merely to free shrink it at the desired temperature for

TABLE VII

Effect of Multiple Hot Stretching Processes on Tensile Strength of Type 5500 Dacron

(Yarns Were Not Heat Stabilized After Stretching)

Treatment: No. of Cycles	Treatment: Stretch (%)	Treatment: Temperature (°F.)	Breaking Strength (grams)	denier	Tenacity (gms/den)	Rupture Extension (%)
None	Control	—	1102	252	4.4	13.7
1	20	400	1446	214	6.8	7.9
1	18	400	1357	221	6.2	7.2
2	18; 8	400	1488	210	7.1	7.2
2	18; 5	400	1382	214	6.5	7.5
1	17	400	1347	219	6.2	6.8
2	17; 10	400	1351	211	6.4	6.8
2	17; 10 (Recheck)	400	1431	213	6.7	7.0
2	17; 5	400	1367	222	6.2	7.0
1	15	400	1409	225	6.3	8.3
2	15; 10	400	1471	213	6.9	7.1
2	15; 5	400	1421	223	6.4	7.7
3	15; 10; 5	390	1388	208	6.7	6.2
3	15; 10; 5 (Recheck)	385	1509	211	7.2	7.4

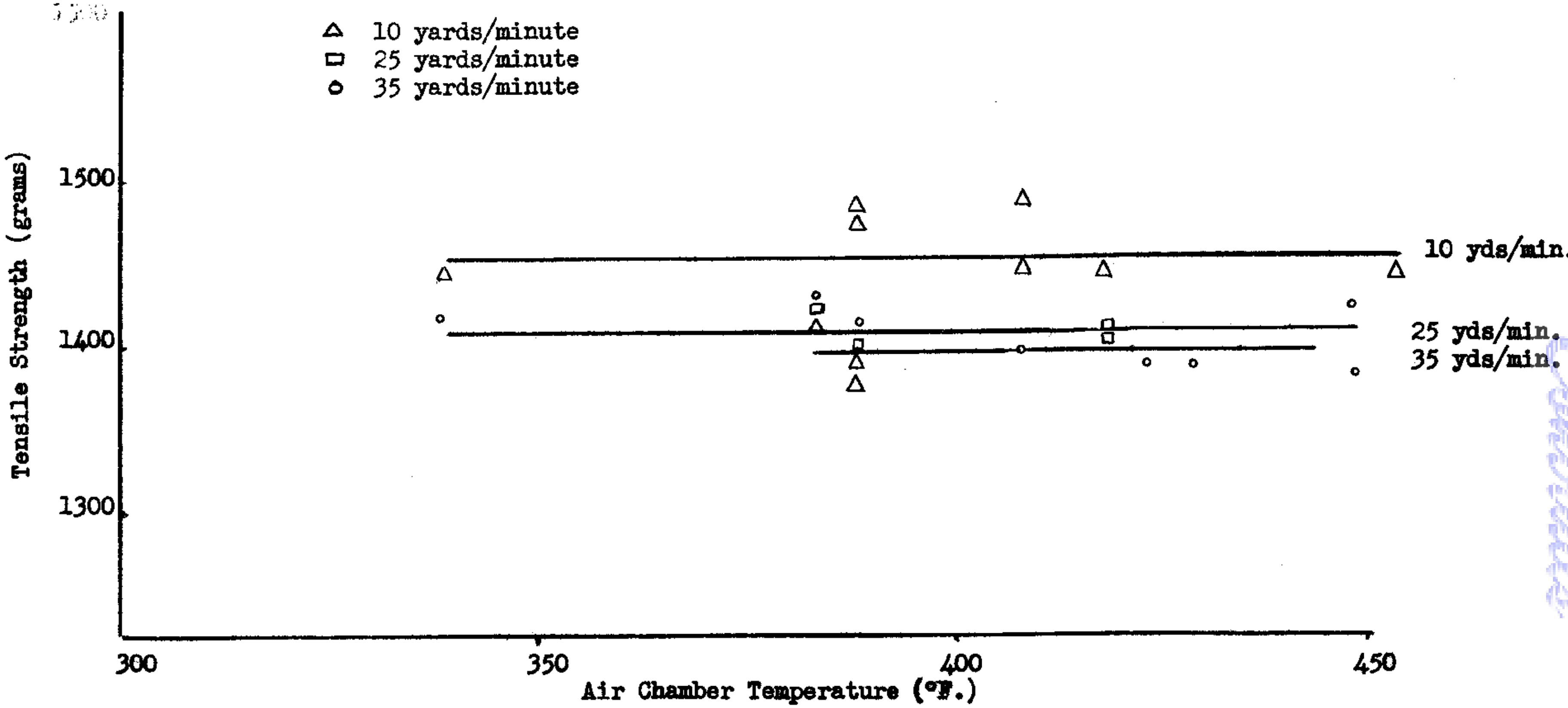

Figure 7. Relationship Between Tensile Strength of Hot Stretched Type 5500 Dacron Yarn and Air Temperature at Which Stretching Was Performed (Yarn was <u>not</u> Stabilized to 350°F.)

a short period of time. While this procedure is the simplest, it does not seem to be necessarily the best from a denier and tenacity viewpoint. Table VIII illustrates this point. A limited number of experiments were performed using four samples of Type 5500 Dacron control yarn. Three of the control samples had previously been hot stretched in the heated chamber at different temperatures. These samples had not been heat stabilized. An untreated control yarn was also included in the experiment (Series A). A portion of each sample was exposed to 350°F. for five minutes and allowed to shrink freely (Series B). A second portion of each sample was held at fixed length for five minutes at 425°F., cooled to room temperature, and exposed to 350°F. for five minutes where it was allowed to shrink freely (Series C). The results of the study are tabulated in Table VIII.

It should be noted from a comparison between the results in Series B and C that the tenacity of the yarn produced by the "fixed length", "free shrink" treatment C, is measurably higher than that produced by the "free shrink" treatment alone. Additional study with the pilot unit confirmed these results as will be noted in Section 3.4.2.2. This work coupled with the initial investigation of various relaxing techniques shown in Table III gives strong indication that the hot stretching-heat relaxing process should be at least a three step one involving:

1. Application of stretch.
2. Maintainance of this stretch by holding at the new length for an added time.
3. Complete removal of load to allow for free shrinkage to occur.

3.3.2.4 Study of Continuous Processing of Type 5100 Dacron

The results of the first attempts at hot stretching-heat relaxing Type 5100 Dacron yarn using the slow speed semi-continuous process are summarized in Table IX.

It is apparent from Table IX that higher strengths than those obtained by hot stretching Type 5500 Dacron can be achieved through the use of Type 5100 as the starting yarn. For this reason, the major part of the work performed with the pilot unit, next to be discussed, involved the use of Type 5100 yarn.

