ELASTIC AND CREEP PROPERTIES
OF
FILAMENTOUS MATERIALS

by

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41 Crescent Street
Cambridge, Mass.
September 26, 1941

Professor George W. Swett,
Secretary of the Faculty,
Massachusetts Institute of Technology

Dear Professor Swett:

I submit herewith a thesis, in partial fulfillment of the requirements for the degree of Doctor of Science, entitled,

ELASTIC AND CREEP PROPERTIES
OF FILAMENTOUS MATERIALS.

Yours truly,

Herbert Leaderman

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PREFACE

The work on which this thesis is based has been carried out during the past three years in the Textile Laboratory of the Massachusetts Institute of Technology. During this time the author has been engaged as a Research Assistant in the Institute. His duties in the Textile Laboratory were concerned mainly with the present investigation, which itself was part of a program of research being carried out for the Textile Foundation.

The author wishes to express in this place his deep appreciation for the encouragement and assistance of Professor E. R. Schwarz, who suggested to the author the problem and who enabled the program to be carried out. He also wishes to acknowledge the kindness of the Textile Foundation in allowing him to use for this thesis the results of this research. The author wishes also to take this opportunity to express his appreciation of the kindness and encouragement of Professor A. V. de Forest. To Mr. H. N. Lee the author is indebted for assistance in the measurement of areas of cross-section.

ABSTRACT OF THESIS

This thesis gives the results of an investigation of the mechanical behavior of certain filamentous materials under steady applied longitudinal loads, and following removal of such loads. The results are discussed in terms of the current concepts of the structure and mechanism of deformation of high polymeric materials.

The materials tested consisted of single filaments of silk, viscose rayon (three specimens), acetate rayon, and nylon (two specimens). All tests have been carried out under standard conditions of temperature (70° F.) and relative humidity (65%). In general, the effect of application of a constant maintained load is to produce an instantaneous extension which is followed by a "delayed" extension or "creep". On removal of such a load there is an instantaneous contraction followed by a "delayed" contraction or "creep recovery". Under certain circumstances, the magnitudes of the instantaneous extension and contraction are equal, as are also the magnitudes of the delayed extension and the delayed contraction. Under these circumstances therefore the specimen at the end of the test regains its original length; the creep and creep recovery may then be considered as of the nature of a "delayed elasticity". This delayed elasticity is denoted by the term "primary creep".

The main object of the experimental work has been to determine the conditions under which non-recoverable or

"secondary" creep is absent, and the laws then governing the instantaneous and delayed deformations. If a specimen of filamentous material be allowed to creep under load for say twenty-four hours, the load then removed and the specimen allowed to recover, it has been found that in general there is a non-recoverable deformation, even at loads well below the conventionally defined yield point. If however the load in this experiment be not too large, then on repeat of the experiment at the same load or at lower loads further non-recoverable deformation will be absent. The specimen is then said to be "mechanically conditioned".

The basic type of test used has been denoted "long-duration creep and recovery test". In this test a previously mechanically conditioned filament is allowed to creep under constant load for twenty-four hours, the extensions being observed as a function of time under load. The load is then removed, and the contractions observed as a function of recovery time. In general, it has been found that the "total" (instantaneous together with delayed) deformation in the creep test as a function of creep time is, within experimental error, identical with the total deformation (i.e., total contraction) in the subsequent recovery test as a function of recovery time. The instantaneous deformations have been found to be very closely proportional to the load, and from these deformations "instantaneous moduli of elasticity" have been computed. The delayed deformations have been found to vary with load only by a scale factor; this scale factor is however not one of simple proportionality. Only in this latter respect do the results of the long duration creep and recovery tests differ from those to be anticipated from the hypotheses of the Superposition Principle of Boltzmann. An analysis has been made of all the significant available data in the literature on the creep of glass and metals. This data has been found to be entirely consistent with the Superposition Principle. It is concluded that the instantaneous and delayed deformations of a mechanically conditioned filament follow the Principle with the above modification, and that the non-proportionality of delayed deformation and load is to be considered as due to the high degree of anisotropy of the filamentous materials. It is pointed out that this non-proportionality prohibits a representation of the mechanical properties of the filamentous materials by means of a distribution of relaxation times following the Wiechert-Becker theory.

In order to confirm these conclusions, short duration ("superposition") tests have been performed. In these tests a constant load is applied to a filament for a short length of time, subsequently removed, later reapplied, and so on. The deformation is observed as a function of time. In these experiments, the deformations were found to be consistent with Boltzmann's Superposition Principle, which states that the deformation due to a complex loading history is the simple summation of the deformations due to the separate loading actions. The instantaneous and delayed deformations of mechanically conditioned filaments under longitudinal load have thus been found to be consistent with the Superposition

Principle of Boltzmann, with the modification mentioned above due to the high anisotropy of the filaments.

The creep properties of nylon at high loads have been found to be of a distinctly different nature. In this case the instantaneous deformation is found to increase somewhat more slowly than the load, while the delayed deformation is independent of load. This is consistent with the fact that nylon at high loads yields a stress-strain loop of the type characteristic of rubber.

In the light of the Joule effect in rubber and muscle, the following mechanism of deformation of conditioned filaments is proposed. In high polymers such as the filamentous materials under consideration, both primary and secondary bonds are present. The gradual breaking up of secondary bonds due to thermal agitation of the atoms results in a gradual transference of load to or relief of load from the primary bonds. The outward manifestation of this transfer is a creep or a recovery. Under conditions where the long molecular chains are relatively stiff or where the deformation is small, the delayed deformation is due to elastic bending and stretching of primary bonds ("crystal elasticity"). Such is the case of rayon and silk under standard conditions of temperature and relative humidity, and of nylon at low loads. Under conditions where the long molecular chains are relatively flexible, they are to be regarded as normally highly kinked as a result of statistical coiling up due to their heat motion. Large reversible deformations are the result of the straightening of such chains against their heat motion ("kinetic elasticity"). It is suggested that the change in creep behavior of nylon at high loads is due to a change in the mechanism of deformation. It is suggested also that other materials which show a high reversible extensibility and stress-strain loops of the type of that of rubber should possess the same creep behavior as nylon.

Part I.

INTRODUCTION AND SUMMARY

1. Scope of Thesis

This thesis is concerned with those time-effects which, in the absence of permanent structural change, are associated with the mechanical deformation of high polymeric materials. Such time effects are usually denoted by the term creep. The thesis contains the results of experimental work which has been carried out on the longitudinal creep properties of certain filamentous materials, namely, silk, nylon, and viscose and acetate rayons.

2. Importance of the Subject

In the case of polycrystalline metals and some other materials deviations from Hooke's Law are usually regarded as an indication of imperfect mechanical behavior. With high molecular weight organic materials such as rubber, plastics, and textile fibers this cannot be the case. These materials owe their valuable physical properties very largely to deviations from Hooke's Law elasticity, in particular to the time effects being considered here. The purpose of the present investigation is to reduce to a simple system the manifestations of the time effects in high molecular weight materials. Such an investigation has not only an immediate technical application in indicating logical testing methods, but also great scientific value in connection with the problems of structure and mechanism of deformation of these substances.

3. Nature of the Problem

It is well-known that when a constant load is applied to a specimen of high polymeric material, the deformation is usually not constant but increases with time. It is less well known that subsequent to removal of load a gradual recovery of deformation may take place. The problem in connection with the investigation of filamentous materials reduces itself simply to the determination of the conditions such that the specimen will eventually regain its original form after removal of load, and of the laws then connecting deformation and time.

The problem of the creep of textile fibers is however but one aspect of a far larger problem, namely, the creep of high polymeric materials. Before a systematic study can be made of the creep properties of any high polymer, it is necessary to review first, phenomena of creep in materials and the laws governing these phenomena, and secondly the present day concepts of the structure of such materials. Accordingly, an important part of this thesis is devoted to such a review, which is considered to form a basis not only for the present study but also for the study in general of the mechanical properties of high polymers.

4. Arrangement of Thesis

The arrangement of the thesis follows the requirements of the problem as indicated above. Part II deals first with the various forms in which creep is manifested in materials. The subject is introduced by considering in historical sequence some of the early but nevertheless very interesting and significant papers; for completeness some of the early theories are included. The Superposition Principle of Boltzmann is then considered from all aspects; this Principle indicates how by means of two plausible assumptions the deformation may be predicted from a given stress history. It is then shown that, especially for glass, the Superposition Principle is valid either in its general form or over limited intervals of time in approximate modifications.

Part III, which deals with some of the mathematical aspects of the problem, is based upon the Wiechert theory. Starting with the concept of a Maxwell relaxation time, a series of mechanical models is developed, which give a physical significance to the mathematical concepts of the theory. The effect of temperature on (reversible) creep is considered, and also the manifestations of the phenomenon of creep in a material under dynamic load.

Part IV presents in outline the development of the modern concepts of the structure of high polymeric materials, and the application of these concepts to the problem of creep.

Part V deals with the experimental work. The apparatus and experimental technique are described in detail. The data presented is discussed both phenomenologically and in terms of the structure of filamentous materials.

Part VI consists of a chronologically arranged bibliography containing papers and books consulted in the course of this work. The bibliography is reasonably complete as far as references to primary creep and associated phenomena are concerned. The work that has been carried out in recent years on the structure and properties of high polymers is however so extensive that it has not been possible to consult or include all the references in this field.

Part II.

PRIMARY CREEP AND THE SUPERPOSITION PRINCIPLE

I. Early Work on Primary Creep.

According to Hooke's Law, the ideal elastic behavior of a material is that in which the deformation of a material is always proportional to the stress causing the deformation. Hard metals and single crystals obey this law very nearly over certain ranges of stress; the gradual change of strain with time under constant stress is accordingly to be regarded as a departure from perfect elasticity. It is to be observed that perfect elasticity is in many cases highly desirable, for example, where it is required to measure a force by the deformation of a spring. About a hundred years ago, the early physicists who were investigating electrical and magnetic phenomena were in the habit of using the torsional elasticity of fine glass, silver, and silk filaments in order to measure electrical and magnetic forces. It was found, however, that these filaments were by no means perfectly elastic. In seeking empirical corrections for the elastic imperfections in these materials, these physicists were led to the study of their creep properties. In the course of this work, which was carried on over a period of more than forty years by Weber and by R. and F. Kohlrausch, the fundamentals of creep were discovered.

Creep and Creep Recovery

Wilhelm Weber[1] in Göttingen in the year 1835 was investigating the elastic properties of raw silk filaments. He found, not unexpectedly, on applying a longitudinal load to a filament that there was an immediate elastic extension which however gradually increased with time. According to notions as much current then as today, this was taken as an indication that raw silk was "imperfectly elastic". On removal of load, there occurred an immediate contraction of the filament equal to the initial immediate extension. Weber found however that if the specimen were left undisturbed and free from load, there took place, most unexpectedly, a gradual further contraction of the filament. If a specimen were allowed to extend under constant load for 24 hours, then after removal of load the magnitude of this gradual contraction after a subsequent period of 24 hours amounted (under certain circumstances) to the gradual extension in the period under load. Weber pointed out that the "flow" under load was therefore not to be regarded as an irreversible yield, but as that part of the reversible deformation which depended on the duration of loading. To indicate that the gradual extension (or creep) under load and the gradual contraction (or creep recovery) following removal of load were manifestations of a single phenomenon, he denoted both these effects by the term "elastische Nachwirkung". This term has been used uniquely by German writers to describe this phenomenon. The literal translation "elastic after effect" is to be avoided, since to many people it refers only to the creep recovery, but not to the associated previous creep.

In the light of the above discovery, we can now introduce some fundamental definitions. On application of a constant load to a body, there occurs first an instantaneous deformation (which may correspond to Hooke's Law), and then a delayed deformation or primary creep. On removal of load there is first a (negative) instantaneous deformation. The creep recovery manifests itself as a residual deformation which gradually decreases and finally disappears in the course of time. These deformations are shown diagrammatically in Fig. 1a.

If the body does not recover back to its original size or shape, then superimposed upon the reversible primary creep when under load there must have been a non-recoverable or secondary creep. Weber indicated how by suitable pretreatment it might be possible to eliminate secondary creep. We shall call this pretreatment mechanical conditioning. The terms viscous flow and plastic flow refer to special types of secondary creep that occur, for example, in glass and metals at elevated temperatures.

Relaxation of Stress

In his very illuminating paper Weber introduced a further concept of great importance, namely, relaxation of stress.

If, for example, a body manifesting the property of primary creep under load be extended suddenly and held at constant extension, there will be a gradual decrease or relaxation of stress. Extending Weber's concept, we see that if the body be subsequently instantaneously restored to its original size or shape, a residual stress (corresponding to the residual deformation in the constant load case) will be set up which will eventually disappear in time. These phenomena are illustrated in Fig. 1b. For example, we can twist a filament through a given angle and measure the relaxation of torque. We can then untwist the filament and measure the residual torque. Alternatively, a mixed type of experiment can be carried out. A filament, if twisted through a fixed angle for some time and then freely released, will show a residual twist. In the absence of secondary creep this will gradually disappear in the course of time.

Weber's Law of Creep

The law of creep originally propounded by Weber is as follows. If t is the time reckoned from some instant following the load application, then the length at time t is given by

$$x = x_0 - \frac{a}{c+t} \qquad (1)$$

where a and c are constants and x_0 is the length at infinite time; similarly for creep recovery

$$x = x_0 + \frac{a}{c+t} \qquad (2)$$

In his second paper[2] Weber found that this simple law could not be made to fit all his data. In discussing the cause of the phenomenon he said: "It appears that following a sudden alteration of the load on a filament, a position of complete equilibrium is not immediately attained, but is in fact approached asymptotically with time. We cannot conceive or observe what is necessary for complete equilibrium. This seems to depend upon a definite orientation of the elastic axes of the particles relative to each other. This orientation is approached only extremely slowly. Presumably the origin of the elastic after-effect lies in the difference in position of the elastic axes of the particles relative to that of the equilibrium position." Weber then suggested that the creep rate dx/dt could be expressed as a function of the deformation,

$$dx/dt = f(x) \tag{3}$$

and in particular, that the function was some power of x. If $f(x) = \frac{x^2}{b}$, then equation (1) above is obtained. If in general

$$f(x) = bx^m \tag{4}$$

then the relation between x and t is of the form

$$x = k\ (t+c)^n \tag{5}$$

where n is of course negative.

F. Kohlrausch later pointed out that since three variables were involved, namely, strain, stress, and time, it was necessary in order to elucidate the relationships to keep either stress or strain constant. Weber did not do so in his experimental arrangement; accordingly the quantitative laws he proposed are of less interest than his remarks concerning the nature of primary creep and creep recovery. Weber pointed out that the magnitude of the after-effect amounted in the case of raw silk to about one-third of the instantaneous elastic deflection, and therefore could not be neglected; he suggested that the extension under given conditions eventually reached a limiting value, and that in the case of silk the equilibrium position might require the passage of one or more days to attain.

The Work of R. Kohlrausch

The next stage in the investigation of creep phenomena is concerned with the work of R. Kohlrausch[3,4]. Though most of this work was later repeated in greater detail by his son, F. Kohlrausch, these early experiments are nevertheless worth considering, in that they show with what simple means the basic phenomena can be demonstrated. As with Weber, R. Kohlrausch's interest in the problem arose from the necessity of knowing the effect of primary creep on the readings of his instruments.

Creep Phenomena in Torsion

The first experiments were concerned with the torsional creep of raw silk and glass, and in particular the residual twist due to twists of various durations and magnitudes. R. Kohlrausch[3] first twisted a raw silk filament through an angle of 1080° for 10 minutes. Immediately after release it showed a residual twist of 60°; at times 2, 7, 16, 30, and 45 minutes after release the residual twist was respectively 37°, 18°, 9°, 5°, 4°. It appears therefore that the recovery from a short loading action requires a much greater length of time than the duration of that action, and that the relaxation during even a brief period can correspond to a large amount of the original twist. This effect was found to be present also in glass, but in this case was of a much smaller order. A twist of 360° for 1 minute showed on release a residual twist of 0.5°, which disappeared in some three minutes. On the other hand, when the twist was maintained for 4, 16, and 480 minutes, the corresponding residual twists were 1.8°, 3°, and 6°, and required respectively 13, 105, and 720 minutes to disappear. We see here that in general the recovery process is slower than the creep, and that creep (or relaxation) due to a stress (or strain) of shorter duration requires a relatively longer time for the effects to disappear. Of course, the recovery effect is an asymptotic one. Finally, R. Kohlrausch twisted the glass filament for 2 minutes through respectively 720° and 1440°. The immediate residual twist on release of the torque was 2.3° and 4.7° respectively. The creep effects thus seem to be proportional to strain.

Creep Effects in Dielectrics

A study by R. Kohlrausch[4] of the decay of charge and the phenomenon of residual charge in a Leyden jar led him to suggest that the behavior of dielectrics was analogous to the creep and recovery properties of solid materials under mechanical load. This view has been generally accepted, and in fact the modern theory of losses in dielectrics is based on concepts developed in connection with mechanical creep. These concepts have also been successfully applied to magnetic creep. R. Kohlrausch found that the law of creep proposed by Weber did not fit his data on dielectric creep. He proposed a somewhat more complex law; this law was adapted several years later by his son, F. Kohlrausch, to mechanical creep.

The Work of F. Kohlrausch

The experimental work of F. Kohlrausch in the field of primary creep extended from 1863 to 1876. This is contained in three lengthy papers[5,6,18], giving results on the creep of glass filaments and fine silver wires in torsion, and also of rubber threads in torsion and tension. Owing to the lack of any fundamental knowledge of creep existing at that time, Kohlrausch tried several different types of test in his work. In the tests on glass, the filaments were twisted through a given angle and later untwisted. The relaxation of the applied torque or the residual torque was then measured. This type of experiment can be considered as fundamental, though difficult to perform. In his experiments on silver wires the specimens were twisted through a given angle and then released, the recovery of residual twist being then measured. This type of experiment, though easy to carry out, is less fundamental. It is capable of interpretation only under certain conditions, namely, when the creep is small compared to the initial elastic deformation. The residual deformation after release from a constant deformation may then be considered as that due to a constant stress. This interpretation is not possible when dealing with high polymers. The large deformations possible in rubber enabled Kohlrausch to study longitudinal as well as torsional creep.

Experiments on Glass: Torque Relaxation and Residual Torque

The first results[5] published by F. Kohlrausch in 1863 contained data on the torque relaxation and residual torque in glass. The torque was applied to a suspended glass filament by the action of the earth's magnetic field on a small suspended magnetic needle; on twisting the suspension through 1080°, the needle was brought into a position nearly at right angles with the earth's magnetic field. Of course relaxation of stress would result in a reduction of the angle of twist; an ingenious arrangement however enabled this twist to be reinserted by hand rotation of the whole apparatus. In this way the torque under constant angle of twist was obtained.

Kohlrausch presented his results in tabular form, expressing the torque at a time measured from the instant of applying the twist in terms of the torque required to hold the needle at right angles to the earth's field. On account of the extended nature of the phenomenon, the most illuminating method of presentation is a plot to a logarithmic time base. Fig. 2 shows the torque relaxation on this basis for two similar glass filaments, Specimens "A" and "B", plotted against the time under strain in minutes (to a logarithmic scale). It is seen that the relaxation properties of the two filaments were markedly different; this suggests that primary creep is a "structure-sensitive" property of materials. While the creep over a limited region of time may be regarded as approximately logarithmic, both the logarithmic plots are seen to be slightly concave downwards up to about 100 minutes, and concave upwards for the rest of the curve. It will be observed that after 24 hours the stress had relaxed to about 97% of its initial value.

Effect of Angle of Twist

Kohlrausch showed that the relaxation effect in a glass filament was nearly proportional to the angle of twist. Specimen "A" of the previous test was held under a twist of respectively 1080° and 720° for 24 hours, and the residual torque measured after restoring the filament to zero twist. These results are shown in Fig. 3. As was suggested by R. Kohlrausch, the residual torques at corresponding instants are seen to be nearly in the same ratio as the angles of twist.

Effect of Length of Time under Strain

If a glass fiber be allowed to relax under constant strain for a given time and the residual torque measured after removal of strain, the residual torque will be greater and will require a longer time to disappear, the longer the time under strain. F. Kohlrausch showed this to be true for a glass filament. Fig. 4 refers to Specimen "B", and shows the residual torque plotted against time from release of strain, the strain being a twist of 1080° in all cases and the time under strain respectively 10, 20, 40, and 1380 minutes. Of course, since recovery to the initial position is an asymptotic effect, this probably required in all cases several days for completion. The initial portion of each recovery curve is seen to be approximately linear on the logarithmic plot. If we draw straight lines through the initial portions of the curves, these lines intersect the time axis at 38, 50, 95 and 1400 minutes respectively, i.e., 3.8, 2.5, 2.4, and 1.0 times the corresponding length of time under strain. Thus roughly speaking, neglecting the "toe" of the recovery curve, we might say that the effect of a strain of short duration requires a relatively longer time to disappear than a strain of longer duration. This again is in agreement with the rough results of R. Kohlrausch.

Kohlrausch's Theory of Creep

Referring to Fig. 4, it can be seen that the longer the period under strain, the slower is the rate of fall of residual torque at any given value of residual torque. Hence Weber's theory of creep, which postulated that the rate of recovery was a function merely of the displacement, cannot hold. To replace Weber's law, F. Kohlrausch proposed a law which was analogous to the one previously proposed by his father in connection with the dielectric problem (p. 12): that the rate of change of torque should be proportional to the torque and inversely proportional to some power of the time from the last strain change. Analogous laws were proposed for creep and recovery experiments. Thus if x is the torque (or angular deformation) and t is the time from the last load or strain change,

$$\frac{dx}{dt} = -\frac{ax}{t^n} \tag{6}$$

then

$$x_t = x_o + ce^{-at^m} \tag{7}$$

where $a = \frac{\alpha}{1-n}$

$m = 1-n$

x_o = final torque or deformation

x_t = deformation at time t.

If $n = 1$, then $m = 0$; Equation (7) becomes

$$x_t = x_o + ct^{-\alpha} \qquad (8)$$

It will be seen that Equation (7) requires three constants to determine a curve and Equation (8) requires two. The latter equation generally applied to the recovery following short duration creep, and the former to recovery following longer duration loading. In a series of tests such as that of Fig. 4 Kohlrausch found that it was necessary to vary at least two of the three constants of Equation (7) in proceeding from one curve to the next. Thus to fit Equation (7) to the curves of Fig. 4 nine constants were required by Kohlrausch. By fitting different constants to each individual curve, Kohlrausch found that a very good fit could be obtained to the experimental data over a wide time-range. In fact, the above Equations (7) and (8) fitted sets of observations obtained by most diverse methods so well, that Kohlrausch suggested at one time that the law of Equation (6) might even be the fundamental law of creep.

Kohlrausch's Work on Silver Wires

The work on the creep properties of silver wires[6] confirmed and extended the previous results. The method of test adopted was simpler than in the previous case, the wires being twisted through a given angle for a given time, and then released. The decrease in the residual angle of twist with time was then measured. Since the magnitude of the creep in silver is small compared to the instantaneous elastic deformation, the observations correspond roughly to the recovery following creep under constant torque. These results are of greater interest than those on glass, in that the residual deformation dies away relatively more slowly.

Silver Wire: Effect of Duration of Twist

The decay of residual twist (creep recovery) of silver wire after twist through constant angle for various lengths of time is closely analogous to similar results for glass (Fig. 5). As in the case of glass, the initial parts of the curves are seen to be nearly linear on the logarithmic plot; the same remarks apply as before.

Silver Wire: Effect of Angle of Twist

Kohlrausch's data on the residual twist against time, i.e., creep recovery, of a silver wire, after being twisted through various angles for one minute, is plotted to a double logarithmic scale in Fig. 6. The curves are seen to be of the same shape, but displaced vertically relative to each other, indicating that the recovery curves differ only in a scale factor. The magnitude of the residual deformation is again found to be very closely proportional to the angle of twist.

The Effect of Temperature on Primary Creep

In the course of this work Kohlrausch discovered a very important property of the primary creep of materials, namely, the temperature effect: the creep properties of a material are markedly affected by variations of temperature of test, even at temperatures far removed from a change of state of aggregation. This discovery arose as a result of an attempt to reproduce some results, in which experiments carried out at a low temperature showed a very small residual deflection.

Some of these results are shown in Fig. 7. This gives the residual twist (to an arbitrary scale) plotted against the logarithm of the recovery time for a silver wire, twisted through 180° for 1 minute, and then released. It is seen that the effect is nearly trebled on raising the temperature from 3.5°C. to 33.4°C. Two conclusions were drawn by Kohlrausch from this discovery: firstly, it was necessary during a test to keep the temperature as constant as possible, and secondly, that a series of tests carried out over a moderate range of temperatures would be likely to yield important information concerning the mechanism of creep. Both these conclusions have been confirmed by subsequent research. At a later stage it will be possible to give a quantitative interpretation to the results of Fig. 7.

Kohlrausch's Work on Rubber

Kohlrausch's tests on rubber threads[18] represent the first systematic work on the group of materials we now call high polymers. This work falls into three sections. The first section, dealing with the residual twist or extension due to twist through constant angle or extension at constant length respectively, is of little interest on account of the large variation in stress during the test. The second section of Kohlrausch's work deals with longitudinal creep under constant load, (with the specimen under load for a long period of time) followed by measurement of the recovery after removal of load. This experiment of course follows the pattern of Weber's original experiment, with the important difference of constancy of load during creep and recovery. The third section of this work is qualitative and consisted in a study of the creep recovery following complex loading history -- a famous investigation which revealed the physical existence of a "memory effect".

Longitudinal Creep of Rubber under Constant Load.

In this test a constant longitudinal load was applied to a rubber thread and the extension due to application of load measured over a period of 24 hours. The load was then removed, and the contraction due to removal of load measured over a further period of 24 hours. These tests were carried out with loads of 1 gm., 2 gms., and 4 gms. respectively. Due to the large extension, in the case of the 4 gms. load, the stress was by no means constant during the creep test. For the other two cases where the variations in stress were smaller the extensions and contractions are plotted in Fig. 8. The results indicate that under constant load the deformation tends to a finite limit in the course of a day or so, as suggested by Weber. The results suggest also that following long-duration creep in which the creep has essentially reached completion, the contraction due to removal of load, as a function of recovery time, is the same as the extension as a function of creep time. The results indicate thirdly that the creep or recovery curves are basically the same shape, the magnitude of the deformation being proportional to the load. This type of test, though time consuming, yields much information; we must accordingly consider it as a basic type of test. On this account we conclude that short time creep tests are of little value, and that to obtain the fundamental information of the creep properties of a material the expenditure of much time is necessary. This is one of the important lessons to be learned from a study of this early work.

The Effect of Temperature on Longitudinal Creep

The basic nature of this type of experiment is further demonstrated by the analysis of the results of an experiment on the effect of temperature on the longitudinal creep of rubber. Kohlrausch measured the deformation with time of a rubber thread when loaded with a weight of 2 gms., at different temperatures. As usual, Kohlrausch presented his results in tabular form. Let us first consider his remarks concerning these results:- "There is here an enormous temperature effect. At a higher temperature the increase in length at a very short time after application of load is very much greater than that at a lower temperature; at later instants, however, the difference decreases with increase of creep time. It might be assumed that the difference finally disappears, and that the increase in length after a day would amount to the same in each of the tests."

His data for various temperatures is plotted in Fig. 9. From this plot it is not unreasonable to suppose that the creep curves are identical in shape but displaced relative to each other along the axis of logarithmic time; the effect of increase in temperature would then be to contract the time scale. This in fact is the conclusion to be drawn from recent research.

The Memory Effect and Primary Creep

At this stage it is necessary to digress from the strictly historical presentation in order to mention that two years before the work of Kohlrausch under discussion was published, Boltzmann[9] had published a paper giving a theoretical treatment of the problem of primary creep and creep recovery. This paper, doubtless based on the very meager amount of experimental material available up to that time, presented a revolutionary concept. The deformation at any instant was assumed to be due to the entire previous loading history, and was in effect the simple summation of the deformations due to each loading action taken separately. This assumption lead to an integral equation for creep, whereas previous theories had involved differential equations (Equations 3 and 6). Such a revolutionary concept of course was bound to meet with opposition[14,27]. Kohlrausch, in spite of the fact that his own formula (Equation 7) gave in all cases a very good fit, preserved an open mind[13]. With a rare scientific detachment, Kohlrausch suggested that his formula might after all be only empirical, and that his data would then be of value in testing alternative theories[18].

With this attitude of mind, Kohlrausch realised that it was possible to demonstrate qualitatively the existence of a superposition process in a very striking manner. He remarked:[18] "In general, the elastic after-effect shows the property, that the creep recovery deflection of a body disappears at a slower rate, the longer the time elapsed since the instant of load removal.

"Now if different after-effects are in some way superposable, it seems possible from the above that a state of affairs can be created in a body such that, without external influence, it can change its direction of motion. For example, suppose that a large deformation or one of long duration is applied to a body, and then a smaller deformation of shorter duration applied in the opposite direction, and the body then released. It would be expected that at first the more recent recovery from the later deformation would be dominant. Since the more recent effect would decline more rapidly, then after some time, with a suitable choice of the quantities involved, the earlier recovery can outweigh the later one. Thus the direction of motion of the body would change its sign.

"This supposition seemed to me to be worthwhile testing. Apart from the remarkable behavior which might be manifested by an elastic body in spontaneously moving temporarily away from the position of equilibrium, I wanted in this way to confirm in a convincing manner this outstanding creep characteristic. Furthermore, the problem of the superposition of different after-effects needed testing.

"As can be seen from the following, the above anticipation is in fact completely realised; as a matter of fact I have produced creep recovery with change of direction in torsion, extension, and bending."

Fig. 10 gives Kohlrausch's graphical presentation of the observations of recovery deflection against time following complex loading histories; the curves refer to the creep recovery of a rubber thread in torsion and in tension and of a hard rubber beam in bending. The details of these tests are given in Kohlrausch's paper. The most remarkable is curve IV, redrawn with threefold abscissa as curve IVa. In this test the creep recovery changed its direction of motion twice. A rubber thread was twisted to the left through 180° for 19 minutes, released for 50 minutes, twisted to the right through 55° for 3 minutes, and immediately afterwards to the left through 180° for 5 seconds. The direction of motion of the recovery deflection is seen to have changed at about 3/4 minute and again at about 6 minutes after the release of the thread, thus indicating the existence of some superposition mechanism. It is necessary, as Kohlrausch pointed out, to choose correctly the relative magnitudes of the loads and their durations, otherwise merely points of inflexion are obtained, as in curve V.

Kohlrausch states: "To my knowledge there are only a few processes as remarkable as this spontaneous change of direction of motion of an inanimate object. While the problem of the elastic after-effect has already shown itself to be most worthy of attention, it has as yet received no satisfactory physical explanation. However, the simultaneous creation of several after-effects in one and the same body requires alteration of the hypotheses on which the theory of elasticity is currently based. By means of the spontaneous reversal of the direction of change of form, it can be shown directly that for one and the same external shape different molecular arrangements are possible, and that there are elastic forces which can temporarily increase the deformation of a body away from the equilibrium position."

With these remarks Kohlrausch indicated the insufficiency of the creep law he had himself propounded in 1863 (p. 15), which required that the direction of creep recovery be always towards the equilibrium position.

Concluding Remarks on the Early Work on Primary Creep

In reviewing the early work on creep, we see that the earliest experiments of F. Kohlrausch were designed to imitate actual service conditions, in order to obtain useful data. Such experiments of short duration, however, lack any fundamental basis and admit of no very simple interpretation. Kohlrausch's later work on rubber, on the other hand, is capable of such a simple interpretation that the fundamental nature of such experiments cannot be doubted. Kohlrausch's proof of the existence of a superposition or "memory" invalidated his own creep law (equation 6), a fact that he himself was quick to indicate. However, both the methods of Kohlrausch's early tests and the equation of Kohlrausch have appeared very frequently in the literature of creep. Though in many cases the results of such tests are amenable to analysis in the light of the Superposition Principle of Boltzmann, they throw little additional light on the phenomenon of primary creep.

II. The Superposition Principle of Boltzmann

The Superposition Principle was proposed by Boltzmann[9] in 1874 as a starting point by which the complex manifestations of primary creep could be reduced to some simple scheme. Apart from subsidiary, later papers defending his viewpoint, the enunciation of the Principle represents the only incursion of Boltzmann into the field of creep. Boltzmann at that time* gave no proof based on theoretical grounds for his rule; indeed, since there was then practically no direct knowledge of the structure of solids, we would not give much weight to any such proof. Boltzmann indeed suggested that his theory was only a first approximation to the creep behavior of solids, so that in applying his general theory he made certain approximations to obtain very simple relationships that could be compared with experimental data. It must be remembered that the Principle was enunciated two years before the publication by Kohlrausch of his data on rubber, and the possibility of the reversal of the direction of creep recovery after a suitable loading history, a direct qualitative confirmation of the superposition effect, was not anticipated by Boltzmann.

The object of this section is to present the Principle in its general form from various mathematical viewpoints.

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* In 1878 Boltzmann[24] indicated the mechanism of creep he had conceived as giving rise to superposition.

The theory will then be applied to the consideration of the creep and relaxation behavior of materials following certain simple loading histories. Next, data of fundamental importance from the very recent literature of primary creep of high polymers will be introduced. This part of the thesis will then be concluded with a presentation of the laws of creep that have been proposed, which represent approximations to the creep curve for constant load over limited ranges of time. These laws, the logarithmic law of Boltzmann and the power law of Hopkinson, are worth considering since under certain conditions they have a technical value in representing the creep properties of materials.

Boltzmann's original presentation is somewhat complex, the viewpoint being that of the relaxation of stress of a body subjected to a given strain history. Though this may be more fundamental from the theoretical point of view, yet it represents a type of experiment which is less convenient to carry out. Boltzmann also assumes a separate relaxation of distortional and dilatational stresses. In this thesis two simplified methods of presentation from the viewpoint of strain creep under a given loading history are given. Boltzmann's original presentation is included for completeness.

Derivation of the Fundamental Equation (First Method)

The following deals only with deformations in the absence of structural change. The basic assumption of the Principle can be stated as follows. At any instant the deformation of a specimen of material manifesting primary creep can be divided into two parts. One part is the instantaneous deformation, proportional to the stress acting at that instant. The other part is the delayed deformation or primary creep component, which depends upon the entire previous loading history.

Let us assume now that a constant load* P be applied to a specimen at zero time. There will be an instantaneous deformation given by $\frac{FP}{E}$, where E is the appropriate modulus of elasticity and F is a form factor. The deformation subsequently increases by the delayed component, which eventually reaches a limiting value. The <u>first assumption</u> is that the magnitude of this delayed component at any given time after the application of load is proportional to the load. The delayed deformation at time t can then be written:

$$\left(\frac{FP}{E}\right)\beta\psi(t)$$

where $\frac{FP}{E}$ is the instantaneous elastic deformation and β is a constant. The function $\psi(t)$ is thus a function of time increasing from zero at zero time to a finite value at infinite time. This function is called the <u>creep function</u>, and represents to some scale the delayed component of the deformation. The total deformation at time t due to a load P applied at zero time is then

$$y_t = \frac{FP}{E}\left[1 + \beta\psi(t)\right] \qquad (9)$$

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* or stress, when the cross-sectional area varies appreciably with deformation.

The variation of this deformation with time is shown in Fig. 11. The deformation dy at a time t due to a load dP applied at a previous time θ is then

$$dy = \frac{F}{E} . dP \left[1 + \beta\psi(t-\theta)\right] \qquad (10)$$

Now let the <u>loading history</u> of the specimen be given by the curve XX in Fig. 12. We wish to find the deformation at a given time t due to the entire previous loading history. If at some previous (current) time θ the rate of increase of load was $\frac{dP}{d\theta}$, then the increase of load in a short interval of time dθ was of course $(dP/d\theta)d\theta$. The deformation at time t due this increment of load at time θ is then from equation (10):

$$dy = \frac{F}{E}\left[\frac{dP}{d\theta} . d\theta + \beta\frac{dP}{d\theta} .\psi(t-\theta) . d\theta\right] \qquad (11)$$

The <u>second assumption</u> is that the deformation at time t is the simple summation of the deformations due to the elementary load increments dP. Hence the deformation at time t is obtained by integrating equation (11) from the present (θ = t) to infinite past time (θ = $-\infty$). Then

$$y_t = \frac{F}{E}\left\{\int_{-\infty}^{t}\frac{dP}{d\theta} . d\theta + \beta\int_{-\infty}^{t}\frac{dP}{d\theta} .\psi(t-\theta) . d\theta\right\}$$

$$= \frac{F}{E}\left\{P_t + \beta\int_{-\infty}^{t}\frac{dP}{d\theta} .\psi(t-\theta) . d\theta\right\} \qquad (12)$$

where P_t is the load at time t. In this integration, we may consider t as fixed and the "elapsed time" $\omega = t-\theta$ as the variable. Then

$$y_t = \frac{F}{E}\left\{ P_t + \beta \int_{\infty}^{0} \frac{dP_{t-\omega}}{d\omega} \psi(\omega) \, . \, d\omega \right\} \qquad (13)$$

This is one form of the general superposition equation.

Derivation of the Fundamental Equation (Alternative Method)

In the above method the deformation at time t was obtained by summing the deformation due to the elementary increments in load. The alternative method, due to Becker[59], considers the residual deformation at time t due to the previous loading history. Let us assume that a load P_θ is applied at a previous time θ, and removed at time $(\theta + d\theta)$. Of course, the deformation due to this loading action will not disappear immediately; there will be a residual deformation, which will gradually die away in time. In this method of approach, we assume that the deformation at time t is equal to the instantaneous elastic deformation due to a load P_t applied at time t, together with the simple sum of all the residual deformations due to all the previous transient load applications P_θ for lengths of time $d\theta$.

Let the loading history be now as represented by XX in Fig. 13. We wish to find the residual deformation at time t due to a load P_θ applied at time θ and removed at time $(\theta + d\theta)$. From equation (9) this is seen to be

$$dy = \frac{F}{E} P_\theta \, \beta \left[\psi(t-\theta) - \psi(t - \overline{\theta + d\theta}) \right]$$

$$= - \frac{F}{E} P_\theta \, \beta \, . \, \frac{d\psi(t-\theta)}{d\theta} \, . \, d\theta \qquad (14)$$

The residual deformation at time t due to the previous loading history is then the integral of this expression from

$\theta = -\infty$ to $\theta = t$. Adding the instantaneous elastic deformation due to the load P_t applied at time t, we get for the deformation at time t:-

$$y_t = \frac{F}{E}\left\{P_t - \beta \int_{-\infty}^{t} P_\theta \frac{d\psi(t-\theta)}{d\theta} \cdot d\theta\right\}$$

$$= \frac{F}{E}\left\{P_t + \beta \int_{0}^{\infty} P_{t-\omega} \frac{d\psi(\omega)}{d\omega} \cdot d\omega\right\} \qquad (15)$$

Equation (15) is seen to be the same as equation (13) and can be derived from the latter by integration by parts.

Since $\psi(\omega)$ represents to some scale the creep component of the deformation due to constant load as a function of the time elapsed from the instant of load application, then $d\psi(\omega)/d\omega$ represents to the same scale the rate of creep. We call the function

$$\phi(\omega) = d\psi(\omega)/d\omega$$

the recollection function since it represents the contribution of a previously applied load $P_{t-\omega}$ to the present deformation y_t. Equation (15) then becomes:-

$$y_t = \frac{F}{E}\left\{P_t + \beta \int_{0}^{\infty} P_{t-\omega}\,\phi(\omega)\ d\omega\right\} \qquad (16)$$

This is the form of the equation as derived by Becker. Though the physical significance of equation (16) is not as obvious as that of equation (13), yet the first-mentioned is in most cases the more useful.

The Superposition Principle (Boltzmann's Presentation)

This presentation gives the stress due to a given strain history. Boltzmann[9] assumes a rectangular isotropic body whose edges are parallel to the axes of the co-ordinates. To the body are applied in general normal strains e_{xx}, e_{yy}, e_{zz} and shear strains e_{xy}, e_{yz}, e_{zx}. Let us consider first the relaxation of one of the shear stress components due to previous strain history. If μ is the modulus of rigidity, the elastic component of the shear stress corresponding to the strain $(e_{xy})_t$ at time t is

$$(T_{xy})_t = \mu(e_{xy})_t$$

We assume as before that the relaxation of this stress due to a strain $(e_{xy})_\theta$ applied at a previous time θ for a length of time $d\theta$ is

$$-(e_{xy})_\theta \cdot \phi_1 (t-\theta) \cdot d\theta$$

where ϕ_1 is the recollection function for shear strain and contains the constant of proportionality. Then assuming a simple summation of the elementary relaxations the shear stress at time t is

$$(T_{xy})_t = \mu(e_{xy})_t - \int_0^\infty (e_{xy})_{t-\omega} \cdot \phi_1(\omega)\, d\omega \qquad (17)$$

where ω is as before the elapsed time reckoned backwards from the instant of time t.

The case of relaxation of tensile stress is more complex, in that a tensile stress produces both a distortion and a dilatation. For the representation of the stress in terms of strain, Boltzmann adopts Lame's notation* in which Δ is the dilatation ($= e_{xx} + e_{yy} + e_{zz}$) and λ is Lame's constant. Then in the absence of creep the stress in the x direction is given by

$$P_x = \lambda\Delta + 2\mu e_{xx} \tag{18}$$

Boltzmann now assumes that the relaxation of dilatational stresses and of shear stresses may behave differently; accordingly, if we write ϕ_2 for the recollection function for dilatational strain, then the tensile stress at time t becomes

$$(P_x)_t = \lambda\Delta_t + 2\mu(e_{xx})_t - \int_0^\infty \left\{\Delta_{t-\omega}\cdot\phi_2(\omega)\,d\omega + 2(e_{xx})_{t-\omega}\cdot\phi_1(\omega)\,d\omega\right\} \tag{19}$$

Boltzmann indicated that by means of these equations it would be possible to determine the relationship between ϕ_1 and ϕ_2. Since the experiments he suggested involved only torsion, the complication of two recollection functions did not arise. He also suggested that it was probable that there was no elastic after-effect for purely dilatational strains. Though this point has never been investigated, it has been generally accepted, and is consistent with present-day knowledge. This assumption is implicit in the Becker presentation. On introducing a form-factor F, equation (19) reduces to the form

$$\frac{F}{E}P_t = y_t - \bar{\beta}\int_0^\infty y_{t-\omega}\cdot\bar{\phi}(\omega)\,d\omega \tag{20}$$

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* See, for example, R. V. Southwell, "Theory of Elasticity", p. 304.

where ϕ is the recollection function for relaxation. This equation is seen to be analogous to equation (16) deduced by Becker. Volterra[80] has pointed out that if a linear superposition is true for relaxation, it is true also for creep, and vice versa, hence equations (16) and (20) are consistent with each other.

Deductions from the General Superposition Principle

If no further assumptions are made regarding the nature of the recollection functions for creep and relaxation, apart from the fact that they decrease to zero as the time increases to infinity, we can deduce certain conclusions from what we might then call the general Superposition Principle.

1. The Creep Curve under Constant Load

The assumptions of the theory led to equation (9). Alternatively, this equation can be derived from equation (16) by substituting the appropriate limits.

2. The Normalised Creep Function

Let the value of the constant β be so chosen that the final value of the creep function, $\psi(\infty)$, is unity. The creep function is then said to be normalized[159]. The following relations are then true. The deformation at "infinite" time due to a constant load P is

$$y = \frac{FP}{E}(1+\beta) = y_o\,(1+\beta) \qquad (21)$$

where y_o is the initial elastic deformation. β thus represents the ratio between the total delayed component of the deformation and the instantaneous component. The creep function

$\psi(t)$ then represents the ratio of the delayed component at time t to the total delayed deformation. The creep behavior of a material at a given temperature is thus completely characterised by the normalised creep function $\psi(t)$ and the constant β.

We shall now see how the creep behavior of a material under certain simple loading histories can be predicted by the Superposition Principle.

3. Recovery

If a load P be applied at time $-t_1$ and removed at zero time, then the residual deformation during the recovery at a subsequent time t, from equation 16, is given by:

$$y_t = \frac{FP\beta}{E} \int_{t}^{t+t_1} \phi(\omega)\, d\omega$$

$$= \frac{FP\beta}{E} \int_{0}^{t+t_1} \phi(\omega)\, d\omega - \int_{0}^{t} \phi(\omega)\, d\omega$$

Then

$$y_t = \frac{FP\beta}{E}\left[\psi(t+t_1) - \psi(t)\right] \qquad (22)$$

$$= y_0\beta\left[\psi(t+t_1) - \psi(t)\right] \qquad (23)$$

where y_0 is the instantaneous elastic deformation. If we write equation (22) in the form

$$y_t = \frac{FP}{E}\left[1 + \beta\psi(t+t_1)\right] - \frac{FP}{E}\left[1 + \beta\psi(t)\right] \qquad (24)$$

we see that the creep recovery deformation may be obtained by assuming that the deformation in the recovery period is that due to the original load application, assumed to continue indefinitely, together with that due to an equal negative load applied at the instant of load removal.

4. Recovery after Long Duration Creep

If the load be removed after the creep has been proceeding for a long time, $\psi(t+t_1)$ will be changing very slowly with time, and will be nearly equal to $\psi(t_1)$ for values of recovery time t which are not too large compared to t_1. Hence from equation (22) we get for recovery following long-duration creep (of duration t_1)

$$y_t = \frac{FP\beta}{E}\left[\psi(t_1) - \psi(t)\right] \tag{25}$$

where y_t is the residual deformation reckoned from the original zero and t is the recovery time. This is seen to be equal to

$$y_t = \frac{FP}{E}\left[1 + \beta\psi(t_1)\right] - \frac{FP}{E}\left[1 + \beta\psi(t)\right] \tag{26}$$

where the latter term represents the contraction or negative deformation due to removal of load, as a function of recovery time. This latter term is seen to be equal to the positive deformation due to application of load as a function of creep time. This result is in agreement with Köhlrausch's experimental data on rubber; it will be used extensively in the experimental work on textile fibers.

5. Recovery When β Is Small

In the case of glass and metals where the creep is small compared to the elastic deformation (β at the most is equal to .03) the error in the recovery deformation caused by applying a constant deformation y_o instead of a constant load P during the period under load introduces an error of the same order. With this approximation, the data of recovery deformation following relaxation under constant strain (a method widely used following Kohlrausch) can be analysed using equation (23).

6. Relaxation under Constant Load

When the creep is small compared to the elastic deflection, then the relaxation of stress P_t under constant strain y_o is found from equation (16) to be

$$P_t = \frac{E}{F} y_o \left[1 - \beta \psi(t) \right] \qquad (27)$$

In this case the recollection function is the same as that for creep, and the relaxation curve should therefore be the mirror image of the creep curve. When the creep is large compared to the elastic deflection (as in all high polymers) this does not hold, but in general we may write

$$P_t = \frac{E}{F} y_o \left[1 - \bar{\beta} \bar{\psi}(t) \right] \qquad (28)$$

where $\bar{\psi}$ is the appropriate function for relaxation and where the relationship between $\bar{\psi}$ and ψ is yet to be determined.

7. Superposition

Let us suppose that a load P is applied at zero time, removed at time t_1, reapplied at time t_2, removed at time t_3, and so on. Such a loading scheme we will call in general superposed loading. Then the deformation at any time t from $t = t_1$ to $t = t_2$ is from equation (22) or directly from equation (9),

$$y_t = \frac{FP\beta}{E}\left[\psi(t) - \psi(t-t_1)\right] \tag{29}$$

The deformation in the creep period from $t = t_2$ to $t = t_3$ calculated from equation (9) or equation (16) is

$$y_t = \frac{FP}{E} + \frac{FP\beta}{E}\left[\psi(t) - \psi(t-t_1) + \psi(t-t_2)\right] \tag{30}$$

and so on. We see that the deformation may be obtained from an extension of the rule given previously: the effect of any load is to be considered as continuing indefinitely, augmentation (or reduction) of load at any instant being equivalent to the addition of a positive (or negative) load, equal in magnitude to that of the load alteration, applied at the instant of load change. Furthermore, we see that if the creep curve up to time t for a constant load P is known, it is possible to compute by means of equations such as equation (29) and equation (30) the anticipated deformations in a superposition test; we thus have a means of testing the Principle. Alternatively, the creep curve can be computed from the superposition test observations, and compared with the observed creep curve. This method has been used in the experimental work for testing the validity of the Superposition Principle for textile fibers.

A superposition experiment considered by Jordan[49] and Becker[59] is of interest. A load P_1 is applied from $t = 0$ until $t = t_1$, augmented to P_2 from $t = t_1$ to $t = t_2$, and reduced again to P_1 at time t_2. The creep deflection at any subsequent time should be

$$y_t = \frac{F}{E}\left[P_1\left\{1 + \beta\psi(t)\right\} + \beta(P_2-P_1)\left\{\psi(t-t_1) - \psi(t-t_2)\right\}\right] \quad (31)$$

Hence the temporary load increment (P_2-P_1) is responsible for the superposition of a normal recovery curve $\frac{\beta F}{E}(P_2-P_1)\left\{\psi(t-t_1) - \psi(t-t_2)\right\}$ on the creep curve $\frac{FP_1}{E}\left[1+\beta\psi(t)\right]$.

8. Creep Recovery Following Constant Load of Very Short Duration

If a constant load be applied to a specimen for a very short length of time, there will be a residual deformation which will gradually disappear in the course of time. We can calculate this residual deformation from equation (14); if the transient application of load P was for a length of time $d\theta = \tau$, then

$$y_t = \frac{F}{E}\beta P\tau\frac{d\psi(t-\theta)}{d\theta} = \frac{F}{E}\beta P\tau . \phi(t-\theta)$$

If the load is applied at zero time $(\theta = 0)$, the residual deformation is

$$y_t = \frac{F}{E}\beta P\tau . \phi(t) \quad (32)$$

In practice, the time under load τ would have to be appreciable in order to get a measurable residual deformation. The load has therefore to be applied at a (finite) time $-\tau/2$ and removed at a time $+\tau/2$. For small values of t which are of the same order as τ, equation (32) does not therefore hold.

9. Creep Recovery Following Constant Deformation of Very Short Duration

We may write equation (32) in the form:

$$y_t = y_o \beta \tau \cdot \phi \, (t) \qquad (33)$$

where y_o is as before the initial elastic deformation due to the load P. Now we may make the same approximation as before (p. 36) when the creep is of a small order; then Equation (33) represents the residual deformation (or creep recovery) due to a *constant deformation* y_o of short duration τ. This type of experiment occurs frequently in the literature, and we now have an approximate method for its evaluation.

III. The Creep Curve for Constant Load

The theoretical deformations to be expected from the loading histories that have been studied above are obtained by applying the Superposition Principle to the equation for creep under constant load, equation (9). This equation was based on the work of Kohlrausch. In this section some recent data on the creep curve for constant load will be presented, verifying the general nature of equation (9). Some suitable analytical approximations for the creep curve under constant load will also be considered.

Soft Rubber

Fig. 14 gives the deformation of a tube of soft rubber under constant torque as a function of the time under load (to a logarithmic scale) for various temperatures[143]. The deformation is plotted to a scale of reciprocal modulus (cm.^{2}/kg.). At any temperature the deformation consists of two parts. One part requires a time corresponding to the velocity of sound in the medium to be created; this is the "instantaneous" or "acoustic"* deformation, corresponding to the "instantaneous" or "acoustic" modulus of elasticity. The second part, which is established gradually in the course of time, and which reaches a definite end-point, is the primary creep or "high elasticity"* deformation, corresponding to the

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* This term is due to Kobeko[143] and his co-workers.

high elasticity modulus. The creep curve at any given temperature when plotted in this way is independent of the actual shear stress, thus at constant temperature the deformation under constant load is represented by equation (9). The effect of change of temperature (in the absence of crystallisation phenomena) is seen merely to displace the curve along the axis of logarithmic time, i.e., to extend or contract the time scale.*

Hard Rubber, Bakelite

The behavior of hard rubber[143] in torsion follows the same pattern as for soft rubber (fig. 15). Fig. 16 refers to bakelite[151,166] in bending.** Again the same general behavior is observed. It is seen that in general the shape of the creep curve on the logarithmic time plot is sigmoidal; the lower asymptote corresponds to the instantaneous or "acoustic" modulus of elasticity, which in all high polymeric materials appears to be of the same order, namely, about 500,000 psi. The high reversible deformability of rubber-like materials corresponds almost entirely to the delayed or primary creep component, and such materials exhibit rubber-like extensibility in a temperature range where the highly-elastic deformation is rapid.

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* It will be remembered that the data of Kohlrausch on the longitudinal creep of rubber suggested this same interpretation.

**The author is indebted to Mr. M. Hetenyi for kindly supplying the data of this plot.

Approximate Analytical Expressions for Creep

In practice, for an unplasticised resin or hard rubber at room temperature, only the "foot" of the sigmoidal creep curve can be investigated. This portion of the curve can sometimes be approximately represented by a straight line on the logarithmic plot, corresponding to a logarithmic creep law. Such a law was originally suggested by Boltzmann[9] as an approximation to the creep curve over a limited portion of its range, and was used by him in the evaluation of this data. His law has been widely used by others up to the present day,[22,25,41,45,52,55,85,139,154,170] without the limitations of the law being clearly understood.* A slightly better fit to the foot of the creep curve may be obtained by a power law**, in which the creep component of the deformation varies as a power of the time, with the index slightly greater than zero.

On the other hand, with rubber-like materials tests at room temperature refer only to the upper part of the creep curve. Under these circumstances a logarithmic law or better still a power law with index slightly less than zero represents a good working approximation for technical purposes. The different approximations are represented diagrammatically in Fig. 17.

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* This criticism applies to the author's own work on the creep of commercial bakelite plastics under room temperature conditions.

**Suggested originally by Hopkinson.

The Creep of Glass

In the case of glass three possibilities[37,70] exist. The deformation under constant load at room temperature may be represented by curves such as A, B, and C in Fig. 18, which shows the complete sigmoidal creep curves on the logarithmic plot, and the range of time values it is possible to use in practice. For curve B, it is seen that the creep curve over the observable range of time is best represented by a straight line, i.e., a logarithmic law; curves A and C are best represented by power laws with indices respectively less and greater than zero.

IV. The Superposition Principle: Experimental Aspects

In the previous two sections the general Superposition Principle has been presented, together with some theoretical results for various special loading histories. In this section the Principle will be applied to the analysis of experimental data available in the literature of primary creep. This will be done in two ways: the Principle will first be applied in its general form, in which no assumptions will be made as to nature of the creep curve under constant load. The Principle will also be applied with the assumption that the relevant portion of the creep curve can be represented by either logarithmic or power formulae.

There exist in the literature no systematic data on the creep of high polymers, presumably due to the superimposition on primary creep of other effects still very little understood. In order to test the validity of the Principle we therefore have to resort to the large body of data in the literature on the creep of glass. This data is due mostly to contemporaries of Boltzmann.

It will be realised that any given set of data is amenable to analysis by several different methods; several of these methods are to be found in the literature. Alternative methods are suggested below, and are used to analyse some of the early data. The general conclusion we arrive at is that the Superposition Principle is true for glass.

The Logarithmic Law of Primary Creep

As we have mentioned before, the logarithmic law was due to Boltzmann. He suggested that the nature of the recollection function was such that it could be represented by:

$$\phi (t) = \frac{f(t)}{t} \tag{34}$$

where f(t) was a constant for moderate values for t, but approached zero as t approached infinity. If we assume also that f(t) approaches zero as t approaches zero, then the total delayed deformation, which is proportional to the limiting value of the creep function

$$\int_0^\infty \phi (\omega)\, d\omega$$

is finite, although the creep for moderate values of time is logarithmic. With these assumptions the general relationships discussed above become simplified for the case of a logarithmic creep law.

1. Creep under Constant Load

For constant load P applied at zero time, equation (9) becomes:

$$y_t = \frac{FP}{E} (1 + \beta \log t) \tag{35}$$

where the modulus E refers to the deformation at unit time.

2. Recovery

The recovery at a time t after removing a constant load of magnitude P which had been acting for a time t_1

becomes from equation (22)

$$y_t = \frac{FP\beta}{E} \log \left(\frac{t+t_1}{t}\right) \tag{36}$$

$$= y_o\beta \log \left(\frac{t+t_1}{t}\right) \tag{37}$$

Where y_o is equal to FP/E. In the case where the creep is small, equation (37) may be interpreted as the residual deformation due to the application of a constant deformation y_o (compare p. 36).

3. Recovery Following Long Duration Creep

If the delayed component of the deformation in the creep period reckoned from unit time under load is given by (FPA/E), then the residual deformation at a time t after removal of load is:

$$y_t = \frac{FP}{E} (A - \beta \log t) \tag{38}$$

4. Superposition Test

Applying the logarithmic law to equations (29) and (30), we see that the deformations in both these cases vary as the logarithm of a function of time. This function of time, which depends on the past loading history, we may call the equivalent time.

5. Residual Deformation Following Load of Very Short Duration

From equation (32) the residual deformation at time t due to a load P applied at a time $-\tau/2$ and removed at a time $+\tau/2$ becomes

$$y_t = \frac{FP\beta}{E} \left(\Upsilon/t \right) \qquad (39)$$

Where the creep is small, the residual deformation due to a constant deformation y_o may be written as before

$$y_t = y_o\beta \left(\Upsilon/t \right) \qquad (40)$$

This was the equation used by Boltzmann.

Boltzmann's Tests of the Superposition Principle

Boltzmann[9] concluded his classical paper on creep with a rough test of the Superposition Principle. He measured the residual twist in a long glass filament which had been twisted through a constant angle for a very short time and then released. In the case of glass this is nearly equivalent to twist under constant torque; we have also seen that the residual deformation, for values of recovery time t which are of a larger order than Υ, gives to some scale the recollection function (equation 33). The recovery time t Boltzmann reckoned very properly from the mid-point of the period under strain; the strain was thus applied at a time $-\Upsilon/2$ and removed at a time $\Upsilon/2$. Assuming logarithmic creep, the recovery curves for different values of Υ should then be rectangular hyperbolas, from equation (40); the magnitude of the residual deformation at any given value of t should be proportional to the time under strain Υ. Boltzmann carried out tests with values of Υ of 1/4 minute, 1/2 minute, 1 minute, and 2 minutes respectively. He found in fact that the residual deformation observations, when multiplied by the recovery time t and divided by the time under load Υ, gave almost identical values for $y_0\beta$ in equation (40). Using the mean value thus obtained from the four sets of data (thus reducing the effect of individual experimental errors), Boltzmann computed the four recovery curves. These together with the experimental observations, are plotted in Fig. 19. Except for small values of time for the two uppermost curves, the agreement seems to be remarkably good. The logarithmic creep law thus appears in this case to be a very good working assumption.

Kohlrausch's Analysis of Boltzmann's Data

Kohlrausch[22] threw more light on the Superposition Principle by analysing the data of Boltzmann by a different method. The recovery data of Boltzmann may be interpreted as the residual effect when the effect of a negative load, applied at the time of load removal, is superimposed on that of the original load, assumed to continue indefinitely (equations 22 and 23). In general, the recovery data for different values of time under load should be related to each other through the Superposition Principle. Kohlrausch showed as follows how the residual deformation after applying a given load for a time nt_1 (where n is an integer) can be calculated from the data corresponding to a time t_1 for the same load. If y_t is the residual deformation at a time t after removing the given load (or deformation) of duration t_1, then y_t is given by equation (23). If the same load (or deformation) be now applied for a length of time nt_1, the residual deformation Y_t at a time t after removal of the load should be:

$$Y_t = y_t + y_{t+t_1} + y_{t+2t_1} \cdots\cdots + y_{t+(n-1)t_1} \qquad (41)$$

With this identity Kohlrausch computed from Boltzmann's data the recovery curves A, B, C, D in Fig. 20. These curves correspond to values of time under load nt_1 of 1/2 minute, 1 minute, 2 minutes and 2 minutes respectively, and were computed from the data corresponding to a time under load of 1/4 minute, 1/2 minute, 1 minute and 1/2 minute respectively. There is seen to be a fairly good agreement between the computed data and the corresponding observations, suggesting that the general Superposition Principle is obeyed.

From equation (41) it is seen that in computing Y_t experimental errors tend to be accumulated; this accounts for the discrepancy between curve D on the one hand and curve C and the experimental observations in Figure 20. This discrepancy indicates to us, not that the Superposition Principle is untrue, but that any method of analysis which tends to accentuate experimental errors is to be regarded with suspicion.

Kohlrausch's Data on Glass and the Superposition Principle

It will be remembered that Boltzmann applied the logarithmic law to the recovery following short duration loading. Kohlrausch next pointed out that the logarithmic law could be applied to his own early tests, in which the time under load was not small. In these tests, a constant twist was applied for a given length of time, and then removed; the residual torque was measured following removal of strain. Kohlrausch[22] showed that equations of the type of equations (37) and (38) applied to the residual torque for respectively moderate and long times under strain; in fact, the data of all the four curves of Figure 4 could be fitted approximately by equation (37), using a single constant. He pointed out that whereas his own formula (equation 7) gave a better fit to the observations, to do this required nine constants. Kohlrausch decided therefore that the Boltzmann theory gave a better representation of the phenomena.

Application of the Concept of Equivalent Time

Kohlrausch's results may be presented graphically in the following way. We see from equation (36) that for moderate values of time under load t_1 the residual deformation (or load) at a time t after removing the load (or deformation) should be proportional to the logarithm of the function of time given by:

$$E = (t+t_1)/t \qquad (42)$$

Such a function of time we have already called equivalent time. If therefore all residual deformations (or loads) be plotted against the appropriate value of equivalent time to a logarithmic scale, the points should all lie on a straight line passing through the origin.* The manner and magnitude of the deviations from a single straight line will indicate

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* This method of analysis is due to Hopkinson[25].

in what direction and to what extent the logarithmic creep assumption is insufficient.

The case of recovery after large values of time under load requires special consideration. The logarithmic law does not hold over long periods of time; we may however use in this case equation (38). We adopt the artifice of inverting the scale of residual deformation (or load). The residual deformation after long duration creep plotted in this way against the logarithm of the recovery time should then give a straight line; this line should be parallel to that obtained by plotting the residual deformations after moderate loading time against the logarithm of the equivalent time.

This analysis has been applied to the residual torque data[5] of Kohlrausch (Figure 4). The observations corresponding to 10 minutes, 20 minutes, and 40 minutes under load have been plotted against the equivalent time to a logarithmic scale (Figure 21). The observations corresponding to 1380 minutes under load have been plotted with ordinate scale inverted against the recovery time to the same logarithmic scale. The former three sets of observations are seen to lie very close to a single straight line, the deviations being due in part to variations of temperature during the test. The last set of observations lies near to a parallel straight line, as predicted by the theory. The logarithmic law thus again represents a satisfactory approximation.

Analysis of Boltzmann's Data by Method of Equivalent Time

If the logarithmic law holds down to small values of time, we are justified in using the method of equivalent time for recovery following application of load for a very short duration of time. This method is here applied to Boltzmann's data (Figure 22). The residual deformations in each of the four sets of tests have been plotted against the appropriate value of equivalent time to a logarithmic scale.* All the observations are seen to lie very close to a single straight line passing through the origin, again confirming the Superposition Principle and again showing that the creep curve is logarithmic over the relevant portion of time. There is seen to be however a slight deviation of the points from the straight line. In this connection the remarks of Hopkinson are of interest.

Hopkinson's Tests of the Superposition Principle

1. Dielectric Creep

We have had occasion to mention previously one or two concepts which were originally due to Hopkinson. This worker, who was responsible for many valuable ideas in connection with primary creep, became interested in the mechanical creep of glass while studying in Leyden jars the dielectric creep properties of this material.[16,17,21]

It has already been mentioned (p.11) that R. Kohlrausch had pointed out the analogy between dielectric and

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* Some of the observations have been omitted from Fig. 22 for clearness.

mechanical creep. This can be best illustrated by the following example. A rubber thread loaded longitudinally with a constant weight will of course creep under load. If after some time the load be removed, creep recovery will take place, and if the specimen be now held at a fixed length, the resisted creep recovery will create a tension in the filament. When plastic flow is absent, this residual tension will rise to a limiting value; but if on the other hand plastic flow is present, this tension will first increase and then decay to zero. In an analogous way if a condenser with a solid dielectric be charged for some time at a constant potential, and then discharged, and finally insulated, a residual charge will gradually appear, of the same sign as the original charge. When the ohmic resistance of the dielectric is very high, this residual charge will rise to a fixed value; when the ohmic resistance is low, this charge will rise to a maximum and gradually leak away[4].

It was suggested to Hopkinson by Clerk Maxwell in 1876 that the problem of residual charge in dielectrics could be treated by the Superposition Principle of Boltzmann[21]. Hopkinson noted that by charging a condenser positively for a long time, negatively for a short time, and then discharging and insulating the condenser, the residual charge would be first negative and then become positive. It occurred to Hopkinson, in an analogous way that it did to Kohlrausch, that the reversal of the sign of residual charge could be explained by the Superposition Principle. He showed this to be true at first qualitatively, and later, semi-quantitatively.

The rate of acquiring charge was computed by summing the recollection functions due to the previous loading effects.

2. Application of the General Superposition Principle

In 1877 Hopkinson[25] extended his work on dielectric creep to mechanical creep of glass. A glass fiber was twisted through a constant angle for respectively 1, 2, 5, 10, 20 and 121 minutes and then released. The residual twist was measured as a function of recovery time. Hopkinson first applied to his data the general Superposition Principle; he introduced for the first time the concept of the creep function, and showed, in an analogous manner to Kohlrausch* how the recovery deformations should be connected with each other. He obtained very poor agreement, presumably due to the accentuation of experimental errors in the calculation. Hopkinson next tried the logarithmic law, and proposed the method of plotting that we have already used (Figures 21 and 22). From slight discrepancies in this he was led to suggest the power law of creep. Applying the Superposition Principle he obtained good agreement between theory and experiment.

Hopkinson designated the integral $\int \phi(t)dt$ by $\psi(t)$. He then stated that if a specimen be twisted for a time T through an angle X and then released, the residual twist at a time t after release according to the Superposition Principle would be

$$X\left[\psi\,(T+t) - \psi(t)\right]$$

This of course is equivalent to equation (23) and the

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* Apparently independently of Kohlrausch.

assumption made on p. 36 . Hopkinson next showed how the residual deformations in any test could be obtained from the data of tests of shorter duration by means of the following identity:

$$X\left[\psi(t) - \psi(T+t)\right] = X\Big\{\left[\psi(t) - \psi(t+t_1)\right] + \left[\psi(t+t_1) - \psi(t+t_1+t_2)\right] + \left[\psi(t+t_1+t_2) - \psi(t+t_1+t_2+t_3)\right] \dots \Big\} \qquad (43)$$

where $t_1 + t_2 + t_3 \;\dots\dots\; + t_n = T.$

The right-hand side is seen to be the sum of the recovery deformation t minutes after release of a twist of duration t_1 minutes, together with the deformation $(t+t_1)$ minutes after release of a twist of duration t_2 minutes and so on.* In this way Hopkinson computed the recovery curves for each test from tests corresponding to shorter times under load. He found in fact a very poor agreement, for reasons previously noted; this result however has led to statements in the literature that the Superposition Principle is untrue.

3. Application of the Logarithmic Law

Hopkinson next pointed out that for a logarithmic creep law, the residual deformations should be proportional to log E (equations 37 and 42) and plotted his observations with log E as abscissa. Hopkinson found that for small values of time under load t_1 the points lay on a straight line passing

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* In the special case where $t_1 = t_2 = t_3 \;\dots\dots = t_n = t/n$, equation (43) reduces to Kohlrausch's equation (41).

through the origin. For large values of t_1 the points for moderate values of t lay on straight lines which passed above the origin. For large values of t_1 and t the points fell below each line in a curve making for the origin. From these discrepancies Hopkinson was led to introduce the power law.

4. Application of the Power Law of Creep

Hopkinson observed that Kohlrausch had found[6] that the recovery following a short twist could be expressed in the form

$$A'/t^{\alpha}$$

where α was less than unity, equation (8), over a limited range of values of t. This must therefore have been proportional to the recollection function $\phi(t)$ by equation (33). Hence Hopkinson obtained for the creep function

$$\psi(t) = At^{1-\alpha} \tag{44}$$

where α was less than but near unity. This corresponds to a creep curve which is slightly concave upwards on the logarithmic plot. Applying the Superposition Principle to the power law of creep, equation (44), Hopkinson obtained for the residual deformation x_t at a time t after release of a deformation X applied for a time t_1:

$$x_t/X = A\left[(t+t_1)^{1-\alpha} - t^{1-\alpha}\right] \tag{45}$$

He found for the glass used that the values $\alpha = 0.95$, $A \simeq .037$ gave the best fit. For the dielectric creep of another glass he found $\alpha = 0.65$. It should be noticed that when the creep curve is slightly concave downwards on the logarithmic plot, α must be slightly greater than unity.

Analysis of the Data of Klemencic

To supplement the analyses considered above, it is of interest to consider in the light of the Superposition Principle the data of Klemencic[26]. We have here a very carefully collected set of observations on the creep recovery of glass following deformation to a constant value for various lengths of time. Both torsion and bending experiments were carried out. Though the work was carried out under the direction of Boltzmann, Klemencic was satisfied to express his results by means of Kohlrausch's equation (equation 8), finding suitable values of the constants for each test. In this form his results are of little value. However, from his data it can be shown that:

1. The Superposition Principle is obeyed by glass in bending and in torsion.
2. The logarithmic law is a fairly good approximation.
3. The creep curve for constant load is slightly concave upwards on the logarithmic time plot.

Test of the Superposition Principle

Fig. 23 shows the residual deformations as a function of recovery time t after bending a glass filament through a given deformation for lengths of time t_1 = 1, 2, 4, 8, and 16 minutes. From the data for t_1 = 1, 2, 4, and 8 minutes were computed by means of equation (41) the recovery curves corresponding to t_1 = 2, 4, 8 and 16 minutes respectively.

These computed curves also are shown in Fig. 23. The agreement with the observations is seen to be very good, indicating that the Superposition Principle is obeyed by glass in bending. Klemencic's data for creep recovery in torsion shows an equally good agreement with the curves computed therefrom.

Application of Logarithmic Creep Law (Equivalent Time)

The data of Fig. 23 has been plotted against the equivalent time for recovery (to a logarithmic scale) in Fig. 24. Roughly speaking, the points lie nearly on a straight line passing through the origin. More exactly, for moderate values of t the points for each value of t_1 lie on straight lines which are displaced above the origin by amounts increasing with t_1. For large values of t the points fall below the appropriate straight line. As we have seen, these results correspond to a creep curve which is slightly concave <u>upwards</u> on the logarithmic time plot.

Calculation of the Creep Function

We can write for the deformation y_t at a time t due to the application of constant load at zero time:

$$y_t/y_o = 1 + \psi(t) \tag{46}$$

where y_o is the deformation at zero time. Then $\psi(t)$ represents the delayed component of the deformation divided by the instantaneous component. The residual deformation y_t at a time t following removal of a constant deformation y_o acting for a time t_1 is, from equation (23), given by

$$y_t/y_o = \psi(t+t_1) - \psi(t) \qquad (47)$$

From Klemencic's data for $t_1 = 1$ we have $\psi(2) - \psi(1)$, $\psi(3) - \psi(2)$, and so on. From his data for $t_1 = 2$ we have $\psi(3) - \psi(1)$, $\psi(4) - \psi(2)$, and so on. By combining the information obtained in this way, we can obtain, without recourse to interpolated data, $\psi(t) - \psi(1)$ up to $t = 36$ minutes. In many cases the same quantity can be obtained in two different ways. All the quantities possible to obtain in this way are plotted in Fig. 25. The points are seen to lie nearly on a curve which is slightly concave upwards on the logarithmic plot. The non-linearity of this curve is of course responsible for the nature of Fig. 24.

Creep of Glass: Bennewitz's Experiments

The work of Bennewitz[52,55] represents a recent contribution to the study of primary creep in glass. He wished to show that the logarithmic creep law was a satisfactory hypothesis from the technical point of view for the explanation of the creep properties of amorphous and isotropic materials. Bennewitz measured the creep recovery of a glass filament which had been deformed in bending by a constant load* for 60, 120, 240, and 2400 seconds respectively. Bennewitz also measured the creep under load for a length of time of 2400 seconds. If the latter deformations be plotted

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* Previous experimenters had of course applied a constant deformation, which is less satisfactory from the theoretical point of view.

against the logarithm of the time under load, the creep curve will be found to be linear up to t = 100 seconds, and thereafter slightly concave downwards. The recovery deformations when plotted against the logarithms of the equivalent times will again be found to lie on straight lines for each value of time under load t_1. In this case, increase of time under load is found to depress these lines below the origin. It will be remembered that in the previous cases considered where the creep curve was concave upwards the opposite was found to occur.

The Primary Creep of Glass: General Conclusions

From the above study of the literature of the primary creep of glass the following general conclusions can be drawn.

1. The delayed or primary creep component of the deformation obeys the Superposition Principle.
2. The creep curve for constant load for glass when plotted against the logarithm of the time under load for moderate values of time may give a straight line, or a curve which may be either slightly concave upwards or slightly concave downwards (Fig. 18).
3. Logarithmic and power formulae for the creep under constant load represent satisfactory approximations over limited ranges of time.
4. Recovery deformations plotted against the logarithm of the appropriate values of equivalent time fall nearly on a straight line passing through the origin. Deviations from this straight line are consistent with the deviations of the creep curve from the logarithmic law.

V. The Creep of Textile Fibers and Plastic Materials

The main part of the theory and of the experimental data that have just been considered has been in existence for many years. It would be imagined that those working in the field of high polymers would have based their work on the results of the study of inorganic materials. Unfortunately this was not the case, and the meager amount of work that has been carried out on the creep of high polymers has therefore in many cases been unsystematic and misleading. The difficulty in the study of high polymers has probably been due to a lack of basic knowledge of structure, and to the superimposition on primary creep of other effects little understood.

In reporting the work that has previously been carried out in the field of high polymers, it is convenient to consider separately work on plastic materials and work on material in fiber or filament form.

Creep of Plastics

As an example of the empirical methods that are frequently adopted, there is the often-quoted work on celluloid by Filon and Jessop[53]. In this work the creep deformation under constant load was measured; no recovery tests and no attempt to distinguish between recoverable and unrecoverable creep were made. The data were fitted to an empirical creep equation of dubious significance due to Andrade[44,48]. The torsion creep and creep recovery of commercial forms of bakelite has been studied, using the Superposition Principle and assuming the logarithmic law of creep[154,170]. Whereas in the case of glass the logarithmic law was always a fair approximation to the true creep curve, this does not appear to be the case with high polymers.

The Creep of Textile Fibers

Textile fibers have creep properties which are in general similar to those of plastics, but in addition to being sensitive to temperature they are also very much affected by changes in relative humidity. On account of the fineness of these fibers, creep testing involves very delicate methods, and reproducibility of results is difficult to attain.

The fundamental concepts of creep as far as textiles are concerned were pointed out clearly by Shorter[57,58,67] and Peirce[54,63,66] many years ago. The former emphasised that textile fibers were not so much plastic bodies as bodies possessing a delayed extensibility; he illustrated his argument with concepts which are embodied in Part III. Peirce clearly differentiated between three types of deformation. On removal of the load causing a deformation one part of the load was recovered immediately; this was the instantaneous elastic deformation. Another part, the primary creep component, was recovered in the course of time; the remainder of the deformation was not recoverable at all. Peirce[54] measured the torque relaxation in cotton hairs and yarns under (nearly) constant angle of twist and found that Kohlrausch's formula (equation 7) gave a very satisfactory fit. The creep of wool under constant load and under constant stress[64,65,68] has been investigated, and also relaxation at constant extension[69], but again without any distinction between primary and secondary creep effects.

The creep under constant load, creep recovery following removal of load, and relaxation under constant strain of synthetic filaments and silk have been studied more systematically by de W. Smith and Eisenschitz[84,85]. These investigators studied the properties of the filaments under different conditions of temperature and relative humidity, and found that the Superposition Principle with the logarithmic law approximation gave a fair representation of their results. The problem of the initial state of the filament was left unsolved. An important result obtained by Smith and Eisenschitz was that though the initial elastic deformation was proportional to load, the creep component of the deformation due to constant load (which gave a curve concave upwards on the logarithmic time plot) increased at a faster rate than the load. This latter phenomenon, which is at variance with one of the assumptions of the Superposition Principle, has been confirmed in the experimental work of the author. The work of Smith and Eisenschitz indicates therefore the general problems to be faced in making a study of the primary creep of filamentous materials. The general theory and data we have previously considered show us how these problems are to be attacked.

Cyclic Loading

Let us suppose that a specimen of glass or of a high polymer is loaded from zero load up to a given value, either at a uniform rate with time or by equal intervals of load in equal time intervals. Let us suppose that the specimen be unloaded in the same manner. This scheme represents a very common type of mechanical test of high polymers. We see that even in the absence of structural changes, due to the memory action of primary creep a stress-strain loop will be formed, the strain on the descending branch for any given value of stress being greater than for the same value of stress on the ascending branch.. On reaching zero load, there will thus be a small "remanent set" due to creep, which will disappear after some time. Such stress-strain loops have often been recorded in the literature; in many cases the authors have omitted to mention whether the "remanent set" eventually disappeared entirely. It is probable that such loops are due entirely to primary creep; as examples are shown a stress-strain loop in bakelite[122] (Fig. 26) and stress-strain loops in silk[105] at different relative humidities (Fig. 27).

Though the derivation of such load-extension and stress-strain loops may be of technical value in particular cases, we see that in general cyclic loading tests are less fundamental than creep tests under constant load. Before such cyclic loading tests can be fully interpreted it is necessary first to study the creep properties of a material under constant load.

Summary

It has been shown that the reversible deformation due to the application of a constant load (in the absence of structural change) can be separated into an instantaneous component and a delayed component. The delayed component can be represented by a sigmoidal curve on the logarithmic time plot. The delayed component is in general a function of the previous loading history and in the case of glass is given by the Superposition Principle.

Part III.

MECHANICAL MODELS AND THE WIECHERT THEORY

I. Mechanical Models

It has been shown in the preceding part of this thesis how complex creep and relaxation effects in materials can be reduced to a simple system by means of the Superposition Principle. The next problem which arises in the study of creep phenomena is the investigation of the mechanism to which these effects are due. Both Boltzmann[24] and Maxwell[23] gave this problem their attention and advanced purely qualitative theories based on atomic structure concepts. Boltzmann indicated how the atomic arrangement inside a body might depend on its previous history, and Maxwell proposed what we would now call a "two-phase" theory. Since at that time knowledge of the structure of solids was extremely vague, further development along these lines was not possible. The next important contribution was therefore of a mathematical character. The theory of Wiechert[37] may be considered as a mathematical formulation of Maxwell's ideas. Based on the concept of time of relaxation, this theory accounts for the general nature of the creep curve under constant load, and includes in its results the Superposition Principle of Boltzmann. Experimental verification of the Superposition Principle may accordingly be taken as verification also of the theory of Wiechert.

The implications of this mathematical theory are by no means obvious; they can however be best illustrated by considering the behavior of an equivalent mechanical model. The first such mechanical model, proposed by Poynting and Thomson[38] in 1902, illustrated in a crude way some of the fundamental creep and relaxation properties of glass. Since that time many such models have been proposed[57, 58, 60, 64, 70, 94, 123, 125, 142]; these models have become more and more complex in an attempt to "explain" more and more phenomena. On these grounds such mechanical models have been objected to[66], and rightly so. In the present case, however, a logical system of models has been studied; these models explain in many cases qualitatively and in some cases quantitatively how the observed behavior of materials under load may be interpreted.

Following the discussion of mechanical models, the effect of temperature on primary creep and the effect of creep on mechanical behavior under dynamic loading are considered. Though these aspects of the theory have no immediate connection with the experimental results presented later, they are included here for completeness and on account of their theoretical and technical importance.

The Maxwell Relaxation Time

Maxwell[7] suggested in 1867 a differential equation to represent the mechanical properties of materials such as pitch. He observed that for the application of a load of very short duration, these materials could be considered as perfectly elastic bodies. Even the smallest load, when applied however for an extended length of time, would cause flow to take place, the materials then behaving like viscous liquids. Let us consider for example a cylinder of such a material in torsion. For very short application of load we could measure a shear modulus G, which would be the ratio of shear stress to shear strain. From the flow resulting from a prolonged application of load we could measure a viscosity η defined in the usual way as the ratio of the shear stress to the rate of shear strain. If now we assume that this cylinder is twisted suddenly through a given angle and held at that angle, then due to the existence of the flow property the torque necessary to hold the cylinder twisted, and hence the shear stress in the material, will decrease with time. If no effects other than those above are present, the stress will then decrease exponentially according to the law:

$$P_t = P_\theta \, e^{-(t-\theta)/\tau} \qquad (48)$$

where P_θ is the stress at time θ, P_t is the stress at a later time t, and τ is a constant of the dimensions of time. This constant, which turns out in this case to be merely the ratio of the viscosity to the shear modulus, η/G, is called the Maxwell relaxation time. Hence if the specimen be held at constant strain for a length of time equal to its Maxwell relaxation time, then at the end of this period of time the stress will have fallen to 1/e or to 0.368 of its initial value. A perfectly elastic material has an infinite relaxation time; that of a mobile fluid such as water is nearly zero.

Mechanical Models

With this new concept of the Maxwell relaxation time we are now in a position to consider mechanical models. These will be thought of as constructed from elastic elements and viscous elements. Each elastic element obeys Hooke's Law and is characterised by a spring; the resistance of such an element is thus proportional to its extension. Then if P is the load in the spring and x is its extension, we may write:

$$P = x/\mu \tag{49}$$

where $1/\mu$ represents the stiffness of the spring. The viscous element is characterised by a dashpot and obeys Newton's Law; its resistance to deformation is proportional to the rate of strain of the element. Then for the dashpot we may write:

$$P = (1/\lambda)(dx/dt) \tag{50}$$

where $1/\lambda$ represents the "viscosity" of the dashpot.

The Maxwell Unit

Let us imagine an elastic element coupled in series with a viscous element. We will call this combination, illustrated in Fig. 28, a Maxwell unit. We will investigate the behavior of this unit under constant deformation and under constant load. First, if this unit be suddenly pulled out to a given extension, the force exerted on the system as a result of the yielding of the dashpot will decrease exponentially with time. The mechanical behavior of the system can thus be characterised by a Maxwell relaxation time given by

$$\tau = \mu/\lambda \tag{51}$$

If on the other hand, we apply to this system a constant load, there will be an immediate extension (due to the spring) followed by flow at a uniform rate with time (due to the dashpot). On removal of load, there will be merely an instantaneous contraction due to the spring, as shown in Fig. 29. It is clear therefore that the single Maxwell element does not represent the creep and recovery properties of high polymers. The mechanical properties of high polymers cannot therefore be represented by a single Maxwell relaxation time.

Two Maxwell Units in Parallel

Let us now consider the system consisting of two Maxwell units in parallel, as shown diagrammatically in Fig. 30. We will assume that the systems have different relaxation times given by $\tau_1 = \mu_1/\lambda_1$, $\tau_2 = \mu_2/\lambda_2$. Let us now consider the behavior of this system on applying instantaneously a constant load. On applying the load there is first an immediate elastic extension of the system due to (equal) extensions in the springs; the load is thus shared between the Maxwell units in the ratio of the stiffnesses of the springs. After the lapse of a long time the system settles down to a uniform flow; the load is now shared between the units in the ratio of the "viscosities" of the dashpots. Since the relaxation times of the two component units are different, it is seen that before the system settles down to uniform flow there must exist a transition period while there takes place a transference of load from one unit to the other. During this process the extension of one of the springs increases, and that of the other decreases. Let us now assume that the load is instantaneously removed. There will be an instantaneous contraction of the system due to the instantaneous contractions of the springs by equal amounts equal to the original instantaneous extensions. One spring will therefore possess a residual compression and the other a residual extension. These forces can only be dissipated by the gradual yielding of the dashpots; this will be accompanied by a gradual further contraction of the whole system, i.e., by a "creep recovery".

The behavior of this system under constant load applied at zero time can be analysed by setting up the differential equation for the system. The deformation x_t at a time t after application of a constant load P will then be found to be:

$$x_t = P\alpha\left[1 + \beta(1-e^{-t/\tau}) + \gamma t\right] \qquad (52)$$

where

$$\alpha = \mu_1\mu_2/(\mu_1+\mu_2)$$

$$\beta = -(1-\tau/\tau_1)(1-\tau/\tau_2)$$

$$\gamma = \tau/(\tau_1\tau_2)$$

$$\tau = (\mu_1+\mu_2)/(\lambda_1+\lambda_2)$$

The instantaneous elastic deformation is given by P_α; this multiplied by γt gives the uniform flow component proportional to time; the term $\beta(1-e^{-t/\tau})$ represents the deformation due to redistribution of load as a result of the existence of two different relaxation times.

Now let us investigate the deformation x after removal of load; the load P will be assumed to be applied at zero time and removed at a time t_1. The deformation at a subsequent time t will then be found to be given by:

$$x_t = P\alpha\left[\gamma t_1 + \beta\left\{(1 - e^{-t/\tau}) - (1 - e^{-(t-t_1)/\tau})\right\}\right] \qquad (53)$$

The residual deformation thus consists of a permanent set given by the $P\alpha\gamma t_1$ term corresponding to the steady viscous flow of the system, and in addition a transient residual deformation which disappears with time. The β term of the deformation has therefore the nature of a primary creep and creep recovery; furthermore, this primary creep is seen to obey the Superposition Principle. The deformation under constant load and following removal of load, as given by equations (52) and (53), is represented in Fig. 31. We can say therefore that on applying to the model consisting of two Maxwell units in parallel a constant load, there is first an immediate elastic deformation proportional to the load, and subsequently an irreversible viscous flow, again proportional to the load. <u>Due to the existence of two different Maxwell relaxation times, there is in addition a primary creep</u> obeying the Superposition Principle. The normalized creep function in this case is given by

$$1 - e^{-t/\tau}$$

It is seen that this model represents, in a qualitative way at least, the creep behavior of such materials as lead[40] and pitch[39,42], and also glass[158] and thermoplastic resins such as polyisobutylene[124].

Maxwell's Theory of Stratified Dielectrics

The basic concept involved in the above model has been borrowed from work by Maxwell[8] on dielectric creep. We can consider a dielectric of a condenser as possessing a relaxation time. This is the time for the potential due to a given charge on the condenser to fall to 1/e of its initial value, as a result of the leaking away of the charge through the dielectric. If the dielectric can be represented by a single relaxation time, the charge and discharge characteristics on applying a given potential and then grounding the condenser correspond to the deformation characteristics of the single Maxwell unit on applying and removing constant load. If the dielectric can be considered as stratified, i.e., as divided into layers with at least two different electrical relaxation times, then residual effects will manifest themselves.

Maxwell Unit in Parallel with Elastic Element

This model, a special case of the one studied above, is illustrated in Fig. 32. It is derived from the previous model by giving one of the units an infinite relaxation time. In this model we will investigate the relaxation due to a given strain, and the creep due to constant load, as well as the residual effect due to removal of strain (or load).

1. Relaxation at Constant Length

If the system is suddenly pulled out to a constant extension x_o, the load P_t applied to the system will decrease with time due to yielding of the dashpot in the Maxwell element. The load is then given by:

$$P_t = x_o \left(\frac{\mu_1 + \mu_2}{\mu_1 \mu_2}\right) \left[1 - \frac{\mu_1}{\mu_1 + \mu_2} (1 - e^{-t/\tau_2})\right] \qquad (54)$$

where

$$\tau_2 = \mu_2 / \lambda_2 \qquad (55)$$

If at any time the model is released, it will gradually return to its original length, hence the relaxation is purely a primary creep effect. If after relaxation at constant extension the model be restored to its original length, there will be a residual load on the model which will die away gradually in accordance with the Superposition Principle. If we write equation (54) in the form

$$\alpha P_t = x_o \left[1 - \beta \Psi(t)\right] \qquad (56)$$

then by analogy with equation (28), α corresponds to the instantaneous modulus of elasticity. The normalised function for relaxation $\Psi(t)$ is given by

$$\Psi(t) = 1 - e^{-t/\tau_2} \qquad (57)$$

The constant β is then given by

$$\beta = \mu_1 / (\mu_1 + \mu_2) \qquad (58)$$

2. Creep under Constant Load

Immediately on application of a constant load P at zero time there occurs an instantaneous deformation $P\alpha$ due to the (equal) extension of the two springs. Due to the "flow" of the dashpot in the Maxwell unit, the load carried by this unit will be gradually transferred to the elastic element, resulting in a gradual increase in extension, or creep. This deformation reaches a limit when the single spring carries all the load. Hence the delayed deformation is due to the transference of load from the Maxwell unit to the elastic element.

If at any time the load be removed, there will be first an instantaneous contraction of the model equal to the previous instantaneous extension $P\alpha$. This instantaneous contraction is due to (equal) contractions of the springs in the model; the single elastic element is thus left with a residual tension and the spring of the Maxwell unit with a residual compression. This "internal stress" in the system dissipates itself slowly as a result of the yielding in the dashpot; we thus get as before a creep recovery, corresponding to the previous creep and obeying the Superposition Principle. The behavior of this model is illustrated in Fig. 33.

The following are the mathematical results for creep and recovery of this model. For constant load P applied at zero time, we get for the extension x_t at time t

$$x_t = P\left(\frac{\mu_1\mu_2}{\mu_1+\mu_2}\right)\left[1 + \frac{\mu_1}{\mu_2}\left(1 - e^{-t/\tau}\right)\right] \qquad (59)$$

where $\tau = (\mu_1 + \mu_2)/\lambda_2$ (60)

Writing this equation in the form:

$$x_t = P\alpha\left[1 + \beta\psi(t)\right] \qquad (61)$$

in an analogous way to equation (9), we get for the normalised creep function

$$\psi(t) = 1 - e^{-t/\tau} \qquad (62)$$

and for the constant β:

$$\beta = \mu_1/\mu_2 \qquad (63)$$

If the load P be removed at time t_1, the residual deformation at a subsequent time t is then given by

$$x_t = \frac{P\mu_1^{\,2}}{\mu_1 + \mu_2}\left[(1 - e^{-t/\tau}) - (1 - e^{-(t-t_1)/\tau})\right] \qquad (64)$$

This model thus manifests under load an instantaneous and also a delayed (or primary creep) deformation, the latter obeying the Superposition Principle; yet it fails in one material particular to give a true representation of the behavior of materials manifesting primary creep. A normalised creep function as given by equation (62) is almost never found; in spite of this, this comparatively simple model can be of great use in indicating relationships between creep and relaxation for different types of material.

Relation between Creep and Relaxation

Since in the experimental study of the properties under discussion both creep and relaxation tests are used, it is important to know the relation between these two types of tests when only primary creep phenomena are present. Let us again assume that a constant extension x_0 is applied at zero time to the model of Fig. 32. Then the ratio of the load in the system at time t to the initial load is given by:

$$P_t/P_0 = 1 - \bar{\beta}\bar{\psi}(t) \qquad (65)$$

On the other hand, if a constant load P_0 be applied at zero time, then the ratio of the deformation at time t to the instantaneous deformation is given by:

$$x_t/x_0 = 1 + \beta\psi(t) \qquad (66)$$

If we now assume that in our model the total delayed deformation is small compared to the instantaneous deformation, as in glass, then μ_1 is small compared to μ_2 in equations (58) and (60). Hence for creep, equation (59) becomes:

$$x_t/x_0 = 1 + (\mu_1/\mu_2)(1 - e^{-t/\tau_2}) \qquad (67)$$

and for relaxation equation (56) becomes:

$$P_t/P_o = 1 - (\mu_1/\mu_2)(1 - e^{-t/\tau_2}) \qquad (68)$$

Hence if we plot x_t/x_o and P_t/P_o against the time t, we obtain two curves which are the mirror-images of each other in the line of ordinate unity as shown in Fig. 34.

Boltzmann[9] and Becker[59] considered the case of a creep function of a general nature and investigated the relationship between creep and relaxation assuming the Superposition Principle to be true. They obtained the same result as above; in their proofs however, there is the implicit assumption that the delayed component of the deformation is small compared with the instantaneous component.

Now let us consider the cases where the delayed component is of the same order as, or of a larger order than, the instantaneous component of the deformation. The former case is represented, as we have seen, by hard rubber and unplasticised resins, and the latter case by soft rubber and highly plasticised materials. Under these circumstances μ_1 is no longer small compared to μ_2 ; the above result is not true, and there is in this case no simple connection between creep and relaxation. The following relation however holds:

$$1/\bar{\beta} = 1 + 1/\beta \qquad (69)$$

It is reasonable to assume that the above remark holds also for a creep function of any shape; we then come to the conclusion that creep and relaxation experiments cannot be simply compared with each other when dealing with high polymers[84, 85].

Model with Distributed Relaxation Times

In the model that has just been studied the normalised creep function is seen to be of the type:

$$1 - e^{-t/\tau}$$

where τ is a constant of the dimension of time, and t is the time under load. If this function be plotted against the logarithm of the time, a sigmoidal curve, with the lines of ordinate zero and unity as asymptotes, is obtained. If now the above function be compared with the experimentally observed functions to be found in the literature, a striking discrepancy will be noticed. The experimental normalised creep functions are in general flatter and extend over a much greater range of values of logarithmic time. It will be observed that alteration of the value of τ in the above normalised creep function merely displaces the curve along the axis of logarithmic time, without otherwise changing its shape. If however the previous mechanical model is generalised by adding to the elastic element a number of Maxwell units in parallel of different relaxation times, the normalised creep function becomes extended along the logarithmic time scale. Such a model with distributed relaxation times gives a closer representation of the primary creep behavior of real materials. This model is shown in Fig. 35.

1. Relaxation under Constant Deformation

Let us first consider the relaxation of load with time due to a constant deformation instantaneously applied at zero time. Let the constants of the springs in Fig. 35 be denoted by μ_1, μ_2, μ_3 .... μ_n; in general by μ_i; let the constants of the corresponding dashpots be denoted by λ_2, λ_3, ... λ_n; in general by λ_i. The initial load in the system due to the instantaneously applied deformation x_o is

$$P_o = x_o \sum_1^n (1/\mu_i) \tag{70}$$

The initial load in any individual unit is

$$P_{io} = x_o/\mu_i \tag{71}$$

The load in this unit after time t is

$$P_{it} = P_{io} \, e^{-t/\tau_i} \tag{72}$$

where $$\tau_i = \mu_i/\lambda_i$$

Hence the total load in the system at time t is

$$P_t = x_o/\mu_1 + x_o \sum_2^n (e^{-t/\tau_i})/\mu_i \qquad (73)$$

Putting this equation in the form of equation (56) we get

$$\left.\begin{aligned} P_t &= \frac{x_o}{\alpha}\left[1 - \bar{\beta}\,\Psi(t)\right] \\ \text{where}\quad \frac{1}{\alpha} &= \sum_1^n (1/\mu_i) \\ \bar{\beta} &= 1 - \frac{1/\mu_1}{\sum_1^n (1/\mu_i)} \\ \Psi(t) &= \frac{\sum_2^n (1 - e^{-t/\tau_i})/\mu_i}{\sum_2^n (1/\mu_i)} \end{aligned}\right\} \qquad (74)$$

This normalised function Ψ is more extended on a logarithmic time plot than a function containing a single exponential term.

2. Creep under Constant Load

The creep of the model with distributed relaxation times (Fig. 35) is indeed complex. In the case of the previous model (Fig. 32) it will be remembered that during creep under constant load there is a continuous transference of load from the Maxwell unit to the elastic element. In the case of the present model, the relaxation behavior under constant deformation can be analysed quite easily since each Maxwell unit relaxes independently of the others. When we come to consider creep of this model under constant load however, it appears that a very complex redistribution of load occurs among the Maxwell units, rendering the mathematical treatment very difficult.

However, by considering the results obtained so far, it is possible to state in general terms the form of the solution and also the mechanism of creep of this model. First, the form of the solution is given in general by equation (61) where β is connected with $\overline{\beta}$ of equation (74) by means of the relation in equation (69). The normalised creep function $\psi(t)$ consists of the sum of a number of weighted exponential terms equal to the number of Maxwell units in the model.

The mechanism of creep under constant load is somewhat as follows. Immediately after application of load, the Maxwell units with very short relaxation times begin to give up their load. Since the units with very long relaxation times give up their load very slowly, they are called upon to carry some of the load given up by these other units. Hence for units with longer relaxation times the load first increases and only later decreases; for units with short relaxation times the load decreases continuously, and for the single elastic element (which has an infinite relaxation time) the load increases continuously.

The Superposition Principle

It is easy to show that the load in the Maxwell units of the models of Figs. 28, 30, 32, and 35 obeys the

Superposition Principle for a <u>given deformation history</u>. Since in the models of Figs. 32 and 35 only primary creep is present, it follows that the load in these models as a function of the deformation history follows the Superposition Principle (equation 20).

It has not been possible at the present time however to show that the model of Fig. 35 obeys the inverse law (equation 16), i.e., that the deformation as a function of the loading history obeys the Superposition Principle. This proof, together with the derivation of the creep under constant load for this model, are the mathematical aspects of the study of mechanical models that remain to be investigated.

It is clear that if, by suitable choice of the relaxation times of the various Maxwell units we can imitate in our model the behavior of a real material under any given history, we can refer the behavior of the real material under any other history to the behavior of the model. Shorter[57] has interpreted the behavior of textile fibers under load in terms of the above model, without of course claiming that the model represented the actual molecular processes inside the fiber. His remarks[58] are worth quoting in extenso:- "The elastic properties of fibers and yarns have been studied by a number of investigators .... who all attribute the peculiarities in the elastic behavior of fibers to plasticity, and speak of 'permanent strains' in fibers. .... I dispute this conclusion and put forward the view that textile fibers are much more perfectly elastic than the results of these investigators would seem to indicate and that the apparent elastic imperfection is largely due (in the case of wool almost entirely due) to the fact that the elastic extension or contraction is impeded by a resistance of a viscous nature. Such viscous or plastic material as exists in a fiber is, so to speak, in parallel with the elastic material and does not interrupt its continuity." Shorter then described a model analogous to that of Fig. 32.

Shorter proceeded: " If a given force be applied rapidly and maintained for a lengthy period of time, we get a rapid extension followed by a slow one. In the case of the model, the process of approach to equilibrium would be very simple -- the rate of approach would be proportional to the distance from the equilibrium. With animal hairs (wool, human hair, etc.) no such simple law is obeyed. The process of extension proceeds for a very lengthy period -- days or even weeks. The explanation of this is, not as might be supposed, that the elastic elements are showing a plastic yield, but that the fiber contains elastic elements with very different degrees of damping, so that on the first application of an external force the more lightly damped elements extend and, as time goes on, the extension of the more highly damped elements begins to show itself. We get a similar effect on removing the external force, and it is undoubtedly the extreme slowness of the recovery of the more highly damped elements that has given rise to the erroneous ideas of 'plasticity' and 'permanent strains'.

"Similar considerations apply to the case where a fiber is held stretched to a definite length. We get an apparent elastic relaxation which however is very different from the effect contemplated in Maxwell's theory of viscosity. It is not the disappearance of a state of strain owing to molecular readjustment, it is merely the transference of a state of strain from lightly damped to highly damped elements."

3. Reversal of Creep Recovery

It will be remembered that Kohlrausch[18] had demonstrated that for a suitably chosen loading history, reversal of the direction of creep recovery can take place in rubber and hard rubber; Hopkinson[16,17] had similarly demonstrated this effect in connection with the residual charge on a dielectric. Though the model of Fig. 32 obeys the Superposition Principle, it does not show the phenomenon of reversal of creep recovery. J. J. Thomson[34] pointed out in effect that in order for n reversals to take place, at least (n+1) Maxwell units are required. This requirement seems to have been appreciated previously by Hopkinson[16,17].

Series of Maxwell Units in Parallel

The previous model can be generalised one step further; we then get a series of Maxwell units in parallel, as in Fig. 36. This model has the primary creep properties of the model of Fig. 35, and also the property of viscous flow under load possessed by the model of Fig. 30. This model probably represents very closely the properties of a material such as glass. At room temperatures the greater relaxation times are so large that the corresponding Maxwell units behave simply as springs; we then get merely primary creep and creep recovery. At high temperatures all the relaxation times are finite and there is consequently an irreversible viscous flow proportional to load superimposed on the primary creep.

This model cannot be interpreted however as representing the flow under large loads of materials such as thermoplastic resins. Except at higher temperatures, the flow of these materials does not follow Newton's law of viscosity[124], but appears if anything to follow Bingham's Law. Furthermore, the secondary creep is in these materials not truly irreversible, but can be recovered in part or in whole under certain circumstances. To represent completely the properties of thermoplastic resins would require such complex models that the whole purpose of such models would be defeated.*

Other Mechanical Models

The model of Fig. 37 is often discussed in the literature[53,94,123,142]. This corresponds to the model of Fig. 32 with the exception that the former shows no instantaneous elastic deformation. The model of Fig. 38 corresponds in behavior[38,57,58,60,94] to that of Fig. 32, and the model[123] of Fig. 39 corresponds to that of Fig. 30.

Electrical Models

The closely analogy between the phenomena of

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* It seems reasonable to assume, that at temperatures which are high enough for the flow to become Newtonian in character, primary creep and "thermo recovery" disappear.

mechanical and dielectric creep has been emphasised, together with the parallel development of the study of these phenomena. In an analogous way to the mechanical models considered above, ideal electrical circuits or electrical models[79,123,125] have been proposed for the study of the anomalous properties of dielectrics. These models consist of pure resistances (corresponding to the viscous elements in the mechanical case) and pure capacitances (corresponding to the elastic elements). Potential corresponds to applied load, and charge (strictly speaking, "electric displacement") to deformation. Corresponding to a Maxwell unit a condenser and resistance are in <u>parallel</u> in the electrical model; parallel units in the mechanical model must be placed in series in the electrical analogue. Thus the electrical model of Fig. 40 corresponds to the mechanical model of Fig. 36.

II. Theories of Primary Creep

We will now consider in more detail the theories of Maxwell and Boltzmann mentioned previously. The Wiechert Theory will then be discussed in the light of the concepts developed in connection with the investigation of mechanical models. The early theories of the mechanism of creep were of a thermodynamical kind; they considered the vibrations and translations of molecules as a result of their heat motion. The treatment of Maxwell is most complete, and explains how primary creep and creep recovery can take place, as well as permanent deformation. Following Maxwell's paper Boltzmann published a short note explaining the ideas underlying his presentation of the Superposition Principle several years previously.

Maxwell's Theory of Creep

Maxwell's theory of creep[23] is to be found in an article written in 1877 for the Encyclopaedia Britannica. In this article the physical behavior of solids and fluids is first discussed. Maxwell remarked: "Solids, however, which are not viscous in the sense of being capable of an unlimited amount of change of form are yet subject to alterations depending on the time during which stress has acted on them. In other words, the stress at any given instant depends, not only on the strain at that instant, but on the previous history of the body. Thus the stress is somewhat greater when the strain is increasing than when it is diminishing, and if the strain is continued for a long time, the body, when left to itself, does not at once return to its original shape, but appears to have taken a set, which, however, is not a permanent set, for the body slowly creeps back towards its original shape with a motion which may be observed to go on for hours and even weeks after the body is left to itself." Maxwell then discussed the reversal of creep recovery and the superposition equation of Boltzmann.

Maxwell proceeded:- "(Boltzmann's equation) however, is not in any sense a physical theory of the phenomena; it is merely a mathematical formula which, though it represents some of the observed phenomena, fails to express the phenomenon of permanent deformation ....

"We know that the molecules of all bodies are in motion. In gases and liquids the motion is such that there is nothing to prevent any molecule from passing from any part of the mass to any other part; but in solids we must suppose that some, at least, of the molecules merely oscillate about a certain mean position, so that, if we consider a certain group of molecules, its configuration is never very different from a certain stable configuration, about which it oscillates.

"This will be the case even when the solid is in a state of strain, provided the amplitude of the oscillations does not exceed a certain limit, but if it exceeds this limit the group does not tend to return to its former configuration, but begins to oscillate about a new configuration of stability, the strain in which is either zero, or at least less than in the original configuration.

"The condition of this breaking up of a configuration must depend partly on the amplitude of the oscillations, and partly on the amount of strain in the original configuration; and we may suppose that the different groups of molecules, even in a homogeneous solid, are not in similar circumstances in this respect.

"Thus we may suppose that in a certain number of groups the ordinary agitation of the molecules is liable to accumulate so much that every now and then the configuration of one of the groups breaks up, and this whether it is in a state of strain or not. We may in this case assume that in every second a certain proportion of these groups break up, and assume configurations corresponding to a strain uniform in all directions.

"If all the groups were of this kind, the medium would be a viscous fluid.

"But if we suppose that there are other groups, the configuration of which is so stable that they will not break up under the ordinary agitation of the molecules unless the average strain exceeds a certain limit, and this limit may be different for different systems of these groups.

"Now if such groups of greater stability are disseminated through the substance in such abundance as to build up a solid framework, the substance will be a solid, which will not be permanently deformed except by a stress greater than a certain given stress.

"But if the solid also contains groups of smaller stability and also groups of the first kind which break up of themselves, then when a strain is applied, the resistance to it will gradually diminish as the groups of the first kind break up, and this will go on until the stress is reduced to that due to the more permanent groups. If the body is now left to itself, it will not at once return to its original form, but will only do so when the groups of the first kind have broken up so often as to get back to their original state of strain."

We therefore assume, according to Maxwell, that in a body showing the phenomenon of primary creep there is first a continuous structure of material bound by primary (chemical valence) bonds. Under ordinary conditions of temperature the molecules forming this framework can merely vibrate about their positions of equilibrium. In the pores of this framework is however material bound by secondary forces; this material is therefore of the nature of a liquid, the molecules continuously changing their positions of equilibrium. Creep and creep recovery are due to the viscosity of the "liquid" phase hindering the deformation of the "solid" phase; permanent set is due to a breaking up of the solid phase.

This two-phase theory has been adopted by chemists to explain the structure of gels. Unfortunately, it has not been possible to demonstrate the existence in materials manifesting primary creep the coexistence of material in widely differing states of aggregation. In fact recent research has shown that there exist in the structure of high polymers not two distinct phases but at least two distinct types of bonds. Maxwell's theory requires however but slight modification to adapt it to modern concepts of structure.

Boltzmann's Theory of Creep

Boltzmann's theory of the mechanism of creep[24] was published with the viewpoint of silencing those critics who claimed that the Superposition Principle was contrary to the contemporary concepts of atomic theory[27]. Boltzmann pointed out that he made no assumption that the forces between atoms possessed some sort of a memory. He assumed rather that the grouping of the atoms was dependent not merely on the instantaneous state but also on the previous states of the body. This dependence could arise as a result of the thermal motion of the atoms. In this connection the remarks of Warburg[28] and also of Neesen[19] are of interest.

Wiechert's Theory of Creep

In studying experimentally the phenomenon of primary creep, we usually measure the changes in strain due to a given stress history. In the theoretical study, however, the inverse viewpoint, namely, the change in stress due to a given strain history, is to be preferred. We have seen this to be true in the study of the model possessing several Maxwell units (Fig. 35). This latter viewpoint was the one adopted by Boltzmann and also by Wiechert[37].

Wiechert first considered the behavior of a body, manifesting only what we have called primary creep phenomena, when suddenly deformed by a constant amount. The stress set up as a result of this deformation will relax from an initial value down to a final value. When relaxation is complete, the body is then in a state of rest or katastasis. The stress corresponding to this katastatic state Wiechert called the katastatic stress. The stress at any previous time could be thought of as consisting of the final or katastatic stress upon which is superimposed a transient or epibolic* stress; the epibolic stress thus decreases gradually from its initial value to zero. Wiechert first assumed that the epibolic stress decays according to Maxwell's law of relaxation, as given by equation (48). This assumption leads to a relaxation behavior identical with that of the model of Fig. 32 (equation 54). For reasons that we have already indicated, Wiechert found that the observed relaxation behavior of materials did not follow this rule. He therefore proposed that the epibolic stress represent many relaxation effects taking place simultaneously but with different relaxation times. Referring now to equation (73), we see that the right-hand side consists of two terms. The first term is constant with time and represents the katastatic stress of the model of Fig. 35. The second term decays from an initial value at zero time to zero at infinite time, and thus represents the epibolic stress in the system. This epibolic stress is seen to be made up of (n-1) components of different "weights" $1/\mu_1$ and of different

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* The term "epibolicity" has been used by Peirce[63,66] and others in referring to what we have called primary creep effects.

relaxation times τ_i. The model of Fig. 35 is thus a mechanical representation of the second proposal of Wiechert. Wiechert then showed that this system obeyed the Superposition Principle as far as the load due to a given deformation is concerned; this result we have already seen to be true. He showed the same to hold for the deformation due to certain simple loading histories; but here it seems that he assumed as did Boltzmann[9] that the delayed deformation was small compared to the instantaneous deformation.

The Distribution of Relaxation Times and the Relaxation Function.

The general equation for relaxation under constant deformation is given by equation (28) or equation (56). The function $\Psi(t)$ we may call the relaxation function by analogy with the creep function $\psi(t)$ of equation (9). If we write for the stiffness of the springs in the model of Fig. 35, $a_i = 1/\mu_i$, then the normalised relaxation function $\Psi(t)$ is given by:

$$1 - \Psi(t) = \frac{\sum_{2}^{n} a_i e^{-t/\tau_i}}{\sum_{2}^{n} a_i} \qquad (75)$$

Equation (75) then indicates how the epibolic stress decays with time. Wiechert computed the change of $1 - \Psi(t)$ with time for various simple distributions of relaxation time, and plotted these against time to a logarithmic scale. Four of the cases investigated by Wiechert are shown in Figs. 41(a) to 41(d). In all cases the heavy vertical lines represent in position the relative relaxation times τ_i and in length the relative "weight" $a_i/(\Sigma a_i)$ of the relaxation time. Thus in Fig. 41(a) the decay of the epibolic stress when only a single relaxation time is present is seen to be rather rapid though smooth. When two relaxation times are present as in Fig. 41(b) the decay of stress is seen to be more gradual but to possess a point of inflection. In Fig. 41(c), five relaxation times have been chosen, distributed symmetrically on a logarithmic time scale. Here again a smooth curve is obtained but somewhat more extended than in Fig. 41(a). Finally, in Fig. 41(d), where the previous set of relaxation times is spread more widely over the logarithmic time scale, the relaxation curve is further extended but this time is seen to possess four points of inflection.