3.4 Construction and Operation of Pilot Unit

Having completed phases 1, 2 and 3 of the original plan of attack, it was possible to design and build a small scale pilot unit embodying all of the principles arrived at through work performed up to this time. The machine as designed and employed for all future studies is shown in Figures 8, 9 and 10.

TABLE VIII

Comparison Between Two Heat Stabilizing Treatments on Tensile Strength of Various Hot Stretched Type 5500 Dacron Yarns

Sample	Breaking Strength (grams)	denier	Tenacity (gms/den.)	Rupture Extension (%)	Shrinkage at 350°F. (%)
A. Controls					
1 Untreated	1102	252	4.4	13.7	21.8
2 20% Stretch @ 390°F.	1417	211	6.7	7.5	9.4
3 20% Stretch @ 340°F.	1458	214	6.8	7.3	12.8
4 20% Stretch @ 455°F.	1442	213	6.8	7.6	6.9
B. The Samples Processed in A Above Were Then Freely Shrunk at 350°F. for 5 mins.					
1B	1148	312	3.7	36.8	0
2B	1369	236	5.8	18.9	0
3B	1351	252	5.4	24.5	0
4B	1268	232	5.5	18.4	0
C. A Second Group of the Samples Processed in A Above Were Held at Fixed Length at 425°F. for Five Minutes - Cooled to Room Temperature, and then Freely Shrunk at 350°F. for Five Minutes.					
1C	1257	272	4.6	14.7	0
2C	1415	236	6.0	11.0	0
3C	1413	233	6.1	12.4	0
4C	1397	230	6.1	16.2	0

Note: Yarns which had been freely shrunk at 350°F. for five minutes were re-exposed to 350°F. for twenty four hours after being cooled to standard conditions. No further shrinkage was noted.

TABLE IX

Effect of One Hot Stretching Heat Stabilizing Treatment on Tensile Strength of 220 Denier, Type 5100 Dacron

Treatment	Breaking Strength (grams)	Denier	Tenacity (gms/den.)	Rupture Extension (%)	Shrinkage at 350°F. (%)
Untreated	1338	225	5.9	9.5	21.0
20% H.S. @ 400°F.	1537	190	8.1	7.5	9.4
20% H.S. @ 400°F. followed by F.S. at 350°F.	1457	201	7.2	14.5	4.2

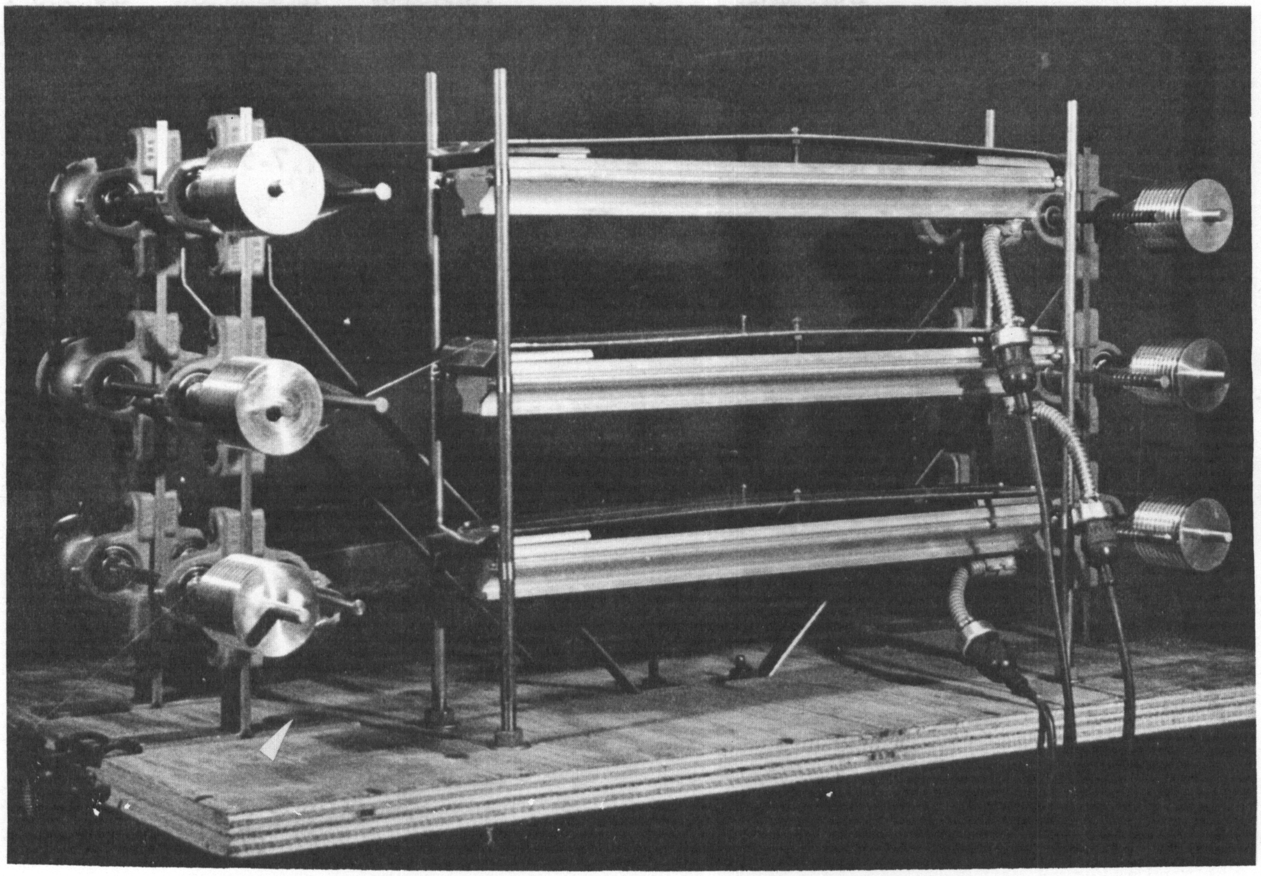

Figure 8. Front View of Pilot Hot Stretching-Heat Stabilizing Unit

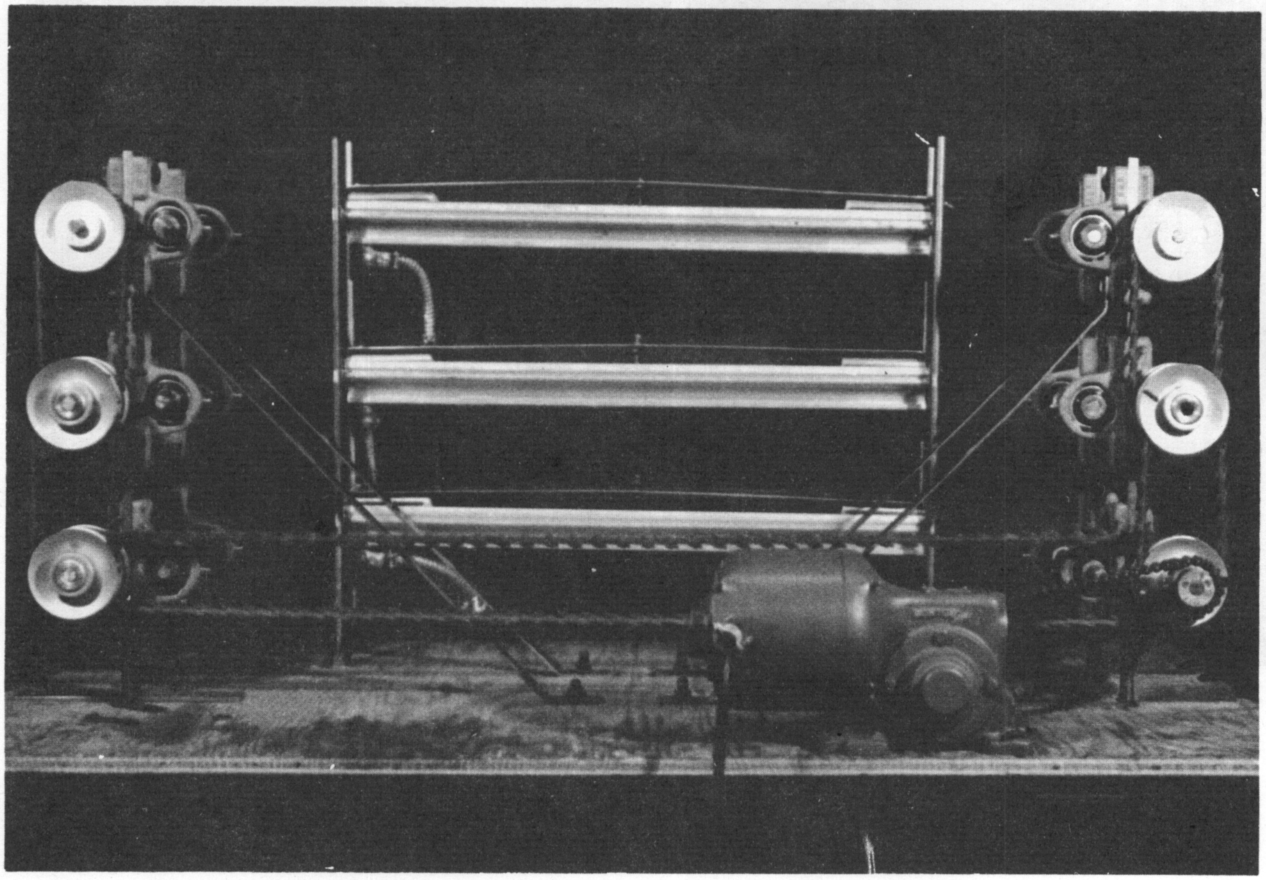

Figure 9. Rear View of Pilot Hot Stretching-Heat Stabilizing Unit

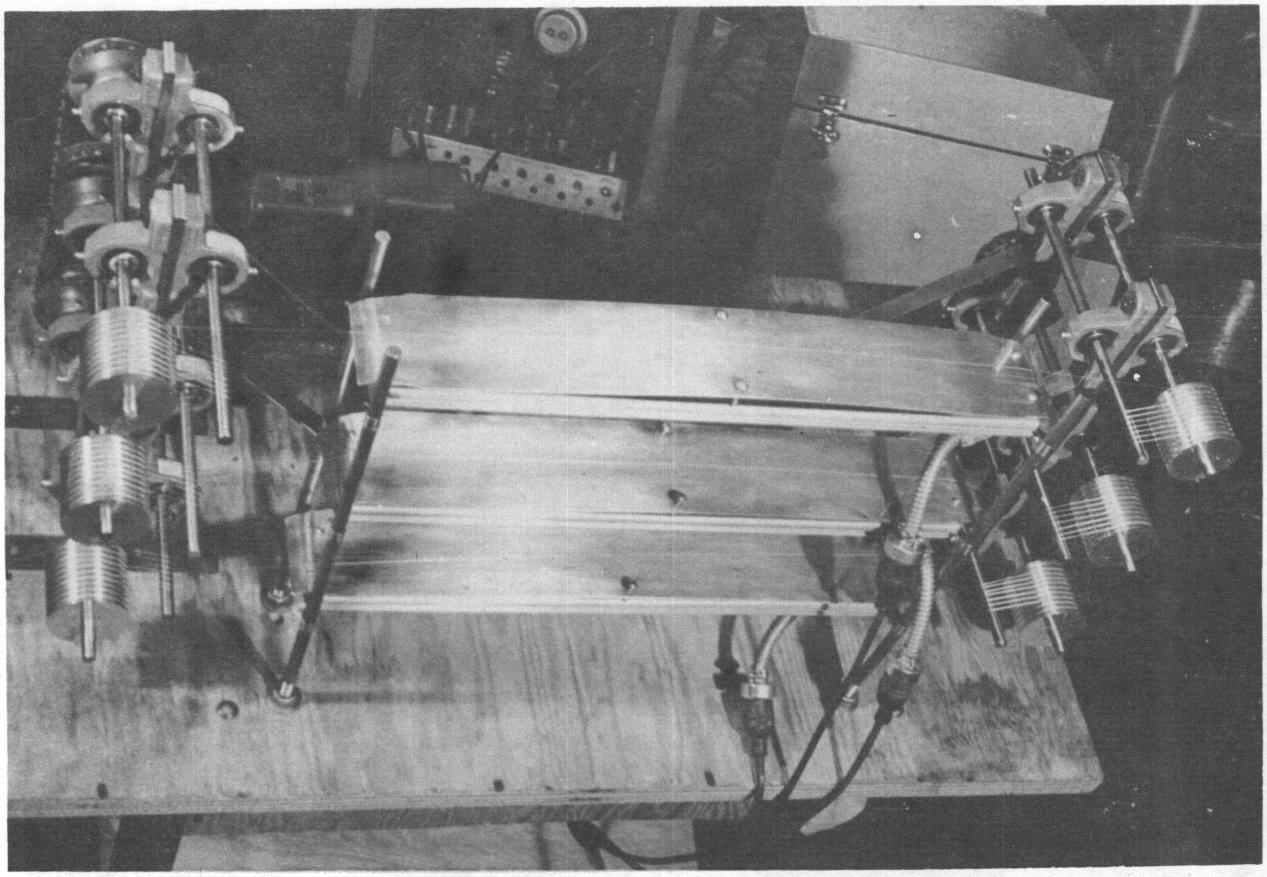

Figure 10. Top Angular View of Pilot Hot Stretching-Heat Stabilizing Unit

3.4.1 Description of Unit

The entire operation may be seen from Figure 8. The yarn was introduced into the system by the lower roll on the left side of the machine. After making several turns around this roll to insure proper holding, it passed across the lower heat source. This was an 800 watt radiant strip heater over which was placed an aluminum plate with a highly polished upper surface.