Continuous Distribution of Relaxation Times

In practice, of course, such points of inflection are never observed in the curves of relaxation under constant deformation. We therefore come to the conclusion that the behavior of a real material can be best represented by abandoning finally the model of Fig. 35 and by assuming a continuous distribution of relaxation times. Let us assume in fact that the proportion of relaxation times lying between Υ and $\Upsilon + d\Upsilon$ is given by $F(\Upsilon)\,d\Upsilon$. The function $F(\Upsilon)$ thus represents the distribution function of the relaxation times. The area under the distribution function curve is of course unity, hence

$$\int_0^\infty F(\Upsilon)\,d\Upsilon = 1 \tag{76}$$

Then the normalised relaxation function is given from equations (75) and (76) by

$$1 - \psi(t) = \int_0^\infty F(\tau)\, e^{-t/\tau}\, d\tau \qquad (77)$$

or $$\psi(t) = \int_0^\infty F(\tau)(1 - e^{-t/\tau})\, d\tau \qquad (78)$$

This is the general equation of the relaxation function in terms of any arbitrary distribution of relaxation times.

Wiechert's Special Distribution

It appears that the calculation of the distribution function of relaxation times from any experimentally observed relaxation curve is a very difficult, if not impossible, mathematical process. However, the reverse process is easily effected by means of equation (78).

The special distribution function assumed by Wiechert was obtained by taking to the limit the discontinuous distributions of Fig. 41. He then obtained for his distribution function a normal error curve on the logarithmic time plot. Then if $z = \ln(t/r)$ where r is the relaxation time corresponding to the mode,

$$F(\tau)\, d\tau = (b/\pi)\, e^{-b^2 z^2}.\, dz \qquad (79)$$

There is thus a singly infinite set of relaxation functions $\psi(t)$ given by this distribution, according to the value chosen for the "coefficient of concentration" b. An infinite coefficient of concentration corresponds to a single relaxation term. Fig. 42 is reproduced from Wiechert's paper. The sigmoidal curves may be interpreted as the values of the function $1 - \Psi(t)$, representing the decay of the epibolic stress, plotted to a logarithmic time scale. The bell-shaped curves are the corresponding distribution curves of relaxation times. It will be observed that in all cases the epibolic stress relaxes to half its value in a time slightly less than that of the mode of the distribution function.

The Importance of Wiechert's Work

Wiechert's Theory shows us first that the primary creep and relaxation properties of real materials may be represented by a series of Maxwell relaxation times, and that in fact the best characterisation is given by a continuous distribution of relaxation times. His theory shows how the distribution of relaxation times is connected with the relaxation under constant deformation. For materials in which the delayed deformation is small and in which the primary creep obeys the Superposition Principle (such as glass) the theory is directly applicable; it is probable that the distribution function of relaxation times could be computed directly from the observed creep curve under constant load. For materials in which the primary creep obeys the Superposition Principle but in which the delayed deformation is not small compared to the instantaneous deformation (in general, high polymers), the theory is not immediately applicable to creep tests under constant load. As has been pointed out above, it is first necessary to investigate mathematically the relation between creep and relaxation.

It will be shown in the experimental section that the textile filaments studied do not obey the Superposition Principle in the form used above. This deviation appears to be peculiar to highly oriented high polymeric materials. The behavior of these materials therefore cannot be thought of in terms of a distribution of relaxation times, and Wiechert's theory is of a qualitative value only. On account of the limited application of Wiechert's theory to the experimental work which follows, only the fundamentals of the mathematical theory have been presented, and it has not been considered worth while at this stage to fill in the gaps in the theory. The further development of Wiechert's theory has been carried out by electrical engineers, to whom the theory has been of great value as a method of representing some of the properties of dielectrics.

Becker's Theory of Creep

It will be remembered that in the simplest model possessing primary creep properties, that of Fig. 32, the creep behavior under constant load and the relaxation behavior under constant deformation were compared. It was shown, in the special case where the creep is relatively small, that the normalised creep function and the normalised relaxation function are the same (equations 67 and 68). On the other hand when the delayed deformation is large compared to the instantaneous deformation, this is not true (equations 57 and 62). We are justified in accepting these results for the general case also of a distribution of relaxation times. Now Becker's theory[59] was developed using the concept of a continuous distribution of relaxation times, from the point of view of deformation due to a given loading history. He obtained however a result for the normalised creep function $\psi(t)$ identical with that obtained above for the normalised relaxation function $\psi(t)$, equation (78). It must be assumed therefore that implicit in the derivation of this result is the assumption that the creep is small.

There are several other theories, of lesser importance. These can be found in a review of the mathematical aspects of creep by Fromm[70] and also in an earlier review by Auerbach[43].

The Creep Curve for Constant Load

The importance of the creep curve under constant load has already been noted; it was mentioned previously that in general the effect of change of temperature is to shift the deformation curve (plotted to the logarithm of the time under load) along the axis of logarithmic time, without significantly changing the shape of the curve. This has been shown to be true for soft rubber (Fig. 14), for hard rubber[143] (Fig. 15) and for bakelite (Fig. 16). It has also been shown to be true for the dielectric creep of phenolphthalein[153]; furthermore the normalised creep functions for the magnetic and mechanical creep of soft iron are very similar and have a very similar dependence on temperature[159].

It is of interest to collect together the normalised creep curves on one graph. Fig. 43 shows the normalised creep functions for rubber, and for bakelite and hard rubber. The curves are adjusted so that unit time corresponds to the attainment of half the total delayed deformation, the curves thus all intersecting at one point. For comparison the curve corresponding to the single Maxwell unit with spring (Fig. 32) is given; this of course corresponds to Wiechert's $b = \infty$ curve. In addition, Wiechert's normalised relaxation curves for $b = 0.2$ and $b = 0.075$ are included for comparison. In Fig. 44 are drawn the normalised creep curves again for a single relaxation time and also for soft iron and hard rubber. It is seen that the effect of continued vulcanisation is not only to reduce the magnitude of the delayed deformation but also to reduce the spread of the relaxation times.

The Time Ratio

A convenient means of representing the spread of the normalised creep or relaxation function along the logarithmic time scale is by means of what we may call the time ratio. We may specify a time ratio for example by the ratio of that time required for 75% of the delayed deformation to be attained, to the time required for 25% of the delayed deformation to appear. The following are the time ratios for the above curves obtained in this way.

Material	Source of Data		Time Ratio (approx.)
Iron (magnetic and mech. creep)	Richter[159]		6.0
Hard Rubber	Kobeko[143]		
Bakelite	Hetenyi[151]		7.8
Soft Rubber	Kobeko[143]		1000
Theoretical	Wiechert:[37]	$b = \infty$	4.7
		$b = 0.2$	210
		$b = 0.075$	48,000

III. Effect of Temperature on Primary Creep

We have seen how Kohlrausch[6] discovered by accident the necessity for keeping temperatures rigidly constant during a creep test; slight variations of the temperature of test are always found to have a marked effect on the observations. We have also seen from the work of Kobeko[143] and the results of Hetenyi[151] (Figs. 14, 15, 16) that the effect of change of temperature on primary creep is to displace the creep curve under constant load in the direction of the axis of logarithmic time, i.e., to expand or contract the time scale. This same result is to be deduced from the early data of Kohlrausch (Fig. 9), and is confirmed by the data on the temperature effect in the dielectric creep of phenolphthalein[153], and in the magnetic and mechanical creep of soft iron[159]. Undoubtedly we have here a very significant phenomenon, from the analysis of which can be drawn important conclusions concerning the mechanism of creep.

Effect of Temperature on Viscosity

It will be remembered that Maxwell's model for the structure of a body manifesting primary creep consists of a sponge formed of material linked by primary bonds. In the pores of this sponge is material linked by secondary bonds; these bonds break up from time to time as a result of the heat motion of the molecules, and in fact this material can be considered as being a liquid. Though there is no chemical evidence for the existence of two distinct phases in such materials[82], it is necessary to modify Maxwell's model only slightly to obtain one which is more consistent with modern ideas[87]. We can say that in such bodies there coexist primary bonds which remain unbroken over the temperature range, as well as secondary bonds which break up as a result of the heat motion of the molecules, and which are strongly affected by temperature. Since these latter bonds behave like the bonds which exist between the molecules in a simple liquid, it is of interest first to consider the mechanism of viscosity of liquids and the temperature effect on viscosity.

It is to be observed that the viscosities of liquids decrease with temperature, while the viscosities of gases increase with temperature; the mechanism of viscosity in liquids must therefore be different from that in gases. Furthermore, the density of a material in the liquid state is usually much greater than in the gaseous state, hence strong cohesive forces must exist between the molecules of a liquid. We can imagine therefore that under the action of these forces a given molecule vibrates due to its heat motion about a position of equilibrium. Now all the molecules do not possess the same thermal kinetic energy; these energies are distributed statistically over a wide range among the molecules of the liquid. There exists thus at any given temperature a certain probability that a particular molecule will possess a kinetic energy in excess of the potential energy of the bonds holding it in place. Hence in a given interval of time a definite proportion of the molecules given by this probability will leave their places and find new places of equilibrium. Ordinarily, this occasional migration of molecules from one position of equilibrium to another is random and undirected. Under an applied shear stress however flow takes place and the rate of shear strain is proportional to this probability. If T is the absolute temperature, and if k is Boltzmann's constant and q the height of the potential barrier that a molecule has to surmount, this probability is given by

$$p \propto e^{-q/kT} \tag{80}$$

Multiplying q and k by Avogadro's number, we get:

$$p \propto e^{-Q/RT} \tag{81}$$

where Q now represents the height of the potential barrier expressed in calories per gram-molecule and R is the gas constant in calories. Q is usually called the <u>energy of activation</u>. A high energy of activation corresponds to strong bonds. The viscosity of a liquid should therefore vary with temperature according to a relation of the form:

$$\eta = A\, e^{B/T} \tag{82}$$

where $B = Q/R$

It appears for simple liquids that this law satisfactorily represents the change of viscosity with temperature[189]. The above law, first proposed[46] in 1913, has since been deduced independently[61] by different methods.

Creep and Temperature

Now let us consider the processes taking place when a load is applied to a body manifesting primary creep. On applying the load to the body, the load is shared between the primary and secondary bonds. The strong primary bonds are unaffected by the heat motion of the molecules; on the other hand, as a result of this heat motion there is a statistical breaking up of the weaker secondary bonds. If the load is maintained constant, there is a gradual transference of load from the secondary to the primary bonds. Thus the primary bonds behave like springs, while the secondary bonds behave like Maxwell units. A distribution of relaxation times arises as a result of a difference in the rate of breaking up of different secondary bonds. Thus this system of primary and secondary bonds would be expected to behave in the same way as the model of Fig. 35.

With increase of temperature these relaxation times would be expected to decrease, since the probability of break-up as given by equation (81) increases. The relaxation times of the secondary bonds should therefore all vary with absolute temperature as $e^{Q/RT}$. Consequently, change of temperature should not alter the distribution of relaxation times; the shape of the creep curve for constant load (on the logarithmic plot) should therefore be unaltered for moderate changes of temperature. This expectation is borne out by experiment. Furthermore, the effect of changing all the relaxation times in a given ratio would be merely to alter the time scale of creep, as is obvious for example by inspection of equation (74).

The effect of change of temperature should be therefore merely to displace the creep curve on the logarithmic time plot along the axis of logarithmic time; this expectation is again borne out by experiment.

Let us now investigate the nature and magnitude of this displacement. Following Kobeko[143], we will call the time required at any given temperature for the delayed deformation to reach half its final value the <u>time constant</u> t_c. Then

$$t_c \propto e^{Q/RT}$$

or

$$\log t_c = Q/(2.3026\ RT) + \text{a constant} \qquad (83)$$

Thus if we plot the common logarithm of the time constant against the corresponding reciprocal absolute temperature, we should obtain a straight line the slope of which is equal to $Q/4.58$, where Q is the <u>energy of activation for creep</u> expressed in calories per gram-molecule. Comparison with values of Q obtained by purely chemical methods should lead to the determination of the mechanism of creep in a given material.

Energy of Activation for Creep

There are three methods for determining the energy of activation for creep. The first method is that outlined above, in which the creep curve under constant load (or recovery following long duration creep under constant load) is obtained over a range of temperatures. The logarithm of the time constant plotted against the reciprocal absolute temperature gives a straight line from which Q may be computed. This method, first used by Richter[159], gave for mechanical creep of soft iron a value of Q and a normalised creep curve almost identical with those obtained for the magnetic creep of the same material. Values of Q have been computed in this way from the data on soft rubber (Fig. 14), hard rubber (Fig. 15), and bakelite (Fig. 16). From data on dynamic tests described in the next section[174] Q has been calculated for chloroprene and for plasticised and unplasticised methyl methacrylate. In the third method outlined below, Q has been calculated from the recovery following constant deformation of short duration.

Calculation of Energy of Activation from Recovery Experiments

It will be remembered that F. Kohlrausch[6] had published very early in his investigations some data on the effect of temperature on the creep of silver (Fig. 7). The decay of residual twist of a silver wire was measured after it had been twisted through 180° for one minute and then released, the experiment being repeated at different temperatures.

We know that we can interpret approximately the data of such an experiment as the residual twist due to a constant twist y_o of very short duration Υ; we have, as in equation (33),

$$y_t = y_o \beta \Upsilon . \phi(t)$$

where the residual twist is y_t and the time t is reckoned from the middle of the time under strain. Now let us suppose that the same experiment be performed at a higher temperature. The effect of increase of temperature is to change the time scale; let us assume that the effect of the increase is to contract the time scale by a factor α. Let the residual deformation at a time t at the higher temperature be now denoted by y_t'. Then from the above equation

$$y_t' = y_o\beta\ (\alpha\Upsilon)\ .\ \phi(\alpha t)$$

$$= \alpha\ y_{\alpha t} \tag{84}$$

In other words, the residual deformation at time t at the higher temperature is equal to α times the residual deformation at a time αt at the lower temperature. Now let us plot the logarithm of the residual deformation against the logarithm of the recovery time for each of the two tests, using equal scales for ordinate and abscissa. It can then be seen from the diagram of Fig. 45 that the effect of change of temperature is to shift the curve on this plot in the 45° direction as shown. If we draw a line at an angle of 45°, the intersections of this line with the curves should correspond to times the logarithms of which should vary with the reciprocal absolute temperature as in equation (83).

Analysis of the data of Kohlrausch on silver and of Rehkuh[33] on glass and silver by this method gives however only a poor agreement with theory; the values given in the table below represent therefore only the order of magnitude of Q for these materials.

Calculation of Energy of Activation from Dynamic Tests

It will be shown later that if a force varying sinusoidally with time of a given amplitude be impressed on a body manifesting primary creep, then at a given temperature the energy loss of the specimen due to primary creep will vary with frequency. At a certain frequency the energy loss reaches a maximum. If the logarithm of this frequency (or of its reciprocal) be plotted against the reciprocal absolute temperature, a straight line will be obtained, from the slope of which the energy of activation can be computed. Fig. 46 shows some results which have been obtained on high polymeric materials[174].

Tabulation of Energies of Activation

The following table gives values of Q found in the literature or computed from published data. The first six figures are to be taken as indicating the order of magnitude only.

Material	Source of Data	Method	Q cals/mole
Silver	Kohlrausch	Recovery	9,600
Silver	Rehkuh	do.	11,000
Glass	Rehkuh	do.	5,800
Bakelite	Hetenyi	Creep	80,000
Rubber	Kobeko	do.	39,000
Hard Rubber	Kobeko	do.	97,000
Iron	Richter	Mechanical Creep	19,500
Iron	Richter	Magnetic Creep	20,300
Phenolphthalein	Kuvshinski	Dielectric Creep	126,000
Rubber (with 3% S)	Alexandrov	Dynamic	37,600
Chloroprene			39,000
Methyl Methacrylate			72,000
do. + 10% Plasticiser			57,800
do. + 20% Plasticiser			52,000

IV. Dynamic Loading

A very important property which is possessed by high polymers is the ability to dissipate mechanical energy as heat, when under alternating stress. This property in natural and synthetic rubbers and also in laminated phenolics makes these materials of value in engineering applications. This property, known as damping capacity or internal friction, has been very little understood, and its variation with stress, frequency, and temperature not properly appreciated.

It was in the first paper ever published on the phenomenon we now call primary creep[1] that the connection between damping capacity and primary creep was suggested; Weber indicated that the decay of torsional oscillations of a torsion pendulum or of sound vibrations in a solid could be attributed to the action of primary creep. Some recent work[174] that has been carried out on the effect of variation of frequency and temperature on the dynamic behavior of high polymers appears to confirm completely the suggestion of Weber.

The variations of capacity and dielectric loss of condensers with frequency and temperature are very complex and of great technical importance. Here again it might be expected that these phenomena could be attributed to the action of dielectric creep. On account of the importance of the problem, much attention has been devoted to it[47,130,186]. Accordingly, the study of the manifestation of dielectric creep under alternating conditions has been in advance of the corresponding study of the dynamic effects of mechanical creep.

Mechanical Properties under Dynamic Loading

In connection with the properties of materials under static load it was found useful to consider the behavior of certain simple mechanical models. In discussing dynamic behavior, these models are again of great assistance. The simplest model which manifests only the property of primary creep is that of Fig. 32, in which a spring is connected in parallel with a Maxwell unit; this model was found to possess qualitatively the same creep properties as real materials. Quantitative correspondence could be obtained by generalising the model, so that a continuous distribution of relaxation times given by some distribution function was obtained.

Model with Single Maxwell Unit

Since this model obeys the Superposition Principle, we may use this Principle to find the behavior of the model under sinusoidal load. The deformation x_t of the model at time t, due to the application of a constant load P at zero time, is, from equation (59), of the form

$$x_t = P\alpha \left[1 + \beta(1 - e^{-t/\Upsilon}) \right] \qquad (85)$$

where the normalised creep function is as given by equation (62). If now we have a sinusoidal applied load given by

$$P = P_0 \sin \omega t$$

the deformation x_t may be obtained from equation (85) and from equation (16) or equation (13); it is:

$$x_t = P_o\alpha\left[\left(1 + \frac{\beta}{1+\omega^2\Upsilon^2}\right)\sin\omega t - \left(\frac{\beta\omega\Upsilon}{1+\omega^2\Upsilon^2}\right)\cos\omega t\right] \qquad (86)$$

This deformation can be represented by the imaginary part of:

$$P_o\alpha\left[1 + \beta/(1 + i\omega\Upsilon)\right] e^{i\omega t}$$

Alexandrov and Lazurkin[174] have given a graphical construction for this deformation as a function of frequency. The deformation is seen to be sinusoidal and to consist of two parts, one of which is in phase with the applied force, and the other in quadrature.

Let us first consider the behavior of the model of Fig. 32 under an alternating force of extremely high frequency. Since the dashpot of the Maxwell unit will be effectively "frozen", the system behaves like two springs in parallel. The deformation is thus in phase with the applied force, the angle of lag is zero, and further, the amplitude of the deformation corresponds to the instantaneous elastic deformation. For very high frequency therefore equation (86) reduces to:

$$x_t = P_o\alpha\sin\omega t \qquad (87)$$

Now let us consider the case where an alternating force is applied extremely slowly. In this case the Maxwell unit is always completely relaxed; the load is carried only by the single spring. The deformation is again in phase with the applied force, but this time the amplitude corresponds to the sum of the instantaneous and delayed deformations as given by:

$$x_t = P_o\alpha(1 + \beta) \sin \omega t \qquad (88)$$

It therefore follows that as the frequency increases from zero to infinity, the apparent stiffness of the system increases continuously, while the angle of lag rises to a maximum and then decreases again. This angle of lag is of course a measure of the damping capacity of the material, and is a maximum at a frequency given by:

$$\omega\Upsilon = (1 + \beta)^{-1/2} \qquad (89)$$

Thus for a material characterised by a single relaxation time, both the apparent modulus and energy loss can vary over a wide range as the frequency varies. Similarly, if the dielectric of a condenser can be considered as possessing a single relaxation time, the change of loss angle and capacity with frequency at constant temperature is given by the above equations[47,130,186].

Effect of Temperature Variation

We can now investigate the effect of a moderate variation in temperature on the dynamic behavior of the model of Fig. 32. We know that if Q is as before the energy of activation for primary creep, the time scale of phenomena associated with primary creep varies with absolute temperature as $e^{Q/RT}$, and hence the frequency scale will vary as $e^{-Q/RT}$. Generally speaking, therefore, we can say that variation of the reciprocal of the absolute temperature at a given frequency corresponds to variation of the logarithm of the frequency at a given temperature. At a very low temperature, therefore, the dashpot of the model of Fig. 32 is "frozen in" due to increase of the time of relaxation of the Maxwell unit to infinity; at a very high temperature, this time of relaxation becomes zero, and the single spring acts alone. Furthermore, we can say that the frequency at which the loss angle is a maximum varies with temperature as $e^{Q/RT}$. Hence the logarithm of this frequency plotted against the reciprocal absolute temperature should give a straight line from the slope of which Q could be obtained[174].

System with Distributed Relaxation Times

We have seen that the model of Fig. 32 failed to express quantitatively the primary creep properties of materials under constant load. Similarly, it has been demonstrated that the properties of a dielectric under alternating voltage cannot be represented quantitatively by the above scheme, since in practice the loss maxima are less pronounced[130,181] as are also the variations with temperature. Wagner[47] therefore applied Wiechert's distribution of relaxation times (equation 79) to the dynamic problem and computed the behavior of condensers according to this distribution for several values of the "coefficient of concentration" b. These calculations were completed by Yager[130], who showed a good agreement to exist between experiment and theory. At least in the case of the dielectrics tested, therefore, the behavior of dielectrics can be described by the Superposition Principle, assuming a distribution of relaxation times according to Wiechert.

The mechanical behavior of high polymeric materials appears to follow the same general rules. The effects of variations of temperature and frequency on the mechanical properties of plastics have been discussed by Alexandrov and Lazurkin[174].

Part IV.

THE STRUCTURE OF HIGH POLYMERS

I. Early Work on Structure

The object of this part of the thesis is to give an account of the development of the contemporary concepts of the ultimate structure of high polymeric materials. These concepts are then used to consider the mechanism of creep in particular, and of mechanical deformation in general, of these materials. As a starting-point for research, many theories, necessarily of an ad hoc nature, were propounded. Subsequent investigation disproved most of these. Successive modification of the remaining concepts has resulted in a picture of the structure of materials which is generally accepted today.

In the main, four experimental methods have been used in the study of the structure of high polymers, the most important being the X-ray diffraction and chemical methods. Study of physical and optical properties (by means of the polarising microscope) has also been made. More recently the problem of structure has been attacked by using combinations of these methods; for example, the changes in X-ray diffraction behavior as a result of specific mechanical treatment have been studied.

This work has resulted in four basic theories of structure. As a result of early X-ray work, which indicated the quasi-crystalline nature of certain high polymers, the _micelle_ or _crystallite theory_ was developed. On the other hand, chemical evidence supported a continuous structure theory. More recently, as a result of further experimental evidence, a new theory has been developed, which combines the essential features of both the above theories. This new theory may be called the fringe theory or the network theory of the structure of quasi-crystalline high polymers. Very recently a further theory, the kinetic theory of high elasticity, has been proposed to account for the high reversible extensibility of rubber-like materials. This may be regarded as complementary to the network theory. Naturally, the work on high polymers has covered a wide field, and it has been impossible in the brief time available to consult and report in detail on the extensive literature. In this part of the thesis, therefore only the main points in the development of modern concepts are discussed.

Early Views of Structure

With the exception of one or two materials, all high molecular weight materials are of an organic nature. Rubber is a pure hydrocarbon; cellulose and its derivatives contain oxygen; proteins such as wool, silk, gelatin and collagen contain nitrogen also and sometimes sulphur in addition. Synthetic materials such as the various commercial plastics, the elastomers ("synthetic rubbers"), and the purely synthetic fibers may contain these elements and possibly halogens as well.

One is struck by the wide variation in physical properties of these materials. Rubber for example when lightly vulcanised is highly extensible, yet it can recover almost immediately its original form. Wool under certain conditions has similar properties. On the other hand, natural fibers such as flax and ramie possess small elastic ex tensibilities, yet they are very strong. As a result of such wide variation in physical properties, many ad hoc structures were proposed to account for the room temperature properties of the various materials. For example, there were many theories to explain the high reversible extensibility in rubber. In one, long molecular chains were assumed to be coiled in helices in the contracted state; these helices opened up on extending the material. The mutual attraction of the double bonds was supposed to keep the helices closed.

Another theory postulated a two-phase structure for rubber identical with that proposed by Maxwell: a skeleton of material linked by primary bonds was filled by material linked by secondary bonds; this latter material could therefore be considered as being in a low degree of polymerisation, while the former was highly polymerised. It was shown however, that many other materials under suitable temperature conditions also manifested rubber-like properties[87,96,101]. Several of these materials, known on chemical grounds to consist of long-chain molecules, could be separated into a series of fractions of differing average molecular weight[82,100]. Similarly, theories of the structure of wool involving folding polypeptide chains[86,103] and of the structure of thermosetting resins involving two distinct phases[114,131,142] have not been found to be consistent with all the experimental evidence.

The contemporary viewpoint is not that the different materials possess distinctly different structures, but that their structures are all variations of one basic scheme. It is generally agreed that high polymeric materials contain long molecular chains consisting of the same unit or of similar repeating units. The differences in the properties of high polymers are due to the differences in the properties of these chains and in the manner by which they are connected together.

Application of X-Rays to the Study of Structure

Very soon after the discovery of X-rays, and of their penetrability of matter, they were put to use to study the crystalline structure of many inorganic materials. It is in the last twenty years or so that the more complicated problem of the structure of high polymers has been studied. Before considering the early X-ray work on these materials, a brief review of the mechanism of X-ray diffraction would not be out of place. When a monochromatic beam of X-rays falls upon a body, the atoms of the body become secondary sources of radiation, and are said to "scatter" the X-rays. Part of the scattered radiation involves a change of wavelength. Part however, is scattered without a change of wavelength, and if the atoms of the scattering body possess some degree of regular arrangement then the "unmodified" secondary X-rays from the different atoms reinforce each other in certain directions and destructively interfere in others. If the body under investigation be placed in a fine pencil of monochromatic X-radiation, then on a photographic film behind the body an interference pattern will be produced. The technique of making and interpreting such patterns constitutes the field of X-ray diffraction.

There are three main types of pattern to be obtained with monochromatic radiation, namely, powder pattern, fiber (rotation) pattern, and amorphous halo[113]. Let us assume that in the X-ray beam is placed a sample comprising a small piece of polycrystalline metal. This metal consists of crystals in each of which the atoms are regularly arranged in the crystal lattice; the crystals are however usually randomly oriented in the specimen. If a flat film be placed normal to the X-ray beam beyond the specimen, the pattern produced on the film will consist of a series of circles of different diameters and intensities, about the axis of the beam as center. This is the <u>powder pattern</u>. Such a pattern is also produced when a single crystal is ground into a fine powder and this powder used as the specimen.

When a single crystal is placed in the X-ray beam with one of its crystallographic axes perpendicular to the beam, and rotated about this axis, a <u>rotation</u> or <u>fiber pattern</u> is produced. When a flat film is used, the pattern consists of a series of points which lie on rectangular hyperbolae. If the photographic film is in the form of a cylinder, the axis of the film being the axis of rotation, the points will lie on straight lines perpendicular to the axis of rotation. These points lie at the intersections of these "layer lines" and of the circles in the corresponding powder pattern.

Finally, if a specimen be used which has no crystalline order but in which the building units are a certain average distance from each other, there will be obtained an amorphous "halo", the diameter of which corresponds to this average distance[113,132]. In general, glasses and liquids give amorphous halos. It is useful to remember that large circles in the powder diagram correspond to small distances between reflecting planes, and vice versa.

The Crystallinity of Textile Fibers

Just over twenty years ago the first significant X-ray work was carried out on textile fibers. It was found that when certain fibers were placed with their axes normal to the X-ray beam, the X-ray pattern obtained was similar to the "rotation" pattern described above. The explanation of this result was as follows. These fibers were crystalline in nature, or at least partly so. The crystals, which necessarily had to be submicroscopic in size, were called crystallites or micelles. In order to produce a rotation pattern, it was necessary for the crystals to be oriented in the fiber in a certain way, namely, for one of the crystallographic axes of all the crystallites to be parallel to the axis of the fiber; the crystallites were otherwise randomly arranged around the fiber axis. When the orientation of the crystallites was not perfect, the points would spread out into arcs of circles, the center of which was the center of the pattern. All cellulosic fibers investigated were found to give the same basic pattern; ramie corresponded to almost perfect orientation. Silk, wool, and hair also gave crystalline patterns. Rayon was shown at first to give a powder pattern (indicating practically no orientation of the crystalline units) but later tests on improved material gave fiber patterns. On the other hand, gelatin was thought to be a mixture of two amorphous substances, while collagen gave a fiber pattern. Rubber again gave an amorphous pattern.

The Micelle Theory

The micelle theory offered an explanation of the structure of materials deduced from their X-ray diffraction data: it was developed chiefly with reference to cellulosic fibers. It was shown from the X-ray patterns that the unit cell of cellulose is quite small, and can accomodate only four glucose residues. Now we know that in ionic and homopolar crystals the lattice points of the unit cell are occupied by ions and atoms respectively. In molecular crystals the lattice points are occupied by molecules. In the latter case, the crystals are very weak, the molecules being bound together only by weak residual forces. If the glucose residues in cellulose were similarly connected, the material should be very weak, and should have the properties of low molecular weight substances. It was concluded therefore that the molecules of cellulose consist of long chains, connected by primary bonds, and that these molecular chains are much longer than the length of the unit cell.

The first picture to be arrived at for the structure of cellulose was therefore as follows. We imagine long regularly arranged parallel chains, bound along their length by primary bonds, and laterally by secondary bonds. Two such chains run through each unit cell, which then contains two cellobiose residues. We imagine a bundle of these chains some 50 A.U. in thickness and at least 500 A.U. long to form the micelle. In ramie these micelles have been pictured as lying in a parallel arrangement, as bricks in a wall, Fig. 47(a). The micelles are presumed to be bound together by weak tertiary forces, by some intercrystalline cementing substance, or by flexible hinges of interconnecting chains. In less well oriented cellulosic materials, the micelles are assumed to have a rather more random arrangement[108]. In order to account for the high molecular weight of cellulose in solution, it is necessary to assume that the micelles go into solution without disintegration.

The above picture was consistent with the X-ray evidence. However, it became clear that many of the physical and chemical properties of textile fibers (and of other high polymers giving diffraction patterns) depended on the amorphous rather than on the crystalline portion of the material[184,187]. The nature of the intercrystalline amorphous material could only be speculated upon; for example, it was proposed that near the surface of the micelle the orientation might be poor, and this region would therefore behave like amorphous material. It was also proposed that the chains run continuously through several micelles, the roentgenographically indicated limits of the micelle corresponding to faults in the continuous structure.

The Continuous Structure Theory

An alternative theory, called the continuous structure theory, was developed by Staudinger[100] and supported by the work of Carothers[83]. Developed largely on chemical evidence, this theory is more in accordance with the chemical and physical properties of high polymers; it accounts for the structure of high polymers such as polystyrene which do not give definite X-ray interference patterns[132]. According to Staudinger, the structure of natural high polymers can be best deduced by synthesising artificial polymers from low up to the highest possible molecular weights. Carothers' viewpoint was that natural high polymers consist of long molecular chains, and that if polymers could be synthesised of sufficiently high molecular weight, a material having properties comparable with those of natural high polymers could be obtained.

Staudinger studied the polymerisation of polyoxymethylene from formaldehyde and of polystyrene from styrene. The former polymer Staudinger took as a "model" for cellulose, and the latter as a "model" for rubber[100]. Carothers argued that the mechanism in such addition-polymerisations was unknown[104]. In condensation-polymerisations, however, if the repeating unit was sufficiently long the possibility of ring closure was small, and hence long molecular chains of known composition were necessarily formed. Carothers[83] indicated methods by which condensation-polymerisation could be carried out, for example, formation of polyesters by self-esterification of hydroxy acids and also from dibasic acids and glycols;

polyamides from amino carboxylic acids, as well as from diamines and dicarboxylic acids; and polyanhydrides from dibasic acids.

Staudinger showed how a repeat pattern could arise in a long-chain polymer containing chains of different length. He pointed out that whereas low polymers could be separated from each other completely, this became less possible as the degree of polymerisation increased. He studied the X-ray diffraction behavior of polyoxymethylene diacetate in a low degree of polymerisation and found interferences corresponding to the length of the $-CH_2O-$ repeat unit, as well as longer period (i.e., smaller angle) interferences corresponding to the length of the molecule. The length of the molecule thus determined was found to increase by the length of the $-CH_2O-$ group for each unit increase in the degree of polymerisation[100]. In the words of Katz[132]:

"While in the case of lower polymers (for instance with 10-20 CH_2O groups) the length of the molecule could be studied, this method failed in the case of the higher polymers. Here it was not possible to separate the polymers into fractions each having one single chain length. Such complex mixtures now showed a very interesting phenomenon. The small interference rings related with the length of the molecule were now failing. This experience is especially interesting, as they have never been found in natural high polymeric substances (like cellulose, rubber) and many synthetic polymers. So we are led to the assumption that in all such cases where these interference rings fail there are mixed crystals built up by molecules of such a different length that these interferences cannot be formed. Staudinger at once applied these results to cellulose, asserting that it had in principle the same structure."

The two cases can be represented by Figs. 48 and 49*. In the former case, representing the low polymer, the influence of the chain ends allows fractionation into pure polymers, in which a repeat distance "a" corresponds to the length of the chain. In the latter case, the influence of the end groups becomes lostin the high polymer, and crystallisation takes place in the form of a continuous structure, the chain ends causing merely local structural distortions. With the high polymer therefore only the interferences corresponding to the repeat distance "b" appear. Such high polymers swell before going into solution owing to the difficulty of penetration of the continuous structure by solvents. Solution takes place by removing individual chains, and the high viscosity and molecular weight in solution can then be attributed to the presence of long chains in the solution. There are many high polymers, such as polystyrene and polyvinyl bromide, which do not give fiber or powder patterns, but merely amorphous halos. Staudinger suggested that this was probably due to the formation of irregular chains; it seems more probable in the light of recent work that the lack of crystallisation is due to the existence of massive side groups (as in polystyrene) preventing the close approach of chains, or the lack of strong

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* See also Fig. 47(b).

attractive forces between the chains. Such non-crystalline structures can thus be considered as formed of a tangled mass of chains, the diameter of the halo corresponding to the average separation of the chains.

Staudinger's continuous structure thus explains many of the chemical and physical properties of both crystalline and non-crystalline high polymers in terms of long molecular chains. We shall see that some experimental data considered below cannot be properly explained either by the continuous structure theory or by the micelle theory, and that it is necessary to evolve a new theory combining the essential aspects of both these theories.

Superpolymers

The first direct connection between average chain length and strength of the polymer was obtained by Carothers. He showed that by a special technique[88] controlled polymerisation up to very high molecular weights could be obtained. He found for a particular polymer the relation between average molecular weight and chain length, on the one hand, and fiber-forming properties on the other[104]. Some of his results are given in the table below.

Av. Molecular Wt.	Chain Length, A	Fiber-forming property
5670	440	Short, very weak fibers
9330	730	Long, very weak fibers which cold-draw.
16,900-20,700	1320-1610	Strong fibers

Mechanical Treatment and Structural Changes

We have seen that the X-ray study of materials in their normal state led to two theories of structure either of which seemed equally plausible. Further progress thus demanded the application of the X-ray method to the study of the changes taking place in high polymers as a result of mechanical and chemical treatment[113]. A series of investigations on rubber and also on changes in structure of collagen and gelatin led to a theory of structure which was consistent with previous evidence and also with the X-ray study of the swelling of high polymers. It is of interest first to discuss this work on collagen and gelatin.

Collagen and Gelatin

Though collagen and gelatin gave distinctly different X-ray diagrams, their chemical properties were found in many respects to be the same[76]. A study of the changes of the X-ray diagram of gelatin due to swelling revealed that two components are present, an amorphous phase and a crystalline phase[76,77]. If now gelatin is swollen, highly stretched and dried under stretch, the resulting material is highly oriented, and gives the X-ray diagram of collagen, though it is nothing more than gelatin[62,99]. On the other hand, if collagen in the form of sinew be heated, the collagen contracts and gives an X-ray pattern corresponding to gelatin[62,96]. By reheating, stretching and recooling in the stretched condition, the collagen can be restored to its original form.

From these experiments it was concluded that collagen can be regarded as a highly oriented form of gelatin; presumably in the former case there are stronger cross-bonds and longer chains. A study of the collagen and gelatin X-ray diagrams led Herrmann and Gerngross to the observation that the crystalline rings in the gelatin diagram become reduced to equatorial and meridianal flecks in the collagen diagram; and the amorphous halo in the gelatin diagram becomes concentrated on the equator in the latter case[76]. These deductions may be verified by referring to Fig. 50, which shows the X-ray diagram for gelatin, and to Fig. 51, which shows the diagram for collagen. The X-ray diagram of stretched gelatin, Fig. 52, is seen to be indistinguishable from that of collagen. It follows therefore that on stretching gelatin or contracted collagen, both the amorphous and the crystalline phases become oriented; on contraction of collagen both phases become simultaneously disoriented.

Herrmann and Gerngross came to the conclusion that collagen and gelatin should not be thought of as having two distinct phases[76], a crystalline phase and an amorphous phase; they postulated instead a "fringed micelle". This concept[75, 76,77] which they slightly modified later[93], is generally accepted today as agreeable with most of the experimental data.

The Crystallinity of Rubber

The remarkable property of rubber and of some elastomers in crystallising under certain circumstances cannot be satisfactorily explained either by the micelle theory or by the continuous structure theory. Rubber normally gives merely an amorphous diagram, although sometimes in unvulcanised rubber crystalline interferences are found[96]. On the other hand, with stretched rubber, superimposed on the amorphous halo a good rotation pattern is obtained, increase of stretch resulting in an increase in intensity of the rotation pattern and decrease in that of the halo. If rubber is strongly cooled, a crystalline pattern is again obtained, but this time it is of course a powder pattern of unoriented crystalline material. Partial stretching combined with partial cooling produces intermediate degrees of orientation[96]. The crystalline patterns obtained from stretched or frozen rubber disappear although not immediately on release of strain or on reheating to room temperature.

In a slight improvement on their original theory, Herrmann and Gerngross found an explanation for these and other properties of rubber in terms of the "fringed micelle" model[92,93]. Here again but slight further modification is required to make this theory confirm with present day ideas.

The X-ray Study of Swelling

An extension of X-ray methods to include the structural changes resulting from specific chemical treatment of high polymers gave further information concerning the structure of these materials. As a result of a study of the effect of swelling on the X-ray diagram, Katz[106,115] divided swelling into three types. Intermicellar swelling takes place between the micelles. There is thus no change in the crystal pattern. An example of such swelling is the swelling of ramie in water. Intramicellar swelling takes place when the swelling agent enters inside the micelles. An example of such swelling is the swelling of gelatin in water; increase in the amount of swelling results in increase of the distance between the parallel chains in the micelles. The interferences corresponding to the chain spacing are consequently altered on swelling; those corresponding to the repeat of the structural unit along the chain are unaltered[76]. Finally, in permutoid swelling a change in the crystal structure takes place. An example is the swelling of cellulose in caustic soda. Here again all these facts can be suitably explained by the fringe theory.

II. The Fringe and Kinetic Theories of Structure

On the basis of the early work on high polymers two equally plausible yet contradictory theories were produced. The continuous structure theory accounted in part for the crystalline order arising from long molecular chains of varying length, yet it failed to account for the complex polycrystalline nature of crystalline high polymers. The micelle theory on the other hand failed to explain the nature of the bonding material between the crystalline regions. Both theories failed to explain the peculiar contractile properties of high polymers to be discussed later under the heading of thermo- and swelling recovery. All these phenomena can however be explained in terms of the fringe theory. Under certain circumstances, flexible chains are encountered the heat motion of which has to be taken into account. The fringe theory has then to be modified by what has been called the kinetic theory of high elasticity.

The Fringed Micelle Theory: Collagen and Gelatin

The fringe theory in its original form[75,76,77] postulated first that the long polypeptide chains in collagen and gelatin formed themselves into bundles, in which the chains were held together by secondary forces. These bundles were arranged in parallel fashion over their middle portion, but by virtue of the varying chain lengths, the ends were splayed out into a ragged "fringe"[163]. The fringes of the different micelles were originally assumed to be connected together by secondary forces, forming a continuous structure. Thus the parallel arranged portion of the bundle could be regarded as the crystalline region, and the fringe portions as the amorphous intercrystalline material. Fig. 53 shows the diagrammatic representation by Herrmann and Gerngross of the structure of unoriented gelatin or of contracted collagen. Neither the crystalline regions nor the amorphous regions possess preferred orientation. On loosening the entangled fringe areas by heat or swelling, it becomes possible to give the material a large extension. Thus stretched gelatin or collagen according to Herrmann and Gerngross is represented by Fig. 54. As a result of stretching, both the crystalline and amorphous regions become oriented. On the other hand, when the oriented form of collagen is heated, then presumably due to the instability of the oriented form the material becomes disoriented resulting in a marked contraction. Because of the continuity of structure it would be expected that this process would be reversible, and such seems to be the case. This theory is thus seen to be entirely in accordance with the X-ray data.

The Fringed Micelle Theory: Rubber

Herrmann and Gerngross suggested that there exists in rubber one basic unit, namely, long hydrocarbon chains. Over part of their length these chains form parallel bundles, which give rise to the X-ray interference and thus constitute the micelles[92,93,142]. Each chain is assumed to pass through several bundles, the portions of the chain between the parallel regions thus passing through regions occupied by disorganised chains; these latter regions or fringe areas then constitute the amorphous component of the material, as shown in Fig. 55. This picture, it will be observed, is an improvement on that of Figs. 53 and 54 in that the chains are now assumed to run unbroken through several micelles. Herrmann and Gerngross assumed that in unstretched rubber some very small crystals are already present, so that on stretching the material the chains are brought closer together, resulting in a growth of the crystals along their length but not in the transverse direction. Decrease in the proportion of "fringe" material results in a decrease in the intensity of the amorphous halo. They attributed the reversible extensibility of rubber to the flexible chains in the fringe areas, and the strength at high elongations to the crystalline regions formed; long-chain polymers which do not crystallise markedly on stretching therefore flow at high loads and are weak[188]. This picture of the structure of rubber is very satisfactory, in that it explains reasonably well most of the observed phenomean.

The process of solution and regeneration from solution can be easily conceived in terms of the fringe theory[168,184] The molecules of intermicellar swelling agents penetrate only the more open fringe areas and act as a lubricant. between the chains, satisfying the weak forces between them. Intramicellar swelling agents penetrate between the chains in the crystalline areas also, "floating-off" individual chains if an excess solvent is present. Similarly, on evaporation of the solvent individual chains come together, forming first "swarms" and then the complete fringe structure.

The Fringe Theory and Filamentous Materials

The filamentous materials considered in Part V of this thesis, namely silk, viscose rayon, acetate rayon, and nylon, are all microscopically homogeneous and give crystalline X-ray interferences. Amorphous rings or some background scattering are also found in the X-ray diagram. These can be attributed to a large proportion of amorphous component[184,187]. Here again the fringe theory of structure seems applicable, and the diagram of Fig. 55 or better still of Fig. 47(c) then represents the structure of these materials. The fringe theory is entirely in accordance with the mechanical and chemical properties of these materials. Some of these properties will be discussed later.

The Kinetic Theory of High Elasticity

By high elasticity is usually meant the large reversible extensibility found for example in lightly vulcanised rubber, in muscle, and to a certain extent in plasticised or heated thermoplastic resins. High elasticity in long-chain polymers can be conceived of as due to the presence of very flexible chains which are normally in highly kinked forms; on the application of load these chains straighten out, but contract again on removal of the load.

There are two mechanisms of deformation to which high elasticity may be due. First, since the atoms in a long molecular chain are connected by homopolar bonds, the application of a load to such a chain should produce a straightening of the chain due to elastic extension and bending of the primary valence bonds. Release of load should cause the chain to tend to spring back to its original shape. Such a mechanism of deformation should apply to chains which are relatively stiff, such as the chain of cellobiose residues in cellulose.

On the other hand, we can conceive of a different picture when we are dealing with the very flexible rubber and nylon chains; these contain a large proportion of single carbon bonds, around which free rotation can take place. It will be remembered that in Part III Maxwell's views on the "Constitution of Bodies" in terms of kinetic concepts were given; these views were based on the premise that due to their heat energy the atoms of all bodies are in motion. We can thus consider the long molecular chains to be similarly in motion. Due to this heat motion, the chains will be in various degrees of contraction, depending on the temperature and the flexibility of the chains. The application of load to such a chain will cause a straightening of the chain which had been statistically rolled up as a result of its heat motion. In stiff chains we would expect the elastic effect to be predominant, and in flexible chains this kinetic effect. The analysis of this effect is the domain of the kinetic theory of high elasticity.

We can apply these new concepts to the fringed micelle model. The extensibility of a material must thus lie chiefly in the fringe areas. In rubber, the extensibility is high because of the initially large amount of fringe material present and because of the flexibility of the chains. The fairly high reversible extensibility of nylon must be due again to very flexible chains and a moderate amount of fringe material. Silk and rayon have lower reversible extensibilities, presumably due to stiffer chains. Finally, that of ramie is very small due to the very small amount of non-crystalline material present.

The Thermoelastic Effect

It has been known for many years that when stretched rubber held at constant elongation be heated, the force required to hold the rubber stretched increases with temperature. On the other hand, for single crystals and polycrystalline metals the reverse is the case. This change of stress with temperature under constant strain is called the thermoelastic effect. We can see that a study of the thermoelastic effect in high polymers is of great importance in connection with the investigation of the mechanism of deformation in these materials. If the deformation is due mainly to extension and bending of primary valencies, we would expect the temperature coefficient of the thermoelastic effect to be negative. If on the other hand the deformation is mainly due to the straightening of chains which were statistically coiled up as a result of their heat motion, the temperature coefficient of the thermoelastic effect would be expected to be positive. Mark[188] has pointed out the analogy between the effect of temperature on such a material under constant extension and on a gas held at constant volume. It is clear therefore that a study of the thermoelastic effect in high polymers, and especially in textile fibers, is of the utmost importance.

The Thermoelastic Effect in Rubber

The first of a series of investigations by K. H. Meyer on the thermoelastic effect was concerned with rubber[126]. For moderate elongations, the stress at constant elongation was found to increase linearly (and reversibly) with temperature. At higher elongations also the temperature coefficient of the effect was still positive, but the results were more complex. At very small elongations rubber has been stated to have a negative temperature coefficient. If this is so, then it seems that for very small elongations the elasticity of rubber is primarily of the crystalline type, but that at higher elongations kinetic elasticity is predominant.

We can now augment the fringe theory for rubber by introducing these concepts, and eliminating the not very plausible assumption of Herrmann and Gerngross that some crystalline material is always present in unstretched vulcanised rubber. The flexible chains in unstretched rubber are ordinarily in thermal agitation. There is thus only a very small probability that two chains will coalesce and crystallise. On reduction of temperature or on stretching the disaggregating tendency is reduced and crystallisation can occur. Further stretching or cooling produces crystal growth in the direction of the length of the crystal. Release of tension or reheating would be expected to result in a return, though not necessarily immediately, to the original state.

The Thermoelastic Effect in Muscle and Textile Fibers

The temperature coefficient of the thermoelastic effect in muscle[145] is negative at low elongations, zero at an intermediate elongation, and positive at high elongations; thus in the first case the mechanism of deformation is primarily of the crystal elasticity type and in the last case primarily of the kinetic elasticity type. Meyer and Lotmar[133] have studied this effect in ramie and hemp, in stretch-spun viscose and acetate filaments, and in cellophane films. Ramie was tested in air and the other materials in water. The micellar regions in these materials would contribute to a negative temperature coefficient, and the fringe regions to a negative or positive coefficient, depending on the stiffness of the chains. Stretch-spun viscose filaments gave a negative temperature coefficient, and cellophane zero coefficient. In the case of acetate the temperature coefficient was positive. It is obvious that much more work on the thermoelastic and other properties of textile fibers is required before we can comment adequately on these results and determine the mechanism of deformation of these materials.

III. Mechanical Behavior and Structure

We are now in a position to interpret mechanical behavior in terms of the structure of high polymers discussed in the foregoing pages. It will be remembered that previously, in Part III, the mechanical behavior of materials was discussed in terms of certain mechanical models. It seems very reasonable that these models represent the behavior of inorganic glasses, as well as monomeric organic glasses. High polymeric materials however possess flow and other properties different from those of glass. It is incorrect, therefore, to apply* the mathematical concepts behind these models to anticipate quantitatively the behavior of high polymers.

First, we will summarise the present-day views on the structure of high polymers. These materials are built up of long chains of the same or of similar repeating units. The properties of a high polymer then depend on chain length, chain flexibility, and nature and magnitude of the cross-bonding[156]. In purely amorphous thermoplastic materials these chains form a tangled mass which can be oriented to some extent but which cannot be crystallised. This is the case for example when bulky side groups are attached to the chain, when the chains are separated by molecules of plasticiser, or

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* As has been done by Kuhn[169].

when attractive forces between the chains are absent. Such materials are therefore basically weak and thermoplastic, though they can manifest rubber-like elasticity under certain conditions of temperature.

In the thermosetting materials such as the phenol-formaldehyde and glyptal resins, and possibly hard rubber, cross links in the form of primary valence bonds may be assumed to link the main chains*. Such materials are normally unoriented, except of course when the cross-bonding takes place under conditions of extreme orientation of the chains[87].

As far as we are concerned, the quasi-crystalline group of materials is the most important. In these materials attractive forces between the chains result in a partial crystallisation, the crystals or "micelles" consisting of parallel bundles of chains. There are however not two distinct phases; each chain traverses several of these bundles or micelles, the portion of the chain between the micelles passing through regions randomly occupied by similar chains. These "fringe" regions we can think of as constituting the non-crystalline portion of the material. The forces between the chains may be hydrogen bonds (as in cellulose) or secondary valence forces. In the latter case, though each bond is weak, the cumulative effect is strong[173]. In the fringe regions weak forces may be assumed to exist between the chains. The chains in the fringe regions may be assumed to

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* See, for example, the view of Meyer[131].

be in a state of thermal agitation, the magnitude of which depends on the temperature and on the flexibility of the chains. Except in the case of natural cellulose, these materials are thermoplastic.

Thermo- and Swelling Recovery

If a high polymer such as raw rubber or a thermoplastic resin be given an apparently permanent deformation, this deformation can be removed in part or in whole by slight heating and then cooling back to the original temperature[87,192]. The removal of part of an apparent permanent set by gentle heat treatment may be called thermorecovery[114,142]. Similarly, Weltzien[81] has shown that if a rayon yarn be stretched in air, and subsequently immersed in water and dried out again, a large part of the permanent set will be removed. This phenomenon we may call by analogy swelling recovery. These effects are of course of very great importance both technically and scientifically, and have been known for a long time; they were mentioned by Maxwell[23] in his famous paper on the "Constitution of Bodies". Maxwell pointed out that gutta percha and rubber after being permanently stretched when cold, could be restored to their original form on being heated, and that similarly gelatin dried in a state of strain could recover its form by absorbing water.

Following Maxwell, we can picture the mechanism of such recovery phenomena to be somewhat as follows. Returning for simplicity to the two-phase "sponge" concept discussed in Part III, we assume that under heavy loads a partial break-up of the primary system takes place, partially destroying its continuity. After release of load the system does not recover its original form. Under the action of heat or of swelling however the residual stresses in the primary system are freed, allowing partial recovery of the apparent permanent set.

The Mechanism of Creep in Filamentous Materials

In the next part of the thesis it will be shown under certain conditions the application of a constant longitudinal load to a filament results in an instantaneous extension, followed by a delayed extension or primary creep. On removal of load there takes place an instantaneous contraction followed by a delayed contraction or creep recovery. The mechanism of deformation in terms of the fringe theory can then be pictured somewhat as follows. Immediately on application of a tensile load, there is an instantaneous deformation due partly to the deformation of primary bonds and partly to the deformation of secondary bonds. The former deformation consists of two parts: one is the extension of the straight chains in the micelle regions, and the other the straightening and stretching of the kinked chains in the fringe regions. Where the chains are relatively stiff, the straightening is of the nature of an elastic bending of primary bonds. When the chains are flexible, the straightening is opposed by the statistical rolling up due to heat motion of the chains. The modulus of elasticity of crystalline cellulose has been calculated[133] to be of the order of

15×10^6 psi. The experimentally observed values for cellulose derivatives are very much lower than this value[95,102,142], hence we conclude that a large proportion of non-crystalline (i.e., "fringe" material) is present. This conclusion is confirmed by X-ray data[187].

The secondary bonds which may be assumed to exist between the fringes correspond to the Maxwell units of the models in Part III. As a result of the breaking down of these bonds due to thermal agitation of the chains a transference of load to the primary system is to be expected, resulting in a delayed deformation or creep. Similarly, on removal of load the resistance to breaking up of the secondary bonds results in a creep recovery. Thus we can consider the micelles as "junction points" connected by flexible chains. The deformation under load is due mainly to the straightening of these chains; primary creep is due to the existence of secondary forces between the chains in the fringe regions.

Permanent Deformation and Swelling Recovery in Filamentous Materials

We can consider permanent deformation first in the sense of deformation remaining after removal of load and after all creep recovery has ceased. Crystal slip as in metals certainly does not take place in high polymers. Permanent deformation is presumably due either to crystal growth in the direction of the length of the crystallites, to fissuring of the crystallites at their ends[187], or to both. The first effect is probably favored in textile fibers by stretching in the wet state, and the latter effect by stretching dry. Swelling recovery may then be due to partial restoration of the micelles to their original state. It is clear that much further research is needed before the mechanisms of permanent deformation and of swelling recovery are made clear.

Conclusion

We have seen that a model representing the phenomean of primary creep could be constructed of springs in parallel with elements having finite relaxation times. We saw also that on general considerations the structural requirements for the manifestation of primary creep were the presence of primary valence bonds which were merely elastically deformed under load, together with secondary bonds which yielded under load[87]. In the light of the fringe theory, the primary bonds can be considered as residing in the main chains, and the secondary bonds as those bonds connecting chains in the fringe regions.

Part V.

THE CREEP AND CREEP RECOVERY OF FILAMENTOUS MATERIALS

I. The Experimental Method

General Considerations

This part of the thesis deals with the experimental work on the creep of filamentous materials. We have seen that with high polymeric materials, due to the existence of "liquid" as well as "solid" bonds, the mechanical properties cannot be described even in the absence of permanent structural change by a stress-strain curve, but time must also be taken into account. By studying these time effects we will be able to acquire more information concerning the mechanism of deformation of these materials, and thereby develop testing methods of technological importance. In the case of filamentous materials we are in practice restricted to the study of creep under longitudinal load. In the light of the discussion in Part II, the objects of an investigation of the creep properties of such materials are then specifically as follow:

1. To study the long-duration creep under constant load and recovery following removal of load.

2. To determine the treatment necessary for the elimination of non-recoverable deformation, i.e., for the recovery to be complete. This treatment we have called mechanical conditioning.

3. To investigate the validity of the Superposition Principle. Since the creep is not small compared to the instantaneous deformation, this cannot be done by comparing creep under constant load with relaxation at constant extension, but must be investigated by the method of superposed loading.

In the following pages are described first the creep apparatus and the experimental technique. Then are discussed the results of the preliminary experiments, from which the above objects have been formulated. Finally, the results are discussed in detail from the phenomenological point of view and from the point of view of the structure and mechanism of deformation of filamentous materials.

Possible Experimental Arrangements

From general considerations*, the experimental arrangement must possess the following qualifications.

1. It must be possible to apply a given load rapidly yet smoothly to a single filament, and it must be possible to measure continuously and rapidly the changes in length of the filament.