It was rather difficult to measure yarn temperature during operation, whereas the temperature of the upper surface of the metal plate could be measured at any time by various means. In these experiments "Templestiks" were employed. These are temperature sensitive materials in crayon-like form which can be rubbed on the surface whose temperature is to be measured. Each "Templestik" has a given melting point. Melting indicates a temperature above, and no melting indicates a surface temperature below, that of the stick. The range of melting points currently available made it impossible to control temperature closer than ± 7°F. Since there was some temperature variation across the surface of the plate, it was not possible to ascertain temperature too accurately. For this reason temperatures are reported (for example) as "400°F" or "450°F". It was felt, however, that some temperature variability was tolerable on the basis of earlier experiments which showed only a slight dependence of stretched yarn properties upon stretching temperature. If it were warranted, more accurate temperature control could have been obtained via such instruments as a surface pyrometer. In any event plate temperature control ultimately leads to yarn temperature control at a given yarn speed. At the operating speed used (about 15-25 yards per minute for a majority of the work) it was assumed that the yarn temperature essentially reached that of the upper surface of the plate during the time of contact, due to the large heating surface area with respect to the yarn surface area in contact with the plate. At high speeds, a longer surface of higher temperature would be necessary to heat the yarn to the desired degree.

A pre-determined stretch was applied to the yarn by regulating the speed of the bottom rolls. This was accomplished by means of variable pitch pulleys connected by a V-belt (See rear view of unit - Figure 9). Proper adjustment of these pulleys was made to establish a speed differential and therefore a stretch of from 0 to 50%. Several wraps were made around the stretch take-up roll on the lower right of the unit, thence the yarn passed to the middle roll directly above. The "fixed length" step was accomplished across the middle heat source, another strip heater covered with an aluminum plate. This time the pulleys were adjusted with no draft so as to hold the yarn at fixed length, i.e., neither to stretch nor relax the yarn as it passed over the heated plate. After passing around the middle roll on the left side of the machine, the yarn was fed to the upper left hand roll. At this point, the upper pulleys on the left and right were so adjusted that the yarn was continually over-fed onto the upper hot plate. The yarn was allowed to shrink freely and completely before being taken up by the upper roll on the right side. Knowledge of the amount of potential shrinkage together with visual examination of the yarn as it left the upper plate enabled the proper amount of overfeeding to be maintained.

Each of the roll shafts noted above was fitted with a variable pitch pulley driven in turn from the pulley below by an adjustable V-belt. It can be seen that by varying the diameter of the pulleys, practically any desired draft between any two successive rolls could be attained. In this way it was possible to establish and maintain any given set of stretching and relaxing conditions on the pilot model.

3.4.2 Experimental Results

Wherever possible, operational data and principles obtained from earlier non-continuous studies were utilized. Five major investigations were conducted.

1. Study of the basic 3-step process. (20% stretch following by "fixed length" and "free shrink" steps).
2. Study of "fixed length" operation.
3. Study of multiple stretch-relax processes.
4. Study of increased production rates.
5. Miscellaneous studies.

3.4.2.1 Study of the Basic Three Step Process

The basic three step non-continuous method found to produce the most uniform high tenacity-heat stable yarn has already been described. This method was, therefore, adapted to a continuous process.

Two lots of Type 5100 Dacron yarn were processed in these pilot plant studies:

a. Control Yarn No. 1 received in June, 1954, used for "non-continuous" as well as some "continuous" experiments.

b. Control Yarn No. 2 received in February, 1955, used for continuous experiments only.

It was found that the tenacity of Control Yarn No. 2 was measurably higher than the previous sample. This meant that the opportunity for increasing the tenacity of Yarn No. 2 was not as great as for Yarn No. 1. Actually, this was found to be the case, the change in yarn No. 2 being lower as can be noted in Table X, Part (d). A summary of the results obtained from the three step process using both Control yarns is shown in Table X. Each test involving Type 5100 Dacron yarn (Section d) was performed at a different time, the maximum time differential being approximately four months. Ten processed yarns randomly selected throughout the package were chosen from each group for evaluation.

Table X also includes some results obtained usi[illegible]wo commercial Type 5500 sewing threads:

(a) 250/3 plied thread (V69) and
(b) 75/3 plied thread (V23).

It was necessary to apply a higher degree of stretch to the sewing thread at elevated temperatures than was used with the producer's yarn. This was due to the particular geometric constructions of the threads, which are highly twisted plied yarns, thus requiring higher strains to attain the same stress level during stretching. Yarn tenacities were determined after hot stretching without stabilization (marked "not relaxed" in Table X) as well as after stretching and stabilizing to 350°F. (marked "relaxed").

The Table X summary shows that a uniform heat stable Type 5100 Dacron yarn of 6.8-7.0 grams per denier tenacity can be produced by the three step process. The percent gain in tenacity is much greater with the two samples of Type 5500 Dacron sewing thread than with the Type 5100 producer's yarn, the improvement approaching 50%. This is to be expected, however, since the molecular structure of Type 5500 Dacron is such that it is more readily re-oriented into a more crystalline type of polymer. The Type 5100 Dacron has been drawn more than the Type 5500 as part of the commercial production by the duPont Company and is therefore a less amorphous material than Type 5500 when introduced into the three step process described above. Furthermore, the geometric arrangement of a plied thread is such that it is more easily rearranged for improved tensile behavior.

No other method investigated to date has, with any degree of consistency, produced such high tenacity yarn. It is realized, however, that with continued research some of the methods employed thus far may be modified in such a way as to provide even greater improvements in tenacity without any loss in heat stability. A study of methods for producing larger quantities of experimental yarn above the amounts prepared thus far is also required in order to thoroughly evaluate the hot stretching-heat stabilizing process. With the above two ideas in mind, much of the remaining work performed on the pilot model was concerned with seeking still greater improvements in yarn tenacity and attempting to increase the rate of yarn production over that shown in Table VIII.

3.4.2.2 Study of Fixed Length Operation

Throughout this research there have been indications that an intermediate fixed-length step between hot stretching and thermal stabilization has produced maximum tenacities. To prove the value of such a step in continuous processing, studies which have separated this variable have been conducted. Production rate was also varied in order to study the effect of increased operating speed on the tensile properties of the processed yarn product.