2. The load must not vary as a result of changes in length of the filament. Since the longitudinal strains in the reversible range are expected to be about 1%, the stress

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* Partly based on a study of the previous papers in this field by de W. Smith and Eisenschitz[84,85].

is essentially constant if the load is constant. It is therefore unimportant at this stage as to whether constant stress or constant strain is the criterion.

3. It must be possible to remove the load smoothly and rapidly at any given instant, and to measure the contractions due to removal of load.

4. The filament must be in an atmosphere, the temperature and relative humidity of which are rigidly controlled.

5. The filament and moving parts of the apparatus must be protected from draughts, and the whole apparatus form a rigid system as free as possible from building and room disturbances.

6. In studying filamentous materials any reasonable gauge length may be selected.

7. The sensitivity of the apparatus must be such that a change in length of ten parts per million can be detected.

There are three possible experimental arrangements.

1. Direct Loading. Weights can be applied by means of a platform which lowers a hooked weight on to the lower end of a freely hanging filament provided with a hook at its lower extremity. The vertical movement of the lower end of the filament can then be observed with a cathetometer or filar micrometer. If a gauge length of ten inches is

chosen, a microscope of magnification of the order of 100 is required to follow this movement. The depth and breadth of field at this magnification are then very small. With this direct type of loading, as a result of possible eccentric application and removal of the loading weight, draughts, room vibration, and so on, oscillation of the filament will be set up, rendering observations almost impossible. On this account this simple method is out of question.

2. Chainomatic Loading. If the load be directly applied to the lower end of a freely hanging filament, by means of a hanging chain, extension of the filament causes a decrease in load, and vice versa. Other arrangements in which the load is applied by attaching the chain to a balance arm have no advantages over the method described below.

3. Balance Arm Method. In this arrangement the lower end of the filament is fixed and the upper end attached to one end of a balance arm. The load is applied to or removed from the other end of the balance-arm. This arrangement can satisfy all the requirements previously specified; in fact, it has been successfully used by previous experimenters. This method has therefore been selected. The arrangement finally adopted combines what has been considered the best features of the apparatus of Smith[84,85] and the apparatus of Speakman[65,68], together with some other refinements which have been shown to be necessary in the course of the preliminary work.

Following Speakman[68], an unequal arm balance has been adopted. In order to keep small the angular motion of the balance-arm, it is necessary to have the length of the arm to which the filament is attached fairly long. The arm to which the load is applied need not be as long, and in fact is preferably short, since more massive weights can then be used. The loads are applied by means of hooked weights engaging with a hook on the balance arm. The weights are applied or removed by means of a platform[65].

Detailed Description of Creep Balance

The Creep Balance constructed according to the above specifications is shown in front view in Fig. 56, and in rear view with case removed in Fig. 57. The whole apparatus in use is shown in Fig. 58.

The base plate (1) is supported by three levelling screws. To the top of the pillar (2) is attached an agate bearing carrying an aluminum alloy balance arm* (3). This arm is of course the most important component of the apparatus. It has been designed for lightness and rigidity; apart from the detachable balance-weights and carriers it weighs but 59 grams. The three steel knife-edges lie in one plane; four balance weights are provided, as follow. A suspended balance weight (4) is attached to the short arm. In the plane of the three knife-edges are provided a coarse balance weight consisting of a heavy brass cylinder (5) together with a fine

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* Constructed to the author's specifications by Christian Becker and Son.

adjustment (6) for adjustment of the lateral position of the center of gravity of the balance arm. There is also a fine adjustment (7) for the vertical position of the center of gravity, placed over the central knife edge. There are two carriers with agate bearings. That on the short arm has a hook which carries the suspended balance weight (4). This balance weight is in turn provided with a hook to carry the loading weight (8). The loading platform(9) is mounted on the top of two columns (10) attached to the base. The load is applied to or removed from the filament by turning the milled knob which lowers or raises the loading platform.

The filament (11) is attached at its lower end to a brass tab and at its upper end to a hook; this hook goes on the carrier on the balance-arm. The tab is clamped into a vise (12) which can be raised or lowered on guides by means of a screw (13) from underneath the base. Two springs keep the vise steadily pressed against the screw.

The changes in length of the filament are measured by observing the vertical motion of the carrier on the balance-arm over the filament. This is done as follows. To the carrier is cemented a fragment of stage micrometer, with the scale markings horizontal. The scale of the stage micrometer is viewed through the microscope of the cathetometer (14), which is adjusted so that a horizontal crosshair in the microscope corresponds with one of the scale markings of the stage micrometer. In this way the vertical movement of the cathetometer corresponds to the vertical movement of the carrier on the balance-arm.

The microscope of the cathetometer is provided with a one inch focal length ocular and a 16 mm. objective, giving a magnification of approximately 100. The cathetometer, made to the author's specifications by William Gaertner and Son, is provided with a screw two inches long of 0.02 inch pitch. The screw has a drum with 200 divisions, thus it is possible to read the cathetometer directly to 0.0001 inch. The cathetometer is rigidly attached to the base of the instrument by means of an aluminum alloy column and block (15).

The instrument is protected by a wooden case provided with doors for access to the loading platform and to the vertical and horizontal fine adjustments on the balance-arm. There is a detachable front window of acetate sheet, through a slot in which projects the microscope. A small concealed bulb illuminates the loading platform.

The illumination for the stage micrometer is shown in Fig. 58. The projector at the right contains a 6-volt 15-ampere projection bulb; light from this projector is reflected by the small mirror on the balance case on to the fragment of stage micrometer.

Description of Aural Timer

In long duration creep and recovery tests it is necessary to commence the timing clock at the instant of application or removal of load, and to make the length observations at given instants thereafter. In a superposition test it is necessary that load removals and applications (apart from the first) take place at given instants. There is however great difficulty in observing simultaneously the movement of the balance arm through the cathetometer and the motion of the seconds' hand of a timing clock. This is especially true immediately after the application or removal of load, when the length of a filament changes rapidly. The problem is solved by having the timing clock sound a buzzer at the appropriate intervals.

The Aural Timer constructed for this purpose is shown in Fig. 59. The clock is essentially a standard self-starting electric clock with seconds' hand. A switch provided in the lead enables the clock, previously set at zero time, to commence operation at the instant of load application or removal. The electrical circuit associated with the clock is arranged to perform the following operations.

1. To sound a buzzer at quarter minute intervals.

2. To sound a buzzer at one minute intervals.

3. Buzzer disconnected.

The operations are controlled by two switches on the buzzer box; one switch controls the minute signal, and the other switch controls the signals at 15, 30 and 45 seconds. The buzzer is operated through a sensitive relay actuated by means of contacts made by the seconds' hand of the clock. The following is a detailed description.

The clock is provided with a split brass ring, attached to but insulated from the frame of the clock. Through this brass ring are screwed four small screws in the 15, 30, 45, and 60 seconds positions. The brass ring is split in such a manner that the screw in the 60 seconds position is not connected electrically to the other three. To the points of these screws are soldered fine (.001" diameter) stainless steel wires. As the seconds' hand moves around, it brushes sucessively against the four fine wires, and thus makes electrical contact between the frame of the clock and the appropriate section of the brass ring. It should be noted that a very fine wire is necessary for the contacts in order that the effort of the seconds' hand in bending the contact wire should not slow down the clock appreciably. The steel wire used has a high elastic limit, and hence the contact wires spring back after the seconds' hand has passed by. This wire has also a high endurance limit, and hence is not likely to fail in fatigue; finally it is of stainless steel and hence there is no contact corrosion trouble. The current such a contact can carry is too small directly to actuate a buzzer, and in any case the contact resistance is too high*. This contact is therefore made to actuate a sensitive relay, which in turn closes the buzzer circuit. The relay has a 2000 ohm coil, and closes rapidly with a current of 3 ma. The heating of the contact wire is therefore negligible. The two sections of the brass ring are provided with separate on-off switches so that the desired operations noted above may be performed. The wooden box shown on the right in

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* It was found to vary between 0 and 60 ohms.

Fig. 59 contains these control switches, relay, buzzer, and batteries for relay and buzzer.

Air Conditioning System

All tests with the exception of some preliminary experiments were carried out in the Air-Conditioned Room of the Textile Laboratory at M. I. T., where conditions were maintained as near as possible to 70° F., and 65% relative humidity. With the air-conditioning system operating as originally designed, there were large short period fluctuations in relative humidity, as well as a gradual systematic drift. During the course of the investigation a modified method of operation was developed, as a result of which the short period fluctuation was absent and any slight drift in conditions could be easily corrected.

The manner of operation of the system is briefly as follow. Air from the room is drawn up a tower down which flows water at the dew point temperature. The air then mixes with some air drawn directly from the room through a trap-door, and is injected into the room by a fan. The heat extracted from the air by the water in the tower just compensates for the heat leaking into the room from outside. If air leaks in from outside at a different absolute humidity than that prevailing in the room, the air is humidified or dehumidified to the right degree on being drawn through the tower. If the heat leaking into the room through the walls increases, it is merely necessary to close the trap-door slightly, so that more air is drawn through the tower. The temperature of the tower is controlled by a thermostat; this thermostat enables cold water to be drawn from a storage tank when the temperature of the tower rises. The storage tank in turn is cooled by a refrigerator. Thus there are two controls, the dew-point thermostat on the tower and the "short-circuiting" trap-door. In practice, only minor adjustments of the latter are necessary.

While it is possible to maintain conditions constant during the day, a slight drift amounting at the most to 1° F. in temperature and 5% in relative humidity may take place during the night. This drift has been the cause of an appreciable discrepancy in the results. In considering the earlier results it must be appreciated that in these tests large variations in relative humidity sometimes occurred.

Balance Arm Data

Weights of Components:	gms.
Balance arm alone, together with brass cylinder for coarse horizontal C.G. adjustment	59.0
C. G. Vertical adjustment screw	0.420
C. G. Horizontal fine adjustment screw	2.66
Weight carrier (short arm)	3.45
Weight carrier (long arm)	3.60
Suspended balance weight	25.38

Significant Dimensions:

Length of short arm	3 ins.
Length of long arm	10.125 ins.
Ratio	3.375
Pitch of horizontal fine adjustment screw	.0140 ins.
One turn of this screw is equivalent to tension in filament of	.00367 gms.

Weights Used in This Research

Weight, gms.	Corresponding Load on Filament, gms.
0.543	0.161
1.168	0.346
1.775	0.526
2.890	0.856
3.555	1.053
4.995	1.480
8.566	2.538
11.537	3.418

Theory of the Balance Arm

The balance arm is provided with three knife-edges in the same plane. With its axis in this plane is the horizontal fine adjustment of the center of gravity. There is also a vertical fine adjustment over the central knife-edge; the purpose of this arrangement is to be able to set the center of gravity of the balance arm exactly on the central-knife-edge, i.e., to be able to put the arm into neutral equilibrium.

Ordinarily, the center of gravity of a balance arm lies below the central knife-edge. This is not permissible in the case of the creep balance, since deflection of the arm would then cause a change in load in the filament, as shown by the following analysis. First, consider the arm with carriers and suspended balance weight in the horizontal position. Let the lengths of the arms be l_1, l_2, and the weights of the carriers and suspended balance weight be R_1, R_2, and B. The arm itself with fixed components has a weight W and its center of gravity is as shown in Fig. 60. Then

$$R_1 l_1 + Wx = (B + R_2) l_2 \tag{90}$$

Let a load P be suspended from the short arm. The tension T due to this load in a filament attached to the long arm is then given by

$$T = Pl_2/l_1 \tag{91}$$

Let the arm be now inclined through an angle θ, as in Fig. 61. Then, neglecting the angularity of the filament, if the tension in the filament is now T_1, we have,

$$\begin{aligned}(R_1 + T_1) l_1 \cos\theta + W(x\cos\theta + y\sin\theta) \\ = (B + R_2 + P) l_2 \cos\theta\end{aligned} \tag{92}$$

Therefore

$$\begin{aligned}T_1 &= Pl_2/\, l_1 - Wy\tan\theta/l_1 \\ &= Pl_2/\, l_1 - Wy\,\theta/l_1 \text{ approximately}\end{aligned} \tag{93}$$

The decrease in tension is thus

$$T - T_1 = Wy\,\theta/l_1 \text{ (approx.)}$$

This is zero when the center of gravity of the arm with carriers and suspended balance weight lies exactly on the central pivot, i.e., when the beam is in neutral equilibrium. Since the balance arm near neutral equilibrium is very sensitive to external disturbances, it is not possible to adjust it exactly to the condition of neutral equilibrium. It can be adjusted however so that the period for small oscillations is about 80 seconds. Taking 3 inches as a reasonable value of the radius of gyration, y is then of the order of 1.45×10^{-4} inches. Under these conditions the change in stress in a filament due to the center of gravity effect is very much smaller than that due to change in cross-sectional area. Hence the balance arm adjustment can be considered satisfactory.

Technique of Filament Mounting

After the center of gravity of the balance-arm has been adjusted, the next step is the insertion of a filament in the apparatus. This involves separating a filament from the yarn, attaching end connections, and inserting the filament thus prepared into the apparatus. After the final adjustments, the filament is ready for test. At no stage in this procedure must the filament be subjected to strain. The following technique has been devised to eliminate this possibility.

The first stage is the preparation and storage of the yarns. A length of yarn of each synthetic material about 16 inches long is carefully untwisted in a twist tester. The untwisted yarn is attached at its ends to a long narrow strip of hard rubber by means of scotch tape, and stored in a stoppered glass tube until required. The second stage is the extraction of a single filament and attachment of the end connections. This is effected with the apparatus shown in Fig. 62. The apparatus consists essentially of a small table provided with a "Lumiline" lamp, the hard rubber strip containing the yarn, and another hard rubber strip, on which are two transverse scratches 11 inches apart. To this latter strip are attached by scotch tape a brass tab fashioned as shown in Fig. 63, and the fiber-attachment hook from the balance arm. These are so arranged that the point A of the hook and the point B of the tab lie on the scribed lines mentioned above. A filament is then separated from the yarn and transferred to the board on which are the tab and hook. One end is threaded through the tab and the other wrapped several times around the hook as shown in Fig. 63. The filament is then cemented to the end-connections. At first sealing wax was used as a cement. Later the suggestion of Steinberger[134], namely, flake shellac heated with a small soldering iron, was adopted. More recently collodion has been found to be perfectly satisfactory, except in the case of acetate filaments when a solution of butyl methacrylate polymer in benzene was used.

Insertion of Filament

The loading platform is raised so that the end of the balance arm from which the filament hangs is pushed down. The vise is raised as high as possible, and of course the front of the balance-case removed. The hook is then hooked on to the carrier on the balance-arm and the brass tab clamped into the vise. This is then lowered into the required position. The protecting cover of the case is put back into position. It is now necessary to carry out the overbalance adjustment.

Overbalance Adjustment

If the balance arm with hook had previously been in neutral equilibrium, the center of gravity of the system is now displaced in the plane of the knife edges on inserting the filament, due to the weight of cement on the hook. The beam can be restored to neutral equilibrium merely by screwing out the fine horizontal C. G. adjustment. Under these circumstances, however, it would not be possible to conduct recovery experiments, since the filament would go slack upon removal of load. It is necessary therefore to have in the filament at all times a small constant load, in addition to that corresponding to the loading weight. This is effected by screwing out the horizontal center of gravity adjustment beyond the position of neutral equilibrium by one and a half turns. This corresponds to a constant overbalance of about 6 mg. Due to the varying weight of cement on the fiber attachment hook from specimen to specimen, this horizontal adjustment has to be reset each time a new filament is inserted; it is of course not necessary to touch the vertical C. G. adjustment. It is then merely necessary to wait overnight to allow the filament to adjust itself to the slight tension of 6 mg.; the filament is then ready for test. Before commencing tests, the length of the filament is measured to 0.1 mm. by means of a distant cathetometer with telescope.

Technique of Performing Tests

The tests fall into two categories: long-duration tests and superposition tests. In the long duration tests a given load is applied and the scale readings corresponding to the length of the filament observed as function of time under load over a period of about twenty-four hours. The load is then removed and the contraction observed as a function of recovery time for about another twenty-four hours. Superposition tests as a rule last forty minutes. A given load is applied at zero time, removed ten minutes later, reapplied after a further ten minutes, and finally removed thirty minutes after the first application. The changes in length over a period of forty minutes are observed. Some superposition tests were composed of six ten-minute periods and four fifteen-minute periods respectively. The details of the technique are given below.

Long-Duration Creep Tests

The aural timer is set with the hour, minute, and seconds hands at zero. The zero reading of the position of filament is obtained by bringing the cross hair in the cathetometer microscope into correspondence with a given scale marking of the stage micrometer over the fiber-carrying hook. Due to backlash in the screw (which amounts to about .0008 inch) all observations have to be made in the direction of increasing scale reading. The cathetometer is then raised to the position where the first observation is expected to be found. The loading platform is rapidly lowered, so that a weight resting on the platform is picked up by the hook under the suspended balance weight; the load is thus applied to the filament. At the same time the clock is started by closing the switch in the lead. The application of load requires about two or three seconds. The cathetometer is then continuously adjusted to follow the extension of the filament, the adjustment being interrupted on aural signals from the clock to note the corresponding observations. Observations are made at the following times reckoned from the instant of application of load: 1/4, 1/2, 3/4, 1 minute; 2, 3, 5, 7, 10, 15, 20, 30, 40, 60, 90 minutes and at convenient times thereafter. After about 24 hours a recovery test is commenced, and carried out in exactly the same way, the times being computed from the instant of removal of load.

Superposition Tests.

Observations are recorded for the times 1/4, 1/2, 3/4, 1 minute; 2, 3, 5, 7, 9 minutes in each ten minute creep or recovery period. After the 9 minute observation the cathetometer is shifted preparatory to the first observation following the loading change at the 10 minute instant. Otherwise the details are identical with those of the long-duration tests.

II. Experimental Results

The results that have been obtained can be considered as falling into two groups, the preliminary investigation and the systematic study.

The preliminary investigation was based, for reasons given below, on an assumption that the creep behavior of the material used (viscose) could be expressed as a viscous or quasi-viscous flow[114,142] superimposed on a logarithmic primary creep[154,170]. The preliminary investigation did not confirm this hypothesis, but indicated that under certain circumstances non-recoverable creep was absent, and that the primary creep was distinctly non-logarithmic in character. The objects of the systematic investigation, which have been formulated earlier, were based on the results of this preliminary investigation.

Preliminary Investigation

The first problem that arises in the study of primary creep is this: is it possible to investigate the primary creep of a material in the absence of non-recoverable creep? We know that this is possible in the case of glass at room temperature, because the viscous flow of glass is then very small. With glass at elevated temperatures however[39,158], or with materials such as lead and pitch[39,40], there is always a secondary creep superimposed on the primary creep while the specimen is under load. The creep recovery of such materials is of course only a primary creep effect. The question is therefore whether the creep of filamentous materials under load is more akin to the creep of glass at room temperature or to the creep of glass at elevated temperatures. The impression to be gained from a study of the literature on the mechanical properties of such materials[120] is that the latter is the case. The literature suggests that such filaments are plastic rather than elastic bodies, and that they flow under load. Since it has previously been demonstrated[85] that creep recovery takes place in such filaments, one is given the impression that the mechanical behavior of these filaments is represented qualitatively by the model of Fig. 36. It would therefore be expected that the creep of these materials consists of a primary creep following the Superposition Principle, superimposed on which is a non-recoverable flow which takes place while the specimen is under load. It would be expected also that the primary creep component could be represented satisfactorily by the logarithmic creep law approximation.

The preliminary experiments, designed to test this hypothesis, consisted of superposition tests of forty minutes' duration as described on p. 164 above. The results for viscose were found not to be consistent with the hypothesis of a plastic flow superimposed upon a logarithmic primary creep. Under certain conditions* it was found that, given a sufficient time after the last load removal in the superposition test,

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* Namely, that the load be less than about 0.6 gm./denier.

the filament regained its original length, and hence primary creep only was present. The obvious conclusion was that the primary creep under constant load did not follow the logarithmic law. This was confirmed by carrying out simple creep tests under constant load, and recovery tests following long-duration creep. These were found to be distinctly non-linear on the logarithmic time plot. The data of the superposition tests were found to be consistent with the above creep and recovery data and the Superposition Principle. The objects of the systematic tests were thus formulated, and these systematic tests were then carried out on a variety of filamentous materials. The remainder of this part of the thesis deals with these tests.

Systematic Tests on Filamentous Materials

Systematic tests were carried out on the following filaments, numbered in order of investigation and listed below in order of consideration.

Specimens Tested

Specimen No.	Material	Nominal Filament Denier	Remarks
7	Silk	--	Degummed single filament
6	Viscose I	3	
5	Viscose I	3	Same material as Specimen 6 (earlier tests)
9	Nylon II	3	Recent Sample
4	Nylon I	--	Very early sample (about 3 years old)
10	Acetate	3	
8	Viscose II	6.5 (before stretching)	Stretched wet about 40%; dried under load.

The systematic tests on each material consisted of long-duration creep and recovery tests, together with superposition tests. The following table gives the lengths in centimeters and the measured cross-sectional areas in square microns of the filaments. The corresponding denier equivalents are also given.

Specimen No.	Material	Length cms	Measured Cross-sectional area	
			μ^2	Denier (approx.)
7	Silk	28.10	102	1.27
6	Viscose I	28.99	-	-
5	Viscose I	27.67	-	-
9	Nylon II	28.66	283	2.90
4	Nylon I	27.34	276	2.83
10	Acetate	28.96	267	3.09
8	Viscose II	29.54	356	5.02

Objects of the Long-Duration Creep and Recovery Tests

The objects of the long-duration creep and recovery tests are as follow:

1. To show that, after mechanical conditioning, the total deformation due to the application of load as a function of creep time is the same as that due to removal of load, as a function of recovery time.

2. To show that the results for any given load are reproducible.

3. To show that the instantaneous elastic extension or contraction is proportional to load.

4. To show that the delayed component of the deformation varies with load only by a scale factor.

5. To find the relation between load and this scale factor.

Mechanical Conditioning

Let us assume that a new filament has been inserted in the creep apparatus, and subjected to a long duration creep test for 24 hours under a load which must be certainly less than that corresponding to the yield point as conventionally defined[175]. Let us assume that a recovery test of 24 hours duration is then carried out. It will then be found at the end of this period that the progress of the creep recovery will be very slow, and that recovery will have almost ceased; however, recovery will be far from complete. This will be true even if the smallest practicable load is used in the creep experiment, and applies also to filaments pretreated according to the method suggested by Smith[85], in which the filament is moistened with water and allowed to dry under no load or very light load.

Let us now assume that the creep and recovery experiment be repeated. It will usually be found, at the end of the 24 hours recovery period that the specimen has contracted very nearly to its length at the beginning of the second test. It is to be presumed that if several days were allowed for recovery, the specimen would regain completely its length at the beginning of the second test. Tests at this load or at smaller loads subsequent to the first test thus produce no further non-recoverable deformation. The first test thus constitutes the mechanical conditioning process, and the filament subsequent to the first test can be considered to be in a mechanically conditioned state. In the case where the load at which the specimen is to be conditioned is relatively large, it may be necessary to carry out the conditioning process twice in order to secure subsequent absence of secondary creep. These results on mechanical conditioning are anticipated to a certain extent by those of Weber[1].

The course of mechanical conditioning can be studied by plotting on the same sheet to the logarithm of the creep or recovery time the actual scale observations for the mechanical conditioning test and for the subsequent test at the same load, carried out as above. If we adopt the artifice of inverting the scale for the recovery observations, the result will be as shown diagrammatically in Fig. 64. The curve marked Ia represents the first creep test, and that marked Ib the first recovery test. The second creep test marked IIa proceeds along a parallel curve somewhat as shown, and the second recovery IIb is again parallel and displaced slightly from the first recovery test. Since for the analysis of the data such a plot is of lesser interest, only two such plots (Figs. 69 and 79) have been included in the graphs presented.

The case of nylon is exceptional, in that only a small permanent set resulted from the mechanical conditioning treatment. Also of interest is the case of the viscose filament which was stretched 40% in the wet state, and dried under a load greater than the conditioning load; again only a small increase of length resulted from the conditioning process.

Swelling Recovery

It is seen that in order to eliminate secondary creep over a given range of load, it is necessary to "condition mechanically" the filament at the highest load to be used. It may be argued that strictly speaking the examination of primary creep is carried out on a filament which is not in the same internal state as the original specimen. Now we know that gross deformations of high-polymeric materials can sometimes be recovered in part by swelling or thermo-recovery treatment. The problem then arises, to what extent does the comparatively small deformation due to mechanical conditioning at a relatively low load correspond to a truly permanent structural change? To answer this question a swelling recovery investigation was made on some of the filaments, as follows. After the mechanical conditioning had been carried out, and the subsequent information collected, the filament was wetted under no load with a spray of water, and then allowed to dry under no load. In some cases this treatment was repeated with a jet of steam. The results in the table below give for each filament the cathetometer reading (in inches) before mechanical conditioning, the reading before swelling recovery treatment, and the reading following treatment with water and steam. In the case of the viscose filament the mechanical conditioning followed a previous swelling recovery treatment.

Spec. No.	Material	Rdg. before Mech. Cond.[9]	Rdg. before Swelling Rec.	Rdg. after Swelling Rec.	Remarks
6	Viscose	.0725 (test 12a)	.2564	.0807	
7	Silk	.1120	.2432	.1850 .1092	water steam
8	Stretched* Viscose	.1507	.1484	off scale	Very large contraction
10	Acetate	.1593	.6117	.5270 .3370	water steam

It appears in the case of filaments Nos. 6 and 7 that the mechanical conditioning involved no permanent structural change. It is possible therefore that the reversible change associated with mechanical conditioning consists of a crystal growth by means of weak bonds along the length of the crystals. Sone of these bonds are loosened by water and the others by steam. It will be observed that the acetate filament, which had been conditioned at a somewhat higher stress than the viscose filament No. 6, showed some permanent deformation. It is probable that the effect of conditioning at higher loads is to increase the proportion of the deformation not removed by the swelling recovery treatment.

The partial or complete removal of the deformation associated with mechanical conditioning results in the filament being no longer conditioned. To investigate this point

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* Stretched wet and dried under load.

further, the silk filament after the swelling recovery treatment was reconditioned at the same load as in the initial mechanical conditioning treatment. Examination of the data reveals that following the reconditioning treatment the filament was virtually in the same state as before the swelling recovery treatment. In Fig. 70 are shown plotted against scale observations the various recovery tests for the conditioning load both before and after the above treatment; the similarity in shape of the curves is evident.

The Long Duration Tests

Following mechanical conditioning, the long duration tests proper were carried out. As has been already remarked, these consisted of creep tests of 24 hours duration followed by recovery tests of the same duration. The tests were not carried out in any systematic order. In the later tests, most of the tests were checked when the results appeared uncertain, either by repeating the test immediately or on a later occasion. The observations for the long-duration tests for the specimens previously listed are presented almost completely below.

Total Deformation

The analysis of the data begins with the computation and plotting of the total deformation curves. The total deformation at any instant in a creep or recovery test is merely the difference between the cathetometer observation at that instant and the initial observation immediately before application or removal of load. According to the Superposition

Principle, the following two statements should be true. First, the whole course of the total deformation curve on the logarithmic time plot should be sigmoidal in shape with horizontal lower and upper asymptotes, the former corresponding to the instantaneous and the latter to the final deformation. Secondly, the total deformation in a recovery test as a function of the recovery time should be the same as the deformation in an immediately preceding long duration creep test as a function of creep time (Equation 26) except when the magnitude of the recovery time approaches that of the creep time (Equation 24). Study of the total deformation curves reveals the following results.

1. For any given load, the total deformation curves are fairly reproducible. Except for large values of creep or recovery time, the creep and recovery total deformations are nearly the same, as predicted by the Superposition Principle. Silk is an exception in that the creep curves are displaced above the recovery curves.

2. In the case of viscose, acetate, and silk, only the foot of the theoretical sigmoidal curve can be obtained in 24 hours creep under the conditions of test. According to the Wiechert theory, this indicates a large value for the average relaxation time under the conditions of test.

3. In the case of nylon, only the upper part of the theoretical curve is obtainable under ordinary conditions.

Factors Affecting Reproducibility of Total Deformation Curves

1. Error in Initial Observation. Any slight disturbance of the apparatus, as for example that occasioned by inserting a new loading weight, will cause a temporary extension of the filament. Since very short disturbances require a relatively much longer time for their effects to be dissipated, several minutes must elapse before the filament again acquires its equilibrium length. If this effect is not taken into account, an appreciable error may be caused in the initial observation.

2. Sudden Application or Removal of Load. The effect of a sudden application or removal of load is presumably to impart a shock to the filament. This would affect the readings in the first few minutes of a creep or recovery test.

3. Variations in Relative Humidity. Slight variations in the temperature of the room cause appreciable changes in relative humidity. Increase of relative humidity causes firstly a reversible longitudinal swelling, and secondly, acceleration of the creep or recovery. The effect of increase of relative humidity is thus to contract the time scale; this effect is of course serious and non-reversible.

Typical Tests

On account of the above factors, only fair agreement between the total deformation curves for any load is to be expected. Accordingly, from each set of total deformation curves at any given load a typical test was selected which was considered best to represent the behavior of the specimen at that load. Further analysis of the data was made from such typical tests.

Instantaneous Elastic Deformation

The instantaneous or initial elastic deformation may be obtained by extrapolating the total deformation curve on a linear time plot to zero time, or on a logarithmic time plot to zero slope. These methods are feasible only when the first few creep observations correspond to the foot of the creep curve; in any case the accuracy of such extrapolation is low. In analysing the data the second method has been used; the instantaneous deformation is then the deformation corresponding to this extrapolated value. This deformation was estimated for the typical tests; in the case of silk this was done for all the tests. For each material (except nylon) this deformation (in inches) has been plotted against filament load (in grams). Except for the instantaneous elastic contraction for silk, the instantaneous deformation was found in all cases to be proportional to load.

The instantaneous elastic contraction for silk falls below the extension for corresponding loads, the discrepancy increasing at increasing loads (Fig. 74). A possible interpretation is that appreciable crystallisation or orientation takes place during the creep, the reverse effect taking place during recovery.

Instantaneous Modulus of Elasticity

Since the instantaneous elastic extensions and contractions are in most cases proportional to the load, it is possible to define an instantaneous modulus of elasticity as the ratio of the instantaneous elastic strain to the stress causing the deformation. This modulus thus depends only on the state of the filament and is independent of time.

In order to calculate the instantaneous modulus, it is necessary to know the slope of the instantaneous deformation/load plot, the length of the filament, and its cross-sectional area. The latter was determined in many cases by removing the filament carefully from the apparatus at the conclusion of the tests on the specimen, and winding it on a small frame. The filament was thus embedded in a suitable embedding medium. For the early specimens, methyl methacrylate monomer with accelerator was used; later on, at the suggestion of Mr. H. N. Lee of the M. I. T. Textile Laboratory* a solution of butyl methacrylate polymer and also plasticised collodion were successfully used. The filament thus embedded was cross-sectioned and mounted on a microscope slide in the usual way. The cross-sectional area was then measured in a projection microscope. It was thus possible to measure the cross-sectional area of the filament at several places along its length. In the case of some of the

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* The author wishes to express his great indebtedness in this connection to Mr. H. N. Lee, who developed the mounting techniques and who cut the cross-sections for the author.

filaments tested the cross-sectional area was not measured, but was computed from the nominal denier of the filament[95]. The following is a list of the instantaneous moduli of elasticity.

Specimen No.	Material	Instantaneous Modulus kg.mm.$^{-2}$	psi
7	Silk	1312	$1.86\text{x}10^6$
6	Viscose I	1094	1.56
5	Viscose I	1050	1.50
8	Viscose II (stretched)	1420	2.06
10	Acetate	576	0.82

In the above table, the cellulosic filaments are seen to have instantaneous moduli very much lower than that corresponding to crystalline cellulose[133], indicating (together with the large primary creep) a relatively large amount of amorphous or "fringe" material present[187]. The two filaments of Viscose I material were conditioned at the same load; the values of modulus are seen to agree very closely. The higher value for Viscose II might be due to the crystallisation in this material as a result of being stretched in the wet condition[187]. The acetate filament gave a very low value of instantaneous modulus, presumably due to the large amount of amorphous material present as a result of the acetate side chains. Until the effect on instantaneous modulus of conditioning at successively higher loads is known, the above conclusions must remain somewhat speculative.

Delayed Deformation and Load

The delayed or primary creep deformation is of course that part of the deformation which takes place subsequent to the application or removal of load, and is obtained by subtracting from the total deformation at any instant the instantaneous deformation.

In order to investigate the effect of load on creep, we could take the typical tests at each load mentioned previously, and then compute for these tests the delayed deformations as above. Owing to the extrapolation error involved in determining the instantaneous deformation, the delayed deformations are however likely to be seriously in error for low loads, and for small values of time when the load is large. Hence the instantaneous deformation cannot be used for further computation.

Delayed Deformation Relative to One Minute

The error involved in using the extrapolated value of instantaneous deformation can be avoided by the following artifice. If we subtract from any total deformation the corresponding total deformation at a time of one minute, we obtain what we might call the delayed deformation relative to one minute*. In this way extrapolation errors, as well as errors due to initial shock on the filament, are avoided; furthermore, it becomes possible to investigate the data on

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* In the following, the phrase "delayed deformation" when enclosed in quotation marks is to be taken as referring for brevity to the above quantity.

nylon.

The "delayed deformation" has been thus calculated for all the tests in the case of silk and for the typical tests with the other specimens. The "delayed deformations" have then been plotted against creep or recovery time to a double logarithmic scale. For a given specimen, the curves for each load have been found to be very nearly of the same shape, the effect of increase in load being to displace the curves along the axis of logarithm of deformation. The interpretation of this result is therefore that for each specimen the delayed deformation curves for the different loads differ only by a scale factor. Inspection shows that in general this scale factor is not a simple proportionality; the delayed deformation is therefore not proportional to load. One of the fundamental hypotheses of the Superposition Principle (equation 9) does not therefore hold for these materials. Smith and Eisenschitz[85] have apparently come to the same conclusion. The filamentous materials tested in the present investigation thus differ in behavior from rubber and hard rubber[143]. <u>The non-proportionality of creep and load must be attributed to the existence of a highly oriented structure[195]</u>. This departure from one of the hypotheses of the Superposition Principle is certainly unexpected, especially since the total deformations in the long-duration creep and recovery experiments agree closely, as predicted by the Principle.

There now remains to investigate in more detail the relation between load and magnitude of delayed deformation. In order to do this, curves have been fitted to the plots of "delayed deformations" against time to a double logarithmic scale. These curves have been adjusted to be as nearly as possible of the same shape and to be merely translations of each other along the log. deformation axis. The intersections of these faired curves with the ordinate corresponding to a time of 90 minutes thus gives a faired value of the delayed deformation at 90 minutes relative to one minute, for each typical test. We may denote this value by d_{90}, which we may call the <u>scale factor for creep</u>.

For each material values of d_{90} (in inches) thus obtained have been plotted together with the instantaneous elastic deformation against the filament load in grams. The curves of d_{90} against load are in general concave upwards. As previously suggested by the author[194], these curves can be represented in many cases by a linear relationship over a range of loads, and this linear relationship has been indicated on many of the plots.

Reduced Deformation

The scale factors for creep were obtained by fitting as closely as possible curves of the same shape to the "delayed deformations" on the double logarithmic plot. The double logarithmic plot is however relatively insensitive in that a deviation of say 10% is not very noticeable on this plot. It was decided therefore that a check was required on the correctness of the scale factors so chosen. This has been done by dividing for each material the "delayed deformations" in each of the typical tests by the corresponding value of the scale factor for creep. The <u>reduced deformations</u>

thus obtained were then plotted against the logarithm of time in the usual way. In general for any given material the reduced deformations obtained from the typical tests agreed very closely. Thus we can conclude that the total deformation in a long-duration creep or recovery test for constant load consists of an instantaneous part proportional to the load and a delayed part the magnitude of which increases at a faster rate than the load.

The Mechanical Behavior of Nylon

In the course of the investigation it was discovered that nylon at large loads has a creep behavior radically different from the normal behavior of filamentous materials or for that matter from the behavior as recorded in the literature of other high polymers. An examination of the stress-strain behavior of nylon yarn in say an inclined-plane tester reveals that this material possesses a high extension at break. If just before the breaking load is reached the load be removed and the specimen be allowed sufficient time to recover, it is found that the specimen will return almost completely to its original length. Nylon thus possesses a reversible extensibility which is of the order of 10% of its original length, and which is much greater than that found in comparable filamentous materials.

Nylon, like rubber, has both good strength and good extensibility characteristics. Chemically these materials are somewhat similar, and this similarity extends also to the general nature of the stress-strain (so-called "hysteresis") loops of these materials. Let us suppose that a nylon yarn be tested in an inclined-plane tester[175]. This machine applies the load to a specimen and removes the load at a uniform rate. The load-deformation loop which is then obtained is shown diagrammatically in Fig. 65, and this is seen to be similar to that of rubber[142]. In this diagram OCA represents the load-deformation behavior for increasing load and ABO for decreasing load and creep recovery. For very small load ranges a loop such as OCD is obtained; this is similar to the stress-strain loop such as is given by silk[105] (Fig. 27).

Now the first sample of nylon tested in the creep tests -- designated Nylon I -- was tested over a small range of loads, and no unusual creep behavior was noted. Later tests on another sample -- designated Nylon II -- revealed a normal creep behavior up to a certain load but abnormal behavior above that load. The boundary between the two regions appears roughly to correspond to the point C in Fig. 65. The curves OCA for the two specimens differ appreciably, and this probably accounts for the fact that the abnormal creep behavior was not noticed during the testing of the first nylon specimen.

Creep Behavior of Nylon at Large Loads

The behavior of the other filamentous materials and of nylon at low loads has already been described: the instantaneous deformation increases proportionately to the load, and the delayed deformation at a greater rate than the load. With nylon at large loads, the instantaneous deformation increases with load, but the delayed deformation does not vary with load. In other words, if we plot the total deformation against the logarithm of time, the curves of total deformation for different loads are of the same shape; the effect of change of load is merely to displace the curves upwards along the deformation axis.

The behavior of nylon at high loads has been brought out by plotting separately the data for Nylon II in this region (Figs. 101 to 106). First in Figs. 101 to 103 the total deformations for creep and recovery are plotted. In Fig. 104 are plotted three total deformation curves, one for each of the three highest loads. The ordinates of the three curves have been displaced in order to emphasize the similar course of the delayed deformation in all three cases. In Fig. 105 are plotted against load, first the increase in deformation from 1 to 90 minutes, and secondly the increase from 1 to 20 minutes. In both cases the difference, representing the magnitude of the delayed deformation, first increases with load and then at higher loads becomes constant. Fig. 100 is of course an enlargement of the low load portion of this diagram. Finally, in Fig. 106 have been plotted against load the total deformations at respectively 1/4 minute, 1 minute, 10 minutes and 90 minutes, after application of load. The fan-shaped portion of the diagram near the origin represents what we have called the "normal" creep behavior (compare Fig. 75 for the silk filament). The system of nearly straight parallel lines represents the extraordinary behavior at high loads. This diagram corresponds roughly with the stress-strain diagram as usually obtained (Fig. 65). As stated above, the "knee" in the diagram must therefore correspond to a transition region between the two types of creep behavior of nylon. It can be seen from the slight downward curvature of the right-hand portion of Fig. 106 that in this region the instantaneous deformation increases somewhat more slowly than the load.

Mechanism of Deformation of Nylon

The following mechanism of the deformation of nylon is proposed in the light of the above results and of the discussion on kinetic elasticity in Part IV. The molecular chains in nylon consist of course of $-CH_2-$ groups with occasional peptide (-CO-NH-) linkages. A very flexible chain is to be expected, together with a certain amount of crystallisation due to hydrogen bonding between the peptide groups in adjacent chains. At low loads the deformation is presumably due mainly to the elastic bending of the primary bonds. The creep under the conditions of test thus follows the same general pattern as that of the other filaments. At high loads however the large deformations are probably due mainly to straightening the chains in the fringe regions against the statistical coiling-up due to their heat motion. In the former case the deformation is opposed by secondary bonds assumed to exist between the chains. In the latter case, it seems possible that during the creep deformation an additional crystallisation takes place; the creep recovery may thus be due partly to the delay in the breaking up of the augmented crystalline material.

Now it has been mentioned that Nylon I showed a similar stress-strain behavior to Nylon II. Such stress-strain loops appear to be given not only by rubber, but also by muscle, wool, and plasticised vinyl resins. The mechanism of deformation in these materials presumably follows the same pattern as in nylon. In nylon, however, the phenomena are manifested over a small range of strain, and hence change of cross-sectional area is not a major complicating factor. It may well be therefore that nylon can serve as a model for the study of the mechanism of deformation in these other materials.

Comparison of Creep Results

The final stage in the analysis of the long-duration tests is the comparison of the scale factors for creep for the different materials. In Fig. 132 are plotted the scale factors, expressed as deformation per unit length (i.e., as a strain) against the stress expressed as grams per denier. While it is not safe to draw any general conclusions from this plot, it is of interest to note that the two nylon filaments (from different types of material) agreed fairly well, as did also the two viscose filaments, which were taken from the same length of yarn.

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III. Experimental Data on the Long Duration Creep Tests

This section of the thesis contains the numerical data on the long-duration creep tests. The data for each filament is considered separately. For each filament the data in general consists of:

1. List of all tests performed.
2. Observations and Total Deformations.
3. Instantaneous Elastic Deformations.
4. Calculation of Instantaneous Modulus of Elasticity.
5. Delayed Deformations relative to one minute (for the typical tests).
6. Scale Factors for Creep.
7. Reduced Deformations.

The data is plotted in Figs. 66 to 132. In these figures are plotted for the filaments in order of consideration:

1. Total Deformation Curves at each load for all tests.
2. Total Deformation Curves of Typical Tests (to real zero)
3. "Delayed Deformations" (double log. plot)
4. Reduced Deformations.
5. Scale Factors and Instantaneous Elastic Deformations against load.

In the case of the early data on Viscose I (Filament No. 5) the data is given in abstract only. For Nylon I the actual observations have not been given. Some of the early tests for the Acetate filament were erratic and have been omitted.

Arrangement of Data and Graphs

Filament No.	Material	Data, pp.	Figs.
7	Silk	189 - 216	66 - 75
6	Viscose I	217 - 239	76 - 84
5	Viscose I	240 - 254	85 - 92
9	Nylon II	255 - 276	93 - 106
4	Nylon I	277 - 286	107 - 114
10	Acetate	287 - 309	115 - 121
8	Viscose II (stretched)	310 - 335	122 - 131

Filament No.	Material	Figure Nos.			
		Typical Tests	"Del. Defn."	Red. Defn.	Scale Factor and Inst.Defn.
7	Silk	71	72	73	74
6	Viscose I	81	82	83	84
5	Viscose I	89	90	91	92
9	Nylon II (low loads)	97	98	99	100
4	Nylon I	111	112	113	114
10	Acetate	--	119	120	121
8	Viscose II (stretched)	128	129	130	131

FILAMENT NO. 7

SILK (DEGUMMED)

Scheme of Tests

Test No.	Type of Test	Filament Load, gms.
1	Long Duration Creep and Recovery (Mechanical Conditioning)	1.053
2,3	Long Duration Creep and Recovery	1.053
4	Superposition	1.053
5,6	Long Duration Creep and Recovery	0.526
7,8	Long Duration Creep and Recovery	0.856
9	Superposition	0.856
---	SWELLING RECOVERY TREATMENT	
10,11	Long Duration Creep and Recovery (Mechanical Conditioning)	1.053
12	Superposition	1.053

Tests 1, 2, 3

Observations 0 - 90 minutes (Scale readings in inches)

Test No.	1a	1b	2a	2b	3a	3b
Initial Obsn.	.1120	.3566	.2101	.3740	.2314	.3793
Time, Mins.						
1/4	.2087	--	.2993	--	.3193	--
1/2	.2122	.2738	.3024	.2904	.3223	.2983
3/4	.2147	.2727	.3041	.2891	.3238	.2955
1	.2168	.2718	.3055	.2883	.3251	.2948
1 1/2	.2201	.2703	.3074	.2866	.3272	.2934
2	.2229	.2688	.3091	.2855	.3285	.2918
3	.2275	.2667	.3118	.2835	.3307	.2900
5	.2345	.2642	.3156	.2810	.3340	.2877
7	.2402	.2622	.3183	.2791	.3363	.2861
10	.2469	.2600	.3213	.2769	.3390	.2841
15	.2558	.2572	.3251	.2742	.3422	.2814
20	.2622	.2550	.3281	.2720	.3445	.2796
30	.2717	.2517	.3321	.2688	.3480	.2767
40	.2793	.2492	.3350	.2663	.3504	.2744
60	.2888	.2453	.3392	.2626	.3540	.2711
90	.2983	.2411	.3432	.2586	.3577	.2677

Tests 1, 2, 3

Observations, 90 minutes onwards

Test 1a		Test 1b		Test 2a	
Time	Scale	Time	Scale	Time	Scale
160	.3107	180	.2334	120	.3461
242	.3189	240	.2330	180	.3502
300	.3229	345	.2261	300	.3553
435	.3292	445	.2237	385	.3577
755	.3427	740	.2148	692	.3652
1410	.3549	1350	.2098	705	.3653
1515	.3569			1420	.3746
				1500	.3750

Test 2b		Test 3a		Test 3b	
Time	Scale	Time	Scale	Time	Scale
160	.2527	135	.3610	130	.2643
280	.2472	185	.3633	186	.2611
362	.2449	275	.3663	420	.2543
500	.2421	675	.3744	720	.2481
1380	.2306	1395	.3800	1420	.2394
				1510	.2380
				1635	.2369
				1760	.2363

Tests 1, 2, 3

Total Deformations, 0 - 90 minutes (in inches)

Test No.	1a	1b	2a	2b	3a	3b
Time, Mins.						
1/4	.0967	--	.0892	--	.0879	--
1/2	.1002	.0828	.0923	.0836	.0909	.0810
3/4	.1027	.0839	.0940	.0849	.0924	.0838
1	.1048	.0848	.0954	.0857	.0937	.0845
1 1/2	.1081	.0863	.0973	.0874	.0958	.0859
2	.1109	.0878	.0990	.0885	.0971	.0875
3	.1155	.0899	.1017	.0905	.0993	.0893
5	.1225	.0924	.1055	.0930	.1026	.0916
7	.1282	.0944	.1082	.0949	.1049	.0932
10	.1349	.0966	.1112	.0971	.1076	.0952
15	.1438	.0994	.1150	.0998	.1108	.0979
20	.1502	.1016	.1180	.1020	.1131	.0997
30	.1597	.1049	.1220	.1052	.1166	.1026
40	.1673	.1074	.1249	.1077	.1190	.1049
60	.1768	.1113	.1291	.1114	.1226	.1082
90	.1863	.1151	.1331	.1154	.1263	.1116

Tests 1, 2, 3

Total Deformations, 90 minutes onwards

	Test 1a
Time	Deformation
160	.1987
242	.2069
300	.2109
435	.2172
755	.2307
1410	.2429
1515	.2449

	Test 1b
Time	Deformation
180	.1232
240	.1236
345	.1305
445	.1329
740	.1418
1350	.1468

	Test 2a
Time	Deformation
120	.1360
180	.1401
300	.1452
385	.1476
692	.1551
705	.1552
1420	.1645
1500	.1649

	Test 2b
Time	Deformation
160	.1213
280	.1268
362	.1291
500	.1319
1380	.1434

	Test 3a
Time	Deformation
135	.1296
185	.1319
275	.1349
675	.1430
1395	.1486

	Test 3b
Time	Deformation
130	.1150
186	.1182
420	.1250
720	.1312
1420	.1399
1510	.1413
1635	.1424
1760	.1430

Tests 1, 2, 3

Delayed Deformations (relative to t = 1 minute)

0 - 90 minutes

Test No.	1b	2b	3a	3b
Time, Mins.				
1	0	0	0	0
1 1/2	.0015	.0017	.0021	.0014
2	.0030	.0028	.0034	.0030
3	.0051	.0048	.0056	.0052
5	.0076	.0073	.0089	.0071
7	.0096	.0092	.0112	.0087
10	.0118	.0114	.0139	.0103
15	.0146	.0141	.0171	.0134
20	.0168	.0163	.0194	.0152
30	.0201	.0195	.0229	.0181
40	.0226	.0220	.0253	.0204
60	.0265	.0257	.0289	.0237
90	.0307	.0297	.0326	.0271

Tests 1, 2, 3

Delayed Deformations (relative to t = 1 minute)

90 minutes onwards

Test 1b

Time	Delayed Deformation
180	.0384
240	.0390
345	.0457
445	.0481
740	.0570
1350	.0620

Test 2b

Time	Delayed Deformation
160	.0356
280	.0411
362	.0434
500	.0462
1380	.0577

Test 3a

Time	Delayed Deformation
135	.0359
185	.0382
275	.0412
675	.0493
1395	.0549

Test 3b

Time	Delayed Deformation
130	.0305
186	.0337
420	.0405
720	.0467
1420	.0554
1510	.0568
1635	.0579
1760	.0585

Tests 5, 6

Observations 0 - 90 minutes (in inches)

Test No.	5a	5b	6a	6b
Initial obsn.	.2331	.3030	.2375	.3036
Time, Mins.				
1/4	.2829	--	.2850	--
1/2	.2838	.2570	.2858	.2575
3/4	.2843	.2566	.2863	.2570
1	.2848	.2564	.2867	.2568
1 1/2	.2853	.2559	.2871	.2563
2	.2856	.2555	.2875	.2559
3	.2863	.2550	.2881	.2553
5	.2872	.2542	.2888	.2546
7	.2879	.2537	.2893	.2541
10	.2887	.2531	.2900	.2534
15	.2896	.2523	.2907	.2526
20	.2903	.2518	.2913	.2521
30	.2913	.2508	.2921	.2513
40	.2921	.2501	.2928	.2505
60	.2934	.2493	.2939	.2496
90	.2948	.2483	.2950	.2486

Tests 5, 6

Observations 90 minutes onwards

Test 5a		Test 5b	
Time	Scale	Time	Scale
140	.2963	145	.2472
190	.2972	250	.2453
290	.2989	355	.2437
430	.3004	493	.2421
750	.3020	1370	.2365
1455	.3036		

Test 6a		Test 6b	
Time	Scale	Time	Scale
152	.2966	150	.2469
203	.2973	230	.2454
360	.2990	320	.2441
460	.2997	375	.2435
525	.3000	670	.2419
750	.3015	1330	.2396
1410	.3050		
1540	.3043		

Tests 5, 6

Total Deformations, 0 - 90 minutes (in inches)

Test No.	5a	5b	6a	6b
Time, Mins.				
1/4	.0498	--	.0475	--
1/2	.0507	.0460	.0483	.0461
3/4	.0512	.0464	.0488	.0466
1	.0517	.0466	.0492	.0468
1 1/2	.0522	.0471	.0496	.0473
2	.0525	.0475	.0500	.0477
3	.0532	.0480	.0506	.0483
5	.0541	.0488	.0513	.0490
7	.0548	.0493	.0518	.0495
10	.0556	.0499	.0525	.0502
15	.0565	.0507	.0532	.0510
20	.0572	.0512	.0538	.0515
30	.0582	.0522	.0546	.0523
40	.0590	.0529	.0553	.0531
60	.0603	.0537	.0564	.0540
90	.0617	.0547	.0575	.0550

Tests 5, 6

Total Deformations, 90 minutes onwards (in inches)

Test 5a Time	Deformation	Test 5b Time	Deformation
140	.0632	145	.0558
190	.0641	250	.0577
290	.0658	355	.0593
430	.0673	493	.0609
750	.0689	1370	.0665
1455	.0705		

Test 6a Time	Deformation	Test 6b Time	Deformation
152	.0591	150	.0567
203	.0598	230	.0582
360	.0615	320	.0595
460	.0624	375	.0601
525	.0625	670	.0617
750	.0640	1330	.0640
1410	.0675		
1540	.0668		

Tests 5,6

Delayed Deformations relative to t = 1 min. (in inches)

0 - 90 minutes

Test No.	5a	5b	6a	6b
Time, Mins.				
1	0	0	0	0
1 1/2	.0005	.0005	.0004	.0005
2	.0008	.0009	.0008	.0009
3	.0015	.0014	.0014	.0015
5	.0024	.0022	.0021	.0022
7	.0031	.0027	.0026	.0027
10	.0039	.0033	.0033	.0034
15	.0048	.0041	.0040	.0042
20	.0055	.0046	.0046	.0047
30	.0065	.0056	.0054	.0055
40	.0073	.0063	.0061	.0063
60	.0086	.0071	.0072	.0072
90	.0100	.0081	.0082	.0082

Tests 5, 6

Delayed Deformations, 90 minutes onwards

Test 5a

Time	Delayed Deformation
140	.0115
190	.0124
290	.0141
430	.0156
750	.0172
1455	.0188

Test 5b

Time	Delayed Deformation
145	.0092
250	.0111
355	.0127
493	.0143
1370	.0199

Test 6a

Time	Delayed Deformation
152	.0099
203	.0106
360	.0123
460	.0132
525	.0133
750	.0148
1410	.0183
1540	.0176

Test 6b

Time	Delayed Deformation
150	.0099
230	.0114
320	.0127
375	.0133
670	.0149
1330	.0172

Tests 7, 8

Observations 0 - 90 minutes (in inches)

Test No.	7a	7b	8a	8b
Initial Obsn.	.2403	.3485	.2397	.3484
Time, Mins.				
1/4	.3153	--	.3139	--
1/2	.3170	.2763	.3154	--
3/4	.3179	.2760	.3163	.2765
1	.3186	.2754	.3170	.2757
1 1/2	.3198	.2746	.3179	.2744
2	.3206	.2738	.3188	.2737
3	.3218	.2727	.3200	.2726
5	.3233	.2713	.3215	.2711
7	.3245	.2703	.3227	.2701
10	.3257	.2691	.3240	.2689
15	.3272	.2676	.3256	.2674
20	.3282	.2664	.3270	.2662
30	.3300	.2648	.3289	.2644
40	.3311	.2635	.3304	.2630
60	.3330	.2614	.3326	.2611
90	.3350	.2593	.3348	.2590

Tests 7,8

Observations, 90 minutes onwards

Test 7a		Test 7b	
Time	Scale	Time	Scale
155	.3376	160	.2562
225	.3392	220	.2540
385	.3422	395	.2507
480	.3427	1020	.2432
1480	.3482	1430	.2425
1800	.3494	1510	.2422
		2565	.2387

Test 8a		Test 8b	
Time	Scale	Time	Scale
152	.3377	150	.2565
260	.3404	445	.2505
380	.3427	960	.2471
700	.3461	1560	.2413
1295	.3490		

Tests 7, 8

Total Deformations, 0 - 90 minutes (in inches)

Test No.	7a	7b	8a	8b
Time, Mins.				
1/4	.0750	--	--	--
1/2	.0767	.0722	.0757	--
3/4	.0776	.0725	.0766	.0719
1	.0783	.0731	.0773	.0727
1 1/2	.0795	.0739	.0782	.0740
2	.0803	.0747	.0791	.0747
3	.0815	.0758	.0803	.0758
5	.0830	.0772	.0818	.0773
7	.0842	.0782	.0830	.0783
10	.0854	.0794	.0843	.0795
15	.0869	.0809	.0859	.0810
20	.0879	.0821	.0873	.0822
30	.0897	.0837	.0892	.0840
40	.0908	.0850	.0907	.0854
60	.0927	.0871	.0929	.0873
90	.0947	.0892	.0951	.0894

Tests 7, 8

Total Deformations, 90 minutes onwards

Test 7a		Test 7b	
Time	Deformation	Time	Deformation
155	.0973	160	.0923
225	.9089	220	.0945
385	.1019	395	.0978
480	.1024	1020	.1053
1480	.1079	1510	.1063
1800	.1091	2565	.1098

Test 8a		Test 8b	
Time	Deformation	Time	Deformation
152	.0980	150	.0919
260	.1007	445	.0479
380	.1030	960	.1013
700	.1064	1560	.1071
1295	.1093		

Tests 7, 8

Delayed Deformations relative to t = 1 min. (in inches)

0 - 90 minutes

Test No.	7a	7b	8a	8b
Time, Mins.				
1	0	0	0	0
1 1/2	.0012	.0008	.0009	.0013
2	.0020	.0016	.0018	.0020
3	.0032	.0027	.0030	.0031
5	.0037	.0041	.0045	.0046
7	.0059	.0051	.0057	.0056
10	.0071	.0063	.0070	.0068
15	.0086	.0078	.0086	.0083
20	.0096	.0090	.0100	.0095
30	.0114	.0106	.0119	.0113
40	.0125	.0119	.0134	.0127
60	.0144	.0140	.0156	.0146
90	.0164	.0161	.0178	.0167

Tests 7, 8

Delayed Deformations relative to t = 1 min.

90 minutes onwards

Test 7a

Time	Delayed Deformation
155	.0190
225	.0206
385	.0236
480	.0245
1480	.0296
1800	.0308

Test 7b

Time	Delayed Deformation
160	.0192
220	.0214
395	.0247
1020	.0322
1510	.0332
2565	.0367

Test 8a

Time	Delayed Deformation
152	.0207
260	.0234
380	.0257
700	.0291
1295	.0320

Test 8b

Time	Delayed Deformation
150	.0192
445	.0252
960	.0286
1560	.0344

Tests 10, 11

Observations 0 - 90 minutes (in inches)

Test No.	10a	10b	11a	11b
Initial Obsn.	.1628	.3497	.1978	.3632
Time, Mins.				
1/4	.2523	.2640	.2867	.2808
1/2	.2538	.2622	.2894	.2788
3/4	.2549	.2607	.2910	.2775
1	.2558	.2594	.2923	.2764
1 1/2	.2571	.2576	.2941	.2750
2	.2581	.2562	.2957	.2739
3	.2598	.2540	.2980	.2720
5	.2620	.2509	.3013	.2694
7	.2638	.2486	.3036	.2677
10	.2660	.2460	.3064	.2655
15	.2687	.2429	.3100	.2626
20	.2710	.2409	.3128	.2607
30	.2746	.2368	.3170	.2576
40	.2776	.2341	.3200	.2552
60	.2820	.2300	.3244	.2517
90	.2874	.2258	.3290	.2480

Tests 10, 11

Observations 90 minutes onwards

Test 10a

Time	Scale
150	.2949
305	.3083
400	.3147
540	.3220
1300	.3502

Test 10b

Time	Scale
150	.2207
260	.2154
360	.2128
395	.2117
2000	.1988
2190	.1983
2790	.1968

Test 11a

Time	Scale
150	.3355
250	.3416
315	.3443
450	.3486
520	.3508
1450	.3637

Test 11b

Time	Scale
160	.2425
240	.2384
370	.2341
465	.2319
520	.2306
1455	.2204
1580	.2192

Tests 10, 11

Total Deformations 0 - 90 minutes (in inches)

Test No.	10a	10b	11a	11b
Time, Mins.				
1/4	.0895	.0857	.0889	.0824
1/2	.0910	.0875	.0916	.0844
3/4	.0921	.0890	.0932	.0857
1	.0930	.0903	.0945	.0868
1 1/2	.0943	.0919	.0963	.0882
2	.0953	.0935	.0979	.0891
3	.0970	.0957	.1002	.0912
5	.0992	.0988	.1035	.0938
7	.1010	.1009	.1058	.0955
10	.1032	.1037	.1086	.0977
15	.1059	.1068	.1122	.1005
20	.1082	.1088	.1150	.1025
30	.1118	.1129	.1192	.1056
40	.1148	.1156	.1222	.1080
60	.1192	.1197	.1266	.1115
90	.1246	.1239	.1312	.1152

Tests 10, 11

Total Deformations 90 minutes onwards (in inches)

	Test 10a		Test 10b
Time	Deformation	Time	Deformation
150	.1321	150	.1290
305	.1455	260	.1343
400	.1519	360	.1369
540	.1592	395	.1380
1300	.1874	2000	.1509
		2190	.1514
		2790	.1529

	Test 11a		Test 11b
Time	Deformation	Time	Deformation
150	.1377	160	.1207
250	.1438	240	.1248
315	.1465	370	.1291
450	.1508	465	.1313
520	.1530	520	.1326
1450	.1659	1455	.1428
		1580	.1440

Silk: Instantaneous Elastic Deformation

Test No.	Filament Load, gms.	I.E.D., ins.
1b	1.053	.0780
2b	1.053	.0780
3a	1.053	.0858
3b	1.053	.0780
5a	0.526	.0470
5b	0.526	.0430
6a	0.526	.0445
6b	0.526	.0430
7a	0.856	.0703
7b	0.856	.0660
8a	0.856	.0703
8b	0.856	.0660

Instantaneous Modulus of Elasticity

Instantaneous elastic deformation = .0828 ins./gm.

= .210 cms./gm.

Length of filament = 28.10 cms.

Cross-sectional area = 102×10^{-8} cm^2.

Instantaneous modulus = 1.312×10^{8} gms./cm^2.

= $\underline{1.86 \times 10^{6} \text{ psi}}$

Scale Factors for Creep

Test No.	2b	8b	6b
Filament Load, gms.	1.053	0.856	0.526
Load, gms./denier	0.830	0.674	0.413
Scale Factor for creep d_{90} (Deformation at 90 mins. - deformation at 1 min.)	.0297	.0167	.0086
Scale Factor expressed as strain D_{90} x 1000	2.68	1.51	0.78

Silk: Reduced Deformations 0 - 90 mins.

Filament load, gms.	1.053	0.856	0.526
Test No.	2b	8b	6b
Scale Factor d_{90}	.0297	.0167	.0086
Time, Mins.			
1	0	0	0
1 1/2	.057	.078	.058
2	.094	.120	.105
3	.162	.186	.174
5	.246	.275	.256
7	.310	.335	.314
10	.384	.407	.395
15	.475	.497	.488
20	.549	.569	.547
30	.657	.677	.640
40	.741	.760	.733
60	.865	.874	.837
90	1.000	1.000	.953

Reduced Deformations (90 minutes onwards)

Test 2b

Time	Reduced Deformation
160	1.199
280	1.384
362	1.461
500	1.556
1380	1.943

Test 8b

Time	Reduced Deformation
150	1.150
445	1.509
960	1.713
1560	2.060

Test 6b

Time	Reduced Deformation
150	1.151
230	1.326
320	1.477
375	1.547
670	1.733
1330	2.000

Total Deformation and Load Curves

		Total Deformation at following times:			
Test No.	Filament Load, gms.	t(mins.) =	1	10	90
2b	1.053		.0857	.0971	.1154
8b	0.856		.0727	.0795	.0894
6b	0.526		.0468	.0502	.0550

FILAMENT NO. 6

VISCOSE I

Scheme of Tests

Test No.		Filament Load, gms.
1	Long Duration Creep and Recovery (Mechanical Conditioning)	1.053
2	Long Duration Creep and Recovery	0.346
3,4	ditto	0.526
5	ditto	0.856
6	ditto	0.526
7	Superposition	0.526
8	ditto	0.856
	FILAMENT STRETCHED 0.33 IN. UNDER ROOM CONDITIONS	
9,10	Long Duration Creep and Recovery (Mechanical Conditioning)	1.053
11	Long Duration Creep and Recovery	0.856
	SWELLING RECOVERY TREATMENT	
12	Long Duration Creep and Recovery (Mechanical Conditioning)	1.053
13	Long Duration Creep and Recovery	0.856
	SWELLING RECOVERY TREATMENT	

Tests 1, 2, 5

Observations 0 - 90 minutes (in inches)

Test No.	1a	1b	2a	2b	5a	5b
Initial Obsn.	.2522	.5552	.3961	.4280	.4037	.4930
Time, Mins.						
1/4	.3221	(.5054)	.4164	--	.4487	.4484
1/2	.3262	(.5037)	.4170	--	.4562	.4468
3/4	.3289	.5023	.4172	--	.4511	.4460
1	.3308	.5017	.4175	.4094	.4519	.4454
1 1/2	.3343	.5000	.4178	.4091	.4527	.4443
2	.3370	.4989	.4182	.4086	.4535	.4434
3	.3420	.4971	.4185	.4080	.4545	.4421
5	.3475	.4940	.4190	.4073	.4562	.4403
7	.3528	.4923	.4192	.4065	.4572	.4393
10	.3601	.4899	.4194	.4061	.4585	.4380
15	.3688	.4876	.4199	.4058	.4600	.4363
20	.3762	.4854	.4203	.4054	.4610	.4351
30	.3898	.4819	.4205	.4048	.4631	.4335
40	.3981	.4798	.4206	.4043	.4645	.4320
60	.4140	.4755	.4210	.4035	.4665	.4303
90	.4301	--	.4216	.4029	.4690	.4286

Tests 1, 2, 5

Observations, 90 minutes onwards

Test 1a

Time	Scale
190	.4592
280	.4743
378	.4878
1210	.5311
1505	.5345
2100	.5461
2940	.5556

Test 1b

Time	Scale
140	.4654
185	.4620
240	.4583
540	.4465
1200	.4332
1980	.4262
3360	.4028
4050	.3959

Test 2a

Time	Scale
120	.4224
190	.4232
280	.4233
350	.4239
390	.4249
795	.4269
1410	.4277
1503	.4286

Test 2b

Time	Scale
135	.4023
245	.4003
340	.3993
410	.3991
1330	.3930

Test 5a

Time	Scale
120	.4704
190	.4730
300	.4761
455	.4788
520	.4804
750	.4881
1380	.4926
1500	.4931

Test 5b

Time	Scale
151	.4260
220	.4234
320	.4209
420	.4187
1210	.4098

Tests 1, 2, 5

Total Deformations, 0 - 90 minutes (in inches)

Test No.	1a	1b	2a	2b	5a	5b
Time, Mins.						
1/4	.0699	--	.0203	--	.0450	.0446
1/2	.0740	--	.0209	--	.0465	.0462
3/4	.0767	.0529	.0211	--	.0474	.0470
1	.0786	.0535	.0214	.0186	.0482	.0476
1 1/2	.0821	.0552	.0217	.0189	.0490	.0487
2	.0848	.0563	.0221	.0194	.0498	.0496
3	.0898	.0581	.0224	.0200	.0508	.0509
5	.0953	.0612	.0229	.0207	.0525	.0527
7	.1006	.0629	.0231	.0215	.0535	.0537
10	.1079	.0653	.0233	.0219	.0548	.0550
15	.1166	.0676	.0238	.0222	.0563	.0567
20	.1240	.0698	.0242	.0226	.0573	.0579
30	.1376	.0733	.0244	.0232	.0594	.0595
40	.1459	.0754	.0245	.0237	.0608	.0610
60	.1618	.0797	.0249	.0245	.0628	.0623
90	.1779	--	.0255	.0251	.0653	.0644

Tests 1, 2, 5

Total Deformations, 90 minutes onwards

Test 1a		Test 1b		Test 2a	
Time	Deformation	Time	Deformation	Time	Deformation
190	.2070	140	.0898	120	.0263
280	.2221	185	.0932	190	.0271
378	.2356	240	.0969	280	.0272
1210	.2789	540	.1087	350	.0278
1505	.2823	1200	.1220	390	.0288
2100	.2939	1980	.1290	795	.0308
2940	.3034	3360	.1524	1410	.0316
		4050	.1593	1503	.0325

Test 2b		Test 5a		Test 5b	
Time	Deformation	Time	Deformation	Time	Deformation
135	.0257	120	.0667	151	.0670
245	.0277	190	.0693	220	.0696
340	.0287	300	.0724	320	.0721
410	.0289	455	.0751	420	.0743
1330	.0350	520	.0767	1210	.0832
		750	.0844		
		1380	.0889		
		1500	.0894		

Tests 3, 4, 6

Observations 0 - 90 minutes (in inches)

Test No.	3a	3b	4a	4b	6a	6b
Initial Obsn.	.3944	.4449	.3978	.4481	.4104	.4571
Time, Mins.						
1/4	.4222	.4182	.4246	.4210	.4376	.4296
1/2	.4230	.4175	.4255	.4202	.4385	.4290
3/4	.4234	.4170	.4260	.4199	.4390	.4285
1	.4237	.4166	.4263	.4196	.4393	.4281
1 1/2	.4242	.4160	.4269	.4192	.4398	.4275
2	.4247	.4155	.4272	.4187	.4401	.4272
3	.4252	.4149	.4278	.4181	.4409	.4267
5	.4259	.4141	.4285	.4174	.4418	.4260
7	.4265	.4136	.4290	.4170	.4423	.4255
10	.4271	.4129	.4297	.4165	.4430	.4249
15	.4279	.4122	.4305	.4157	.4436	.4239
20	.4285	.4118	.4311	.4151	.4443	.4236
30	.4293	.4110	.4320	.4144	.4452	.4229
40	.4303	.4105	.4328	.4133	.4460	.4221
60	.4312	.4098	.4339	--	.4469	.4213
90	.4326	.4092	.4355	.4127	.4478	.4207

Tests 3, 4, 6

Observations, 90 minutes onwards

Test 3a		Test 3b		Test 4a	
Time	Scale	Time	Scale	Time	Scale
120	.4338	120	.4083	120	.4363
180	.4354	180	.4067	220	.4381
300	.4374	350	.4049	335	.4401
390	.4387	390	.4041	700	.4433
460	.4403	1455	.3970	1560	.4450
1390	.4453			1660	.4457
1522	.4458			1770	.4470
				2850	.4482

Test 4b		Test 6a		Test 6b	
Time	Scale	Time	Scale	Time	Scale
140	.4114	125	.4488	120	.4204
240	.4112	195	.4499	170	.4198
320	.4105	310	.4510	270	.4189
1310	.4029	375	.4516	325	.4188
		530	.4538	415	.4184
		1380	.4568	1335	.4113

Tests 3, 4, 6

Total Deformations, 0 - 90 minutes (in inches)

Test No.	3a	3b	4a	4b	6a	6b
Time, Mins.						
1/4	.0278	.0267	.0268	.0271	.0272	.0275
1/2	.0286	.0274	.0277	.0279	.0281	.0281
3/4	.0290	.0279	.0282	.0282	.0286	.0286
1	.0293	.0283	.0285	.0285	.0289	.0290
1 1/2	.0298	.0289	.0291	.0289	.0294	.0296
2	.0303	.0294	.0294	.0294	.0297	.0299
3	.0308	.0300	.0300	.0300	.0305	.0304
5	.0315	.0308	.0307	.0307	.0314	.0311
7	.0321	.0313	.0312	.0311	.0319	.0316
10	.0327	.0320	.0319	.0316	.0326	.0322
15	.0335	.0327	.0327	.0324	.0332	.0332
20	.0341	.0331	.0333	.0330	.0339	.0335
30	.0349	.0339	.0342	.0337	.0348	.0342
40	.0359	.0344	.0350	.0348	.0356	.0350
60	.0368	.0351	.0361	--	.0365	.0358
90	.0382	.0357	.0377	.0354	.0374	.0364

Tests 3, 4, 6

Total Deformations 90 minutes onwards (in inches)

Test 3a Time	Test 3a Deformation	Test 3b Time	Test 3b Deformation	Test 4a Time	Test 4a Deformation
120	.0394	120	.0366	120	.0385
180	.0410	180	.0382	220	.0403
300	.0430	350	.0400	335	.0423
390	.0443	390	.0408	700	.0455
460	.0459	1455	.0479	1560	.0472
1390	.0509			1660	.0479
1522	.0514			1770	.0492
				2850	.0504

Test 4b Time	Test 4b Deformation	Test 6a Time	Test 6a Deformation	Test 6b Time	Test 6b Deformation
140	.0367	125	.0384	120	.0367
240	.0369	195	.0395	170	.0373
320	.0376	310	.0406	270	.0382
1310	.0452	375	.0412	325	.0383
		530	.0434	415	.0387
		1380	.0464	1335	.0458

Tests 9, 10, 12

Observations 0 - 90 minutes (in inches)

Test No.	9a	9b	10a	10b	12a	12b
Initial Obsn.	.2992	.4365	.3224	.4347	.0725	.3858
Time, Mins.						
1/4	.3497	.3893	.3719	.3866	.1353	.3297
1/2	.3518	.3874	.3736	.3849	.1390	.3282
3/4	.3531	.3858	.3749	.3839	.1412	.3267
1	.3542	.3849	.3757	.3831	.1430	.3254
1 1/2	.3558	.3835	.3771	.3818	.1459	.3234
2	.3570	.3826	.3781	.3809	.1480	.3219
3	.3589	.3810	.3796	.3794	.1521	.3195
5	.3618	.3790	.3818	.3774	.1584	.3162
7	.3640	.3774	.3834	.3759	.1633	.3136
10	.3667	.3756	.3852	.3743	.1695	.3106
15	.3702	.3732	.3876	.3722	.1781	.3069
20	.3731	.3715	.3896	.3706	.1853	.3038
30	.3778	.3688	.3927	.3681	.1978	.2993
40	.3815	.3664	.3951	.3662	.2077	.2960
60	.3869	.3629	.3988	.3630	.2231	.2911
90	.3932	.3587	.4028	.3598	.2403	.2858

Tests 9, 10, 12

Observations, 90 minutes onwards (in inches)

Test 9a

Time	Scale
150	.4015
196	.4059
275	.4113
360	.4163
660	.4260
1340	.4345
1460	.4367

Test 9b

Time	Scale
160	.3527
270	.3465
350	.3438
450	.3398
1480	.3218

Test 10a

Time	Scale
160	.4092
225	.4128
300	.4164
600	.4276
1290	.4337
1395	.4349

Test 10b

Time	Scale
150	.3551
240	.3504
300	.3484
347	.3475
630	.3411
1355	.3294

Test 12a

Time	Scale
140	.2600
230	.2831
280	.2920
405	.3097
1365	.3848
1425	.3864

Test 12b

Time	Scale
195	.2743
275	.2696
345	.2672
1380	.2475
1465	.2467

Tests 9, 10, 12

Total Deformations, 0 - 90 minutes (in inches)

Test No.	9a	9b	10a	10b	12a	12b
Time, Mins.						
1/4	.0505	.0472	.0495	.0481	.0628	.0561
1/2	.0526	.0491	.0512	.0498	.0665	.0576
3/4	.0539	.0507	.0525	.0508	.0687	.0591
1	.0550	.0516	.0533	.0516	.0705	.0604
1 1/2	.0566	.0530	.0547	.0529	.0734	.0624
2	.0578	.0539	.0557	.0538	.0755	.0639
3	.0597	.0555	.0572	.0553	.0796	.0663
5	.0626	.0575	.0594	.0573	.0859	.0696
7	.0648	.0591	.0610	.0588	.0908	.0722
10	.0675	.0609	.0628	.0604	.0970	.0752
15	.0710	.0633	.0652	.0615	.1056	.0789
20	.0739	.0650	.0672	.0631	.1128	.0820
30	.0786	.0677	.0703	.0666	.1253	.0865
40	.0823	.0701	.0727	.0685	.1352	.0898
60	.0877	.0736	.0764	.0717	.1506	.0947
90	.0940	.0778	.0804	.0749	.1678	.1000

Tests 9, 10, 12

Total Deformations, 90 minutes onwards (in inches)

Test 9a		Test 9b		Test 10a	
Time	Deformation	Time	Deformation	Time	Deformation
150	.1023	160	.0838	160	.0868
196	.1067	270	.0900	225	.0904
275	.1121	350	.0927	300	.0940
360	.1171	450	.0967	600	.1052
660	.1268	1480	.1147	1290	.1113
1340	.1353			1395	.1125
1460	.1375				

Test 10b		Test 12a		Test 12b	
Time	Deformation	Time	Deformation	Time	Deformation
150	.0796	140	.1875	195	.1115
240	.0843	230	.2106	275	.1162
300	.0863	280	.2195	345	.1186
347	.0872	405	.2372	1380	.1383
630	.0936	1365	.3123	1465	.1391
1355	.1053	1425	.3139		

Tests 11, 13

Observations, 0 - 90 minutes (in inches)

Test No.	11a	11b	13a	13b
Initial Obsn.	.3303	.4246	.2475	.3608
Time, Mins.				
1/4	.3737	.3815	.2946	.3152
1/2	.3754	.3806	.2968	.3138
3/4	.3763	.3798	.2979	.3127
1	.3770	.3792	.2989	.3120
1 1/2	.3780	.3783	.3003	.3108
2	.3788	.3777	.3014	.3099
3	.3800	.3764	.3029	.3086
5	.3816	.3752	.3053	.3066
7	.3828	.3740	.3072	.3051
10	.3841	.3729	.3092	.3037
15	.3858	.3713	.3121	.3016
20	.3872	.3703	.3141	.3000
30	.3894	.3686	.3174	.2977
40	.3912	.3672	.3200	.2960
60	.3936	.3649	.3233	.2932
90	.3963	.3623	.3274	.2901

Tests 11, 13

Observations, 90 minutes onwards (in inches)

Test 11a		Test 11b	
Time	Scale	Time	Scale
130	.3989	165	.3584
180	.4011	255	.3550
240	.4031	320	.3530
360	.4064	650	.3468
660	.4132	1365	.3378
1620	.4189		
2105	.4219		
2850	.4239		
2940	.4246		

Test 13a		Test 13b	
Time	Scale	Time	Scale
170	.3350	155	.2853
230	.3388	395	.2780
550	.3502	670	.2729
625	.3519	1420	.2653
1355	.3609	2130	.2597
1380	.3613	2800	.2564

Tests 11, 13

Total Deformations 0 - 90 minutes (in inches)

Test No. Time, Mins.	11a	11b	13a	13b
1/4	.0433	.0431	.0471	.0456
1/2	.0451	.0440	.0493	.0470
3/4	.0460	.0448	.0504	.0481
1	.0467	.0454	.0514	.0488
1 1/2	.0477	.0463	.0528	.0500
2	.0485	.0469	.0539	.0509
3	.0497	.0482	.0554	.0522
5	.0513	.0494	.0578	.0542
7	.0525	.0506	.0597	.0557
10	.0538	.0517	.0617	.0571
15	.0555	.0533	.0646	.0592
20	.0569	.0543	.0666	.0608
30	.0591	.0560	.0699	.0631
40	.0609	.0574	.0725	.0648
60	.0633	.0597	.0758	.0676
90	.0660	.0623	.0799	.0707

Tests 11, 13

Total Deformations 90 minutes onwards (in inches)

Test 11a		Test 11b	
Time	Deformation	Time	Deformation
130	.0686	165	.0662
180	.0708	255	.0696
240	.0728	320	.0716
360	.0761	650	.0778
660	.0829	1365	.0868
1620	.0886		
2105	.0916		
2850	.0936		
2940	.0943		

Test 13a		Test 13b	
Time	Deformation	Time	Deformation
170	.0875	155	.0755
230	.0913	395	.0828
550	.1027	670	.0879
625	.1044	1420	.0955
1355	.1134	2130	.1011
1380	.1138	2800	.1044

Viscose:

Initial Elastic Deformation

Test No.	I.E.D., Ins.
3,4,6	.0256 (mean)
5a	.0420
2a	.0197
1b	.0516

Instantaneous Modulus of Elasticity

Instantaneous Deformation = .0490 ins./gm.
= .1244 cms./gm.

Length of Filament = 28.99 cms.

Cross-Sectional Area (assuming 3 denier/fil. and 1 denier = 71.0 μ^2) = 213×10^{-8} cms.^{2}

Instantaneous Modulus of Elasticity = 1.094×10^{8} gms./cm.^{2}
= 1.56×10^{6} psi

Viscose: Delayed Deformations relative to t = 1 minute

1 - 90 minutes (in inches)

Test No.	1b	2a	3a	5a
Time, Mins.				
1	0	0	0	0
1 1/2	.0017	.0003	.0005	.0008
2	.0028	.0007	.0010	.0016
3	.0046	.0010	.0015	.0026
5	.0077	.0015	.0022	.0043
7	.0094	.0017	.0028	.0053
10	.0118	.0019	.0034	.0066
15	.0141	.0024	.0042	.0081
20	.0163	.0028	.0048	.0091
30	.0198	.0030	.0056	.0112
40	.0219	.0031	.0066	.0126
60	.0262	.0035	.0075	.0146
90	. --	.0041	.0089	.0171

Delayed Deformation relative to t = 1 minute, 90 minutes onward

Test 1b	
Time	Delayed Deformation
140	.0363
185	.0397
240	.0434
540	.0552
1200	.0685
1980	.0755
3360	.0989
4050	.1058

Test 2a	
Time	Delayed Deformation
120	.0049
190	.0057
280	.0058
350	.0064
390	.0074
795	.0094
1410	.0102
1503	.0111

Test 3a	
Time	Delayed Deformation
120	.0101
180	.0117
300	.0137
390	.0150
460	.0166
1390	.0216
1522	.0221

Test 5a	
Time	Delayed Deformation
120	.0185
190	.0211
300	.0242
455	.0269
520	.0285
750	.0362
1380	.0407
1500	.0412

Scale Factors for Creep

Test No.	1b	5a	3a	2a
Filament Load, gms.	1.053	0.856	0.526	0.346
Load, gms./denier	0.351	0.285	0.175	0.115
Scale Factor for Creep d_{90} (Deformation at 90 mins. --deformation at 1 min.)	.0310	.0168	.0090	.0045
Scale Factor expressed as strain D_{90} x 1000	2.72	1.47	0.79	0.39

Viscose: Reduced Deformations (1 - 90 minutes)

Fil. Load, gms.	1.053	0.856	0.526	0.346
Test No.	1b	5a	3a	2a
Scale Factor d_{90}	.0310	.0168	.0090	.0045
Time, Mins.				
1	0	0	0	0
1 1/2	.055	.048	.056	.067
2	.090	.095	.111	.156
3	.148	.155	.167	.222
5	.248	.256	.244	.333
7	.303	.315	.311	.378
10	.381	.393	.378	.422
15	.455	.482	.467	.533
20	.526	.542	.533	.622
30	.639	.667	.622	.667
40	.706	.750	.733	.689
60	.845	.869	.833	.778
90	--	1.018	.989	.911

Reduced Deformations (90 minutes onwards)

Test 1b

Time	Reduced Deformation
140	1.171
185	1.281
240	1.400
540	1.781
1200	2.210
1980	2.435

Test 5a

Time	Reduced Deformation
120	1.101
190	1.256
300	1.440
455	1.601
520	1.696
750	2.155
1380	2.423
1500	2.452

Test 3a

Time	Reduced Deformation
120	1.122
180	1.300
300	1.522
390	1.667
460	1.844
1390	2.400
1522	2.456

Test 2a

Time	Reduced Deformation
120	1.089
190	1.267
280	1.289
350	1.422
390	1.644
795	2.089
1410	2.267
1503	2.467

FILAMENT NO. 5

VISCOSE I

Scheme of Tests

Test No.	Type of Test	Filament Load, gms.
1	Long Duration Creep and Recovery (Mechanical Conditioning)	1.053
3	Long Duration Creep and Recovery	0.526
4	ditto	0.856
5	ditto	1.053
6,7	ditto	0.856
8,9	ditto	0.526
15	ditto	0.346
17	ditto	1.053
18	Superposition	1.053

Filament Load 1.053 gms.

Total Deformations, 0-90 minutes (in inches)

Test No.	17a	17b	5b
Time, Mins.			
1/4	.0518	--	.0502
1/2	.0534	.0531	.0516
3/4	.0543	.0541	.0528
1	.0550	.0550	.0542
1 1/2	.0562	.0562	.0551
2	.0571	.0571	.0565
3	.0584	.0589	.0582
5	.0603	.0609	.0604
7	.0615	.0621	.0615
10	.0629	.0636	.0634
15	.0646	.0653	.0655
20	.0661	.0665	.0670
30	.0681	.0686	--
40	.0696	.0700	.0708
60	.0718	.0721	.0728
90	.0739	.0742	--

Total Deformations, 65 minutes onwards

Test 17a		Test 17b		Test 5b	
Time	Deformation	Time	Deformation	Time	Deformation
150	.0763	130	.0762	110	.0758
195	.0775	180	.0778	140	.0768
300	.0801	240	.0795	190	.0781
360	.0813	320	.0804	280	.0803
400	.0820	420	.0822	395	.0813
635	.0846	460	.0825	440	.0826
1440	.0902	1425	.0883	1400	.0895

Filament Load 0.856 gm.

Total Deformations, 0-90 minutes (in inches)

Test No.	7a	7b	6a	4b
Time, Mins.				
1/4	.0466	--	.0464	--
1/2	.0477	.0470	.0477	.0472
3/4	.0490	.0480	.0486	.0483
1	.0498	.0491	.0492	.0490
1 1/2	.0509	.0497	.0501	.0498
2	.0517	.0504	.0509	.0508
3	.0529	.0517	.0520	.0521
5	.0545	.0535	.0536	.0533
7	.0558	.0546	.0548	.0548
10	.0570	.0560	.0562	.0563
15	.0588	.0567	.0578	.0581
20	.0600	.0587	.0590	.0592
30	.0619	.0605	.0611	.0608
40	.0632	.0618	.0625	.0622
60	.0651	.0640	--	--
90	.0672	.0661	--	--

Total Deformations, 65 minutes onwards

Test 7a Time	Deformation
120	.0686
175	.0706
230	.0720
320	.0735
400	.0745
450	.0747
792	.0800
1465	.0823

Test 7b Time	Deformation
120	.0677
165	.0694
245	.0713
375	.0737
480	.0754
760	.0772
1405	.0812

Test 6a Time	Deformation
75	.0662
140	.0701
220	.0736
310	.0759
415	.0783
835	.0907
1570	.0976

Test 4b Time	Deformation
65	.0645
100	.0668
135	.0683
170	.0696
215	.0708
270	.0716
335	.0728
495	.0747
1440	.0791

Filament Load 0.526 gm.

Total Deformations, 0 - 90 Minutes

Test No.	3b	8a	8b	9b
Time, Mins.				
1/4	--	.0280	.0277	
1/2	.0280	.0286	.0286	.0280
3/4	.0288	.0290	.0290	.0287
1	.0291	.0295	.0293	.0292
1 1/2	.0297	.0297	.0298	.0296
2	.0300	.0300	.0301	.0300
3	.0306	.0305	.0305	.0303
5	.0314	.0311	.0310	.0311
7	.0320	.0316	.0316	.0315
10	.0324	.0322	.0322	.0320
15	.0331	.0327	.0329	.0327
20	.0335	.0331	.0336	.0333
30	.0345	.0341	.0344	.0345
40	.0351	.0345	.0351	.0352
60				.0360
90				.0369

Filament Load 0.526 gm.

Total Deformations, 65 minutes onwards

Test 3b	
Time	Deformation
86	.0368
125	.0380
175	.0389
241	.0401
345	.0414
490	.0423
1460	.0463

Test 8a	
Time	Deformation
100	.0363
150	.0380
180	.0387
230	.0392
335	.0402
435	.0419
480	.0419
1440	.0468

Test 8b	
Time	Deformation
65	.0366
80	.0370
120	.0383
150	.0388
220	.0399
300	.0408
370	.0415
465	.0422
1385	.0444

Test 9b	
Time	Deformation
140	.0380
180	.0389
230	.0396
290	.0401
415	.0402
1335	.0442

Filament Load 0.346 gm.

Total Deformations, 0 - 90 minutes (in inches)

Test No.	15a	15b
Time, Mins.		
1/4	.0185	--
1/2	.0188	--
3/4	.0190	--
1	.0191	.0186
1 1/2	.0193	.0192
2	.0195	.0194
3	.0196	.0198
5	.0200	.0201
7	.0202	.0203
10	.0205	.0206
15	.0207	.0209
20	.0209	.0211
30	.0213	.0215
40	.0215	.0218
60	.0219	.0221
90	--	.0225

Filament Load 0.346 gm.

Total Deformations, 90 minutes onwards

Test 15a Time	Test 15a Deformation	Test 15b Time	Test 15b Deformation
100	.0222	120	.0228
150	.0225	170	.0232
210	.0231	225	.0241
245	.0232	340	.0246
295	.0232	390	.0249
535	.0247		
1240	.0257		

Instantaneous Elastic Deformation

Test No.	Fil. Load, gms.	Instantaneous Deformation, ins.
17,5	1.053	.0497
7	0.856	.0445
3,8,9	0.526	.0269
15a	0.346	.0179

Instantaneous Modulus of Elasticity

Instantaneous Deformation = .0487 ins./gm.

= 0.1236 cms./gm.

Length of Filament = 27.67 cms.

Area of Filament, assumed to be 3 denier = 213×10^{-8} cms.^{2}

Instantaneous Modulus = 1.050×10^{8} gms./cm.^{2}

= 1.50×10^{6} psi

Viscose I Filament No. 5

Delayed Deformations relative to t = 1 min., 1 - 90 minutes

Test No.	17a	7b	8a	15a
Time, Mins.				
1	0	0	0	0
1 1/2	.0012	.0006	.0002	.0002
2	.0021	.0013	.0005	.0004
3	.0034	.0026	.0010	.0005
5	.0053	.0044	.0016	.0009
7	.0065	.0055	.0021	.0011
10	.0079	.0069	.0027	.0014
15	.0096	.0086	.0032	.0016
20	.0111	.0096	.0036	.0018
30	.0131	.0114	.0046	.0021
40	.0146	.0127	.0050	.0024
60	.0168	.0149		.0028
90	.0189	.0170		

Viscose I Filament No. 5

Delayed Deformations (90 minutes onwards)

Test 17a Time	Delayed Deformation
150	.0213
195	.0225
300	.0251
360	.0263
400	.0270
635	.0296
1440	.0352

Test 7b Time	Delayed Deformation
120	.0186
165	.0203
245	.0222
375	.0246
480	.0263
760	.0281
1405	.0319

Test 8a Time	Delayed Deformation
100	.0068
150	.0085
180	.0092
230	.0097
335	.0107
435	.0124
480	.0124
1440	.0173

Test 15a Time	Delayed Deformation
100	.0031
150	.0034
210	.0040
245	.0041
295	.0041
535	.0056
1240	.0066

Scale Factors for Creep

Test No.	17a	7b	8a	15a
Filament Load, gms.	1.053	0.856	0.526	0.346
Load, gms./denier	0.351	0.285	0.175	0.115
Scale Factor d_{90} (Deformation at 90 mins. - deformation at 1 min.)	.0189	.0168	.0068	.0033
Scale Factor expressed as strain D_{90}x 1000	1.73	1.54	0.625	0.30

<u>Reduced Deformations, 1 - 90 minutes</u> (in inches)

Test No.	17a	7b	8a	15a
Fil. Load, gms.	1.053	0.856	0.526	0.346
Scale Factor, d_{90}	.0189	.0168	.0068	.0033
Time, Mins.				
1	0	0	0	0
1 1/2	.063	.036	.029	.061
2	.111	.077	.074	.121
3	.180	.155	.147	.152
5	.280	.262	.235	.273
7	.344	.327	.309	.333
10	.418	.411	.397	.424
15	.508	.512	.471	.485
20	.587	.571	.529	.545
30	.693	.679	.676	.636
40	.772	.756	.735	.727
60	.889	.887		.848
90	1.000	1.012		

Viscose I   Filament No. 5

Reduced Deformations (90 minutes onwards)

Test 17a	
Time	Reduced Deformation
150	1.127
195	1.190
300	1.328
360	1.392
400	1.429
635	1.566
1440	1.862

Test 7b	
Time	Reduced Deformation
120	1.107
165	1.208
245	1.321
375	1.464
480	1.565
760	1.673
1405	1.899

Test 8a	
Time	Reduced Deformation
100	1.000
150	1.250
180	1.353
230	1.426
335	1.574
435	1.824
480	1.824
1440	2.544

Test 15a	
Time	Reduced Deformation
100	0.939
150	1.030
210	1.212
245	1.242
295	1.242
535	1.697
1240	2.000

FILAMENT NO. 9

NYLON II

Scheme of Tests

Test No.	Type of Test	Filament Load, gms.
1,2	Long Duration Creep and Recovery	1.480
3,4	ditto	1.053
5	ditto	0.856
6	ditto	0.526
7	ditto	0.346
8	Superposition	1.053
9	ditto	1.480
10	Long Duration Creep and Recovery	2.538
11	ditto	3.418

Tests 1, 2

Observations 0 - 90 minutes (in inches)

Test No.	1a	1b	2a	2b
Initial Obsn.	.2877	.5497	.2962	.5605
Time, Mins.				
1/4	.4566	.3986	.4664	.3971
1/2	.4674	.3862	.4774	.3858
3/4	.4740	.3788	.4845	.3786
1	.4791	.3734	.4897	.3734
1 1/2	.4861	.3660	.4969	.3662
2	.4912	.3607	.5019	.3614
3	.4978	.3538	.5084	.3649
5	.5054	.3452	.5157	.3472
7	.5097	.3400	.5200	.3427
10	.5142	.3349	.5238	.3382
15	.5188	.3296	.5278	.3333
20	.5217	.3261	.5304	.3302
30	.5255	.3217	.5337	.3258
40	.5278	.3190	.5360	.3231
60	.5307	.3155	.5388	.3194
90	.5338	.3114	.5416	.3161

Tests 1, 2

Observations 90 minutes onwards

Test 1a

Time	Scale
135	.5365
195	.5390
360	.5431
460	.5442
567	.5449
1580	.5506

Test 1b

Time	Scale
140	.3081
230	.3052
500	.3032
1285	.2952

Test 2a

Time	Scale
160	.5456
275	.5493
370	.5511
410	.5521
1405	.5616

Test 2b

Time	Scale
155	.3120
235	.3092
320	.3063
480	.3046
1385	.2987

Tests 1, 2

Total Deformations, 0 - 90 minutes (in inches)

Test No.	1a	1b	2a	2b
Time, Mins.				
1/4	.1689	.1511	.1702	.1634
1/2	.1797	.1635	.1812	.1747
3/4	.1863	.1709	.1883	.1819
1	.1914	.1763	.1935	.1871
1 1/2	.1984	.1837	.2007	.1943
2	.2035	.1890	.2057	.1991
3	.2101	.1959	.2122	.2056
5	.2177	.2045	.2195	.2133
7	.2220	.2097	.2238	.2178
10	.2265	.2148	.2276	.2223
15	.2311	.2201	.2316	.2272
20	.2340	.2236	.2342	.2303
30	.2378	.2280	.2375	.2347
40	.2401	.2307	.2398	.2374
60	.2430	.2342	.2426	.2411
90	.2461	.2385	.2454	.2444

Tests 1, 2

Total Deformations 90 minutes onwards

Test 1a

Time	Deformation
135	.2488
195	.2513
360	.2554
460	.2565
567	.2572
1580	.2629

Test 1b

Time	Deformation
140	.2416
230	.2445
500	.2465
1285	.2545

Test 2a

Time	Deformation
160	.2494
275	.2531
370	.2549
410	.2559
1405	.2654

Test 2b

Time	Deformation
155	.2485
235	.2513
320	.2542
480	.2559
1385	.2618

Tests 3, 4

Observations, 0 - 90 minutes (in inches)

Test No.	3a	3b	4a	4b
Initial Obsn.	.2996	.4752	.3023	.4722
Time, Mins.				
1/4	.3991	.3821	.3968	--
1/2	.4051	.3765	.4025	.3736
3/4	.4090	.3730	.4058	.3703
1	.4120	.3703	.4087	.3676
1 1/2	.4168	.3658	.4130	.3635
2	.4201	.3632	.4163	.3607
3	.4250	.3589	.4208	.3563
5	.4313	.3535	.4267	.3509
7	.4351	.3498	.4306	.3473
10	.4393	.3457	.4348	.3436
15	.4438	.3409	.4393	.3394
20	.4468	.3378	.4423	.3364
30	.4509	.3333	.4462	.3320
40	.4536	.3303	.4489	.3292
60	.4567	.3262	.4524	.3254
90	.4595	.3222	.4555	.3221

Tests 3, 4

Observations, 90 minutes onwards (in inches)

Test 3a	
Time	Scale
165	.4628
240	.4645
360	.4662
405	.4679
765	.4750
1650	.4760

Test 3b	
Time	Scale
150	.3178
255	.3141
540	.3082
1275	.3018
1290	.3015

Test 4a	
Time	Scale
135	.4584
225	.4602
350	.4639
395	.4641
615	.4665
1370	.4732

Test 4b	
Time	Scale
160	.3169
210	.3144
275	.3123
420	.3093
515	.3083
1450	.3020

Tests 3, 4

Total Deformations, 0 - 90 minutes (in inches)

Test No.	3a	3b	4a	4b
Time, Mins.				
1/4	.0995	.0931	.0945	--
1/2	.1055	.0987	.1002	.0986
3/4	.1094	.1022	.1035	.1019
1	.1124	.1049	.1164	.1046
1 1/2	.1172	.1094	.1107	.1087
2	.1205	.1120	.1140	.1115
3	.1254	.1163	.1185	.1159
5	.1317	.1217	.1244	.1213
7	.1355	.1254	.1283	.1249
10	.1397	.1295	.1325	.1286
15	.1442	.1343	.1370	.1328
20	.1472	.1374	.1400	.1358
30	.1514	.1419	.1439	.1402
40	.1540	.1449	.1466	.1430
60	.1571	.1490	.1501	.1468
90	.1599	.1530	.1532	.1501

Tests 3, 4

Total Deformations, 90 minutes onwards (in inches)

	Test 3a
Time	Deformation
165	.1632
240	.1649
360	.1666
405	.1683
765	.1754
1650	.1764

	Test 3b
Time	Deformation
150	.1574
255	.1611
540	.1670
1290	.1737

	Test 4a
Time	Deformation
135	.1561
225	.1579
350	.1616
395	.1618
615	.1642
1370	.1709

	Test 4b
Time	Deformation
160	.1553
210	.1578
275	.1599
420	.1629
515	.1639
1450	.1702

Tests 5, 6, 7

Observations 0 - 90 minutes (in inches)

Test No.	5a	5b	6a	6b	7a	7b
Initial Obsn.	.3033	.4549	.3051	.3969	.3052	.3578
Time, Mins.						
1/4	.3845	--	.3546	.3474	.3377	.3262
1/2	.3890	.3679	.3570	.3453	.3390	.3252
3/4	.3918	.3655	.3583	.3440	.3398	.3244
1	.3942	.3635	.3595	.3429	.3405	.3237
1 1/2	.3977	.3604	.3611	.3413	.3414	.3228
2	.4002	.3578	.3623	.3401	.3421	.3222
3	.4040	.3544	.3641	.3383	.3431	.3213
5	.4091	.3500	.3666	.3362	.3445	.3202
7	.4125	.3469	.3682	.3347	.3454	.3195
10	.4162	.3438	.3701	.3330	.3463	.3185
15	.4201	.3400	.3723	.3311	.3474	.3174
20	.4229	.3372	.3738	.3297	.3481	.3167
30	.4266	.3334	.3758	.3275	.3493	.3156
40	.4293	.3307	.3771	.3259	.3503	.3148
60	.4326	.3273	.3797	.3236	.3514	.3136
90	.4361	.3236	.3823	.3211	.3528	.3125

Tests 5, 6, 7

Observations 90 minutes onwards (in inches)

Test 5a		Test 5b		Test 6a	
Time	Scale	Time	Scale	Time	Scale
150	.4400	135	.3205	165	.3865
210	.4421	235	.3159	270	.3889
360	.4461	360	.3129	410	.3912
465	.4485	480	.3114	520	.3922
558	.4511	1440	.3042	1440	.3981
1390	.4560				

Test 6b		Test 7a		Test 7b	
Time	Scale	Time	Scale	Time	Scale
130	.3197	145	.3546	150	.3113
190	.3165	240	.3557	315	.3090
305	.3138	540	.3581	455	.3075
420	.3131	1260	.3585	2955	.3023
825	.3105				
1640	.3043				

Tests 5, 6, 7

Total Deformations, 0 - 90 minutes (in inches)

Test No.	5a	5b	6a	6b	7a	7b
Time, Mins.						
1/4	.0812	--	.0495	.0495	.0325	.0316
1/2	.0857	.0870	.0519	.0516	.0338	.0326
3/4	.0885	.0894	.0532	.0529	.0346	.0334
1	.0909	.0914	.0544	.0540	.0353	.0341
1 1/2	.0944	.0945	.0560	.0556	.0362	.0350
2	.0969	.0971	.0572	.0568	.0369	.0356
3	.1007	.1005	.0590	.0586	.0379	.0365
5	.1058	.1049	.0615	.0607	.0393	.0376
7	.1092	.1080	.0631	.0622	.0402	.0383
10	.1129	.1111	.0650	.0639	.0411	.0393
15	.1168	.1149	.0672	.0658	.0422	.0404
20	.1196	.1177	.0687	.0672	.0429	.0411
30	.1233	.1215	.0707	.0694	.0441	.0422
40	.1260	.1242	.0720	.0710	.0451	.0430
60	.1293	.1276	.0746	.0733	.0462	.0442
90	.1328	.1313	.0772	.0758	.0476	.0453

Tests 5, 6, 7

Total Deformations 90 minutes onwards (in inches)

	Test 5a		Test 5b		Test 6a
Time	Deformation	Time	Deformation	Time	Deformation
150	.1367	135	.1344	165	.0814
210	.1388	235	.1390	270	.0838
360	.1428	360	.1420	410	.0861
465	.1452	480	.1435	520	.0871
558	.1478	1440	.1507	1440	.0930
1390	.1527				

	Test 6b		Test 7a		Test 7b
Time	Deformation	Time	Deformation	Time	Deformation
130	.0772	145	.0494	150	.0465
190	.0804	240	.0507	315	.0488
305	.0831	540	.0529	455	.0503
420	.0838	1260	.0533	2955	.0555
825	.0864				
1640	.0926				

Tests 10, 11

Observations 0 - 90 minutes (in inches)

Test No.	10a	10b	11a	11b
Initial Obsn.	.0743	.4900	.0763	.6046
Time, Mins.				
1/4	--	.1771	--	--
1/2	.4002	.1593	.5281	.1655
3/4	.4068	.1506	.5345	.1568
1	.4119	.1447	.5392	.1512
1 1/2	.4187	.1374	.5451	.1442
2	.4233	.1327	.5493	.1396
3	.4296	.1265	.5548	.1336
5	.4366	.1192	.5610	.1272
7	.4408	.1155	.5644	.1233
10	.4449	.1114	.5677	.1195
15	.4493	.1072	.5711	.1153
20	.4522	.1044	.5735	.1124
30	.4561	.1006	.5767	.1086
40	.4588	.0980	.5789	.1058
60	.4625	.0950	.5821	.1020
90	.4662	.0920	.5851	.0984

Tests 10, 11

Observations, 90 minutes onwards

Test 10a

Time	Scale
165	.4718
250	.4758
370	.4793
420	.4806
660	.4840
1360	.4904

Test 10b

Time	Scale
210	.0870
310	.0847
400	.0830
525	.0814
1420	.0748

Test 11a

Time	Scale
155	.5887
230	.5915
375	.5950
810	.5990
1665	.6052

Test 11b

Time	Scale
150	.0943
240	.0909
510	.0858
1155	.0784
1510	.0778
2900	.0726

Tests 10, 11

Total Deformations, 0 - 90 minutes (in inches)

Test No.	10a	10b	11a	11b
Time, Mins.				
1/4	--	.3129	--	--
1/2	.3259	.3307	.4518	.4391
3/4	.3325	.3394	.4582	.4478
1	.3376	.3453	.4629	.4534
1 1/2	.3444	.3526	.4688	.4602
2	.3490	.3573	.4730	.4650
3	.3553	.3635	.4785	.4710
5	.3623	.3708	.4847	.4774
7	.3665	.3745	.4881	.4813
10	.3706	.3776	.4914	.4851
15	.3750	.3828	.4948	.4893
20	.3779	.3856	.4972	.4922
30	.3818	.3894	.5004	.4960
40	.3845	.3920	.5026	.4988
60	.3882	.3950	.5058	.5026
90	.3919	.3980	.5088	.5062

Tests 10, 11

Total Deformations, 90 minutes onwards (in inches)

Test 10a

Time	Deformation
165	.3975
250	.4015
370	.4050
420	.4063
660	.4097
1360	.4161

Test 10b

Time	Deformation
210	.4030
310	.4053
400	.4070
525	.4086
1420	.4152

Test 11a

Time	Deformation
155	.5124
230	.5152
375	.5187
810	.5227
1665	.5289

Test 11b

Time	Deformation
150	.5103
240	.5137
510	.5188
1155	.5262
1510	.5268
2900	.5320

Nylon II: Delayed Deformations (Relative to t = 1 minute)

0 - 90 minutes (in inches)

Test No.	3b	5a	6a	7b
Time, Mins.				
1	0	0	0	0
1 1/2	.0045	.0035	.0016	.0009
2	.0071	.0060	.0028	.0015
3	.0114	.0098	.0046	.0024
5	.0168	.0149	.0071	.0035
7	.0205	.0183	.0087	.0042
10	.0246	.0220	.0106	.0052
15	.0294	.0259	.0128	.0063
20	.0325	.0287	.0143	.0070
30	.0370	.0324	.0163	.0081
40	.0400	.0351	.0176	.0089
60	.0441	.0384	.0202	.0101
90	.0481	.0419	.0228	.0112

Nylon II: Delayed Deformations

90 minutes onwards

Test 3b

Time	Delayed Deformation
150	.0525
255	.0562
540	.0621
1275	.0685
1290	.0688

Test 5a

Time	Delayed Deformation
150	.0458
210	.0479
360	.0519
465	.0543
558	.0569
1390	.0618

Test 6a

Time	Delayed Deformation
165	.0270
270	.0294
410	.0317
520	.0327
1440	.0386

Test 7b

Time	Delayed Deformation
150	.0124
315	.0147
455	.0162
2955	.0214

Scale Factors for Creep

Test No.	3b	5a	6a	7b
Filament Load, gms.	1.053	0.856	0.526	0.346
Load, gms./denier	0.363	0.295	0.182	0.119
Scale Factor d_{90} (Deformation at 90 mins. - deformation at 1 min.)	.0481	.0425	.0230	.0112
Scale Factor expressed as strain D_{90} x 1000	4.26	3.76	2.04	0.99

Filament Data

Length of Filament	= 28.66 cms.
Cross-sectional area (measured)	= 283×10^{-8} cm.^{2}
Cross-sectional area computed on basis of 3 denier/ filament and specific gravity = 1.14	= 292×10^{-8} cm.^{2}

Nylon II: Reduced Deformations (1 - 90 minutes)

Test No.	3b	5a	6a	7b
Filament Load, gms.	1.053	0.856	0.526	0.346
Scale Factor, d_{90}	.0481	.0425	.0230	.0112
Time, Mins.				
1	0	0	0	0
1 1/2	.094	.082	.070	.080
2	.148	.141	.122	.134
3	.237	.231	.200	.214
5	.349	.351	.309	.312
7	.426	.431	.378	.375
10	.511	.518	.461	.464
15	.611	.609	.557	.562
20	.676	.675	.622	.625
30	.769	.762	.709	.723
40	.832	.826	.765	.795
60	.917	.904	.878	.902
90	1.000	.986	.991	1.000

Nylon II: Reduced Deformations

90 minutes onwards

Test 3b

Time	Reduced Deformation
150	1.091
255	1.168
540	1.291
1275	1.424
1290	1.430

Test 5a

Time	Reduced Deformation
150	1.078
210	1.127
360	1.221
465	1.278
558	1.339
1390	1.454

Test 6a

Time	Reduced Deformation
165	1.174
270	1.278
410	1.378
520	1.422
1440	1.678

Test 7b

Time	Reduced Deformation
150	1.107
315	1.312
455	1.446
2955	1.911

FILAMENT NO. 4

NYLON I

Scheme of Tests

Test No.	Type of Test	Filament Load, gms.
1	Long Duration Creep and Recovery	0.856
2	ditto	0.526
3	Superposition	0.526
4	Superposition	0.346
5	Creep	0.346
6	Long Duration Creep and Recovery	0.346
7	ditto	0.161
8	ditto	0.856
9	Superposition	0.856
10	Creep, Recovery	0.856

Tests 1, 8, 2

Total Deformations, 0 - 90 minutes (in inches)

Test No.	1b	8a	8b	2a	2b
Time, Mins.					
1/4	--	.1127	--	.0717	.0689
1/2	--	.1200	.1218	.0754	.0726
3/4	.1354	.1247	.1267	.0778	.0748
1	.1398	.1282	.1304	.0798	.0771
1 1/2	.1460	.1335	.1366	.0826	.0804
2	.1505	.1375	.1404	.0849	.0823
3	.1571	.1443	.1461	.0880	.0850
5	.1656	.1505	.1538	.0925	.0884
7	.1717	.1553	.1552	.0956	.0908
10	.1778	.1604	.1645	.0987	.0938
15	.1846	.1661	.1708	.1028	.0972
20	.1890	.1695	.1753	.1052	.1001
30	.1954	.1760	.1813	.1094	.1036
40	--	.1803	.1861		
60	.2054	.1859			
90		.1913			

Tests 1, 8, 2

Total Deformations, 50 minutes onwards (in inches)

Test 1b		Test 8a		Test 8b	
Time	Deformation	Time	Deformation	Time	Deformation
85	.2097	145	.1980	50	.1892
97	.2116	195	.2026	70	.1941
212	.2199	250	.2061	110	.1997
280	.2225	300	.2089	150	.2031
351	.2249	340	.2105	245	.2092
1360	.2354	1515	.2298	310	.2108
		1895	.2325	340	.2116
		2820	.2363	720	.2183
				1660	.2281

Test 2a		Test 2b	
Time	Deformation	Time	Deformation
70	.1174	50	.1090
120	.1227	70	.1119
170	.1262	100	.1157
290	.1308	160	.1203
332	.1316	240	.1230
393	.1332	320	.1258
1411	.1421	375	.1271
		465	.1285
		1442	.1371

Tests 6, 7

Total Deformations, 0 - 90 minutes (in inches)

Test No.	6a	6b	7a	7b
Time, Mins.				
1/4	.0445	--	.0212	--
1/2	.0465	.0450	.0221	.0231
3/4	.0477	.0461	.0226	.0236
1	.0486	.0471	.0231	.0239
1 1/2	.0499	.0486	.0237	.0248
2	.0505	.0497	.0242	.0253
3	.0519	.0516	.0248	.0259
5	.0536	.0534	.0255	.0268
7	.0551	.0542	.0260	.0273
10	.0564	.0552	.0266	.0280
15	.0581	--	.0272	.0287
20	.0587	.0584	.0277	.0291
30	.0609	.0603	.0287	.0299
40	.0618	.0614	.0291	.0305
60		.0626	.0299	.0315
90		.0631	--	.0324

Tests 6, 7

Total Deformations, 40 minutes onwards (in inches)

Test 6a

Time	Deformation
50	.0632
95	.0665
160	.0695
280	.0720
391	.0734
1395	.0862

Test 6b

Time	Deformation
155	.0647
225	.0666
350	.0681
400	.0688
1480	.0760

Test 7a

Time	Deformation
75	.0305
120	.0325
165	.0340
210	.0353
240	.0356
375	.0369
418	.0378
1420	.0394

Test 7b

Time	Deformation
160	.0330
217	.0332
305	.0337
355	.0339
1430	.0396

Nylon I: Delayed Deformations (relative to t = 1 minute)

1 - 90 minutes

Test No.	8b	2b	6a	7b
Time, Mins.				
1	0	0	0	0
1 1/2	.0062	.0033	.0013	.0009
2	.0100	.0052	.0019	.0014
3	.0157	.0079	.0033	.0020
5	.0234	.0113	.0050	.0029
7	.0248	.0137	.0065	.0034
10	.0341	.0167	.0078	.0041
15	.0404	.0201	.0095	.0048
20	.0449	.0230	.0101	.0052
30	.0509	.0265	.0123	.0060
40	.0557		.0132	.0066
60				.0076
90				.0085

Nylon I: Delayed Deformations

50 minutes onwards

Test 8b

Time	Delayed Deformation
50	.0588
70	.0637
110	.0693
150	.0727
245	.0788
310	.0804
340	.0812
720	.0879
1660	.0977

Test 2b

Time	Delayed Deformation
50	.0319
70	.0348
100	.0386
160	.0432
240	.0459
320	.0487
375	.0500
465	.0514
1442	.0600

Test 6a

Time	Delayed Deformation
50	.0146
95	.0179
160	.0209
280	.0234
391	.0248
1395	.0316

Test 7b

Time	Delayed Deformation
160	.0091
217	.0093
305	.0098
355	.0100
1430	.0157

Scale Factors for Creep

Test No.	8b	2b	6a	7b
Filament Load, gms.	0.856	0.526	0.346	0.161
Load, gms./denier	0.302	0.186	0.122	0.057
Scale Factor d_{90} (Deformation at 90 mins. - deformation at 1 min.)	.0694	.0370	.0178	.0083
Scale Factor expressed as strain D_{90} x 1000	6.45	3.44	1.66	0.77

Filament Data

Length of Filament = 27.34 cms.