Examination of the data in Table XI discloses that there is a measurable difference between the results obtained by using the three step stretching-relaxing treatment rather than the two stage process, especially rates of from 15 to 50 yards per minute. Below 15 and above 50 yards per minute the advantage of the fixed length step is not borne out. However, this is believed due to variability in residual shrinkage of the processed yarn. This incomplete shrinkage produces a lower denier-higher

TABLE X

Summary of Results Obtained via Three Step Hot Stretching-Stabilizing Process[(1)]
(Production Rate Approximately 25 yds/min.)

Treatment	Breaking Strength (grams)	Denier	Tenacity (gms/den)	Rupture Extension (%)	Shrinkage at 350°F. (%)
a. 250 Denier, Type 5500 Dacron Producer's Yarn					
Control - Untreated	1076	254	4.2	11.6	21.8
20% Hot Stretch - Not Relaxed	1430	217	6.6	8.4	8.7
20% Hot Stretch - Relaxed	1344	233	5.8	15.6	1.7
b. 250/3, Type 5500 Dacron Sewing Thread (V-69)					
Control - Untreated	3490	820	4.3	30.1	18.4
52% Stretch - Not Relaxed	3981	558	7.1	7.7	7.0
52% Stretch - Relaxed	4065	627	6.5	17.8	1.4
c. 75/3 Type 5500 Dacron Sewing Thread (V-23)					
Control - Untreated	1021	238	4.3	27.3	14.5
34% Stretch - Not Relaxed	1348	182	7.4	8.1	6.2
34% Stretch - Relaxed	1282	204	6.3	17.8	0.6
d. 220 Denier, Type 5100 Dacron Producer's Yarn					
Control #1 - Untreated	1338	225	5.9	9.5	21.0
20% Hot Stretch - Not Relaxed	1488	193	7.7	8.0	8.3
#1 20% Hot Stretch - Relaxed	1410	206	6.8	17.6	1.9
#2 20% Hot Stretch - Relaxed	1388	203	6.9	14.3	1.4
#3 20% Hot Stretch - Relaxed	1398	206	6.8	14.9	1.0
#4 20% Hot Stretch - Relaxed	1425	207	6.9	15.2	2.0
#5 20% Hot Stretch - Relaxed	1431	207	6.9	16.1	2.0
#6 20% Hot Stretch - Relaxed	1392	207	6.7	15.4	1.3
#7 20% Hot Stretch - Relaxed	1377	202	6.8	15.3	1.0
#8 20% Hot Stretch - Relaxed	1394	208	6.7	16.5	1.2
Control #2 - Untreated	1416	218	6.5	10.0	19.2
20% Hot Stretch - Not Relaxed	1575	190	8.3	7.4	8.2
#1 20% Hot Stretch - Relaxed	1428	204	7.0	14.9	2.4
#2 20% Hot Stretch - Relaxed	1380	204	6.8	14.0	2.4
#3 20% Hot Stretch - Relaxed	1427	204	7.0	14.4	2.4
#4 20% Hot Stretch - Relaxed	1457	210	6.9	15.8	2.0

(1)The Process involves: (a) Stretching @ 400°±F. (plate temperature)
(b) Holding at fixed length @ 400°±F.
(c) Free shrinking @ 388°F.

TABLE XI

Comparison Between Two Hot Stretching-Stabilizing Techniques at Various Operating Speeds on Tensile Properties of Type 5100 Dacron Yarn

Production Rate (yds/min.)	Treatments: Hot Stretched - Freely Shrunk: Bk.Str. (gms.)	denier	Tenacity (gms/den.)	% Rupture Extension	% Shrink at 350°F.	Treatments: Hot Stretched - Fixed Length - Freely Shrunk: Bk.Str. (gms.)	denier	Tenacity (gms/den.)	% Rupture Extension	% Shrink at 350°F.
Control Yarn #1	1338	225	5.9	9.5	21.0					
3	1372	212	6.5	17.3	1.7	1353	213	6.4	18.2	0.7
6	1345	216	6.2	18.6	3.8	1330	212	6.3	16.8	1.4
10	1347	213	6.3	16.4	1.7	1396	210	6.7	15.7	0.7
15	1318	208	6.3	15.3	1.0	1392	207	6.7	15.4	1.3
15	1324	208	6.3	15.4	1.0	1377	202	6.8	15.3	1.0
15	1347	208	6.4	16.9	1.0	1394	208	6.7	16.5	1.2
15	1335	208	6.4	16.6	1.0					
25						1428	204	7.0	14.9	2.4
25						1380	204	6.8	14.0	2.4
25						1427	204	7.0	14.4	2.4
25						1338	204	6.6	13.9	2.4
50	1244	221	5.6	21.4	0.6	1411	209	6.8	15.9	3.3
75	1369	222	6.2	16.1	1.7	1409	211	6.7	17.2	1.4
125	1384	227	6.1	15.6	2.8	1384	208	6.7	16.0	0.7
175	1334	207	6.4	14.7	4.0	1252	210	6.0	14.8	0.7

tenacity yarn which at a first glance is as good as yarn given the three step process. However, the heat shrinkage of this two step yarn is greater than that considered acceptable.

3.4.2.2.1 Stretching Conditions for Type 5100 Dacron Control Yarn Number 2.

The process conditions listed in Table XI were those established for Control Yarn No. 1 but were applied to Control Yarn No. 2. In order to ascertain whether such process conditions were actually optimum for Control Yarn No. 2, a study of hot stretching magnitude was conducted. Table XII tabulates the results.

As was found in previous experiments the higher the stretch, the higher the tenacity of the yarn produced within a given temperature range. Despite the fact that the original tenacity of Control Yarn No. 2 is higher than that previously tested, it is still possible to gain maximum improvement by hot stretching 20%. As the yarn is stretched less, the absolute strength decreases and the denier increases resulting in a two way tenacity loss.

2.4.2.3 Study of Multiple Stretch-Relax Processes

It has always been the opinion of Fabric Research Laboratories, Inc, that repeated stretching and relaxing might provide a means for realizing improvements in yarn tensile behavior. Up to the moment, however, no regularly definable improvement has been shown by any of the non-continuous repeated stress methods selected. It was felt that in making the process continuous it might be possible to realize the uniform improvements desired. By proper adjustment and utilization of the six rolls shown in Figure 8, the following repeated stressing conditions were established. The entire multiple stretching operation was continuous. Relaxation, however, was accomplished as a separate step.

Step 1	20% Stretch
Step 2	Relax from 20% down to 10% stretch
Step 3	Stretch from 10% back up to 20%
Step 4	Relax from 20% down to 10%
Step 5	Stretch again from 10% up to 20%
Step 6	Relax from 20% down to 10%
Step 7	Stretch a fourth time from 10% up to 20%
Step 8	Relax from 20% down to 10%
Step 9	Free shrink at 350°F.

Samples were taken after successive stretchings and allowed to shrink freely at 350°F.