Cross-sectional area (measured) = 276×10^{-8} cm.^{2}

Nylon I: Reduced Deformations (1 - 90 minutes)

Test No.	8b	2b	6a	7b
Fil. Load, gms.	0.856	0.526	0.346	0.161
Scale Factor d_{90}	.0694	.0370	.0178	.0083
Time, Mins.				
1	0	0	0	0
1 1/2	.089	.089	.073	.108
2	.144	.141	.107	.169
3	.226	.214	.185	.241
5	.337	.305	.281	.349
7	.357	.370	.365	.410
10	.491	.451	.438	.494
15	.582	.543	.534	.578
20	.647	.622	.567	.627
30	.733	.716	.691	.723
40	.803		.742	.795
60				.916
90				1.024

Nylon I: Reduced Deformations (50 minutes onwards)

Test 8b	
Time	Reduced Deformation
50	.847
70	.918
110	.999
150	1.048
245	1.135
310	1.158
340	1.170
720	1.267
1660	1.408

Test 2b	
Time	Reduced Deformation
50	.862
70	.941
100	1.043
160	1.168
240	1.241
320	1.316
375	1.351
465	1.389
1442	1.622

Test 6a	
Time	Reduced Deformation
50	.820
95	1.006
160	1.174
280	1.315
391	1.393
1395	1.775

Test 7b	
Time	Reduced Deformation
160	1.096
217	1.120
305	1.181
355	1.204
1430	1.892

FILAMENT NO. 10

ACETATE

Scheme of Tests

Test No.	Type of Test	Filament Load, gms.
1	Long Duration Creep and Recovery (Mechanical Conditioning)	1.480
2	Long Duration Creep and Recovery	1.480
3,4	ditto	1.053
5	ditto	0.856
6,7	ditto	0.526
8	ditto	0.856
9	Superposition	0.856
10	ditto	1.053
11	ditto	1.480
12	Long Duration Creep and Recovery	0.856
13,14	ditto	1.053
15,16	ditto	1.480
17	60 minutes Creep; Recovery	1.053
18	Superposition 6 x 10 minutes	1.053
19	ditto 4 x 15 minutes	
20	60 minutes Creep; Recovery	
21	Superposition 6 x 10 minutes	1.053
22	ditto 4 x 15 minutes	
23	60 minutes Creep; Recovery	
24	Long Duration Creep and Recovery	1.053
25	ditto	0.856
26	ditto	1.480

Tests 15, 16, 26

Observations 0 - 90 minutes (in inches)

Test No.	15a	15b	16a	16b	26a	26b
Initial Obsn.	.5908	.7835	.5915	.8032	.6012	.7951
Time, Mins.						
1/4	.7104	.6614	.7255	.6824	.7203	.6760
1/2	.7132	.6585	.7290	.6797	.7229	.6728
3/4	.7148	.6566	.7311	.6778	.7243	.6707
1	.7160	.6553	.7328	.6762	.7256	.6689
1 1/2	.7177	.6529	.7352	.6739	.7271	.6667
2	.7189	.6512	.7370	.6721	.7283	.6651
3	.7205	.6485	.7399	.6695	.7302	.6625
5	.7232	.6452	.7437	.6660	.7328	.6593
7	.7249	.6426	.7463	.6635	.7348	.6569
10	.7268	.6400	.7492	.6607	.7370	.6545
15	.7291	.6367	.7529	.6574	.7395	.6515
20	.7307	.6345	.7553	.6549	.7413	.6492
30	.7333	.6310	.7589	.6511	.7442	.6461
40	.7350	.6286	.7614	.6485	.7468	.6436
60	.7379	.6252	.7648	.6448	.7502	.6404
90	.7408	.6219	.7685	.6411	.7542	.6372

Tests 15, 16, 26

Observations 90 minutes onwards (in inches)

Test 15a		Test 15b		Test 16a	
Time	Scale	Time	Scale	Time	Scale
170	.7460	175	.6164	150	.7734
260	.7501	230	.6141	300	.7803
360	.7548	365	.6101	365	.7825
485	.7600	435	.6089	480	.7870
733	.7668	1415	.5906	1440	.8042
1430	.7842				

Test 16b		Test 26a		Test 26b	
Time	Scale	Time	Scale	Time	Scale
150	.6361	180	.7610	120	.6349
250	.6313	270	.7660	305	.6276
340	.6285	370	.7712	435	.6250
682	.6222	500	.7753	1440	.6166
765	.6212	640	.7804		
1130	.6156	1470	.7959		

Tests 15, 16, 26

Total Deformations, 0 - 90 minutes (in inches)

Test No.	15a	15b	16a	16b	26a	26b
Time, Mins.						
1/4	.1196	.1221	.1340	.1208	.1191	.1191
1/2	.1224	.1250	.1375	.1235	.1217	.1223
3/4	.1240	.1269	.1396	.1254	.1231	.1244
1	.1252	.1282	.1413	.1270	.1244	.1262
1 1/2	.1269	.1306	.1437	.1293	.1259	.1284
2	.1281	.1323	.1455	.1311	.1271	.1300
3	.1297	.1350	.1484	.1337	.1290	.1326
5	.1324	.1383	.1522	.1372	.1316	.1358
7	.1341	.1409	.1548	.1397	.1336	.1382
10	.1360	.1435	.1577	.1425	.1358	.1406
15	.1383	.1468	.1614	.1458	.1383	.1436
20	.1399	.1490	.1638	.1483	.1401	.1459
30	.1425	.1525	.1674	.1521	.1430	.1490
40	.1442	.1549	.1699	.1547	.1456	.1515
60	.1471	.1583	.1733	.1584	.1490	.1547
90	.1500	.1616	.1770	.1621	.1530	.1579

Tests 15, 16, 26

Total Deformations, 90 minutes onwards (in inches)

Test 15a

Time	Deformation
170	.1552
260	.1593
360	.1640
485	.1692
733	.1760
1430	.1934

Test 15b

Time	Deformation
175	.1671
230	.1694
365	.1734
435	.1746
1415	.1929

Test 16a

Time	Deformation
150	.1819
300	.1888
365	.1910
480	.1955
1440	.2127

Test 16b

Time	Deformation
150	.1671
250	.1719
340	.1747
682	.1810
765	.1820
1130	.1876

Test 26a

Time	Deformation
180	.1598
270	.1648
370	.1700
500	.1741
640	.1792
1470	.1947

Test 26b

Time	Deformation
120	.1602
305	.1675
435	.1701
1440	.1785

Tests 13, 14, 24

Observations, 0 - 90 minutes (in inches)

Test No.	13a	13b	14a	14b	24a	24b
Initial Obsn.	.5856	.6913	.5891	.6915	.5966	.7052
Time, Mins.						
1/4	.6621	.6144	.6652	.6147	.6715	.6291
1/2	.6630	.6136	.6664	.6140	.6729	.6281
3/4	.6636	.6129	.6671	.6132	.6736	.6274
1	.6640	.6124	.6677	.6127	.6741	.6268
1 1/2	.6647	.6115	.6684	.6119	.6749	.6260
2	.6652	.6108	.6690	.6114	.6754	.6253
3	.6660	.6100	.6699	.6105	.6763	.6243
5	.6672	.6088	.6712	.6093	.6775	.6230
7	.6681	.6079	.6720	.6085	.6782	.6220
10	.6690	.6069	.6729	.6076	.6793	.6210
15	.6700	.6057	.6740	.6064	.6804	.6197
20	.6708	.6048	.6747	.6055	.6813	.6186
30	.6723	.6034	.6761	.6043	.6826	.6173
40	.6734	.6024	.6768	.6033	.6836	.6163
60	.6753	.6010	.6779	.6018	.6852	.6147
90	.6770	.5996	.6794	.6005	.6868	.6131

Tests 13, 14, 24

Observations, 90 minutes onwards (in inches)

Test 13a

Time	Scale
140	.6790
220	.6808
365	.6832
750	.6862
1420	.6921

Test 13b

Time	Scale
160	.5974
270	.5953
360	.5942
510	.5933
1485	.5885

Test 14a

Time	Scale
180	.6816
290	.6834
625	.6876
1450	.6916

Test 14b

Time	Scale
165	.5985
240	.5970
525	.5946
700	.5937
1335	.5900

Test 24a

Time	Scale
140	.6890
240	.6917
345	.6944
460	.6961
1405	.7063

Test 24b

Time	Scale
148	.6111
216	.6093
395	.6062
520	.6051
770	.6039
1450	.6018

Tests 13, 14, 24

Total Deformations, 0 - 90 minutes (in inches)

Test No.	13a	13b	14a	14b	24a	24b
Time, Mins.						
1/4	.0765	.0769	.0761	.0768	.0749	.0761
1/2	.0774	.0777	.0773	.0775	.0763	.0771
3/4	.0780	.0784	.0780	.0783	.0770	.0778
1	.0784	.0789	.0786	.0788	.0775	.0784
1 1/2	.0791	.0798	.0793	.0796	.0783	.0792
2	.0796	.0805	.0799	.0801	.0788	.0799
3	.0804	.0813	.0808	.0810	.0797	.0809
5	.0816	.0825	.0821	.0822	.0809	.0822
7	.0825	.0834	.0829	.0830	.0816	.0832
10	.0834	.0844	.0838	.0839	.0827	.0842
15	.0844	.0856	.0849	.0851	.0838	.0855
20	.0852	.0865	.0856	.0866	.0847	.0866
30	.0867	.0879	.0870	.0872	.0860	.0879
40	.0878	.0889	.0877	.0882	.0870	.0889
60	.0897	.0903	.0888	.0897	.0886	.0905
90	.0914	.0917	.0903	.0910	.0902	.0921

Tests 13, 14, 24

Total Deformations, 90 minutes onwards (in inches)

Test 13a		Test 13b		Test 14a	
Time	Deformation	Time	Deformation	Time	Deformation
140	.0934	160	.0939	180	.0925
220	.0952	270	.0960	290	.0943
365	.0976	360	.0971	625	.0987
750	.1006	510	.0980	1450	.1025
1420	.1065	1485	.1028		

Test 14b		Test 24a		Test 24b	
Time	Deformation	Time	Deformation	Time	Deformation
165	.0930	140	.0924	148	.0941
240	.0945	240	.0951	216	.0959
525	.0969	345	.0978	395	.0990
700	.0978	460	.0995	520	.1001
1335	.1015	1405	.1097	770	.1013
				1450	.1034

Tests 8, 12, 25

Observations, 0 - 90 minutes (in inches)

Test No.	8a	8b	12a	12b	25a	25b
Initial Obsn.	.5840	.6742	.5855	.6761	.6028	.6935
Time, Mins.						
1/4	.6518	.6074	.6531	.6085	.6694	.6260
1/2	.6527	.6063	.6544	.6077	.6704	.6252
3/4	.6532	.6058	.6550	.6070	.6711	.6247
1	.6535	.6053	.6554	.6065	.6716	.6242
1 1/2	.6541	.6047	.6561	.6059	.6722	.6235
2	.6545	.6042	.6565	.6053	.6727	.6231
3	.6552	.6034	.6572	.6045	.6735	.6223
5	.6561	.6024	.6583	.6035	.6746	.6211
7	.6568	.6018	.6589	.6029	.6755	.6206
10	.6576	.6010	.6597	.6019	.6762	.6197
15	.6584	.5999	.6607	.6010	.6773	.6188
20	.6590	.5993	.6613	.6003	.6780	.6182
30	.6599	.5982	.6622	.5992	.6793	.6172
40	.6605	.5973	.6630	.5984	.6802	.6167
60	.6616	.5961	.6641	.5971	.6815	.6156
90	.6628	.5947	.6652	.5960	.6830	.6148

Tests 8, 12, 25

Observations, 90 minutes onwards (in inches)

Test 8a

Time	Scale
125	.6639
185	.6650
270	.6662
400	.6679
1595	.6752

Test 8b

Time	Scale
155	.5932
215	.5922
287	.5914
460	.5898
600	.5887
1395	.5854

Test 12a

Time	Scale
140	.6664
235	.6680
350	.6691
450	.6702
1405	.6767

Test 12b

Time	Scale
150	.5943
200	.5932
315	.5915
400	.5904
500	.5898
1440	.5850

Test 25a

Time	Scale
155	.6848
203	.6860
385	.6887
460	.6896
690	.6916
870	.6925
1470	.6937

Test 25b

Time	Scale
130	.6143
530	.6079
770	.6029

Tests 8, 12, 25

Total Deformations, 0 - 90 minutes (in inches)

Test No.	8a	8b	12a	12b	25a	25b
Time, Mins.						
1/4	.0678	.0668	.0676	.0676	.0666	.0675
1/2	.0687	.0679	.0689	.0684	.0676	.0683
3/4	.0692	.0684	.0695	.0691	.0683	.0688
1	.0695	.0689	.0699	.0696	.0688	.0693
1 1/2	.0701	.0695	.0706	.0702	.0694	.0700
2	.0705	.0700	.0710	.0708	.0699	.0704
3	.0712	.0708	.0717	.0716	.0707	.0712
5	.0721	.0718	.0728	.0726	.0718	.0724
7	.0728	.0724	.0734	.0732	.0727	.0729
10	.0736	.0732	.0742	.0742	.0734	.0738
15	.0744	.0743	.0752	.0751	.0745	.0747
20	.0750	.0749	.0758	.0758	.0752	.0753
30	.0759	.0760	.0767	.0769	.0765	.0763
40	.0765	.0769	.0775	.0777	.0774	.0768
60	.0776	.0781	.0786	.0790	.0787	.0779
90	.0788	.0795	.0797	.0801	.0802	.0787

Tests 8, 12, 25

Total Deformations, 90 minutes onwards (in inches)

Test 8a	
Time	Deformation
125	.0799
185	.0810
270	.0822
400	.0839
1595	.0912

Test 8b	
Time	Deformation
155	.0810
215	.0820
287	.0828
460	.0844
600	.0855
1395	.0888

Test 12a	
Time	Deformation
140	.0809
235	.0825
350	.0846
450	.0857
1405	.0912

Test 12b	
Time	Deformation
150	.0818
200	.0829
315	.0846
400	.0857
500	.0863
1440	.0911

Test 25a	
Time	Deformation
155	.0820
203	.0832
385	.0859
460	.0868
690	.0888
870	.0897
1470	.0909

Test 25b	
Time	Deformation
130	.0792
530	.0856
770	.0906

Tests 6, 7

Observations, 0 - 90 minutes (in inches)

Test No.	6a	6b	7a	7b
Initial Obsn.	.5876	.6429	.5852	.6382
Time, Mins.				
1/4	.6290	.6003	.6263	.5963
1/2	.6298	.6002	.6270	.5962
3/4	.6302	.5998	.6273	.5959
1	.6304	.5996	.6276	.5956
1 1/2	.6309	.5992	.6279	.5952
2	.6312	.5989	.6281	.5949
3	.6316	.5985	.6285	.5946
5	.6323	.5980	.6291	.5941
7	.6327	.5975	.6295	.5937
10	.6332	.5971	.6299	.5934
15	.6338	.5966	.6304	.5929
20	.6342	.5961	.6310	.5925
30	.6348	.5955	.6315	.5920
40	.6353	.5950	.6320	.5916
60	.6360	.5943	.6327	.5910
90	.6367	.5934	.6334	.5904

Tests 6, 7

Observations, 90 minutes onwards (in inches)

Test 6a

Time	Scale
195	.6382
490	.6413
750	.6419
1440	.6432

Test 6b

Time	Scale
175	.5918
580	.5889
1440	.5842

Test 7a

Time	Scale
150	.6346
270	.6354
370	.6360
470	.6367
1430	.6389

Test 7b

Time	Scale
140	.5896
186	.5889
320	.5878
445	.5870
490	.5868
1410	.5835

Tests 6, 7

Total Deformations, 0 - 90 minutes (in inches)

Test No.	6a	6b	7a	7b
Time, Mins.				
1/4	.0414	.0426	.0411	.0419
1/2	.0422	.0427	.0418	.0420
3/4	.0426	.0431	.0421	.0423
1	.0428	.0433	.0424	.0426
1 1/2	.0433	.0437	.0427	.0430
2	.0436	.0440	.0429	.0433
3	.0440	.0444	.0433	.0436
5	.0447	.0449	.0439	.0441
7	.0451	.0454	.0443	.0445
10	.0456	.0458	.0447	.0448
15	.0462	.0463	.0452	.0453
20	.0466	.0468	.0458	.0457
30	.0472	.0474	.0463	.0462
40	.0477	.0479	.0468	.0466
60	.0484	.0486	.0475	.0472
90	.0491	.0495	.0482	.0478

Tests 6, 7

Total Deformations, 90 minutes onwards

Test 6a

Time	Deformation
195	.0504
490	.0537
750	.0543
1440	.0556

Test 6b

Time	Deformation
175	.0511
580	.0540
1440	.0587

Test 7a

Time	Deformation
150	.0494
270	.0502
370	.0508
470	.0515
1430	.0537

Test 7b

Time	Deformation
140	.0486
186	.0493
320	.0504
445	.0512
490	.0514
1410	.0547

Acetate: Instantaneous Elastic Deformations

Test No.	Filament Load, gms.	I.E.D, ins. (mean)
15, 16b, 26	1.480	.1150
13, 14, 24	1.053	.0743
8, 12, 13	0.856	.0652
6,7	0.526	.0394

Instantaneous Modulus of Elasticity

Instantaneous Deformation = .0740 ins./gm.

= .188 cms./gm.

Cross-sectional area (measured) = 267×10^{-8} cm.^{2}

Length of Filament = 28.96 cms.

Instantaneous modulus = 0.576×10^{8} gms./cm.^{2}

= 820,000 psi

Delayed Deformations (relative to t = 1 minute)

1 - 90 minutes

Test No.	26b	13b	12a	7a
Time, Mins.				
1	0	0	0	0
1 1/2	.0022	.0009	.0007	.0003
2	.0038	.0016	.0011	.0005
3	.0064	.0024	.0018	.0009
5	.0096	.0036	.0029	.0015
7	.0120	.0045	.0035	.0019
10	.0144	.0055	.0043	.0023
15	.0174	.0067	.0053	.0028
20	.0197	.0076	.0059	.0034
30	.0228	.0090	.0068	.0039
40	.0253	.0100	.0076	.0044
60	.0285	.0114	.0087	.0051
90	.0317	.0128	.0098	.0058

Delayed Deformations (90 minutes onwards)

Test 26b

Time	Delayed Deformation
120	.0340
305	.0413
435	.0439
1440	.0523

Test 13b

Time	Delayed Deformation
160	.0150
270	.0171
360	.0182
510	.0191
1485	.0239

Test 12a

Time	Delayed Deformation
140	.0110
235	.0126
350	.0147
450	.0158
1405	.0213

Test 7a

Time	Delayed Deformation
150	.0070
270	.0078
370	.0084
470	.0091
1430	.0113

Scale Factors for Creep

Test No.	26b	13b	12a	7a
Filament Load, gms.	1.480	1.053	0.856	0.526
Load, gms./denier	0.478	0.341	0.277	0.170
Scale Factor d_{90} (Deformation at 90 mins. - deformation at 1 min.)	.0324	.0128	.0103	.0059
Scale Factor expressed as strain D_{90} x 1000	2.84	1.12	0.90	0.52

Acetate: Reduced Deformations (0 - 90 minutes)

Load, gms.	1.480	1.053	0.856	0.526
Test No.	26b	13b	12a	7a
Scale Factor d_{90}	.0324	.0128	.0103	.0059
Time, Mins.				
1	0	0	0	0
1 1/2	.068	.070	.068	.051
2	.117	.125	.107	.085
3	.198	.188	.175	.153
5	.296	.281	.282	.254
7	.370	.352	.340	.322
10	.444	.430	.417	.390
15	.537	.523	.515	.475
20	.608	.594	.573	.576
30	.704	.703	.660	.661
40	.781	.781	.738	.746
60	.880	.891	.845	.864
90	.978	1.000	.951	.983

Acetate: Reduced Deformations (90 minutes onwards)

Test 26b

Time	Reduced Deformation
120	1.049
305	1.275
435	1.355
1440	1.614

Test 13b

Time	Reduced Deformation
160	1.172
270	1.336
360	1.422
510	1.492
1485	1.867

Test 12a

Time	Reduced Deformation
140	1.068
235	1.223
350	1.427
450	1.534
1405	2.068

Test 7a

Time	Reduced Deformation
150	1.186
270	1.322
370	1.424
470	1.542
1430	1.915

FILAMENT NO. 8

VISCOSE II

Scheme of Tests

Test No.	Type of Test	Filament Load, gms.
	FILAMENT STRETCHED ABOUT 40% IN WATER; DRIED UNDER LOAD.	
1	Long Duration Creep and Recovery (Mechanical Conditioning)	1.480
2,3	Long Duration Creep and Recovery	1.480
4,5	ditto	1.053
6	ditto	0.856
7	Superposition	1.480
8	Creep	1.480
	SWELLING RECOVERY	
9	Long Duration Creep and Recovery (Mechanical Conditioning)	1.480
10,11	Long Duration Creep and Recovery	1.480
12,13	ditto	1.053

Tests 1, 2, 3

Observations, 0 - 90 minutes (in inches)

Test No.	1a	1b	2a	2b	3a	3b
Initial Obsn.	.1507	.2377	.1553	.2193	.1566	.2173
Time, Mins.						
1/4	-	.2016	.1906	.1839	.1911	.1821
1/2	.2127	.2007	.1916	.1832	.1920	.1812
3/4	.2127	.2000	.1922	.1827	.1925	.1807
1	.2127	.1993	.1926	.1822	.1930	.1803
1 1/2	.2129	.1985	.1933	.1816	.1936	.1796
2	.2131	.1978	.1939	.1811	.1941	.1792
3	.2135	.1965	.1947	..1804	.1948	.1784
5	.2142	.1951	.1959	.1794	.1958	.1775
7	.2149	.1938	.1967	.1787	.1965	.1767
10	.2156	.1923	.1977	.1777	.1973	.1758
15	.2167	.1907	.1989	.1766	.1984	.1747
20	.2175	.1890	.1999	.1759	.1992	.1739
30	.2188	.1867	.2013	.1745	.2005	.1726
40	.2199	.1849	.2025	.1735	.2014	.1717
60	.2216	.1822	.2042	.1720	.2029	.1701
90	.2233	.1792	.2061	.1703	.2044	.1686

Tests 1, 2, 3

Observations 90 minutes onwards

Test 1a

Time	Scale
150	.2253
250	.2275
320	.2288
370	.2295
1260	.2384

Test 1b

Time	Scale
180	.1742
240	.1714
400	.1665
505	.1646
567	.1642
1545	.1545

Test 2a

Time	Scale
195	.2099
315	.2122
440	.2134
1610	.2197

Test 2b

Time	Scale
190	.1668
285	.1647
575	.1610
1200	.1566
1320	.1566

Test 3a

Time	Scale
145	.2067
265	.2093
395	.2112
1335	.2182

Test 3b

Time	Scale
165	.1662
285	.1639
420	.1620
485	.1613
714	.1596
1380	.1560

Tests 1, 2, 3

Total Deformations, 0 - 90 minutes (in inches)

Test No.	1a	1b	2a	2b	3a	3b
Time, Mins.						
1/4		.0361	.0353	.0354	.0345	.0352
1/2	.0620	.0370	.0363	.0361	.0354	.0361
3/4	.0620	.0377	.0369	.0366	.0359	.0366
1	.0620	.0384	.0373	.0371	.0364	.0370
1 1/2	.0622	.0392	.0380	.0377	.0370	.0377
2	.0624	.0399	.0386	.0382	.0375	.0381
3	.0628	.0412	.0394	.0389	.0382	.0389
5	.0635	.0426	.0406	.0399	.0392	.0398
7	.0642	.0439	.0414	.0406	.0399	.0406
10	.0649	.0454	.0424	.0416	.0407	.0415
15	.0660	.0470	.0436	.0427	.0418	.0426
20	.0668	.0487	.0446	.0434	.0426	.0434
30	.0681	.0510	.0460	.0448	.0439	.0447
40	.0692	.0528	.0472	.0458	.0448	.0456
60	.0709	.0555	.0489	.0473	.0463	.0472
90	.0726	.0585	.0508	.0490	.0478	.0487

Tests 1, 2, 3

Total Deformations, 90 minutes onwards (in inches)

Test 1a		Test 1b		Test 2a	
Time	Deformation	Time	Deformation	Time	Deformation
150	.0746	180	.0635	195	.0546
250	.0768	240	.0663	315	.0569
320	.0781	400	.0712	440	.0581
370	.0788	505	.0731	1610	.0644
1260	.0877	567	.0735		
		1545	.0832		

Test 2b		Test 3a		Test 3b	
Time	Deformation	Time	Deformation	Time	Deformation
190	.0525	145	.0501	165	.0511
285	.0546	265	.0527	285	.0534
575	.0583	395	.0546	420	.0553
1200	.0627	1335	.0616	485	.0560
1320	.0637			714	.0577
				1380	.0613

Tests 4, 5

Observations, 0 - 90 minutes (in inches)

Test No.	4a	4b	5a	5b
Initial Obsn.	.1568	.1903	.1540	.1880
Time, Mins.				
1/4	.1792	.1683	.1761	.1649
1/2	.1797	.1680	.1767	.1647
3/4	.1800	.1676	.1769	.1643
1	.1802	.1671	.1771	.1642
1 1/2	.1805	.1668	.1773	.1640
2	.1807	.1663	.1775	.1638
3	.1810	.1659	.1778	.1635
5	.1814	.1654	.1782	.1631
7	.1818	.1651	.1785	.1628
10	.1821	.1648	.1789	.1624
15	.1826	.1643	.1793	.1621
20	.1829	.1639	.1796	.1615
30	.1834	.1634	.1801	.1607
40	.1839	.1629	.1805	.1603
60	.1847	.1622	.1811	.1595
90	.1854	.1614	.1819	.1589

Tests 4, 5

Observations, 90 minutes onwards (in inches)

Test 4a		Test 4b	
Time	Scale	Time	Scale
135	.1861	140	.1606
175	.1867	240	.1592
270	.1875	330	.1582
390	.1880	440	.1578
480	.1885	690	.1564
620	.1891	1430	.1531
1387	.1905		

Test 5a		Test 5b	
Time	Scale	Time	Scale
150	.1830	135	.1599
305	.1841	287	.1590
395	.1848	345	.1585
485	.1850	2885	.1508
1430	.1882		

Tests 4, 5

Total Deformations, 0 - 90 minutes (in inches)

Test No.	4a	4b	5a	5b
Time, Mins.				
1/4	.0224	.0220	.0221	.0231
1/2	.0229	.0223	.0227	.0233
3/4	.0232	.0227	.0229	.0237
1	.0234	.0232	.0231	.0238
1 1/2	.0237	.0235	.0233	.0240
2	.0239	.0240	.0235	.0242
3	.0242	.0244	.0238	.0245
5	.0246	.0249	.0242	.0249
7	.0250	.0252	.0245	.0252
10	.0253	.0255	.0249	.0256
15	.0258	.0260	.0253	.0259
20	.0261	.0264	.0256	.0265
30	.0266	.0269	.0261	.0273
40	.0271	.0274	.0265	.0277
60	.0279	.0281	.0271	.0285
90	.0286	.0289	.0279	.0291

Tests 4, 5

Total Deformations, 90 minutes onwards (in inches)

Time	Test 4a Deformation
135	.0293
175	.0299
270	.0307
390	.0312
480	.0317
620	.0323
1387	.0337

Time	Test 4b Deformation
140	.0297
240	.0311
330	.0321
440	.0325
690	.0339
1430	.0372

Time	Test 5a Deformation
150	.0290
305	.0301
395	.0308
485	.0310
1430	.0342

Time	Test 5b Deformation
135	.0281
287	.0290
345	.0295
2885	.0372

Test 6

Observations and Deformations, 0 - 90 minutes (in inches)

	Observations		Deformations	
Test No.	6a	6b	6a	6b
Initial Obsn.	.1516	.1803		
Time, Mins.				
1/4	.1711	.1600	.0195	.0203
1/2	--	.1599	--	.0204
3/4	.1718	.1597	.0202	.0206
1	.1720	.1595	.0204	.0208
1 1/2	.1722	.1592	.0206	.0211
2	.1724	.1591	.0208	.0212
3	.1727	.1589	.0211	.0214
5	.1730	.1585	.0214	.0218
7	.1733	.1582	.0217	.0221
10	.1736	.1579	.0220	.0224
15	.1740	.1575	.0224	.0228
20	.1745	.1573	.0229	.0230
30	.1750	.1569	.0234	.0234
40	.1753	.1566	.0237	.0237
60	.1757	.1560	.0241	.0243
90	.1762	.1553	.0246	.0250

Test 6

Observations and Deformations, 90 minutes onwards

Test 6a

Time	Scale	Deformation
140	.1767	.0251
250	.1776	.0260
390	.1782	.0266
475	.1788	.0272
1395	.1810	.0294

Test 6b

Time	Scale	Deformation
160	.1546	.0257
255	.1537	.0266
345	.1529	.0274
510	.1521	.0282
1410	.1498	.0305

Stretched Viscose: Delayed Deformations

0 - 90 minutes (in inches)

Test No.	2b	4a	6b
Time, Mins.			
1	0	0	0
1 1/2	.0006	.0003	.0003
2	.0011	.0005	.0004
3	.0018	.0008	.0006
5	.0028	.0012	.0010
7	.0035	.0016	.0013
10	.0045	.0019	.0016
15	.0056	.0024	.0020
20	.0063	.0027	.0022
30	.0077	.0032	.0026
40	.0087	.0037	.0029
60	.0102	.0045	.0035
90	.0119	.0052	.0042

Stretched Viscose: Delayed Deformations

90 minutes onwards

	Test 2b
Time	Deformation
190	.0154
285	.0175
575	.0212
1200	.0256
1320	.0260

	Test 4a
Time	Deformation
135	.0059
175	.0065
270	.0073
390	.0078
480	.0083
620	.0089
1387	.0103

	Test 6b
Time	Deformation
160	.0049
255	.0058
345	.0066
510	.0074
1410	.0097

Tests 9, 10, 11

Observations 0 - 90 minutes (in inches)

Test No.	9a	9b	10a	10b	11a	11b
Initial Obsn.	.0530	.2213	.1323	.2165	.1487	.2247
Time, Mins.						
1/4	.1097	.1823	.1710	.1801	.1863	--
1/2	--	.1811	.1720	.1791	.1873	.1875
3/4	.1132	.1808	.1726	.1790	.1880	.1868
1	.1143	.1801	.1731	.1783	.1886	.1864
1 1/2	.1162	.1791	.1739	.1771	.1893	.1854
2	.1173	.1783	.1745	.1764	.1898	.1849
3	.1195	.1770	.1754	.1755	.1908	.1840
5	.1227	.1753	.1767	.1741	.1920	.1825
7	.1250	.1740	.1777	.1731	.1929	.1816
10	.1278	.1724	.1788	.1720	.1939	.1805
15	.1317	.1705	.1802	.1706	.1954	.1791
20	.1349	.1691	.1813	.1695	.1965	.1781
30	.1400	.1668	.1833	.1679	.1981	.1764
40	.1440	.1649	.1848	.1665	.1994	.1754
60	.1508	.1624	.1872	.1647	.2012	.1738
90	.1587	.1595	.1898	.1627	.2030	.1721

Tests 9, 10, 11

Observations 90 minutes onwards (in inches)

Test 9a

Time	Scale
140	.1677
220	.1776
300	.1842
420	.1920
475	.1950
1330	.2217

Test 9b

Time	Scale
120	.1575
170	.1548
220	.1521
320	.1492
445	.1473
2940	.1312

Test 10a

Time	Scale
120	.1917
180	.1946
250	.1974
360	.2010
420	.2026
1410	.2174

Test 10b

Time	Scale
135	.1607
195	.1592
330	.1557
435	.1543
1400	.1480

Test 11a

Time	Scale
125	.2046
185	.2071
255	.2090
380	.2111
440	.2123
1470	.2253

Test 11b

Time	Scale
160	.1695
215	.1675
345	.1652
420	.1640
615	.1621
1380	.1580

Tests 9, 10, 11

Total Deformations,0 - 90 minutes (in inches)

Test No.	9a	9b	10a	10b	11a	11b
Time, Mins.						
1/4	.0567	.0390	.0387	--	.0376	--
1/2	--	.0402	.0397	--	.0386	--
3/4	.0602	.0405	.0403	.0369	.0393	.0379
1	.0613	.0412	.0408	.0382	.0399	.0383
1 1/2	.0632	.0422	.0416	.0394	.0406	.0393
2	.0643	.0430	.0422	.0401	.0411	.0398
3	.0665	.0443	.0431	.0410	.0421	.0407
5	.0697	.0460	.0444	.0424	.0433	.0422
7	.0720	.0473	.0454	.0434	.0442	.0431
10	.0748	.0489	.0465	.0445	.0452	.0442
15	.0787	.0508	.0479	.0459	.0467	.0456
20	.0819	.0522	.0490	.0470	.0478	.0466
30	.0870	.0545	.0510	.0486	.0494	.0483
40	.0910	.0564	.0525	.0500	.0507	.0493
60	.0978	.0589	.0549	.0518	.0525	.0509
90	.1057	.0518	.0575	.0538	.0543	.0526

Tests 9, 10, 11

Total Deformations, 90 minutes onwards (in inches)

	Test 9a		Test 9b		Test 10a
Time	Deformation	Time	Deformation	Time	Deformation
140	.1147	120	.0638	120	.0594
220	.1246	170	.0665	180	.0623
300	.1312	220	.0692	250	.0651
420	.1390	320	.0721	360	.0687
475	.1420	445	.0740	420	.0703
1330	.1687	2940	.0901	1410	.0851

	Test 10b		Test 11a		Test 11b
Time	Deformation	Time	Deformation	Time	Deformation
135	.0558	125	.0559	160	.0552
195	.0573	185	.0584	215	.0572
330	.0608	255	.0603	345	.0595
435	.0622	380	.0624	420	.0607
1400	.0685	440	.0636	615	.0626
		1470	.0766	1380	.0667

Tests 12, 13

Observations 0 - 90 minutes (in inches)

Test No.	12a	12b	13a	13b
Initial Obsn.	.1589	.1979	.1555	.1949
Time, Mins.				
1/4	.1833	--	.1797	--
1/2	.1840	--	.1803	--
3/4	.1843	--	.1805	--
1	.1845	--	.1808	--
1 1/2	.1849	--	.1810	.1699
2	.1852	--	.1813	.1695
3	.1856	.1731	.1816	.1687
5	.1862	.1720	.1821	.1681
7	.1866	.1715	.1825	.1677
10	.1871	.1710	.1828	.1673
15	.1877	.1705	.1832	.1668
20	.1882	.1700	.1836	.1664
30	.1889	.1694	.1842	.1657
40	.1895	.1690	.1846	.1652
60	.1903	.1683	.1854	.1646
90	.1912	.1674	.1862	.1639

Tests 12, 13

Observations 90 minutes onwards (in inches)

Test 12a		Test 12b	
Time	Scale	Time	Scale
170	.1931	135	.1668
220	.1938	180	.1660
310	.1946	300	.1642
410	.1954	415	.1634
515	.1959		
1410	.1986		

Test 13a		Test 13b	
Time	Scale	Time	Scale
160	.1876	180	.1626
245	.1886	285	.1614
330	.1893	360	.1608
515	.1913	430	.1604
745	.1919	1410	.1576
1440	.1950		

Tests 12, 13

Total Deformations, 0 - 90 minutes (in inches)

Test No. Time, Mins.	12a	12b	13a	13b
1/4	.0244	--	.0242	--
1/2	.0251	--	.0248	--
3/4	.0254	--	.0250	--
1	.0256	--	.0253	--
1 1/2	.0260	--	.0255	.0250
2	.0263	--	.0258	.0254
3	.0267	.0248	.0261	.0262
5	.0273	.0259	.0266	.0268
7	.0277	.0264	.0270	.0272
10	.0282	.0269	.0273	.0276
15	.0288	.0274	.0277	.0281
20	.0293	.0279	.0281	.0285
30	.0300	.0285	.0287	.0292
40	.0306	.0289	.0291	.0297
60	.0314	.0296	.0299	.0303
90	.0323	.0305	.0307	.0310

Tests 12, 13

Total Deformations, 90 minutes onwards (in inches)

Test 12a		Test 12b	
Time	Deformation	Time	Deformation
170	.0342	135	.0311
220	.0349	180	.0319
310	.0357	300	.0337
410	.0365	415	.0345
515	.0370		
1410	.0397		

Test 13a		Test 13b	
Time	Deformation	Time	Deformation
160	.0321	180	.0323
245	.0331	285	.0335
330	.0338	360	.0341
515	.0358	430	.0345
745	.0364	1410	.0373
1440	.0395		

Tests 11a, 13a

Delayed Deformations, relative to t = 1 minute (in inches)

Test No.	11a	13a
Time, Mins.		
1	0	0
1 1/2	.0007	.0002
2	.0012	.0005
3	.0022	.0008
5	.0034	.0013
7	.0043	.0017
10	.0053	.0020
15	.0068	.0024
20	.0079	.0028
30	.0095	.0034
40	.0108	.0038
60	.0126	.0046
90	.0144	.0064

Test 11a	
Time	Deformation
125	.0160
185	.0185
255	.0204
380	.0225
440	.0237
1470	.0367

Test 13a	
Time	Deformation
160	.0068
245	.0078
330	.0085
515	.0165
745	.0111
1440	.0142

Instantaneous Elastic Deformation

Test No.	Filament Load, gms.	Instantaneous Deformation
2,3	1.480	.0343 (mean)
4,5	1.053	.0220 (mean)
6b	0.856	.0195
11	1.480	.0350, .0363
12a,13a	1.053	.0236

Instantaneous Modulus of Elasticity

Instantaneous deformation = .023 ins./gm.

= .0584 cms./gm.

Cross sectional area (measured) = 356×10^{-8} cms.^{2}

Length = 29.54 cms.

Instantaneous modulus of elasticity = 1.42×10^{8} gms./cm.^{2}

= 2.06×10^{6} psi

Scale Factors for Creep

Test No.	2b	4a	6b
Filament Load, gms.	1.480	1.053	0.856
Load, gms./denier	.295	.210	.168
Scale Factor d_{90} (Deformation at 90 mins. - deformation at 1 min.)	.1180	.0516	.0425
Scale Factor expressed as strain D_{90} x 1000	10.1	4.43	3.66

Reduced Deformations, 1 - 90 minutes

Test No.	2b	4a	6b
Fil. Load, gms.	1.480	1.053	0.856
Scale Factor, d_{90}	.01180	.00516	.00425
Time, Mins.			
1	0	0	0
1 1/2	.051	.058	.071
2	.093	.097	.094
3	.153	.155	.141
5	.237	.232	.235
7	.297	.310	.306
10	.381	.368	.376
15	.475	.465	.471
20	.534	.523	.518
30	.653	.620	.612
40	.737	.717	.682
60	.864	.872	.824
90	1.008	1.007	.988

Reduced Deformations, 90 minutes onwards

	Test 2b		Test 4a		Test 6b
Time	Reduced Deformation	Time	Reduced Deformation	Time	Reduced Deformation
190	1.305	135	1.143	160	1.153
285	1.483	175	1.260	255	1.365
575	1.797	270	1.415	345	1.553
1200	2.169	390	1.512	510	1.741
1320	2.203	480	1.609	1410	2.283
		620	1.725		
		1387	1.996		

IV. Superposition Tests

The long-duration creep and recovery tests on filamentous materials give the laws of deformation of these materials for creep under constant load, and for the recovery following such long-duration creep. The object of the Superposition Tests is to determine the laws of deformation for shorter loading times and for arbitrary loading histories. Now we saw when considering mechanical models and the Wiechert theory, that the plausible assumption of a distribution of relaxation times led to a creep proportional to load (as given by equation 9) and a linear superposition of separate loading effects. One result of this theory was that the deformation due to removal of load during a recovery test following a long-duration creep test should correspond to the deformation due to application of load in the creep test. The experimental data for the most part appeared to confirm this theoretical result; however, the delayed deformation under constant load was <u>not</u> found to be proportional to load, and hence the system of distributed relaxation times does not represent the behavior of the filamentous materials under consideration.

The problem then arises, as to whether in this case the deformation due to several loading actions is the simple superposition of the deformations due to the individual loading actions occurring separately. In view of the experimental difficulties involved, it does not seem possible to confirm this point directly. However, because of the correspondence experimentally found between the total deformation in a recovery test and in the preceding long-duration creep test, this would appear to be true.

We can now give a formal representation to the case of linear superposition where the delayed deformation under constant load is not proportional to the load. Let the delayed deformation vary with load P by a scale factor which we will denote by s(P), and let $\psi(t)$ represent a creep function, as before. Assuming that the instantaneous elastic deformation is proportional to load, the total deformation y_t at time t due to a load P applied at zero time is:

$$y_t = F\left[\frac{P_t}{E} + s(P) \;.\; \psi(t)\right] \qquad (94)$$

where the symbols have the same significance as in equation (9). For an arbitrary loading history this becomes by analogy with equation (13),

$$y_t = F\left\{\frac{P_t}{E} + \int_{\infty}^{0} \frac{ds\,(P_{t-\omega})}{d\omega} \;.\; \psi(\omega)\; d\omega\right\} \qquad (95)$$

Experimental Verification of the Superposition Principle.

The modified Superposition Principle can be tested in several ways. The following are possible methods.

1. A constant load is applied, and after some time this load is augmented.

2. A constant load is applied, and after some time part of this load is removed.

3. A constant load is applied, the entire load being removed after some time and the creep recovery observed.

4. In the above case, the load may be later reapplied and later still removed and so on.

5. In the previous case, the second load application may be of a different magnitude to that of the first load application.

The linear superposition of the separate loading effects can then be tested by comparing the observed data with predicted values; the latter are computed from the curves of total deformation at each of the relevant loads. For example, if in the first scheme the load is augmented from P_1 to P_2 it is necessary to know the total deformation curves as well as the instantaneous elastic deformations at these two loads. It is necessary also to assume that the instantaneous deformations for creep and for recovery are the same. Now we have seen that the great difficulty in connection with the long-duration creep and recovery tests was the only fair degree of reproducibility. Similarly, we would expect only a fair agreement between successive short-duration tests, and furthermore on account of this same variability we are at a loss to know to which of a set of long-duration tests these tests are to be compared. This difficulty is seen to be doubled when two loads are used in the short duration creep tests, as in the first, second, and fifth schemes above. A further difficulty with regard to the first and second schemes, and to a lesser extent the fifth scheme, is that the changing of the load will introduce a certain amount of shock to the filament. Since the third scheme is contained in the fourth scheme this latter seems to be the most suitable method of testing the Superposition Principle.

The Superposition Tests thus follow the superposed loading scheme of Part II; in which a load is applied, removed after some time, later reapplied, and so on. If the deformations in the creep and recovery periods agree with those computed from the creep curve for constant load by the method given in Part II (equations 29 and 30, and similar equations) then it seems fairly certain that equation (95) is true, i.e., that there is a linear superposition of the separate loading effects.

Theory of the Superposition Tests.

Let the deformation at time t due to a constant load applied at zero time be y_t. Then let

$$y_t = e + f(t) \qquad (96)$$

for such a creep test, where e is the instantaneous elastic extension and f(t) is the delayed deformation. Let us assume that such a creep test has been carried out up to some value of time t. Now let us suppose instead that a superposition test had been carried out with this load. By means of the Superposition Principle it is possible to calculate the deformations to be expected in the superposition test from the deformations observed in the long-duration test.

Let us consider for simplicity the following scheme for the superposition test: the load is applied at zero time, removed after ten minutes, reapplied at twenty minutes, and finally removed after thirty minutes. Let Y_t represent the deformation at a time t in the superposition test. Then from t = 0 minutes to t = 10 minutes

$$Y_t = y_t \,, \tag{97a}$$

from t = 10 minutes to t = 20 minutes

$$Y_t = y_t - y_{t-10} \,, \tag{97b}$$

from t = 20 minutes to t = 30 minutes

$$Y_t = y_t - y_{t-10} + y_{t-20} \,, \tag{97c}$$

and finally from t = 30 minutes to t = 40 minutes

$$Y_t = y_t - y_{t-10} + y_{t-20} - y_{t-30} \tag{97d}$$

In equations (97b) and (97d) Y_t of course represents the residual deformation. In this way deformations in the Superposition Test can be computed from the deformations in the long-duration test. In the computation of Y_t by this method a great deal of interpolation for values of y_t is required.

In an alternative method of analysis, the long-duration test "creep curve" can be computed from the data of the superposition test. We have for the period from t = 10 minutes to t = 20 minutes, from equations (97a) and (97b),

$$Y_t = y_t - Y_{t-10}$$

hence

$$y_t = Y_t + Y_{t-10} \tag{98}$$

In other words, if we know the total deformation in the first creep period ($0 < t < 10$) and the residual deformation in the first recovery period ($10 < t < 20$) we can calculate from the Superposition Principle what the total deformation would have been from t = 10 minutes to 20 minutes if the load had not been removed. If, for example in equation (98), Y_{t-10} represents the (total) deformation at 5 minutes and Y_t represents the (residual) deformation at 15 minutes, then the (total) deformation in a long-duration creep test at a time of 15 minutes should be given by equation (98). Now let us consider the second creep period, from t = 20 minutes to t = 30 minutes. We have from equation (97c)

$$\begin{aligned} Y_t &= y_t - (y_{t-10} - y_{t-20}) \\ &= y_t - Y_{t-10} \end{aligned}$$

Hence
$$y_t = Y_t + Y_{t-10}$$

which is of the same form as equation (98). The same result is obtained for the recovery period from t = 30 minutes to t = 40 minutes. Hence if in the superposition test, a given load is repeatedly applied and removed, and if the durations of the times under load and of the recovery times are all equal, the Superposition Principle enables us to predict as follows the creep curve for constant load from the superposition test data. From all the observations we first deduct the initial observation, thus giving us the deformations. If to the deformation at a given instant in any creep or recovery period we add the deformation at the corresponding instant in the preceding recovery or creep period, we obtain the deformation at the corresponding time for a simple creep test. In this way without the necessity for interpolation the total deformation for creep under constant load can be computed, and compared with the experimentally obtained curve for the same load.

Sources of Error.

The deformations computed from the superposition test data should lie on a smooth curve. The following are however possible sources of error.

1. Backlash: the initial observation taken just before the commencement of the test is taken in the direction of increasing deformation. If this reading is used to compute the residual deformations in the recovery periods, there will be a discrepancy by this amount. The values computed from the first recovery period onwards will then be too small by this amount.

2. Application of Load: several seconds are required to apply or remove the load. It is possible that the effective instant of load application be slightly early or slightly late; the computed values of the creep curve will thus be slightly in error for a few minutes following the change in load. Similarly the effect of shock on the filament as a result of application or removal of load will be to cause a transient error.

3. Other Errors: (a) The instantaneous extensions and contractions may differ. This will result in a constant error for the first recovery and subsequent periods. (b) The initial observation may be in error for the reasons discussed

previously. This will result in an error for the first creep period equal to this error and for the first recovery and subsequent periods equal to double this error. (c) The initial elastic extension appears to vary somewhat from test to test. If the superposition test is compared with a long-duration test performed some time previously, this must be taken into account. (d) Secondary creep may be present in tests at high loads.

Arrangement of Superposition Tests.

In general, the superposition tests were fitted in the scheme of long-duration tests whenever convenient. Owing to the shortage of time less attention could be paid to these tests. In many cases, no simple connection could be found between the data of a superposition test, and of the corresponding long-duration tests at the same load. These tests have been rejected; the remaining tests are considered below.

A more detailed investigation of the superposition tests was made in the case of two filaments, namely, acetate and viscose. In the first case, two sets of tests were performed at the same load; each set was comprised of a superposition test of six ten-minute creep and recovery periods, another test of four fifteen-minute periods, and a creep test of sixty minutes duration followed by recovery. In the case of the viscose filament, several superposition tests following the above two schemes were performed at the two highest loads, in order to find to what extent the tests were reproducible. The results of these latter tests were somewhat disappointing, probably due to the presence of secondary creep. In two other cases special short duration creep tests were run immediately after the superposition test; otherwise the superposition test data were compared to the most suitable of the long-duration creep tests at the relevant load.

Analysis of Results.

The superposition test data have been analysed by the second method described above. Let us first consider the results of the tests made on the acetate filament as described previously. From the superposition tests Nos. 21 and 22 the (total deformation) creep curve from 0 minutes to 60 minutes has been computed, and from the creep test No. 23 the creep curve from 0 minutes to 100 minutes. These curves are plotted in Fig. 133. In all these curves a discontinuity will be observed at the instant of the first load removal; this discontinuity is in the form of a downward displacement to the right by an amount roughly the same in all three cases. This displacement as we have seen can be due to backlash, non-equality of instantaneous extension and contraction, and possible error in the initial reading. Correcting for this displacement, we obtain the curves as shown in Fig. 134.

In this case for all three tests the computed points lie on smooth curves which agree very closely with each other. In another set of tests, Nos. 18, 19, 20 (Fig. 135), nearly as good agreement is obtained. It should be pointed out, however, that these two sets of curves differ slightly, the difference being accountable by a slight difference in instantaneous deformation.

In the other superposition tests listed below, the discontinuity in the computed curve has been removed by applying similar corrections. The computed values have been plotted as points and the total deformations in the corresponding long duration creep tests as circles. In most cases there is seen to be good agreement. In two of the tests it appears that the instantaneous deformations in the comparison creep tests differed slightly from those in the superposition tests. In plotting the results of these tests it has accordingly been necessary to displace slightly the ordinate scales for the observed and computed curves in order to bring these into correspondence.

It therefore appears, from the results presented, that in the cases considered the creep and recovery due to successive application and removal of a given load over relatively short periods of time is satisfactorily accounted for by the Superposition Principle. In view of the non-proportionality of creep and load for filamentous materials, we have to assume for these substances the Superposition Principle in the modified form given by equation (95). It is true that many of the superposition tests have not yielded satisfactorily to analysis by the methods given above. It seems possible however that negative results can be ascribed to the presence of secondary creep, and to the extremely variable behavior of such filaments. Much further investigation is therefore required by means of such short-time tests before definite conclusions can be drawn.

Data of Superposition Tests

LIST OF SUPERPOSITION TESTS

Filament No.	Material	Filament Load, gms.	Super-position Test No.	Comparison Creep Test No.	Correction, in.
10	Acetate	1.053	21	23	.0018
		1.053	22	23	.0018
		1.053	18	20	.0016
		1.053	19	20	.0016
		0.856	9	8b	.0014
4	Nylon I	0.856	9	1b	.0060
		0.526	3	2b	.0030
		0.346	4	5a	.0021
5	Viscose I	1.053	18	17a	.0023
8	Viscose II	1.480	7	8	.0002
9	Nylon II	1.480	9	2a	.0040
		1.053	8	3b	.0057

Filament No. 10. Acetate

Test 21. Filament Load 1.053 gms.
Initial Observation .6057
6 x 10 minutes

Creep and Recovery Deformations (uncorrected)

Time in Loading Period, mins.	Creep I	Rec.I	Creep II	Rec.II	Creep III	Rec.III
1/4	.0756	.0063	.0781	.0077	.0791	.0088
1/2	.0770	.0055	.0795	.0067	.0804	.0076
3/4	.0778	.0048	.0803	.0061	.0812	.0069
1	.0783	.0043	.0807	.0055	.0817	.0064
1 1/2	.0791	.0037	.0814	.0050	.0825	.0057
2	.0798	.0032	.0819	.0044	.0830	.0053
3	.0807	.0026	.0827	.0038	.0837	.0046
5	.0820	.0020	.0837	.0031	.0847	.0038
7	.0830	.0015	.0845	.0026	.0853	.0034
9	.0837	.0012	.0850	.0023	.0859	.0030

Test 21

Computed Creep Curve 0 - 60 minutes (uncorrected)

Time, mins.	0-10 mins.	10-20 mins.	20-30 mins.	30-40 mins.	40-50 mins.	50-60 mins.
1/4	.0756	.0819	.0844	.0858	.0868	.0879
1/2	.0770	.0825	.0850	.0862	.0871	.0880
3/4	.0778	.0826	.0851	.0864	.0873	.0881
1	.0783	.0826	.0850	.0862	.0872	.0881
1 1/2	.0791	.0828	.0851	.0864	.0875	.0882
2	.0798	.0830	.0851	.0863	.0874	.0883
3	.0807	.0833	.0853	.0865	.0875	.0883
5	.0820	.0840	.0857	.0868	.0878	.0885
7	.0830	.0845	.0860	.0871	.0879	.0887
9	.0837	.0849	.0862	.0873	.0882	.0889

Test 21

Computed Creep Curve 0 - 60 minutes (corrected)

Correction .0018 in.

Time, mins.	0-10 mins.	10-20 mins.	20-30 mins.	30-40 mins.	40-50 mins.	50-60 mins.
1/4	.0756	.0837	.0862	.0876	.0886	.0897
1/2	.0770	.0843	.0868	.0880	.0889	.0898
3/4	.0778	.0844	.0869	.0882	.0891	.0899
1	.0783	.0844	.0868	.0880	.0890	.0899
1 1/2	.0791	.0846	.0869	.0882	.0893	.0800
2	.0798	.0848	.0869	.0881	.0892	.0801
3	.0807	.0851	.0871	.0883	.0893	.0801
5	.0820	.0858	.0875	.0886	.0896	.0803
7	.0830	.0863	.0878	.0889	.0897	.0805
9	.0837	.0867	.0880	.0891	.0900	.0807

Filament No. 10. Acetate

Test 22. Filament Load 1.053 gms.