The above series was repeated for multiple stretching between 20% and 15% and between 20% and 5% stretches. Again samples were taken after successive stretchings and allowed to shrink freely at 350°F. A comparison between physical properties of the non-relaxed yarn from each step and its relaxed counterpart is shown in Table XIII.

TABLE XII

Effect of Degree of Hot Stretch Imparted to Type 5100 Dacron on Tenacity of Yarn Produced. Yarns were not Thermally Stabilized[1]

Description	Breaking Strength (grams)	denier	Tenacity (gms/den.)	Rupture Extension (%)	Shrinkage at 350°F. (%)
Control Yarn #2	1416	218	6.5	10.0	19.2
20% Stretch	1575	190	8.3	7.4	8.2
17% Stretch	1576	200	7.9	7.2	6.8
15% Stretch	1566	207	7.5	7.9	7.6
12% Stretch	1532	204	7.5	7.7	7.9
10% Stretch	1517	216	7.3	8.3	8.2
7.5% Stretch	1506	218	6.9	9.4	8.0
5.0% Stretch	1466	223	6.6	13.6	4.6

[1] Stretching temperature 400°F.

TABLE XIII

Effect of Various Repeated Stretching-Relaxing Treatments on the Tensile Properties of Type 5100 Dacron Yarn

Treatment	Breaking Strength (grams)	denier	Tenacity (gms/den.)	Rupture Extension (%)	Shrinkage at 350°F. (%)
a. None - Control Yarn #1	1338	225	5.9	9.5	21.0
b. Multi-Stretched four times between 20 and 10% stretch					
After 1	1530	199	7.7	8.7	9.0
After 1 and Heat Relax	1447	218	6.6	20.5	0.7
After 3	1500	198	7.6	8.4	—
After 3 and Heat Relax	1380	212	6.5	17.3	0.7
After 5	1430	198	7.3	8.4	7.0
After 5 and Heat Relax	1330	218	6.1	20.2	0.7
After 7	1460	196	7.5	7.8	8.0
After 7 and Heat Relax	1410	213	6.6	16.3	1.4
c. Multi-Stretched as above but between 20 and 15% stretch					
After 1	1540	197	7.8	9.1	10.0
After 1 and Heat Relax	1450	213	6.8	21.1	1.0
After 3	1510	193	7.8	8.5	8.7
After 3 and Heat Relax	1420	212	6.8	18.8	1.7
After 5	1510	212	7.1	8.4	9.4
After 5 and Heat Relax	1380	219	6.3	22.4	0.7
After 7	1460	195	7.5	8.0	7.6
After 7 and Heat Relax	1440	221	6.5	19.0	1.0
d. Multi-Stretched four times as in (a) and (b), but between 20 and 5%					
After 1	1500	207	7.2	10.1	8.7
After 1 and Heat Relax	1460	225	6.5	22.0	0.7
After 3	1510	195	7.5	9.1	7.6
After 3 and Heat Relax	1440	212	6.8	18.2	1.0
After 5	1480	188	7.9	8.3	8.3
After 5 and Heat Relax	1430	211	6.8	18.1	1.4
After 7	1490	201	7.5	7.9	9.0
After 7 and Heat Relax	1452	212	6.8	18.2	0.7

In addition to the regular free shrinking after such treatment, one group of samples (Step 7) was given an alternate stabilization via holding at fixed length followed by the free shrinking step. Results of this treatment are given in Table XIV.

It can be seen from Tables XIII and XIV that the multi-cycle operation provides no definite improvement in the tensile behavior of the yarns tested. This method, however, is only one of several possible multiple stretching processes. Others have been investigated and the results of the various experiments are reported in Table XV.

It appears, generally, that while multi-stretch processing of the types described above may produce spasmodic higher tenacities, these methods do not provide sufficient increase to warrant incorporation of the multiple stretching system into the standard process. Further study of this method of stretching is required before more positive assertions can be made concerning multiple stretching. It is felt therefore, that the three step single stretch processing technique currently employed as standard can provide an adequate system for producing experimental quantities of hot stretched, thermally stable Dacron yarn.

3.4.2.4 Increased Production Rates

Realizing that the 15 yards/minute production rate employed in the above experiments was much too slow for even semi-commercial production, an attempt was made to speed up the basic process. Elevated plate temperatures were used in order to attain the desired yarn temperatures. No difficulty was encountered in the stretching or fixed length phases. However, it was not always possible to free shrink the yarn sufficiently in one pass over the top plate in order to heat stabilize to a residual shrinkage of less than 2% at 350°F.

Various operational speeds were studied and modifications in the basic process made in an attempt to reduce shrinkage without a loss in tensile behavior. A summary of the increased speed experiments is shown in Table XVI.

In order to minimize the chance of yarn damage during increased speed operations, the control yarn was twisted 5 turns per inch. Certain speed studies were conducted using this twisted yarn while others were performed using the untwisted producer's yarn. For this reason there are two control yarns listed in the table of results which follows. One is noted as "Twisted Control", the other "Untwisted Control".

It can be seen from Table XVI that when production rate is increased using the present pilot model, it becomes much more difficult to reach the desired shrinkage level in a short period of time. Inspection of treatments 5 and 8 reveals that if the time in contact with the heated surface is increased, it is possible to heat stabilize at the higher speed. It should be possible to heat relax without introducing yarn damage on a larger unit of greater heating capacity than the small pilot machine currently employed.

TABLE XIV

Effect of Various Heat Stabilizing Treatments on Tensile Properties of Repeatedly Stretched and Relaxed Type 5100 Dacron Yarn

Treatment	Breaking Strength (grams)	denier	Tenacity (gms/den)	Rupture Extension (%)	Shrinkage at 350°F. (%)
After Step 7 - No relax	1450	196	7.5	8.3	6.9
Step 7 + Fixed length no relax	1440	197	7.3	8.4	6.0
Step 7 + Fixed length + free shrink	1413	213	6.6	17.2	0.0
Step 7 + Free shrink only	1387	215	6.5	18.2	0.4

TABLE XV

Results of Miscellaneous Multi-Cycling Experiments

Treatment	Breaking Strength (grams)	denier	Tenacity (gms/den.)	Rupture Extension (%)	Shrinkage at 350°F. (%)
None - Control Yarn #1	1338	225	5.9	9.5	21.0
1) 20% H.S. at 400±°F., F.L. at 400±°F., F.S. at 363±°F.	1410	206	6.8	17.6	1.9
2) #1 + 10% H.S. at 400±°F. F.L. at 400±°F., F.S. at 363±°F.	1392	208	6.7	17.4	0.7
3) #2 + 10% H.S. at 400±°F. F.L. at 400±°F., F.S. at 363±°F.	1446	204	7.1	13.6	3.2
4) Repeat of #3	1465	211	6.9	16.3	0.8
5) 20% H.S. at 400±°F., F.L. at 400±°F., F.S. 363±°F.	1414	205	6.9	14.8	2.8
6) #5 + 12.5% H.S. at 400±°F. F.L. at 400±°F., F.S. at 363°F.	1391	203	6.9	15.2	2.1
7) Repeat of #6	1450	203	7.1	15.6	1.7
8) #6 + 12.5% H.S. at 400±°F. F.L. at 400±°F., F.S. at 363±°F.	1400	200	7.0	14.5	2.8
9) Repeat of #8	1410	201	7.0	17.1	1.7

TABLE XV (Continued)

Results of Miscellaneous Multi-Cycling Experiments

Treatment	Breaking Strength (grams)	denier	Tenacity (gms/den.)	Rupture Extension (%)	Shrinkage at 350°F. (%)
10) None - Control Yarn #2	1416	218	6.5	10.0	19.2
11) 20% H.S. at 388°_{+}F., F.L. at 388°_{+}F., F.S. at 375°_{+}F.	1418	210	6.8	17.8	1.0
12) #11 + 12.5% H.S. at 388°_{+}F. F.L. at 388°_{+}F., F.S. at 375°_{+}F.	1464	209	7.0	15.3	1.8
13) 10% H.S. at 388°F. + 10% at 400°_{+}F., F.S. at 375°_{+}F.	1380	215	6.4	15.7	2.2
14) 10% H.S. at 388°_{+}F. + 7% H.S. at 388°_{+}F., F.S. at 375°_{+}F.	1423	218	6.5	17.0	2.4
15) 5% H.S. at 388°_{+}F., + 15% H.S. at 388°_{+}F., F.S. at 375°_{+}F.	1379	214	6.4	18.0	3.1
16) 7% H.S. at 400°_{+}F. + 7% H.S. at 400°_{+}F. + 6% H.S. at 400°_{+}F. - Not relaxed	1424	201	7.1	6.8	10.5
17) #16 + F.S. at 375°_{+}F.	1355	217	6.3	16.4	3.9
18) #16 + F.L. at 388°_{-}F., F.S. at 388°_{-}F.	1306	216	6.4	15.0	1.7
19) 20% H.S. at 450°_{-}F., F.L. at 450°_{-}F., F.S. at 388°_{-}F.	1464	210	7.0	15.2	0.5
20) #19 + 10% at 450°_{-}F., F.L. at 450°_{-}F., F.S. at 388°_{-}F.	1465	211	6.9	16.3	0.8

Abbreviations Used: H.S. (Hot Stretched) F.L. (Held at Fixed Length) F.S. (Freely Shrunk) $^{\circ}_{+}$F. (Slightly above temp. noted) $^{\circ}_{-}$F. (Slightly below temp. noted)

TABLE XVI

Effect of Production Rate on Tensile Behavior of Hot Stretched Heat Stabilized Type 5100 Dacron Yarn

Treatment	Breaking Strength (grams)	denier	Tenacity (gms/den.)	Rupture Extension (%)	Shrinkage at 350°F. (%)
Twisted Control Yarn	1332	227	5.9	12.5	16.0
1) 20% H.S. at 450°F., F.L. at 450°F., F.S. at 450°F. - 57 yards/min.	1402	207	6.8	14.6	4.5
2) 20% H.S. at 450°F. F.L. at 450°F. F.S. at 450°F. - 78 yards/min.	1478	212	7.0	14.3	1.6
3) 20% H.S. at 450°F., F.L. at 450°F. F.S. at 450°F. - 94 yards/min.	1501	207	7.3	14.5	5.7
4) 20% H.S. at 450°F. F.L. at 450°F. F.S. at 450°F. - 136 yards/min.	1437	217	6.6	17.7	3.8
5) 20% H.S. at 450°F. 10% Partial Shrinkage at 450°F., F.S. at 450°F. - 67 yds/min.	1515	208	7.3	14.6	1.8

TABLE XVI (Continued)

Effect of Production Rate on Tensile Behavior of Hot Stretched Heat Stabilized Type 5100 Dacron Yarn

Treatment	Breaking Strength (grams)	denier	Tenacity (gms/den.)	Rupture Extension (%)	Shrinkage at 350°F. (%)
Untwisted Control Yarn	1355	223	6.1	11.0	21.0
6) 20% H.S. at 450°F. F.L. at 450°F. F.S. at 388°F. - 150 yards/min.	1439	214	6.8	16.6	4.2
7) 20% H.S. at 400°F. F.L. at 400°F. F.S. at 388°F. - 200 yards/min.	1494	214	7.0	15.4	6.2
8) 20% H.S. at 450°F. 2 passes of F.S. at 400°F. - 150 yds/min.	1394	212	6.6	17.3	2.0

3.4.2.4.1 Multi-End Processing

Another method which can be used to speed up production is multi-end processing. Several yarns were passed through the machine side by side at the same time. Such a method permits, after hot stretching and stabilizing, the separation of the yarns and winding them onto individual packages for subsequent end item production. Thus, production is increased directly with the number of yarns passing through the machine at one time. Attempts were made to run as many as seven yarns through the pilot unit.

3.4.2.4.1.1 Effect of Production Rate on Multiple End Processing

At the time that the multiple end experiments were being conducted it was thought that a speed of 50 to 75 yards per minute could be used. When the data were assembled, it was found that when more than three yarns were passed through the unit it was not possible to reach the temperature level necessary to cause proper shrinkage, due to the increased operating speed. This resulted in reduced tensile improvements. It is felt however, that shrinkage difficulties at high speeds can be overcome with the use of a somewhat larger stretching-stabilizing machine, wherein a longer heating path would permit attainment of proper yarn temperature. The results of these experiments are shown in Table XVII.

Examination of Table XVII shows that once again increased production rates turned out to be a major problem because of incomplete shrinkage. It was also found that the yarns were not all being hot stretched to the same degree during the multiple end stretching experiments. Any variability in yarn tensioning as the multiple yarn structure passed across the hot stretching surface resulted in non-uniform stretching which, in turn, produced a yarn of variable tenacity. It should be remembered, however, that these experiments were the first and only ones conducted using this method. Further refinements in operating procedure may make it possible to attain the desired product with a minimum of yarn to yarn tensile variability.

3.4.2.5 Miscellaneous Studies

Throughout the current program there have been certain experiments conducted which, while not being part of a definite phase of the work, contributed to the overall development of the basic hot stretching procedure. Some of the studies conducted merely eliminated future modifications in the standard process. Other experiments produced results which indicated the need for further study in certain areas. The inclusion of certain of these experiments in the phase of the final report is deemed advisable to serve as a guide and reference for future research. Table XVIII is a summary of the experimental results.