Initial Observation .6070

4 x 15 minutes

Creep and Recovery Deformations (uncorrected)

Time in Loading Period, mins.	Creep I	Rec. I	Creep II	Rec. II
1/4	.0758	.0074	.0786	.0089
1/2	.0771	.0066	.0800	.0076
3/4	.0778	.0058	.0805	.0069
1	.0783	.0052	.0811	.0064
1 1/2	.0791	.0044	.0817	.0057
2	.0798	.0040	.0820	.0051
3	.0805	.0032	.0828	.0045
5	.0818	.0025	.0837	.0036
7	.0826	.0020	.0845	.0031
10	.0836	.0016	.0854	.0026
14	.0847	.0011	.0861	.0020

Test 22

Computed Creep Curve 0 - 60 minutes (uncorrected)

Time, mins.	0-15 mins.	15-30 mins.	30-45 mins.	45-60 mins.
1/4	.0758	.0832	.0860	.0875
1/2	.0771	.0837	.0866	.0876
3/4	.0778	.0836	.0863	.0874
1	.0783	.0835	.0863	.0875
1 1/2	.0791	.0835	.0861	.0874
2	.0798	.0838	.0860	.0871
3	.0805	.0837	.0860	.0873
5	.0818	.0843	.0862	.0873
7	.0826	.0846	.0865	.0876
10	.0836	.0852	.0870	.0880
14	.0847	.0858	.0872	.0881

Test 22.

Computed Creep Curve 0 - 60 minutes (corrected)

Correction .0018 in.

Time, mins.	0-15 mins.	15-30 mins.	30-45 mins.	45-60 mins.
1/4	.0758	.0850	.0878	.0893
1/2	.0771	.0855	.0884	.0894
3/4	.0778	.0854	.0881	.0892
1	.0783	.0853	.0881	.0893
1 1/2	.0791	.0853	.0879	.0892
2	.0798	.0856	.0878	.0889
3	.0805	.0855	.0878	.0891
5	.0818	.0861	.0880	.0891
7	.0826	.0864	.0883	.0894
10	.0836	.0870	.0888	.0898
14	.0847	.0876	.0890	.0899

Filament No. 10. Acetate

Test 23. Filament Load 1.053 gms.
Initial Observation .6072
60 minutes creep; recovery
Correction .0018 in.

CREEP

Time	Deformation
1/4	.0761
1/2	.0774
3/4	.0781
1	.0785
1 1/2	.0793
2	.0799
3	.0808
5	.0820
7	.0829
10	.0838
15	.0850
20	.0859
30	.0873
40	.0883
50	.0892
59	.0898

RECOVERY

Time	Deformation	Computed Creep Curve	
		Uncorrected	Corrected
60 1/4	.0122	.0883	.0901
1/2	.0110	.0884	.0902
3/4	.0103	.0884	.0902
61	.0096	.0881	.0899
61 1/2	.0088	.0881	.0899
62	.0083	.0882	.0900
63	.0074	.0882	.0900
65	.0064	.0884	.0902
67	.0056	.0885	.0903
70	.0049	.0887	.0905
75	.0041	.0891	.0909
80	.0036	.0895	.0913
90	.0028	.0901	.0919
100	.0023	.0906	.0924

Filament No. 10. Acetate.

Test 18. Filament Load 1.053 gms.
Initial Observation .6168
6 x 10 minutes

Creep and Recovery Deformations (uncorrected)

Time in Loading Period, mins.	Creep I	Rec.I	Creep II	Rec.II	Creep III	Rec.III
1/4	.0766	.0078	.0793	.0088	.0805	.0095
1/2	.0782	.0066	.0810	.0078	.0820	.0087
3/4	.0793	.0059	.0817	.0070	.0829	.0079
1	.0800	.0054	.0825	.0065	.0835	.0074
1 1/2	.0809	.0045	.0832	.0058	.0843	.0065
2	.0817	.0040	.0839	.0053	.0849	.0060
3	.0827	.0033	.0847	.0044	.0857	.0053
5	.0842	.0024	.0859	.0035	.0868	.0042
7	.0853	.0019	.0866	.0030	.0874	.0057
9	.0861	.0015	.0872	.0026	.0880	.0033

Test 18.

Computed Creep Curve 0 - 60 minutes (corrected)

Correction .0016 in.

Time, mins.	0-10 mins.	10-20 mins.	20-30 mins.	30-40 mins.	40-50 mins.	50-60 mins.
1/4	.0766	.0860	.0887	.0897	.0909	.0916
1/2	.0782	.0864	.0892	.0904	.0914	.0923
3/4	.0793	.0866	.0892	.0903	.0915	.0924
1	.0800	.0870	.0895	.0906	.0916	.0925
1 1/2	.0809	.0870	.0893	.0906	.0917	.0924
2	.0817	.0873	.0895	.0908	.0918	.0925
3	.0827	.0876	.0896	.0907	.0917	.0926
5	.0842	.0882	.0899	.0910	.0919	.0926
7	.0853	.0888	.0901	.0912	.0920	.0927
9	.0861	.0892	.0903	.0914	.0922	.0929

Filament No. 10. Acetate

Test 19. Filament Load 1.053 gms.
Initial Observation .6161
4 x 15 minutes

Creep and Recovery Deformations (uncorrected)

Time in Loading Period, mins.	Creep I	Rec. I	Creep II	Rec. II
1/4	.0766	.0089	.0797	.0102
1/2	.0781	.0078	.0811	.0092
3/4	.0790	.0070	.0820	.0084
1	.0797	.0064	.0826	.0077
1 1/2	.0806	.0056	.0834	.0069
2	.0815	.0051	.0841	.0064
3	.0823	.0042	.0849	.0055
5	.0839	.0033	.0861	.0045
7	.0849	.0027	.0868	.0041
10	.0860	.0022	.0877	.0033
14	.0872	.0017	.0885	.0027

Test 19.

Computed Creep Curve 0 - 60 minutes (corrected)

Correction .0016 in.

Time, mins.	0-15 mins.	15-30 mins.	30-45 mins.	45-60 mins.
1/4	.0766	.0871	.0902	.0915
1/2	.0781	.0875	.0905	.0919
3/4	.0790	.0876	.0906	.0920
1	.0797	.0877	.0906	.0919
1 1/2	.0806	.0878	.0906	.0919
2	.0815	.0882	.0908	.0921
3	.0823	.0881	.0907	.0920
5	.0839	.0888	.0910	.0922
7	.0849	.0892	.0911	.0925
10	.0860	.0898	.0915	.0926
14	.0872	.0905	.0918	.0928

Filament No. 10. Acetate.

Test 20. Filament Load 1.053 gms.
Initial Observation .6126
60 minutes creep; recovery
Correction .0016 in.

CREEP

Time	Deformation
1/4	.0755
1/2	.0774
3/4	.0782
1	.0789
1 1/2	.0798
2	.0806
3	.0816
5	.0830
7	.0840
10	.0856
15	.0864
20	.0875
30	.0890
40	.0903
50	.0913
59	.0920

RECOVERY

Time	Deformation	Computed Creep Curve	
		Uncorrected	Corrected
60 1/4	.0140	.0895	.0911
1/2	.0127	.0901	.0917
3/4	.0120	.0902	.0918
61	.0114	.0903	.0919
1/2	.0104	.0902	.0918
62	.0097	.0903	.0919
63	.0088	.0904	.0920
65	.0077	.0907	.0923
67	.0065	.0905	.0921
70	.0059	.0909	.0925
75	.0052	.0916	.0932
80	.0045	.0920	.0936
90	--	--	--
100	.0033	.0936	.0952

Filament No. 10. Acetate.

Test 9. Filament Load 0.856 gm.

Initial Observation .5859

4 x 10 minutes

Creep and Recovery Deformations (uncorrected)

Time in Loading Period, mins.	Creep I	Rec. I	Creep II	Rec.II
1/4	.0666	.0046	.0684	.0053
1/2	.0680	.0038	.0695	.0047
3/4	.0685	.0034	.0701	.0041
1	.0690	.0030	.0705	.0038
1 1/2	.0696	.0026	.0712	.0034
2	.0702	.0022	.0715	.0029
3	.0708	.0017	.0722	.0023
5	.0719	.0011	.0729	.0016
7	.0725	.0008	.0733	.0013
9	.0730	.0004	.0739	.0011

Test 9.

Computed Creep Curve (corrected)

Correction .0014

Time, mins.	0-10 mins.	10-20 mins.	20-30 mins.	30-40 mins.
1/4	.0666	.0728	.0744	.0751
1/2	.0680	.0732	.0747	.0756
3/4	.0685	.0733	.0749	.0756
1	.0690	.0734	.0749	.0757
1 1/2	.0696	.0736	.0752	.0760
2	.0702	.0738	.0751	.0758
3	.0708	.0739	.0753	.0759
5	.0719	.0744	.0754	.0759
7	.0725	.0747	.0755	.0760
9	.0730	.0748	.0757	.0764

Filament No. 4. Nylon I.

Test 9. Filament Load 0.856 gm.
Initial Observation .4640
4 x 10 minutes

Creep and Recovery Deformations (uncorrected)

Time in Loading Period, mins.	Creep I	Rec. I	Creep II	Rec. II
1/4	.1167	--	.1375	--
1/2	.1249	.0312	.1457	.0372
3/4	.1304	.0269	.1506	.0330
1	.1347	.0240	.1540	.0299
1 1/2	.1411	.0204	.1591	.0256
2	.1460	.0179	.1626	.0230
3	.1530	.0148	.1671	.0195
5	.1617	.0116	.1727	.0157
7	.1672	.0098	.1760	.0137
9	.1712	.0086	.1784	.0122

Test 9.

Computed Creep Curve 0 - 40 minutes (corrected)

Correction .0060

Time, mins.	0-10 mins.	10-20 mins.	20-30 mins.	30-40 mins.
1/4	.1167	--	--	
1/2	.1249	.1621	.1829	.1889
3/4	.1304	.1633	.1835	.1896
1	.1347	.1647	.1840	.1899
1 1/2	.1411	.1675	.1855	.1907
2	.1460	.1699	.1865	.1916
3	.1530	.1738	.1879	.1926
5	.1617	.1793	.1903	.1944
7	.1672	.1830	.1918	.1957
9	.1712	.1858	.1930	.1966

Filament No. 4. Nylon I.

Test 3. Filament Load 0.526 gm.
Initial Observation .4605
4 x 10 minutes

Creep and Recovery Deformations

Time in Loading Period, mins.	Creep I	Rec. I	Creep II	Rec. II
1/4	.0695	.0201	.0765	--
1/2	.0732	.0169	.0804	.0204
3/4	.0754	.0148	.0825	.0181
1	.0773	.0133	.0843	.0165
1 1/2	.0799	.0113	.0869	.0141
2	.0819	.0100	.0886	.0127
3	.0850	.0083	.0910	.0107
5	.0890	.0064	.0937	.0087
7	.0919	.0047	.0959	.0076
9	.0936	.0041	.0977	.0063

Test 3.

Computed Creep Curve 0 - 40 minutes (corrected)

Correction .0030

Time, mins.	0-10 mins.	10-20 mins.	20-30 mins.	30-40 mins.
1/4	.0695	.0926	.0996	--
1/2	.0732	.0931	.1003	.1038
3/4	.0754	.0932	.1003	.1036
1	.0773	.0936	.1006	.1038
1 1/2	.0799	.0942	.1012	.1040
2	.0819	.0949	.1016	.1043
3	.0850	.0963	.1023	.1047
5	.0890	.0974	.1031	.1054
7	.0919	.0996	.1036	.1065
9	.0936	.1007	.1048	.1070

Filament No. 4. Nylon I.

Test 4. Filament Load 0.346 gm.
Initial Observation .4557
4 x 10 mins.

Creep and Recovery Deformations (uncorrected)

Time in Loading Period, mins.	Creep I	Rec. I	Creep II	Rec. II
1/4	.0450	--	.0478	.0133
1/2	.0470	.0092	.0499	.0113
3/4	.0481	.0081	.0512	.0101
1	.0490	.0073	.0521	.0090
1 1/2	.0504	.0059	.0536	.0076
2	.0514	.0052	.0546	.0062
3	.0529	.0042	.0558	.0051
5	.0551	.0032	.0570	.0039
7	.0566	.0020	.0583	.0035
9	.0573	.0016	.0594	.0027

Test 4.

Computed Creep Curve 0 - 40 minutes (corrected)

Correction .0021

Time, mins.	0 - 10 mins.	10-20 mins.	20-30 mins.	30-40 mins.
1/4	.0450	--	--	.0636
1/2	.0470	.0583	.0612	.0633
3/4	.0481	.0583	.0614	.0634
1	.0490	.0584	.0615	.0632
1 1/2	.0504	.0584	.0616	.0633
2	.0514	.0587	.0619	.0629
3	.0529	.0592	.0621	.0630
5	.0551	.0604	.0623	.0630
7	.0566	.0607	.0624	.0639
9	.0573	.0610	.0631	.0642

Filament No. 4. Nylon I.

Test 5a. Filament Load 0.346 gm.

Initial Observation .4514

Creep test 100 mins. duration

Creep Deformations

Time	Deformation	Time	Deformation
1/4	.0450	7	.0558
1/2	.0469	10	--
3/4	.0480	15	.0591
1	.0490	20	.0608
1 1/2	.0503	30	.0628
2	.0512	50	.0648
3	.0524	70	.0660
5		100	.0679

Filament No. 5. Viscose I.

Test 18. Filament Load 1.053 gms.

4 x 10 mins.

Creep and Recovery Deformations (uncorrected)

Time in Loading Interval mins.	Creep I	Rec.I	Creep II	Rec.II
1/4	.0511	--	.0546	.0106
1/2	.0529	.0075	.0567	.0095
3/4	.0540	.0066	.0575	.0084
1	.0547	.0060	.0583	.0078
1 1/2	.0559	.0052	.0592	.0068
2	.0568	.0045	.0599	.0061
3	.0581	.0037	.0610	.0052
5	.0599	.0028	.0623	.0042
7	.0612	.0022	.0632	.0037
9	.0623	.0019	.0639	.0032

Test 18.

Computed Creep Curve 0 - 40 minutes (corrected)

Correction .0023

Time, mins.	0-10 mins.	10-20 mins.	20-30 mins.	30-40 mins.
1/4	.0511	--	--	.0675
1/2	.0529	.0627	.0665	.0685
3/4	.0540	.0629	.0664	.0682
1	.0547	.0630	.0666	.0684
1 1/2	.0559	.0634	.0667	.0683
2	.0568	.0636	.0667	.0683
3	.0581	.0641	.0670	.0685
5	.0599	.0650	.0674	.0688
7	.0612	.0657	.0677	.0692
9	.0623	.0665	.0681	.0694

Filament No. 8. Viscose II.

Test 7. Filament Load 1.480 gms.

Initial Observation .1504

4 x 10 minutes

Creep and Recovery Deformations (uncorrected)

Time in Loading Cycle mins.	Creep I	Rec.I	Creep II	Rec.II
1/4	---	.0040	.0351	.0047
1/2	.0346	.0035	.0360	.0040
3/4	.0351	.0031	.0364	.0036
1	.0355	.0028	.0368	.0034
1 1/2	.0359	.0024	.0372	.0030
2	.0363	.0021	.0375	.0026
3	.0369	.0018	.0379	.0023
5	.0377	.0014	.0385	.0019
7	.0382	.0011	.0389	.0016
9	.0386	.0009	.0392	.0014

Test 7.

Computed Creep Curve 0 - 40 minutes (corrected)

Correction .0002

Time, mins.	0-10 mins.	10-20 mins.	20-30 mins.	30-40 mins.
1/4	--	--	.0393	.0400
1/2	.0346	.0383	.0397	.0402
3/4	.0351	.0384	.0397	.0402
1	.0355	.0385	.0398	.0404
1 1/2	.0359	.0385	.0398	.0404
2	.0363	.0386	.0398	.0403
3	.0369	.0389	.0399	.0404
5	.0377	.0393	.0401	.0406
7	.0382	.0395	.0402	.0407
9	.0386	.0397	.0403	.0408

Filament No. 8. Viscose II.

Test 8. Filament Load 1.480 gms.

Initial Observation .1504

Creep Test 40 mins. duration

Creep Deformations

Time, mins.	Deformation	Time, mins.	Deformation
1/4	.0339	7	.0381
1/2	.0346	10	.0387
3/4	.0351	15	.0393
1	.0354	20	.0398
1 1/2	.0359	25	.0402
2	.0362	30	.0406
3	.0367	35	.0409
5	.0376	40	.0410

Filament No. 9. Nylon II.

Test 9. Filament Load 1.480 gms.
Initial Observation .3033
4 x 10 minutes

Time in Loading Period, mins.	Creep I	Rec.I	Creep II	Rec.II
1/4	.1535	.0335	.1704	.0378
1/2	.1635	.0254	.1793	.0297
3/4	.1691	.0215	.1842	.0252
1	.1734	.0185	.1876	.0221
1 1/2	.1795	.0153	.1922	.0184
2	.1838	.0131	.1952	.0159
3	.1898	.0104	.1992	.0131
5	.1969	.0075	.2037	.0100
7	.2010	.0060	.2065	.0082
9	.2038	.0050	.2085	.0071

Test 9.

Computed Creep Curve 0 - 40 minutes (corrected)

Correction .0040

Time, mins.	0-10 mins.	10-20 mins.	20-30 mins.	30-40 mins.
1/4	.1535	.1910	.2079	.2122
1/2	.1635	.1929	.2087	.2130
3/4	.1691	.1946	.2097	.2134
1	.1734	.1959	.2101	.2137
1 1/2	.1795	.1988	.2115	.2146
2	.1838	.2009	.2123	.2151
3	.1898	.2042	.2136	.2163
5	.1969	.2084	.2152	.2177
7	.2010	.2110	.2165	.2187
9	.2038	.2128	.2175	.2196

Filament No. 9. Nylon II.

Test 8. Filament Load 1.053 gms.
Initial Observation .3027
4 x 10 minutes

Creep and Recovery Deformations (uncorrected)

Time in Loading Period, mins.	Creep I	Rec.I	Creep II	Rec.II
1/4	.0899	.0236	.1000	.0265
1/2	.0948	.0189	.1048	.0217
3/4	.0978	.0163	.1077	.0191
1	.1001	.0144	.1098	.0172
1 1/2	.1037	.0120	.1128	.0146
2	.1064	.0104	.1150	.0129
3	.1103	.0085	.1178	.0108
5	.1154	.0063	.1214	.0085
7	.1187	.0050	.1236	.0071
9	.1211	.0042	.1253	.0061

Test 8.

Computed Creep Curve 0 - 40 minutes (corrected)

Correction .0057

Time, mins.	0-10 mins.	10-20 mins.	20-30 mins.	30-40 mins.
1/4	.0899	.1192	.1293	.1322
1/2	.0948	.1194	.1294	.1322
3/4	.0978	.1198	.1297	.1325
1	.1001	.1202	.1299	.1327
1 1/2	.1037	.1214	.1305	.1329
2	.1064	.1225	.1311	.1336
3	.1103	.1245	.1320	.1343
5	.1154	.1274	.1334	.1356
7	.1187	.1294	.1343	.1363
9	.1211	.1310	.1352	.1371

V. Conclusion

Summary of Results.

In this thesis it has been shown that the deformation of filamentous materials under constant longitudinal load consists of an instantaneous part and a part which varies with time; the latter or "creep" deformation in turn consists of part (primary creep) which is recoverable after removal of load and part (secondary creep) which is not immediately recoverable. Under certain conditions, a state of strain can be imposed upon a filament, so that no further secondary creep takes place; it is then said to be "mechanically conditioned". In such a filament the instantaneous deformation is proportional to load; the delayed deformation does not appear to be proportional to load, but varies with load by a scale factor; it obeys the Superposition Principle of Boltzmann. The strain associated with mechanical conditioning appears to be removable in part or in whole by suitable "swelling recovery" treatment. All these phenomena can be explained very easily in terms of the "fringed micelle" theory of structure; the concept of mechanical models can be applied only qualitatively because of the non-proportionality of creep and load.

Future Work.

It is hardly necessary to point out that the field of fiber physics is an ever-widening one. In the present line of work, namely, creep research, many problems remain to be investigated. The creep behavior of nylon at high loads and the temperature effect on this behavior will throw light on the mechanism of kinetic elasticity. The creep behavior of wool in water and presumably also in air at different humidities appears to be analogous to that of nylon. Finally rubber and synthetic resins both plasticised and unplasticised should be studied by the general methods outlined above.

To parallel the creep study on wool and nylon a study is required of the thermoelastic behavior under different conditions and strains; and finally this work should be correlated, in the case of nylon and other materials yielding sharp X-ray patterns, with changes of the X-ray pattern due to strain.

Part VI.

BIBLIOGRAPHY

1. Weber, W. Ueber die Elasticität von Seidenfaden.
   Pogg. Ann. der Physik 110, 247 (1835).

2. Weber, W. Ueber die Elasticität fester Körper.
   Pogg. Ann. der Physik 54, 1 (1841).

3. Kohlrausch, R. Nachtrag über die elastische Nachwirkung beim Cocon und Glasfaden, etc.
   Pogg. Ann. der Physik (3) 2, 393 (1847).

4. Kohlrausch, R. Theorie des elektrischen Rückstandes in der Leidener Flasche.
   Pogg. Ann. der Physik 91, 56, 179 (1854).

5. Kohlrausch, F. Ueber die elastische Nachwirkung bei der Torsion.
   Pogg. Ann. der Physik (4) 29, 337 (1863).

6. Kohlrausch, F. Beiträge zur Kenntniss der elastischen Nachwirkung.
   Pogg. Ann. der Physik (5) 8, 1, 207, 399 (1866).

7. Maxwell, J. Clerk. The Dynamical Theory of Gases.
   Phil. Trans. Roy. Soc. 157, 52 (1867)= Scientific Papers 2, 26, Cambridge, 1890.

8. Maxwell, J. Clark. Electricity and Magnetism.
   Oxford 1873. Chapter X.

9. Boltzmann, L. Zur Theorie der elastischen Nachwirkung.
   Sitzungsberichte der K. Akad. der Wissenschaften, Wien; Math.-Naturw. Classe 70, 275 (1874) = Pogg. Ann. der Physik, 7, 624 (1876).

10. Meyer, O.E. Theorie der elastischen Nachwirkung.
    Pogg. Ann. der Physik (6) 1, 108 (1874).

11. Neesen, F. Beitrag zur Kenntniss der elastischen Nachwirkung bei Torsion.
    Pogg. Ann. der Physik (6) 3, 498 (1874).

12. Streintz, H. Ueber die Dämpfung der Torsionsschwingungen von Drähten.
    Pogg. Ann. der Physik (6) 3, 387 (1874).

13. Kohlrausch, F. Bemerkungen, etc.
Pogg. Ann. der Physik (6) 5, 579 (1875).

14. Meyer, O.E. Bemerkungen, etc.
Pogg. Ann. der Physik (6) 4, 354 (1875).

15. Streintz, H. Erwiderung, etc.
Pogg. Ann. der Physik (6) 5, 588 (1875).

16. Hopkinson, J. The Residual Charge of a Leyden Jar.
Proc. Roy. Soc. Lond. 24, 407 (1876) = Phil. Mag. (5) 2, 314 (1876).

17. Hopkinson, J. The Residual Charge of the Leyden Jar.
Phil. Trans. Roy. Soc. Lond. 166, 489 (1876).

18. Kohlrausch, F. Experimental-Untersuchung über die elastische Nachwirkung bei der Torsion, Ausdehnung, und Biegung.
Pogg. Ann. der Physik (6) 8, 187, 337 (1876).

19. Neesen, F. Ueber die elastische Nachwirkung.
Pogg. Ann. der Physik (6) 7, 579 (1876).

20. Boltzmann, L. Ueber einige Probleme der Theorie der elastischen Nachwirkung, etc.
Sitzungsberichte der K. Akad. der Wissenschaften, Wien. 76, 815 (1877).

21. Hopkinson, J. Residual Charge of the Leyden Jar.
Phil. Trans. Roy. Soc. Lond. 167, 599 (1877).

22. Kohlrausch, F. Beitrag zu Boltzmann's Theorie der elastischen Nachwirkung.
Pogg. Ann. der Physik (6) 10, 225 (1877).

23. Maxwell, J. Clerk. Constitution of Bodies.
Encyclopaedia Britannica 6th Edn. 9, 315 (1877) = Collected Works 2, 616. Cambridge, 1890.

24. Boltzmann, L. Zur Theorie der elastischen Nachwirkung.
Wied. Ann. der Physik 5, 430 (1878).

25. Hopkinson, J. On the Torsional Strain which Remains in a Glass Fibre after Release from Twisting Stress.
Proc. Roy. Soc. Lond. 28, 148 (1878).

26. Klemencic, I. Beobachtungen über die elastische Nachwirkung am Glase.
Sitzungsberichte der K. Akad. der Wissenschaften, Wien. 78, 481 (1878).

27. Meyer, O.E. Ueber die elastische Nachwirkung.
Wied. Ann. der Physik 4, 249 (1878).

28. Warburg, E. Ueber das Gleichgewicht eines Systems ausgedehnter Molecüle und die Theorie der elastischen Nachwirkung.
Wied. Ann. der Physik. 4, 232 (1878).

29. Neesen, F. Versuche über die elastische Nachwirkung bei Längsdehnung.
Wied. Ann. der Physik 7, 460 (1879).

30. Pulfrich, C. Ueber die elastische Nachwirkung eines Kautschukschlauches, etc.
Wied. Ann. der Physik 28, 87 (1886).

31. Schröder, T. Experimentaluntersuchung über den Einfluss der Temperatur auf die elastische Nachwirkung.
Wied. Ann. der Physik 28, 370 (1886).

32. Weidmann, G. Ueber den Zusammenhang zwischen elastischer und thermischer Nachwirkung des Glases.
Wied. Ann. der Physik 29, 214 (1886).

33. Rehkuh, F. Die elastische Nachwirkung bei Silber, Glas, Kupfer, Gold, und Platin, etc.
Wied. Ann. der Physik 35, 476 (1888).

34. Thomson, J.J. Applications of Dynamics to Physics and Chemistry.
Macmillan, 1888. Chapter 8: On Residual Effects.

35. Schwedoff, T. Recherches Experimentales sur la Cohesion des Liquides.
Jour. de Physique 8, 341 (1889).

36. Austin, L. Experimentaluntersuchungen über die elastische Längs- und Torsionsnachwirkung in Metallen.
Wied. Ann. der Physik 50, 659 (1893).

37. Wiechert, E. Gesetze der elastischen Nachwirkung für constante Temperatur.
Wied. Ann. der Physik 50, 335, 546 (1893).

38. Poynting, J.H.; Thomson, J.J. Properties of Matter.
London, 1902.

39. Trouton, F.T.; Andrews, E.S. On the Viscosity of Pitch-Like Substances.
Phil. Mag. (6) 7, 347 (1904) = Proc. Phys. Soc. 19, 47 (1904).

40. Trouton, F.T.; Rankine, A.O. On the Stretching and Torsion of Lead Wire Beyond the Elastic Limit.
Phil. Mag. (6) 8, 538 (1904).

41. Phillips, P. The slow Stretch of Indiarubber Glass, and Metal Wires when Subjected to a Constant Pull. Phil. Mag. (6) 9, 513 (1905) = Proc. Phys. Soc. Lond. 19, 491 (1905).

42. Trouton, F.T. On the Coefficient of Viscous Traction and its Relation to that of Viscosity. Proc. Roy. Soc. A. 78, 426 (1906).

43. Auerbach, F. Elastische Nachwirkung. Winkelmann's Handbuch der Physik (2nd Edn.) 1, 796. Berlin, 1908.

44. Andrade, E.N. da C. On the Viscous Flow in Metals and Allied Phenomena. Proc. Roy. Soc. 84, 1 (1910).

45. Schwartz, A. The Testing of Rubber for Electrical Work. J. Inst. Elec. Eng. 44, 693 (1910).

46. de Guzmán, J. Relación entre la Fluidez y el Calor de Fusión. Anales de la Sociedad Española de Física y Química 11, 353 (1913).

47. Wagner, K.W. Zur Theorie der unvollkommenen Dielektrica. Ann. der Physik (4) 40, 817 (1913).

48. Andrade, E.N. da C. Flow in Metals under Large Constant Stresses. Proc. Roy. Soc. A. 90, 329 (1914).

49. Jordan, H. Ueber eine Störung der elastischen Nachwirkung durch elastische Hysteresis. Verh. der d. Phys. Gesell. 13, 579 (1915).

50. Warburg, E.; Heuser, W. Elastische Nachwirkung und elastische Hysteresis. Verh. der d. Phys. Gesell. 13, 206 (1915).

51. von Wartenberg, H. Ueber elastische Nachwirkung bei Metallen. Verh. der d. Phys. Gesell. 20, 113 (1918).

52. Bennewitz, K. Ueber die elastische Nachwirkung. Phys. Zeits. 21, 703 (1920).

53. Filon, L.N.G.; Jessop, H.T. Stress-Optical Effect in Transparent Solids. Phil. Trans. Roy. Soc. A. 223, 89 (1923).

54. Peirce, F.T. The Plasticity of Cotton and Other Materials. J.T.I., 14, T390 (1923).

55. Bennewitz, K. Ueber elastische Nachwirkung, elastische Hysteresis, und Innere Reibung.
Phys. Zeits. 25, 417 (1924).

56. Jordan, H. Ueber elastische Nachwirkung, elastische Hysteresis und Innere Reibung.
Phys. Zeits. 25, 579 (1924).

57. Shorter, S.A. An Investigation of the Nature of the Elasticity of Fibres.
J.T.I., 15, T207, (1924).

58. Shorter, S.A. The Physical Properties of Textile Fibres in Relation to Technical Processes and to General Colloid Theory.
Trans. Far. Soc. 20, 228 (1924).

59. Becker, R. Elastische Nachwirkung und Plastizität.
Zeits. für Physik 33, 185 (1925).

60. Poole, H.J. The Elasticity of Gelatin Jellies, etc.
Trans. Far. Soc. 21, 114 (1925).

61. Dunn, J.S. A Simple Kinetic Theory of Viscosity.
Trans. Far. Soc. 22, 401 (1926).

62. Gerngross, O.; Katz, J.R. Roentgenspektrographische Untersuchungen über die Hitze-Kontraktion von ungegerbten und formaldehydgegerbten Sehnen.
Kolloidchem. Beihefte 23, 368 (1926).

63. Mann, J.C.: Peirce, F.T. The Time Factor in Hair Testing.
J.T.I., 17, T83 (1926).

64. Speakman, J.B. The Gel Structure of Wool Fibre.
J.T.I., 17, T457 (1926).

65. Speakman, J.B. The Extension of Wool Fibres under Constant Stress.
J.T.I., 17, T472 (1926).

66. Peirce, F.T. Time Effects.
J.T.I., 18, T481 (1927).

67. Shorter, S.A. The Gel Structure of the Wool Fibre.
J.T.I., 18, T78 (1927).

68. Speakman, J.B. The Intracellular Structure of the Wool Fibre.
J.T.I., 18, T431 (1927).

69. Speakman, J.B. The Plasticity of Wool.
Proc. Roy. Soc. B. 103, 377 (1928).

70. Fromm, H. Nachwirkung und Hysteresis.
Handbuch der Physikalischen und Technischen Mechanik
4, pt. 1., 436-457; 504-550 (Leipzig, 1929).

71. Rocha, H.J. Fraktionierte Fällung von aceton-löslicher Acetylcellulose.
Koll. Chem. Beih. 30, 230 (1929).

72. Speakman, J.B. The Rigidity of Wool and its Change with Adsorption of Water Vapour.
Trans. Far. Soc. 25, 92 (1929).

73. Speakman, J.B. Elastic Properties of Wool in Water at High Temperatures.
Trans. Far. Soc. 25, 169 (1929).

74. Eckling, K.; Kratky, O. Texturbestimmung an Ramie-Einzelfasern, etc.
Z. Phys. Chem. B. 10, 368 (1930).

75. Gerngross, O.; Herrmann, K.; Abitz, W. Zur röntgenographischen Strukturerforschung des Gelatinmicells.
Naturw. 34, 754 (1930).

76. Gerngross, O.; Herrmann, K.; Abitz, W. Ueber den Feinbau des Gelatinmicells.
Biochem. Z. 228, 409 (1930).

77. Herrmann, K.; Gerngross, O.; Abitz, W. Zur röntgenographischen Strukturerforschung des Gelatinmicells.
Z. Phys. Chem. B., 10, 371 (1930).

78. Meyer, K.H.; Mark, H. Der Aufbau der hochpolymerer organischer Naturstoffe.
Berlin, 1930.

79. Murphy, E.J.; Lowry, H.H. The Complex Nature of Dielectric Absorption and Dielectric Loss.
J. Phys. Chem. 34, 598 (1930).

80. Volterra, Vito. Theory of Functionals.
London, 1930.

81. Weltzien, W. Chemische und physikalische Technologie der Kunstseiden.
Leipzig, 1930.

82. Whitby, G.S. Some Fundamental Rubber Problems.
Trans. Inst. Rubber Ind., 6, 40 (1930).

83. Carothers, W.H. Polymerisation.
Chem. Reviews 8, 353 (1931).

84. de Witt Smith, H. Apparatus for the Measurement of Flow and Relaxation of Textile Filaments.
J. T. I., 22, T158 (1931).

85. de Witt Smith, H.; Eisenschitz, R. Flow and Relaxation of Rayon Filaments.
J.T.I., 22, T170 (1931).

86. Astbury, W.T.; Woods, H.J. The Molecular Structure of Textile Fibres.
J.T.I., 23, T17 (1932).

87. Busse, W.F. The Physical Structure of Elastic Colloids.
J. Phys. Chem. 36, 2862 (1932).

88. Carothers, W.H.; Hill, J.W. The Use of Molecular Evaporation as a Means for Propagating Chemical Reactions.
J. Am. Chem. Soc. 54, 1557 (1932).

89. Carothers, W.H.; Hill, J.W. Linear Superpolyesters.
J. Am. Chem. Soc. 54, 1559 (1932).

90. Carothers, W.H.; Hill, J.W. Polyamides and Mixed Polyester-Polyamides.
J. Am. Chem. 54, 1566 (1932).

91. Carothers, W.H.; Hill, J.W. Artificial Fibers from Synthetic Linear Condensation Superpolymers.
J. Am. Chem. Soc. 54, 1579 (1932).

92. Gerngross, O.; Herrmann, L.; Lindemann, R. Ueber die reversible Sol-Gel Umwandlung, die "Kristallisation" der Gelatine und den Feinbau elastischer Gele insbesondere von Gelatine und Kautschuk im Lichte der Röntgenoptik.
Koll. Z. 60, 276 (1932).

93. Herrmann, K.; Gerngross, O. Die Elastizität des Kautschuks.
Kautschuk 8, 181 (1932).

94. Jeffreys, H. On Plasticity and Creep in Solids.
Proc. Roy. Soc. A., 138, 283 (1932).

95. Mark, H. Physik und Chemie der Cellulose.
Springer, 1932.

96. Meyer, K.H.; Susich, G. von; Valko, E. Die elastischen Eigenschaften der organischen Hochpolymeren und ihre kinetische Deutung.
Koll. Z. 59, 208 (1932).

97. Schofield, R.H.; Scott-Blair, G.W. The Relationship between Viscosity, Elasticity, and Plastic Strength of Soft Materials, etc.
Proc. Roy. Soc. A., 138, 707 (1932).

98. Sheppard, S.E.; Houck, R.C. The Structure of Gelatin Sols and Gels.. IV. Fluidity and Hydrolysis.
J. Phys. Chem. 36, 2319 (1932).

99. Sheppard, S.E.; Houck, R.C. The Structure of Gelatin Sols and Gels. V. The Insolubilization of Gelatin by Heat.
J. Phys. Chem. 36, 2885 (1932).

100. Staudinger, H. Die hochmolekularen organischen Verbindungen. Kautschuk und Cellulose. Springer 1932.

101. Staudinger, H. Ueber die Elastizität des Kautschuks.
Koll. Z. 60, 296 (1932).

102. Valko, E. Der Elastizitätsmodul der Cellulosederivate bei tiefen Temperaturen.
Melliand Textilberichte 13, 461 (1932).

103. Astbury, W.T. The Fundamentals of Fibre Structure.
Oxford, 1933.

104. Carothers, W.H.; van Natta, F.J. Polyesters from ω-Hydroxy-decanoic Acid.
J. Am. Chem. Soc. 55, 4714, 1933.

105. Denham, W.S.; Lonsdale, T. The Tensile Properties of Silk Filaments.
Trans. Far. Soc. 29, 305 (1933).

106. Katz, J.R. The Laws of Swelling.
Trans. Far. Soc. 29, 279 (1933).

107. Lloyd, D.J.; Marriot, R.H. The Swelling of Protein Fibres, II.
Trans. Far. Soc. 29, 1228 (1933).

108. Mark, H. Fine Structure and Mechanical Properties of Fibres.
Trans. Far. Soc. 29, 6 (1933).

109. Preston, J.M. Relations between the Refractive Indices and the Behavior of Cellulose Fibres.
Trans. Far. Soc. 29, 65 (1933).

110. Sisson, W.A. X-Ray Analysis of Textile Fibres: I. Literature Survey.
Text. Rsch. 3, 242, 295 (1933).

111. Sisson, W.A.; Clark, L. X-Ray Method for Quantitative Comparison of Crystallite Orientation in Cellulose Fibers.
Ind. Eng. Chem. 5, 296 (1933).

112. Thompson, J.H.C. On the Theory of Viscoelasticity, etc.
Phil. Trans. Roy. Soc. A. 231, 339 (1933).

113. Halle, F. Roentgenoscopie organischer Gele.
Koll. Z. 69, 324 (1934).

114. Houwink, R. Physikalische Eigenschaften und Feinbau von Natur- und Kunstharzen.
Leipzig, 1934.

115. Katz, J.R. Die Roentgenspektrographie als Untersuchungsmethode, etc.
Berlin, 1934. (also in Abderhalden's Handbuch der Biologischen Arbeitsmethoden Abt. 2,Teil 3, 2.)

116. Sisson, W.A. X-Ray Analysis of Textile Fibres. II. Experimental Methods.
Text. Rsch. 4, 286 (1934).

117. Sisson, W.A. X-Ray Analysis of Textile Fibres. IA. Literature Survey.
Text. Rsch. 4, 429 (1934).

118. Steinberger, R.L. The Stress-Strain Relation in Textile Fibers.
Physics 5, 53 (1934).

119. Steinberger, R.L. Elastic and Plastic Properties of Textile Fibers. I.
Text. Rsch. 4, 207 (1934).

120. Steinberger, R.L. Elastic and Plastic Properties of Textile Fibers. II.
Text. Rsch. 4, 271 (1934).

121. Steinberger, R.L. The Stress-Strain Relation in Celanese Single Fibres.
Text. Rsch. 4, 543 (1934).

122. Weibel, E.E. Studies in Photoelastic Stress Determination.
Trans. A.S.M.E. 56, APM-56-13 (1934).

123. Amsterdam, University of. First Report on Viscosity and Plasticity.
Amsterdam, 1935.

124. Ferry, J.D.; Parks, G.S. Viscous Properties of Polyisobutylene.
Physics 6, 356 (1935).

125. Gemant, A. Compressional Waves in Media with Complex Viscosity.
Physics 6, 363 (1935).

126. Meyer, K. H.; Ferri, C. Sur l'elasticite du caoutchouc.
Helv. Chim. Acta 18, 570 (1935).

127. Sisson, W.A. X-Ray Analysis of Textile Fibres. III. Structure of the Cellulose Crystallite as Interpreted from X-Ray Diffraction Data.
Text. Rsch. 5, 119 (1935).

128. Sisson, W.A. X-Ray Studies of Crystallite Orientation in Cellulose Fibers.
Ind. Eng. Chem. 27, 51 (1935).

129. Wikstrom, A. Some Electrical Properties of Ceresin Wax.
Physics 6, 86 (1935).

130. Yager, W.A. The Distribution of Relaxation Times in Typical Dielectrics.
Physics 7, 434 (1935).

131. Houwink, R. High Elasticity of Three Dimensionally Polymerised Amorphous Materials in Relation to their Structure.
Trans. Far. Soc. 32, 131 (1936).

132. Katz, J.R. X-Ray Spectrography of Polymers and in Particular those having a Rubber-Like Extensibility.
Trans. Far. Soc. 32, 77 (1936).

133. Meyer, K.H.; Lotmar, W. Sur l'elasticite de la cellulose.
Helv. Chim. Acta 19, 68 (1936).

134. Steinberger, R.L. Creep in Cellulose Acetate Filaments.
Text. Rsch. 6, 191 (1936).

135. Steinberger, R.L. Creep in Cuprammonium Filaments.
Text. Rsch. 6, 267 (1936).

136. Steinberger, R.L. Creep in Single Fibres of American Delta Cotton.
Text. Rsch. 6, 325 (1936).

137. Steinberger, R.L. Torque Relaxation and Torsional Energy in Crepe Yarn.
Text. Rsch. 7, 83 (1936).

138. Alexandrov, A. Problems of Technical Physics in the Leningrad Physical Technical Institute. III. The Properties of Amorphous Bodies. IV. The Control of Relaxation Effects.
Tech. Phys. U.S.S.R. 4, 929 (1937).

139. Carson, R.W. Measuring Elastic Drift.
Proc. Am. Soc. Test. Mat. 37, 661 (1937).

140. Halle, F. Ueber den Aufbau der Eiweissmoleküle.
Koll. Z. 81, 334 (1937).

141. Hermans, P.H.; de Leeuw, A.J. Deformationsmechanismus Quellungsanisotropie und mechanische Eigenschaften stark gequollener Hydratcellulosegele.
Koll. Z. 81, 300 (1937).

142. Houwink, R. Elasticity, Plasticity, and the Structure of Matter.
Cambridge, 1937.

143. Kobeko, P.; Kuvshinskij, E.; Gurevitch, G. Elasticity of Amorphous Bodies.
Techn. Phys. U.S.S.R. 4, 622 (1937).

144. Kratky, O.; Mark, H. Zur Frage der individuellen Cellulosemicellen.
Z. Phys. Chem. B. 36, 129 (1937).

145. Meyer, K.H.; Picken, L.E.R. The Thermoelastic Properties of Muscle and their Molecular Interpretation.
Proc. Roy. Soc. B. 124, 29 (1937).

146. Misch, L.; Picken, L. Ueber den Aufbau von Polyvinylacetat.
Z. Phys. Chem. B. 36, 398 (1937).

147. Sauter, E. Elementarzellendiagramme und Mikrostruktur von Kautschuk Einkristallen.
Z. Phys. Chem. B. 36, 405 (1937).

148. Alexandrov, A.; Dzhian, J. Dielectric Losses in Swelled Rubbers.
Techn. Phys. U.S.S.R. 5, 836 (1938).

149. Gross, S.T.; Clark, G.L. A Test of the Alternative Structures Proposed for Cellulose.
Text. Rsch. 9, 7 (1938) = Z. für Krist. 99, 357 (1938).

150. Hermans, P.H.; de Leeuw, A.J. Deformations mechanismus und Quellungsanisotropie bei Hydratcellulose-Gelen verschiedenen Quellungsgrades.
Koll. Z. 82, 58 (1938).

151. Hetenyi, M. The Fundamentals of Three-Dimensional Photoelasticity.
Trans. A.S.M.E. 60, A-149 (1938).

152. Kobeko, P.; Kuvshinskij, E.; Shishkin, N. Viscosity, Electrical Conductivity, and Dielectric Losses in Alcohols and Glycerol.
Techn. Phys. U.S.S.R., 5, 413 (1938).

153. Kuvshinskij, E.; Kobeko, P. Dielectric Relaxation in Amorphous Phenolphthalein.
Techn. Phys. U.S.S.R., 5, 401 (1938).

154. Leaderman, H. Creep, Elastic Hysteresis and Damping in Bakelite.
M.I.T. Thesis (1938).

155. Mark, H. Natural and Artificial Rubber: The Elasticity of Long Chain Molecules.
Nature 141, 670 (1938).

156. Mark, H. Aspects of High Polymeric Chemistry.
Nature 142, 937 (1938) = J.T.I., 30, P39 (1939).

157. Mikhailov, G.; Kirilina, V. Study of the Elastic Relaxation by a Resonance Method.
Techn. Phys. U.S.S.R., 5, 842 (1938).

158. Morey, G.W. Properties of Glass.
Reinhold Publishing Corp., 1938.

159. Richter, G. Ueber magnetische und mechanische Nachwirkung.
Article in Probleme der Technischen Magnetisierungskurve. Springer, 1938.

160. Scott Blair, G.W. Introduction to Industrial Rheology.
Philadelphia, 1938.

161. Sisson, W.A. X-Ray Diffraction Behavior of Cellulose Derivatives.
Ind. Eng. Chem. 30, 530 (1938).

162. Thiessen, P.A.; Wittstadt, W. Erzwungene und spontane Aenderung der molekularen Ordnung im gedehnten Kautshuk.
Z. Phys. Chem. B. 41, 33 (1938).

163. Thiessen, P.A. Contribution to discussion on paper by P. H. Hermans.
Angew. Chemie 51, 170 (1938).

164. Astbury, W.T. The X-Ray Study of Proteins and Related Structures.
Science Progress 34, 1, (1939).

165. Bateson, S. Note on the Elastic Properties of Vinyl Sheeting.
J. Appl. Physics 10, 887 (1939).

166. Hetenyi, M. The Application of Hardening Resins in Three-Dimensional Photoelastic Studies.
J. App. Phys. 10, 295 (1939).

167. Kargin, V.A.; Michailov, N.V. An X-Ray Study of the Orientation of Artificial Fibre. Acta Physicochimica U.R.S.S., 11, 343 (1939).

168. Kratky, O. The Network Structure of Cellulose. Silk and Rayon 13, 480, 571, 634 (1939).

169. Kuhn, W. Beziehungen zwischen Viscosität und elastischen Eigenschaften amorpher Stoffe. Z. Phys. Chem. B. 42, 1 (1939).

170. Leaderman, H. Creep, Elastic Hysteresis, and Damping in Bakelite under Torsion. Trans. A.S.M.E. 61, A-79 (1939).

171. Mark, H. Structure of the Rayon Fibre. Nature 144, 313 (1939).

172. Marsden, R.J.B. Cellulose Textile Chemistry. Article in: Reports of the Progress of Applied Chemistry 24 (1939).

173. Rideal, E.K. Polymerisation and its Bearing on the Production of New Synthetic Fibres and Finishes for Textile Fibres. J.T.I. 30, P238 (1939).

174. Alexandrov, A.P.; Lazurkin, J.S. Highly Elastic Deformation in Polymers. Acta Physicochimica U.R.S.S. 12, 647 (1940).

175. Bellinson, H.R. Viscose Rayon: Stress-Strain Properties. Text. Rsch. 10, 287, 316, 372 (1940).

176. Carothers, W.H. Collected Papers on Polymerisation (ed. H. Mark, G.S. Whitby). High Polymers, vol. 1. New York, 1940.

177. Farwell, H.W. Tension and Birefringence in a Vinylite Plastic. J. App. Phys. 11, 274 (1940).

178. Fuller, C.S. The Investigation of Synthetic Linear Polymers by X-Rays. Chem. Reviews 26, 143 (1940).

179. Gehman, S.D. The Contribution of X-Ray Research to the Knowledge of Rubber. Chem. Reviews 26, 203 (1940).

180. Gurevitch, G.; Kobeko, P. On the Technique of the Mechanical Testing of Soft and Hard Rubber and Plastics. Acta Physicochimica U.R.S.S. 12, 681 (1940).

181. Hartshorn, L.; Megson, N.J.L.; Rushton, E. The Dielectric Properties of some Thermoplastics. Proc. Phys. Soc. 52, 796 (1940).

182. Hartshorn, L.; Megson, N.J.L.; Rushton, E. Molecular Relaxation and the Elastic and Dielectric Properties of Plastics. Proc. Phys. Soc. 52, 817 (1940).

183. Kargin, V.A.; Slonimsky, G.L. Ueber die Gesetze der Deformation realer Materialen II. Die Deformation hochpolymerer Materialen. Acta Physicochimica U.R.S.S. 12, 931 (1940).

184. Kratky, O. Der micellare Aufbau der Cellulose und ihrer Derivate. Angew. Chemie 53, 153 (1940).

185. Lazurkin, J.S. On a Dynamic Method for the Study of Elastic Materials. Acta Physicochimica U.R.S.S. 12, 669 (1940).

186. Manning, M.F.; Bell, M.E. Electrical Conduction and Related Phenomena in Solid Dielectrics. Rev. Mod. Phys. 12, 215 (1940).

187. Mark, H. Intermicellar Hole and Tube System in Fiber Structure. J. Phys. Chem. 44, 764 (1940).

188. Mark, H. Elasticity of Natural and Synthetic Rubber. Trans. Inst. Rubber Ind. 15, 271 (1940).

189. Nissan, A.H.; Clark, L.V.W.; Nash, A.W. The Dependence of Viscosity of Liquids on Constitution. Jour. Inst. Petroleum. 26, 155 (1940).

190. Sisson, W.A. X-Ray Studies Regarding the Structure and Behavior of Native Cellulose Membranes. Chem. Reviews 26, 187 (1940).

191. Slonimsky, G.L. On the Laws of Deformation of Real Materials I. Acta Physicochimica U.R.S.S. 12, 99 (1940).

192. Treloar, L.R.G. Elastic Recovery and Plastic Flow in Raw Rubber. Trans. Far. Soc. 36, 538 (1940).

193. Davies, J.M.; Miller, R.F.; Busse, W.F. Dielectric Properties of Plasticised Polyvinyl Chloride. J. Am. Chem. Soc. 63, 361 (1941).

194. Leaderman, H. Textile Materials and the Time Factor. I. Mechanical Behavior of Textile Fibers and Plastics. Text. Rsch. 11, 171 (1941).

195. Leaderman, H. The Primary Creep of Materials with Rubber-like Extensibility. Unpublished Report to the Textile Foundation (1941).

APPENDIX: BIOGRAPHICAL NOTE.

Herbert Leaderman was born in London, England, on November 4, 1913. He received his primary and high school education in London. He was in residence at Cambridge University from 1931 to 1934 as an undergraduate of Queens' College. He graduated in 1934 with first class Honours in the Mechanical Sciences Tripos, and obtained first class Honours in the External Examination for Bachelor of Science (Engineering) of the University of London.

From October 1934 to September 1936 he was engaged in the aircraft industry, first in stress analysis for the Fairey Aircraft Company and later in aerodynamic computations and investigations for Hawker Aircraft Limited. During part of this time he was honorary secretary of the Students' Section of the Royal Aeronautical Society. A paper on Boundary Layer Theory published in the Journal of the Royal Aeronautical Society (40, 65, 1936) gained for the author the Pilcher Memorial Prize awarded by the Society.

From September 1936 to July 1937 the author was employed, under the auspices of the Department of Scientific and Industrial Research, as an assistant to Dr. N. A. de Bruyne of Trinity College, Cambridge; his duties were concerned with the investigation of the fundamental properties of plastic materials. The academic year 1937-1938 was spent as holder of a Robert Blair Travelling Fellowship in the

Graduate School of the Massachusetts Institute of Technology. During this time the author was interested in the creep and internal friction properties of materials. In October 1938 he was awarded a Master of Science degree by the Massachusetts Institute of Technology. His thesis on "Creep, Elastic Hysteresis and Damping in Bakelite" was later published in the Journal of Applied Mechanics (Trans. A.S.M.E., 61, A-79, 1939).

Since September 1938 the author has been engaged as Research Assistant at the Institute. For the first two years part of his time was spent working under Professor A. V. de Forest on strain gage research; the results of this work have been published in N.A.C.A. Technical Note No. 744. The author has been engaged, part-time during this period and full-time subsequently, in the Textile Laboratory of the Institute in research on the creep properties of filamentous and other materials. A preliminary paper entitled "Textile Materials and the Time Factor. I. Mechanical Behavior of Textile Fibers and Plastics" has been published in Textile Research (11, 171, 1941). The author is a member of the Society of Sigma Xi.