In general, the results shown in Table XVIII were widely scattered and quite variable. The moistening and chilling experiments did not show any promise. On the other hand, a measurable gain in absolute breaking strength can be made by merely holding at fixed length before applying any

TABLE XVII

Results of Multiple End Processing of Type 5100 Dacron Yarns[1]

Number of Ends	Production Rate (yds/min.)	Breaking Strength (grams)	denier	Tenacity (gms/den.)	Rupture Extension (%)	Shrinkage at 350°F. (%)
1	65	1515	208	7.3	14.6	1.8
2	15	1482	220	6.7	19.6	0.2
3	15	1463	221	6.6	20.7	0.0
3	50	1406	219	6.4	16.0	2.4
4	40	1405	225	6.2	19.3	1.0
5	50	1379	231	6.0	18.2	3.9
6	75	1404	237	5.9	19.3	6.5
7	75	1455	238	6.1	18.4	6.9

(1) All yarns received same hot stretching - relaxing treatment, i.e., 20% hot stretch at 450°F., 10% partial shrinkage at 450°F., free shrinkage at 450°F.

TABLE XVIII

Summary of Results Obtained From Miscellaneous Stretching-Relaxing Experiments (Type 5100 Dacron Used Except Where Otherwise Noted)

Treatment	Breaking Strength (grams)	denier	Tenacity (gms/den.)	Rupture Extension (%)	Shrinkage at 350°F. (%)
Untwisted Type 5100 Dacron Control Yarn	1416	218	6.5	10.0	19.2
1) No Stretch, F.L. at 400±°F. F.S. at 388±°F.	1529	230	6.6	15.8	5.7
2) 20% H.S. at 450±°F., F.L. at 450°F., F.S. at 400±°F. 40 yds/min. (Chilled after F.L. with dry ice)	1414	202	7.0	10.9	2.8
3) 20% H.S. at 450±°F., F.L. at 450°F., F.S. at 400±°F. 40 yds/min. (Chilled after F.S. with dry ice)	1409	206	6.8	13.2	2.6
4) 20% H.S. at 450°F., F.L. at 450°F., F.S. at 388°F. 15 yds/min. (Chilled with ice (H_2O) after H.S. and F.S.	1409	204	7.0	14.9	2.4
5) 20% H.S. at 450°F., F.L. at 450°F., F.S. at 388°F. 15 yds/min. (Moistened with water before F.L.)	1443	203	7.1	14.7	2.8
6. Recheck of #5	1413	211	6.7	16.6	1.0
7) 20% H.S. at 388±°F., F.L. at 388°F., F.S. at 363±°F. (Moistened with water before H.S.)	1361	212	6.4	17.2	2.0
8) F.L. at 450°F., 20% H.S. at 450°F., F.S. at 400±°F. 40 yds/min.	1528	232	6.6	19.2	2.8

TABLE XVIII (Continued)

Summary of Results Obtained From Miscellaneous Stretching-Relaxing Experiments
(Type 5100 Dacron Used Except Where Otherwise Noted)

Treatment	Breaking Strength (grams)	denier	Tenacity (gms/den.)	Rupture Extension (%)	Shrinkage at 350°F. (%)
9) 20% H.S. at 400±°F., F.L. at 400±°F., F.S. at 388±°F. 15 yds/min. (One week time interval between H.S. and F.L. + F.S.)	1461	208	7.0	15.5	0.8
10) Type 300 Nylon Control Yarn	1492	213	7.0	16.2	
11) Type 300 Nylon 20% H.S. at 450±°F., F.L. at 450±°F. - No Relax	1410	182	7.7	12.4	
12) Type 300 Nylon, 20% H.S.at 400±°F., F.L. at 400±°F., F.S. at 363±°F.	1255	187	6.7	13.8	2.8

further treatments (Experiments 1 and 8). In these two tests, however, the denier was increased rather than lowered and hence a very slight increase in tenacity was evidenced. Further experimentation should be undertaken in order to thoroughly investigate this simple holding at fixed length.

Attempts were made to hot stretch and stabilize Type 300 nylon using the same process as is currently used for Type 5100 Dacron. It can be seen from Experiments 10, 11 and 12 that while the absolute strength level was lowered, it was possible to reduce shrinkage without too much loss in tenacity due to the denier reduction brought about by the hot stretching phase of the operation. It may be possible, by choice of proper conditions to produce a higher tenacity, heat stable nylon yarn which may contribute still further to the overall deceleration parachute problem.

IV. CONCLUSIONS:

The conclusions to be drawn from the results of this work may be summarized as follows:

1. Dacron yarn, either Type 5500 or Type 5100, may be converted into a higher strength, nominal elongation, thermally stable yarn by means of stretching at an elevated temperature, holding the yarn at this temperature for a short period of time, and then allowing the yarn to shrink freely at the desired temperature.

2. The conditions required for production of optimum strength-heat stable Dacron yarn at the rate of 25 yards/minute are as follows:

   a. 20% stretch at yarn temperatures of 340-390°F.

   b. Fixed length at yarn temperatures of 430-450°F.

   c. Free shrink at yarn temperatures of 350-370°F.

3. Variation in any or all of the above conditions produces yarn of varying mechanical properties.

4. Further study of the variables involved in the hot stretching-heat relaxing process is required for a more complete solution of the problem.

The development of a high tenacity, nominal elongation, thermally stable Dacron yarn has progressed from a critical review of published technical literature through to the construction and operation of a pilot processing machine. Production on this unit has been such that only relatively small yarn samples could be processed during a reasonable operating period. The basic stretching-stabilizing technique, however, has been well established by the methods employed thus far. The point has now been reached where larger quantities of yarn should be processed in order that various parachute components, e.g., webbings, tapes, and braids could be prepared commercially and evaluated in the laboratory for ultimate end use requirements. This requires a continuation of the study with particular emphasis on commercial prototype yarn production.

While it may be possible to modify existing commercial hot stretching equipment in order to accomplish the desired ends, the construction of a commercial prototype machine should also be considered. The process developed during the previous study is such that it presents certain problems to the commercial manufacturer. Design and construction of a new machine would provide for the embodiment of all of the principles developed to date into one unit, planned to do a specific job, namely, to produce high tenacity, heat stable Dacron yarn.

Although measurable improvements have been made in the tensile and thermal properties of Dacron, there is a continuing need for study of the basic processing technique. Certain results were obtained toward the close of the present program which indicated that still greater yarn improvements could be realized through modifications in the three step process currently employed. It is for this reason that some allocation of time is proposed for further study of processing variables.

Summarizing, therefore, it can be stated that there are three major phases to be considered in a program for future research.

1. Production of sufficient quantities of hot stretched heat stable yarn for commercial preparation and subsequent laboratory evaluation of selected parachute component end items.

2. Design and construction of a commercial prototype machine.

3. Continuation of basic research on processing techniques.