H. Leaderman

Elastic and Creep Properties of Filamentous Materials

Figs. 1-143

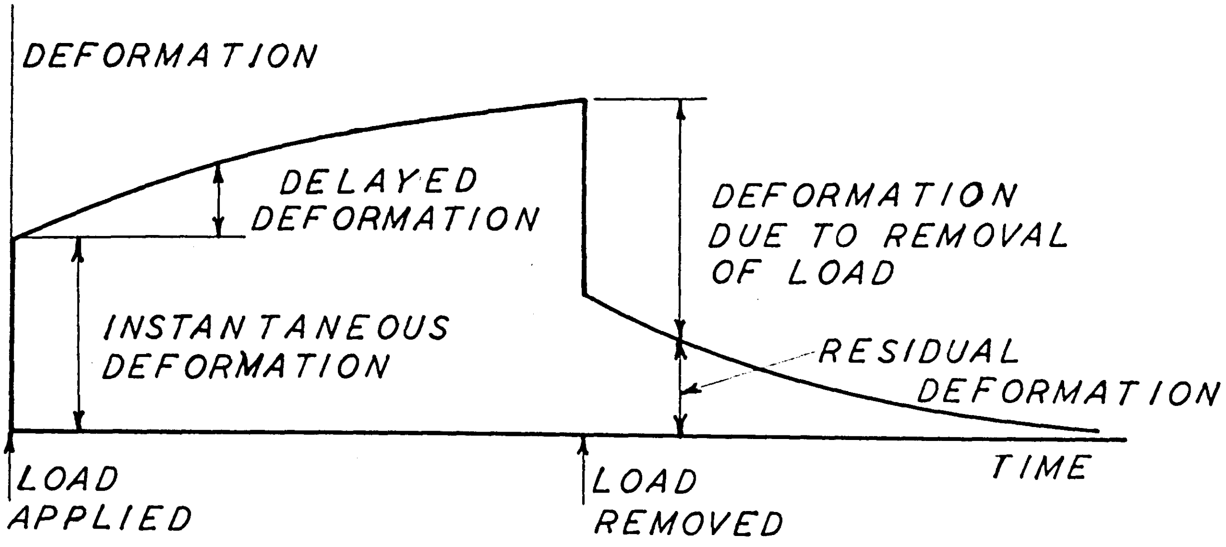


FIG. 1a
CREEP AND CREEP RECOVERY

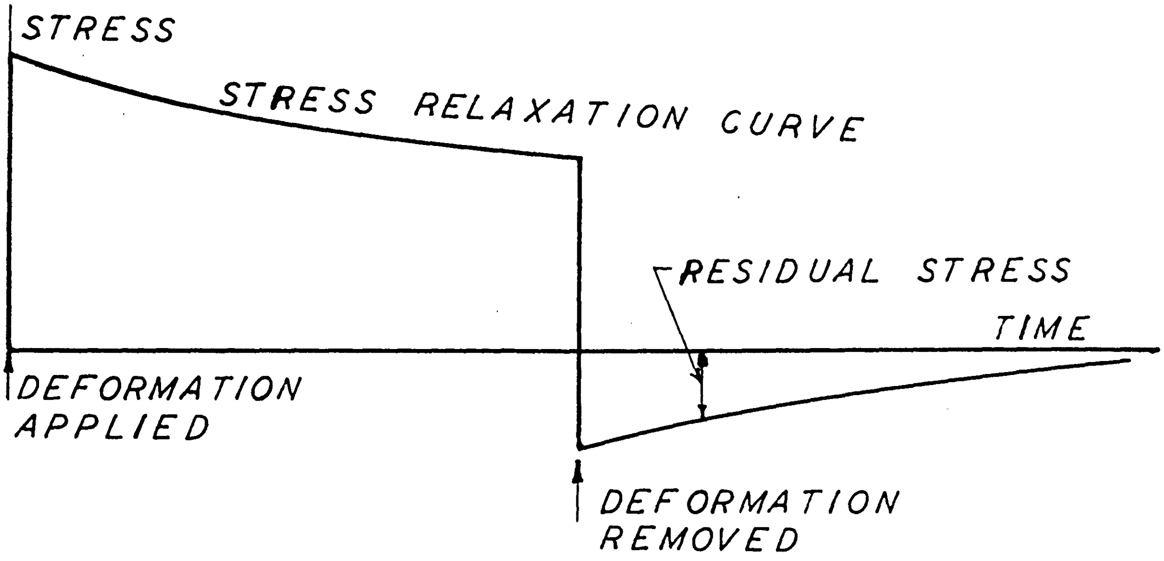
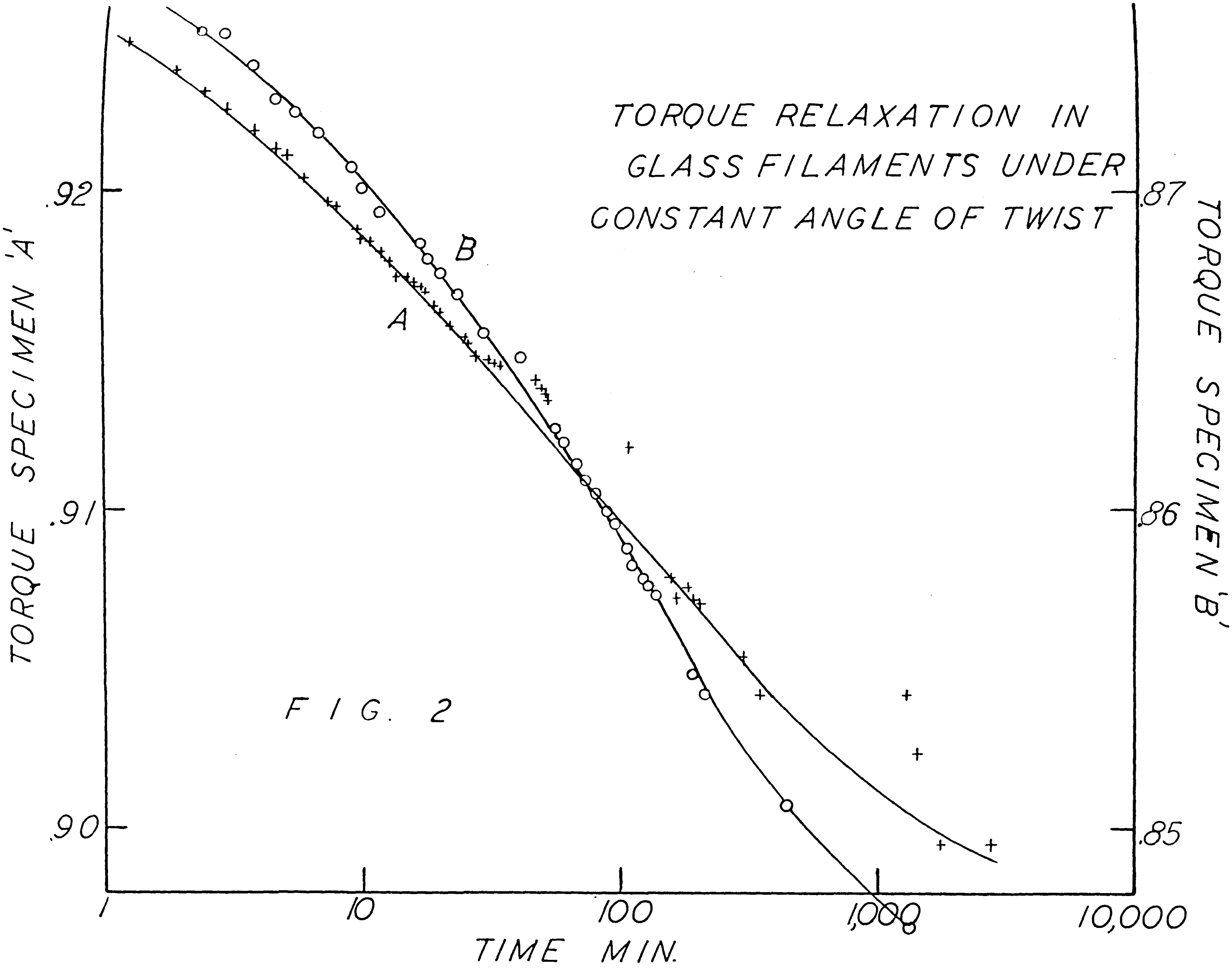


FIG. 1b
RELAXATION OF STRESS AND RESIDUAL STRESS



TORQUE RELAXATION IN GLASS FILAMENTS UNDER CONSTANT ANGLE OF TWIST

FIG. 2

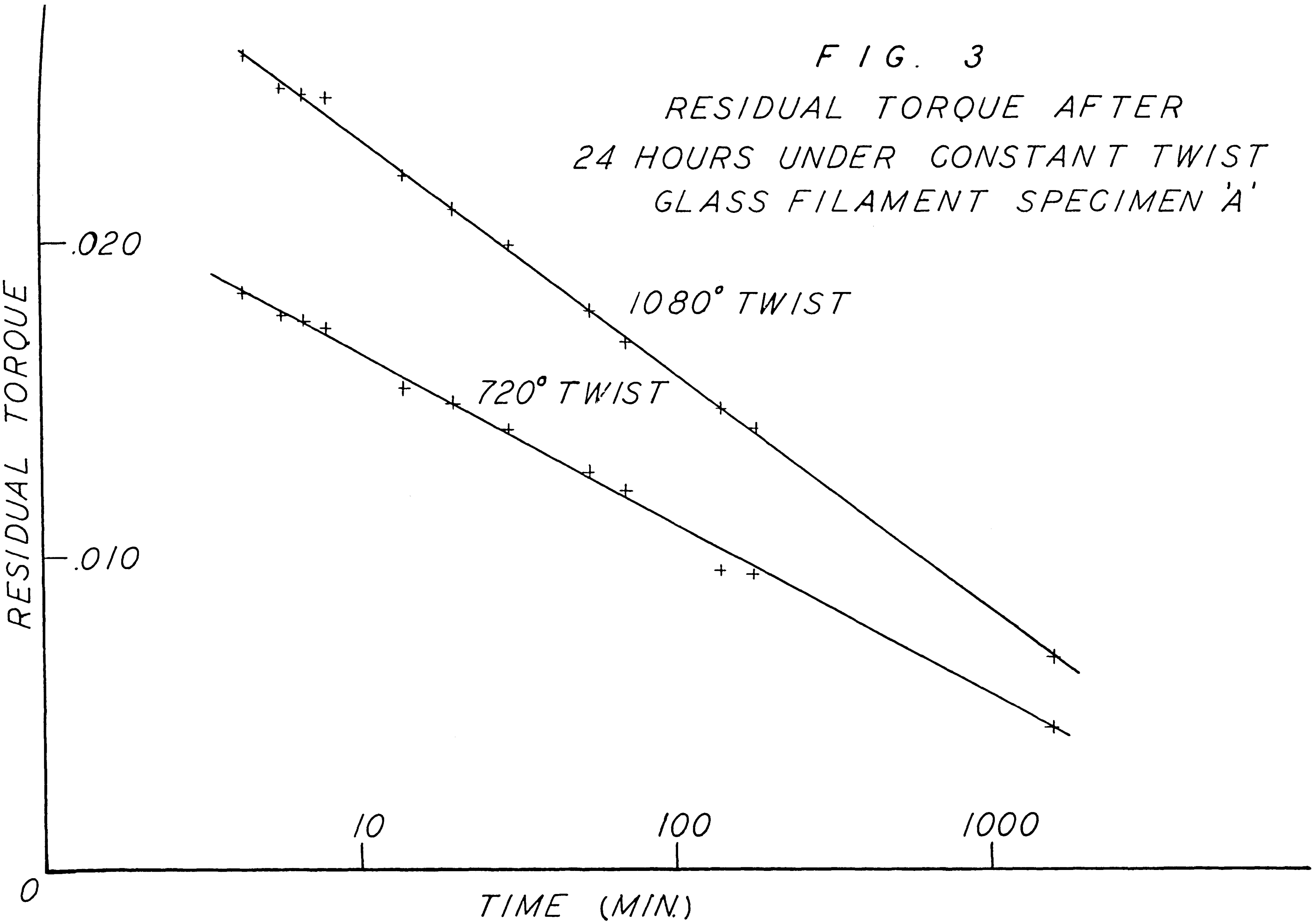
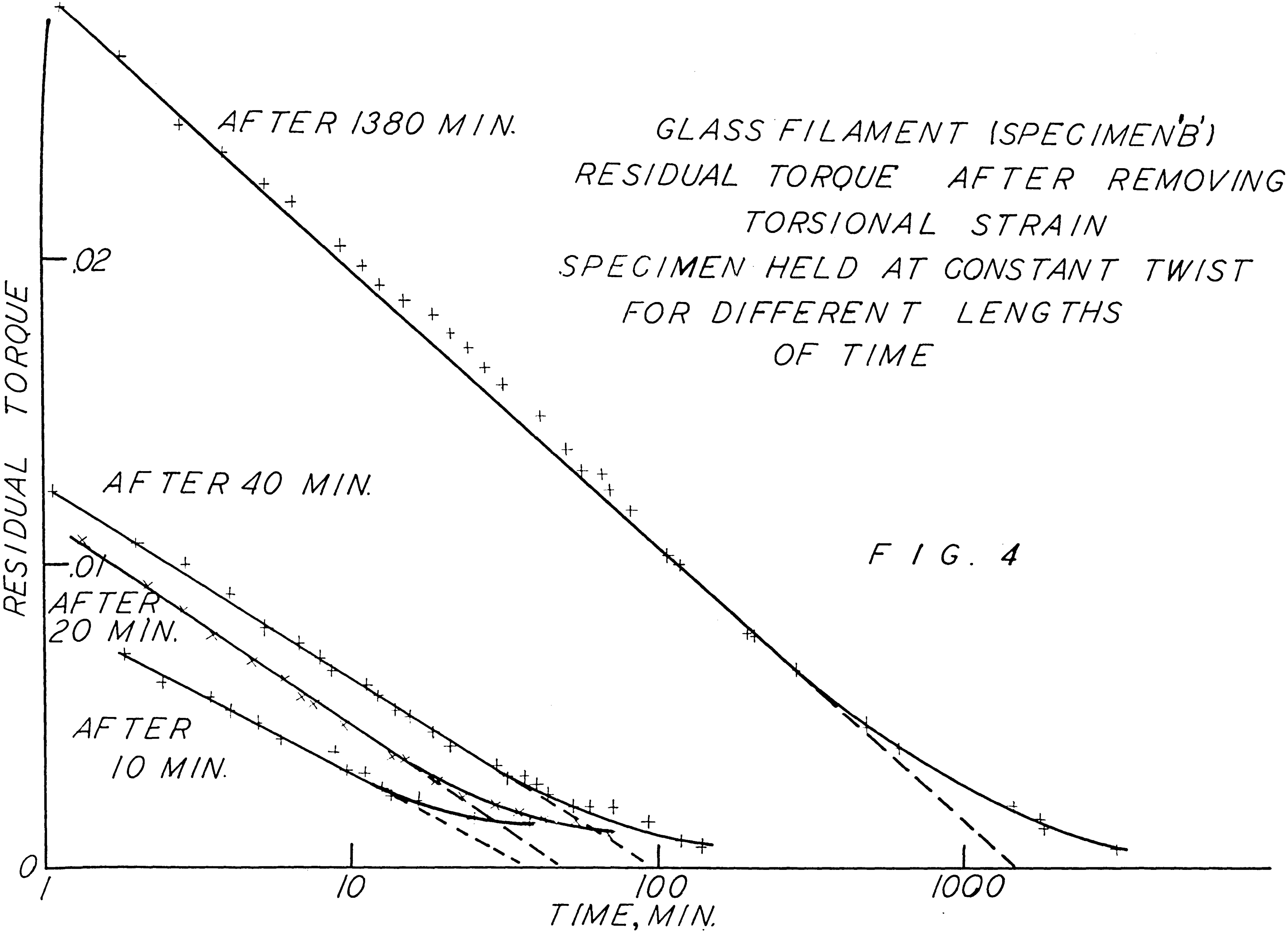


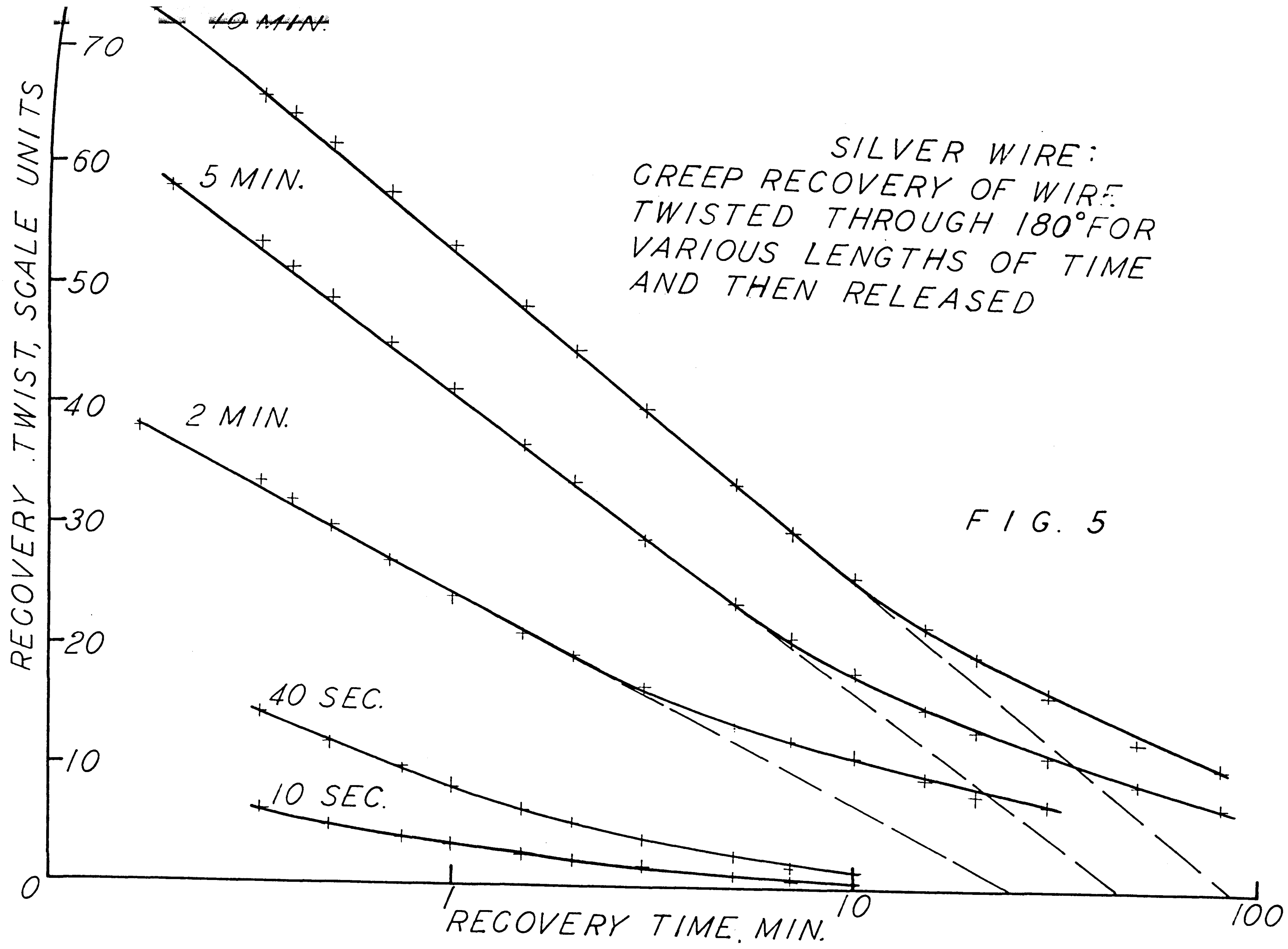
FIG. 3

RESIDUAL TORQUE AFTER
24 HOURS UNDER CONSTANT TWIST
GLASS FILAMENT SPECIMEN 'A'



GLASS FILAMENT (SPECIMEN 'B')
RESIDUAL TORQUE AFTER REMOVING
TORSIONAL STRAIN
SPECIMEN HELD AT CONSTANT TWIST
FOR DIFFERENT LENGTHS
OF TIME

FIG. 4

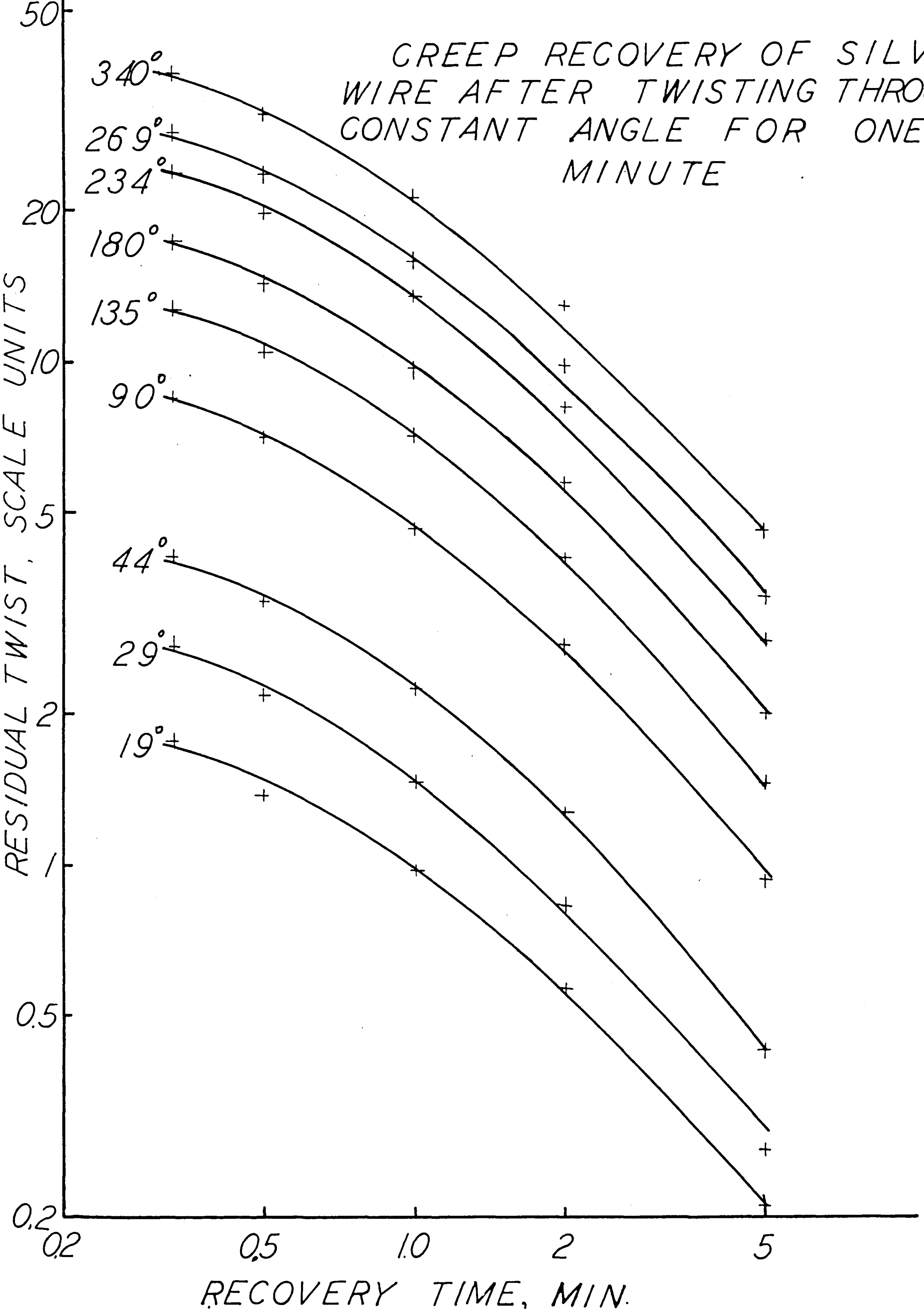


SILVER WIRE:
CREEP RECOVERY OF WIRE TWISTED THROUGH 180° FOR VARIOUS LENGTHS OF TIME AND THEN RELEASED

FIG. 5

FIG. 6

CREEP RECOVERY OF SILVER WIRE AFTER TWISTING THROUGH CONSTANT ANGLE FOR ONE MINUTE



EFFECT OF TEMPERATURE ON CREEP
SILVER WIRE TWISTED 180° FOR 1 MINUTE
AND THEN RELEASED

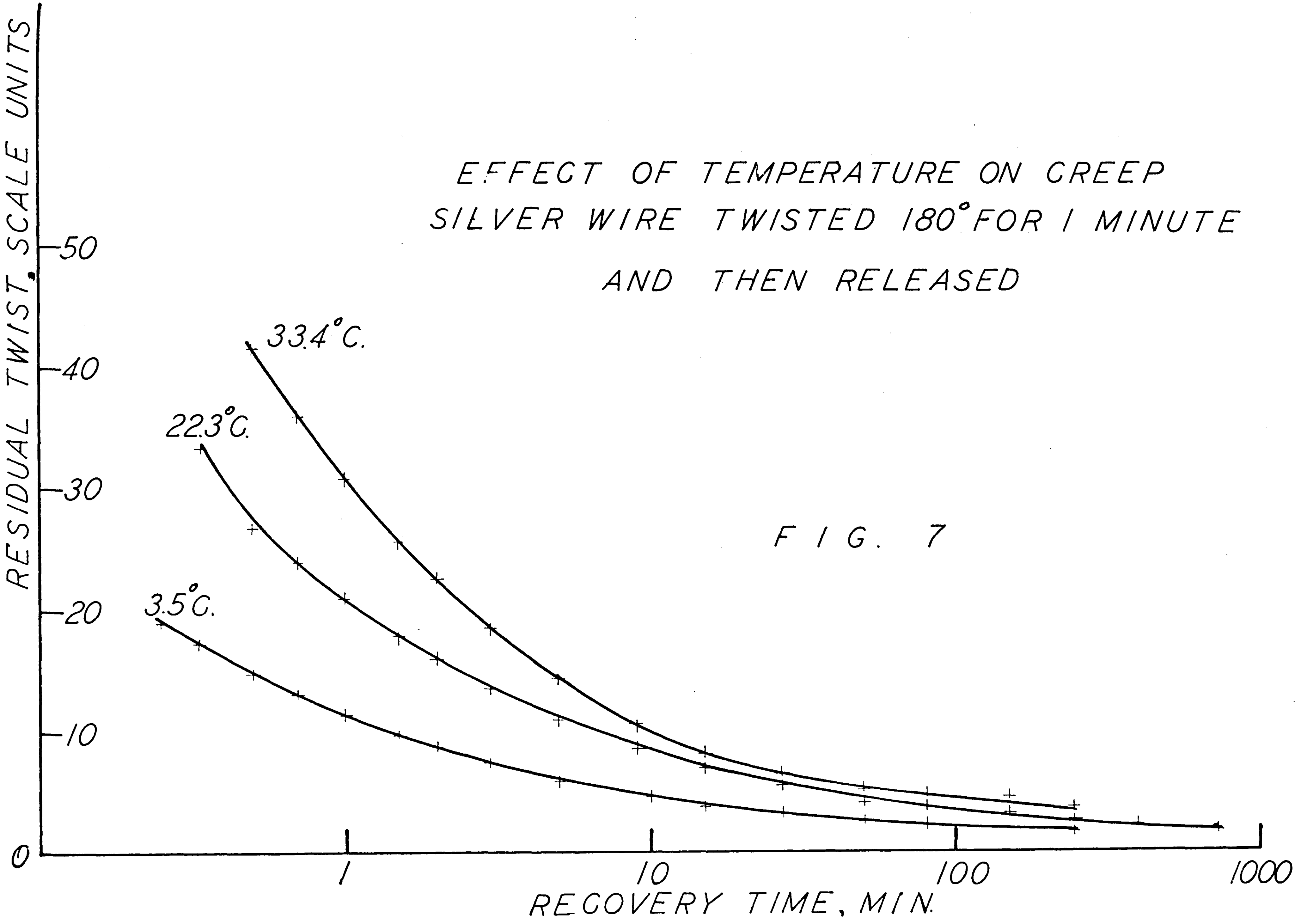


FIG. 7

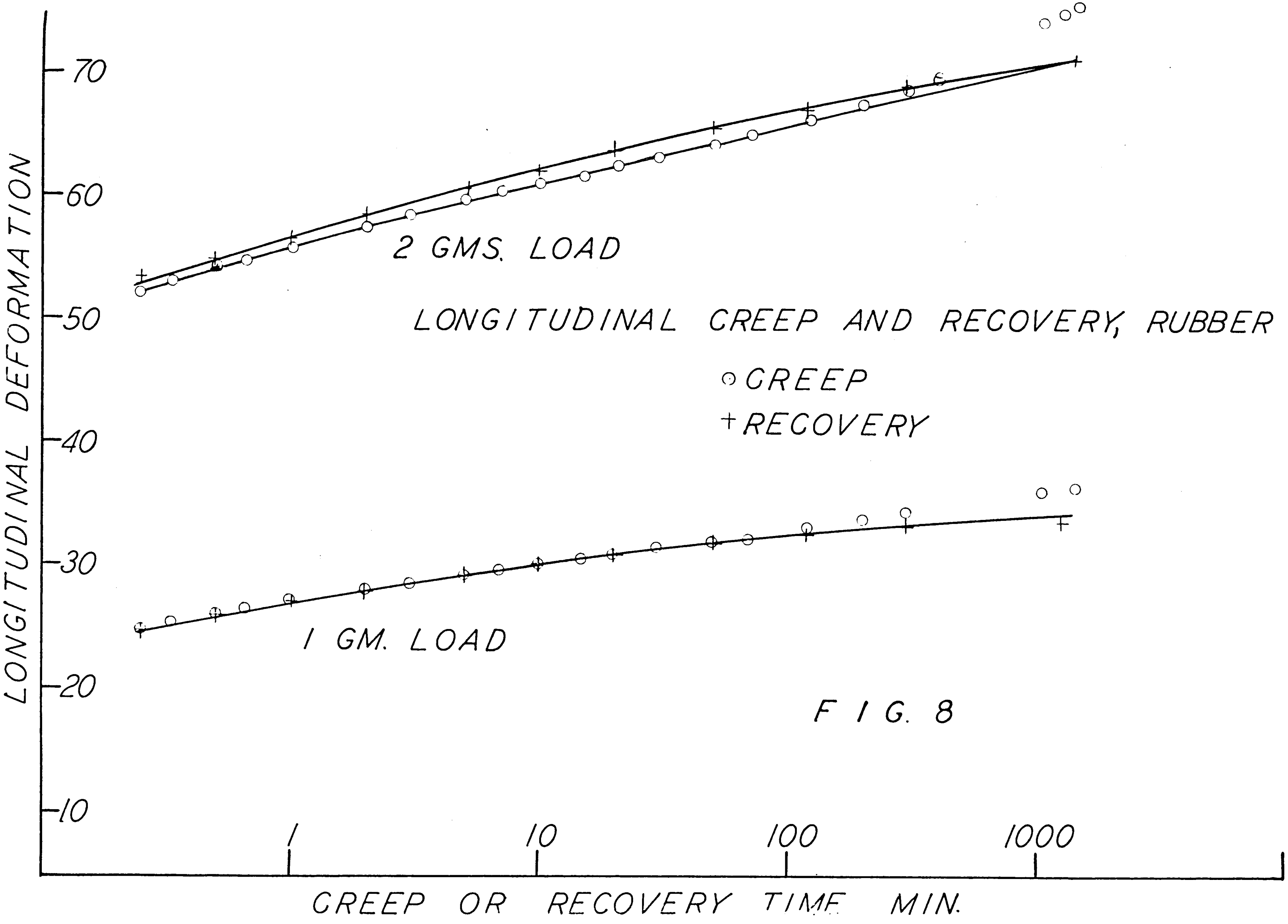

LONGITUDINAL CREEP AND RECOVERY, RUBBER
○ CREEP
+ RECOVERY
2 GMS. LOAD
1 GM. LOAD
LONGITUDINAL DEFORMATION
70
60
50
40
30
20
10
1
10
100
1000
CREEP OR RECOVERY TIME MIN.

FIG. 8

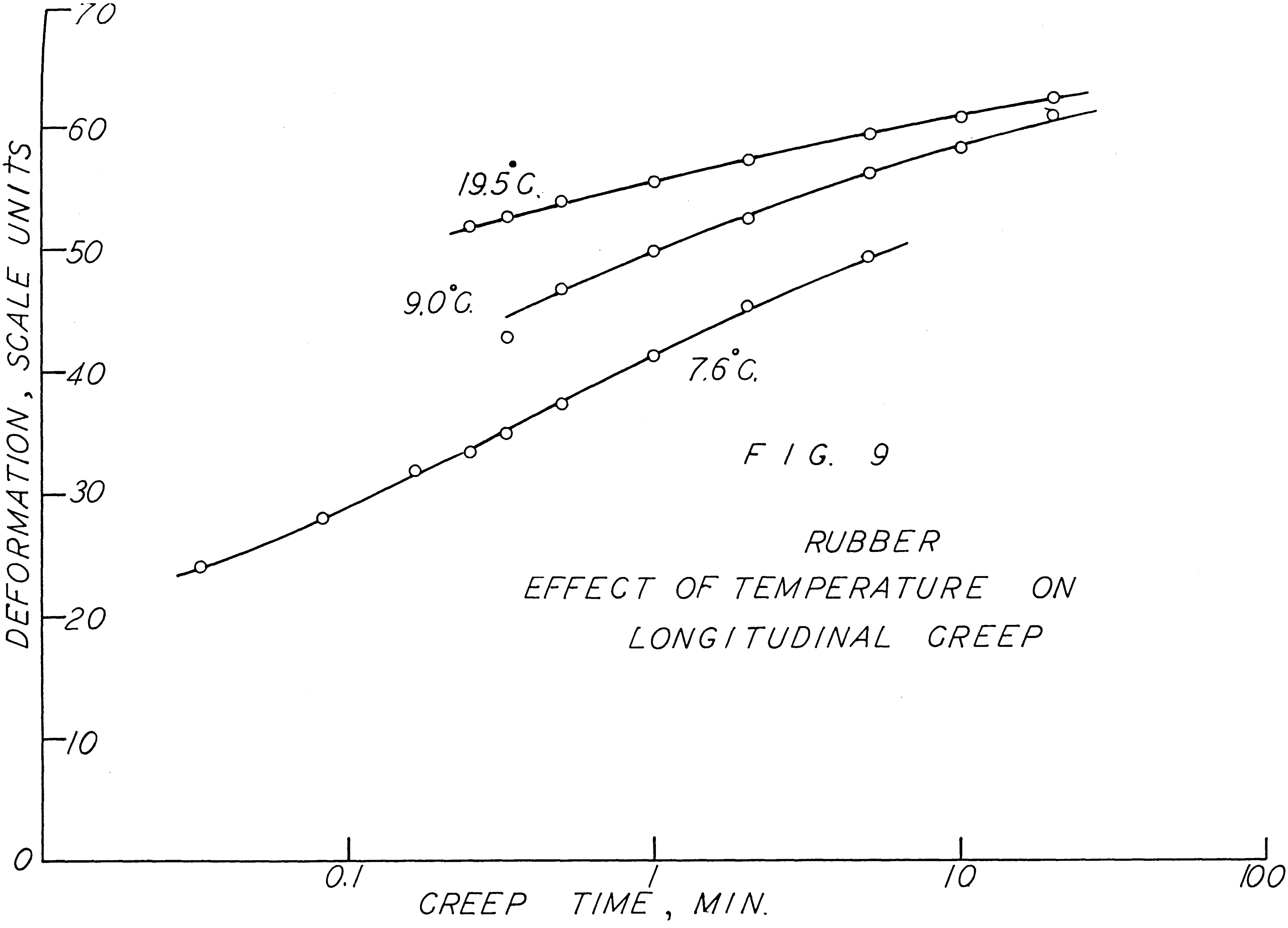


FIG. 9

RUBBER
EFFECT OF TEMPERATURE ON
LONGITUDINAL CREEP

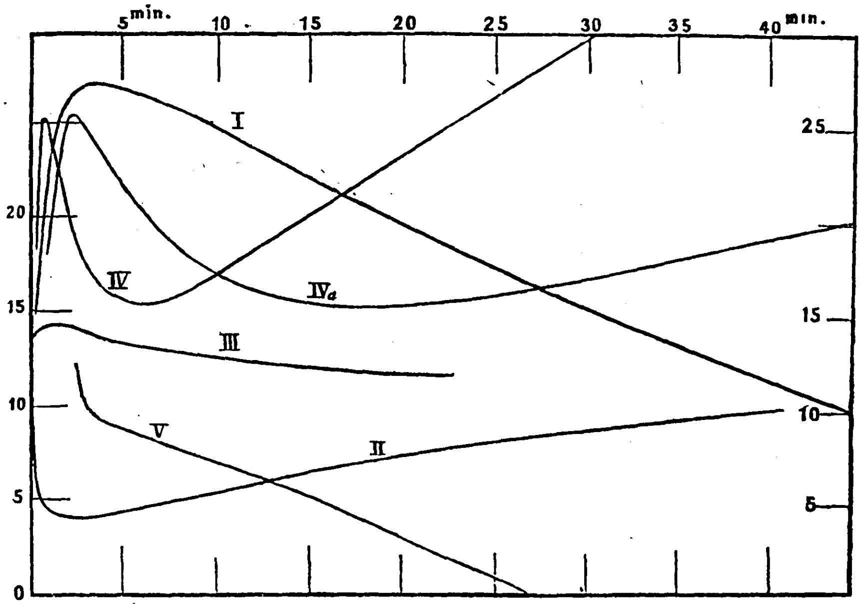


Fig. 10

The Memory Effect (Kohlrausch)

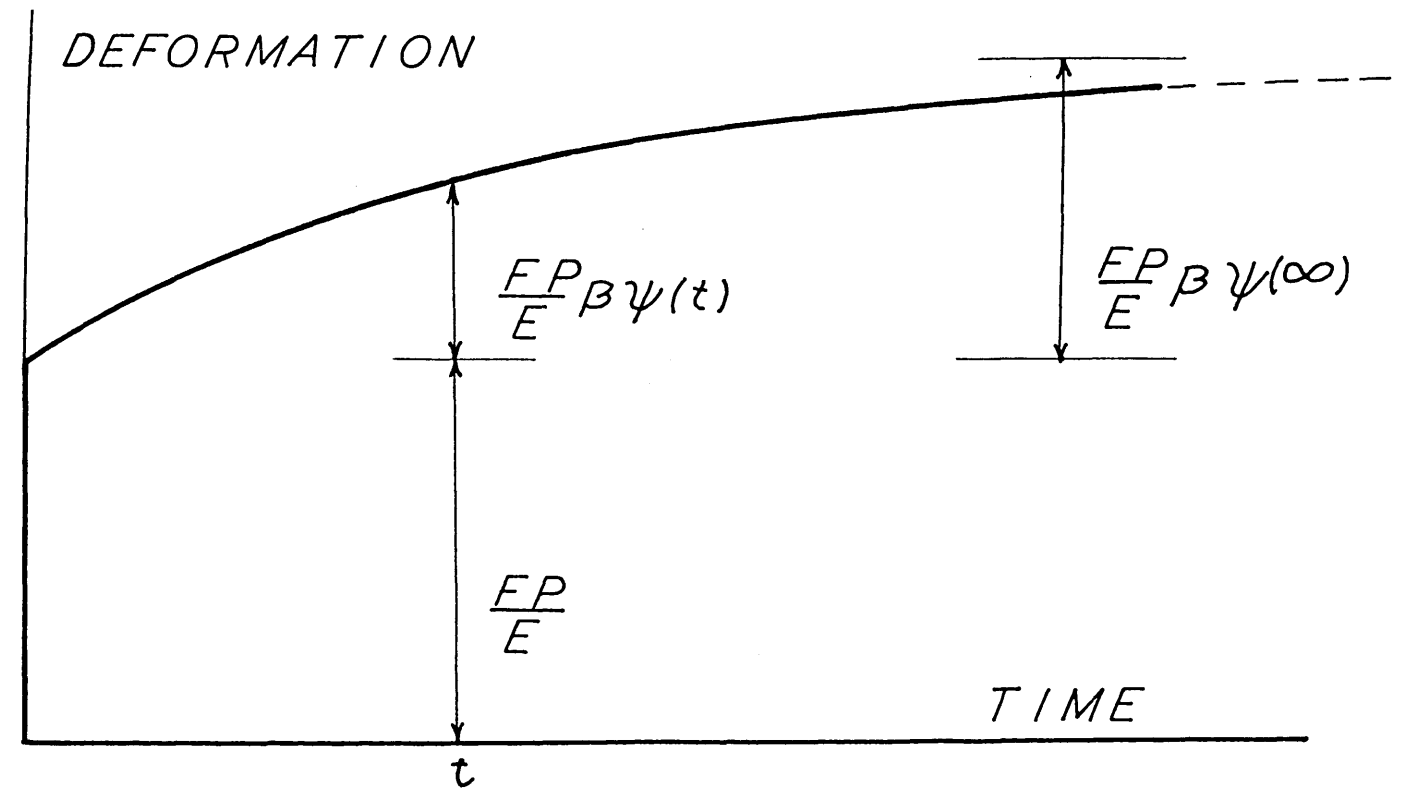

DEFORMATION
$\frac{FP}{E}\beta\psi(t)$
$\frac{FP}{E}\beta\psi(\infty)$
$\frac{FP}{E}$
TIME
t

FIG. 11

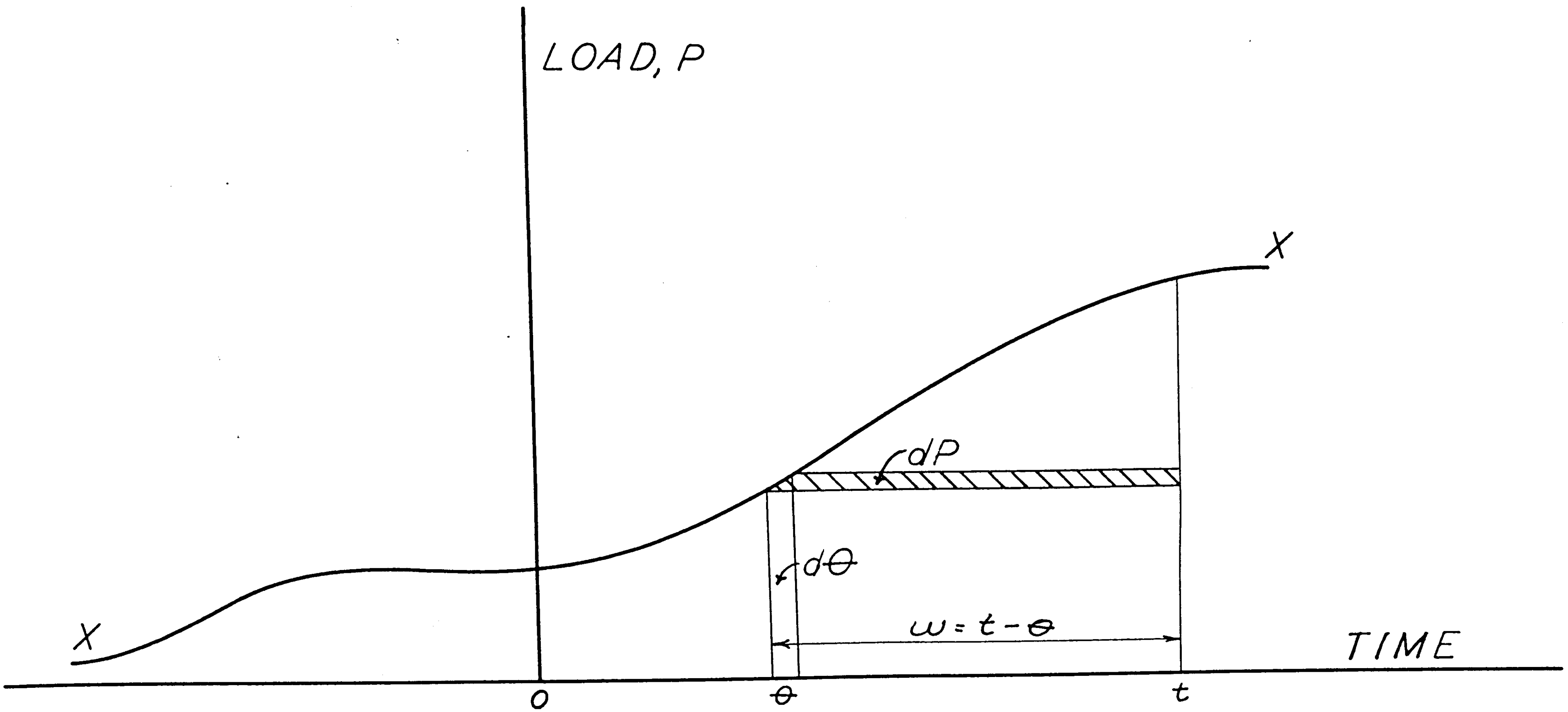


FIG. 12

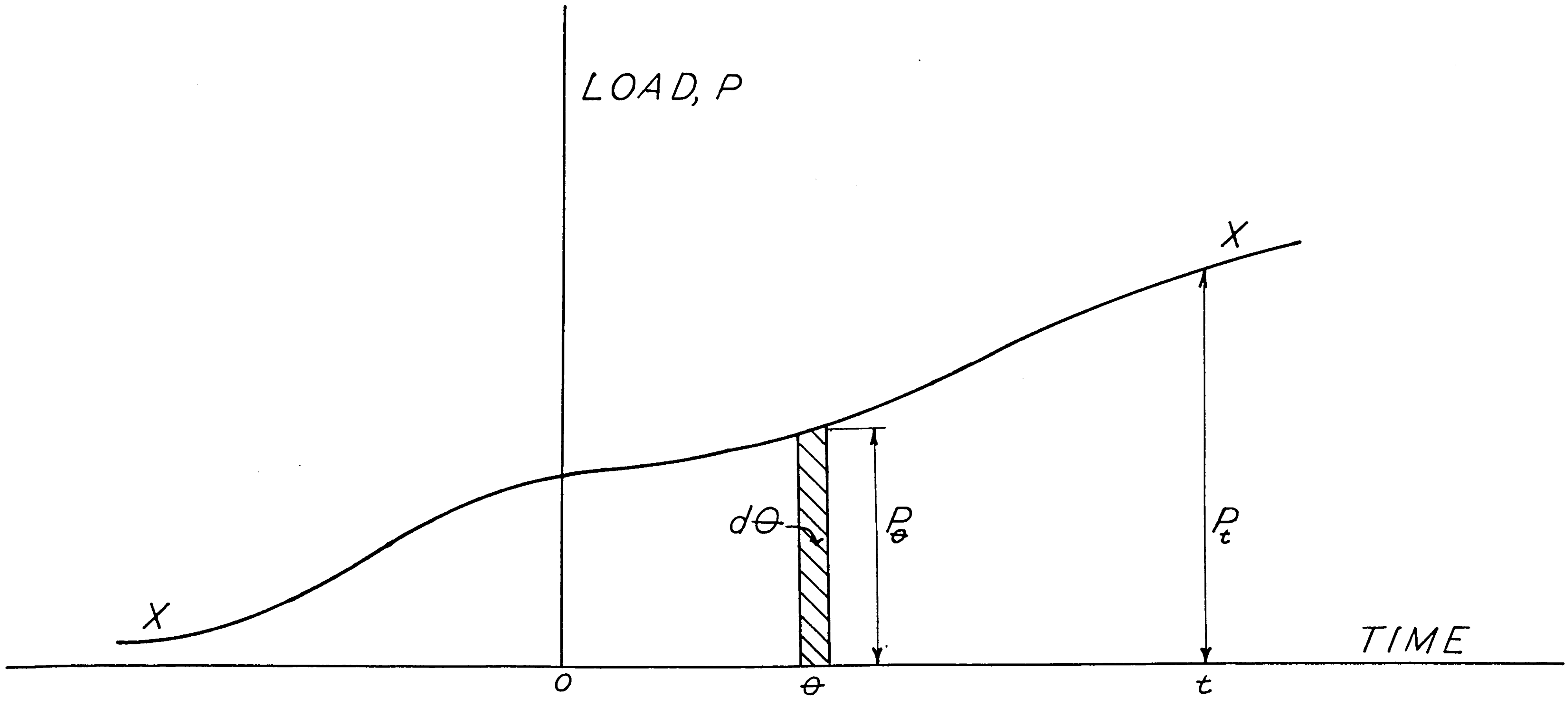


FIG. 13

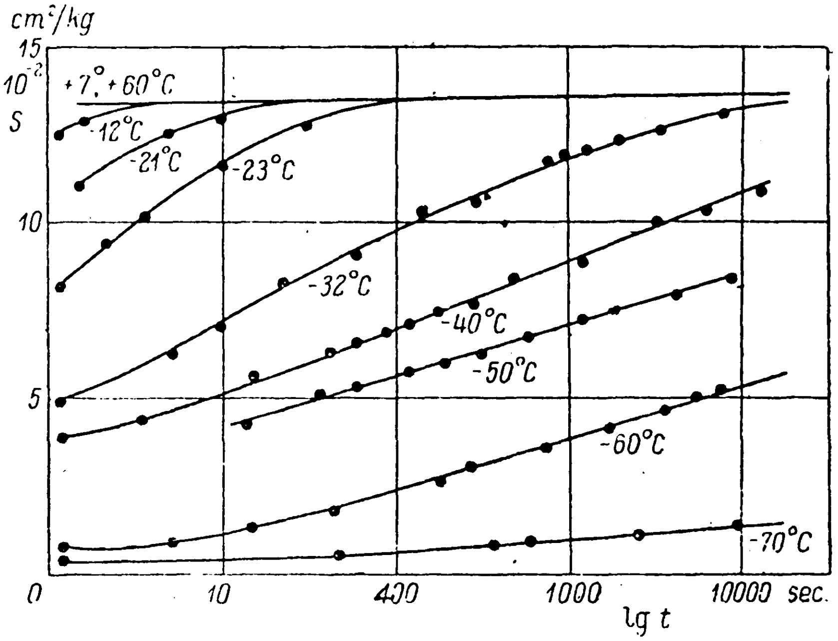
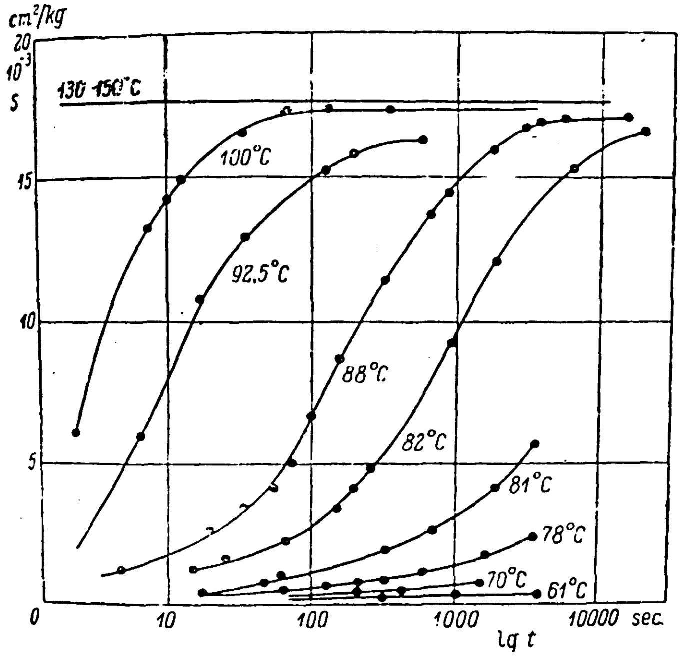


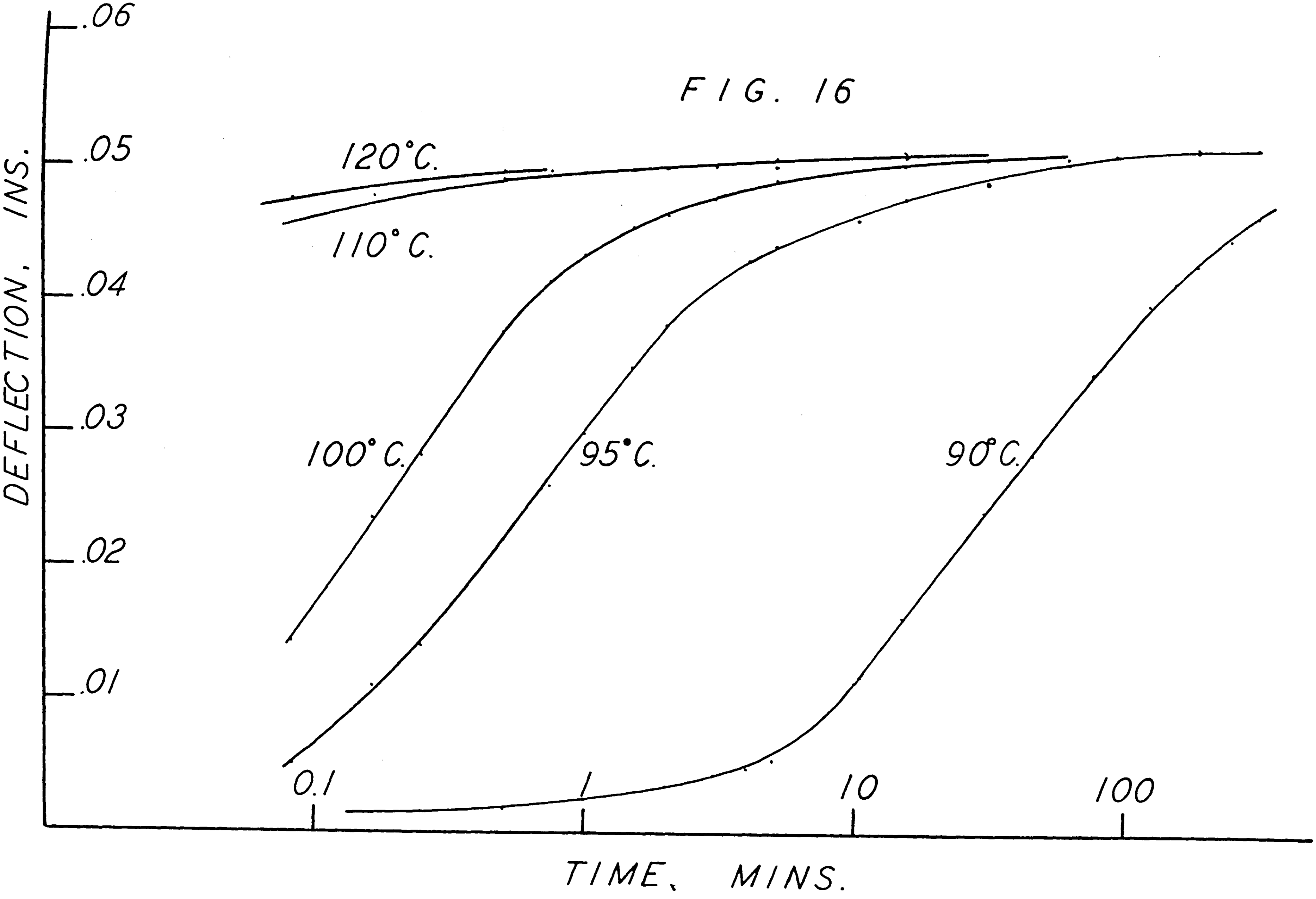
Fig. 14



Curves showing the setting-in of highly elastic deformation in hard rubber.

Fig. 15

FIG. 16


.06
.05
.04
.03
.02
.01
DEFLECTION, INS.
120°C.
110°C.
100°C.
95°C.
90°C.
0.1
1
10
100
TIME, MINS.

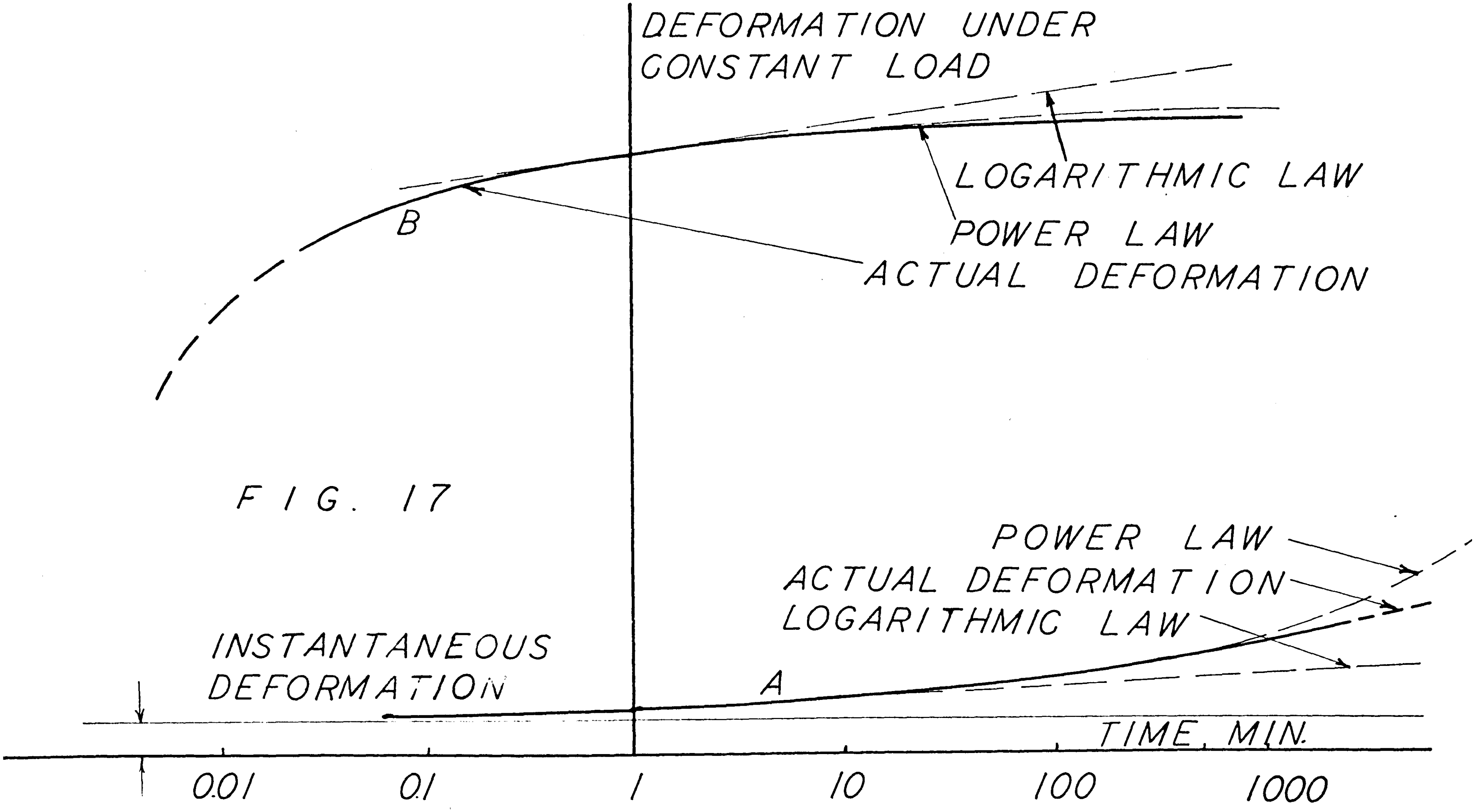


FIG. 17

CURVE A: UNPLASTICIZED RESINS
CURVE B: RUBBER-LIKE MATERIALS

CREEP AT ROOM TEMPERATURE
OF HIGH POLYMERS

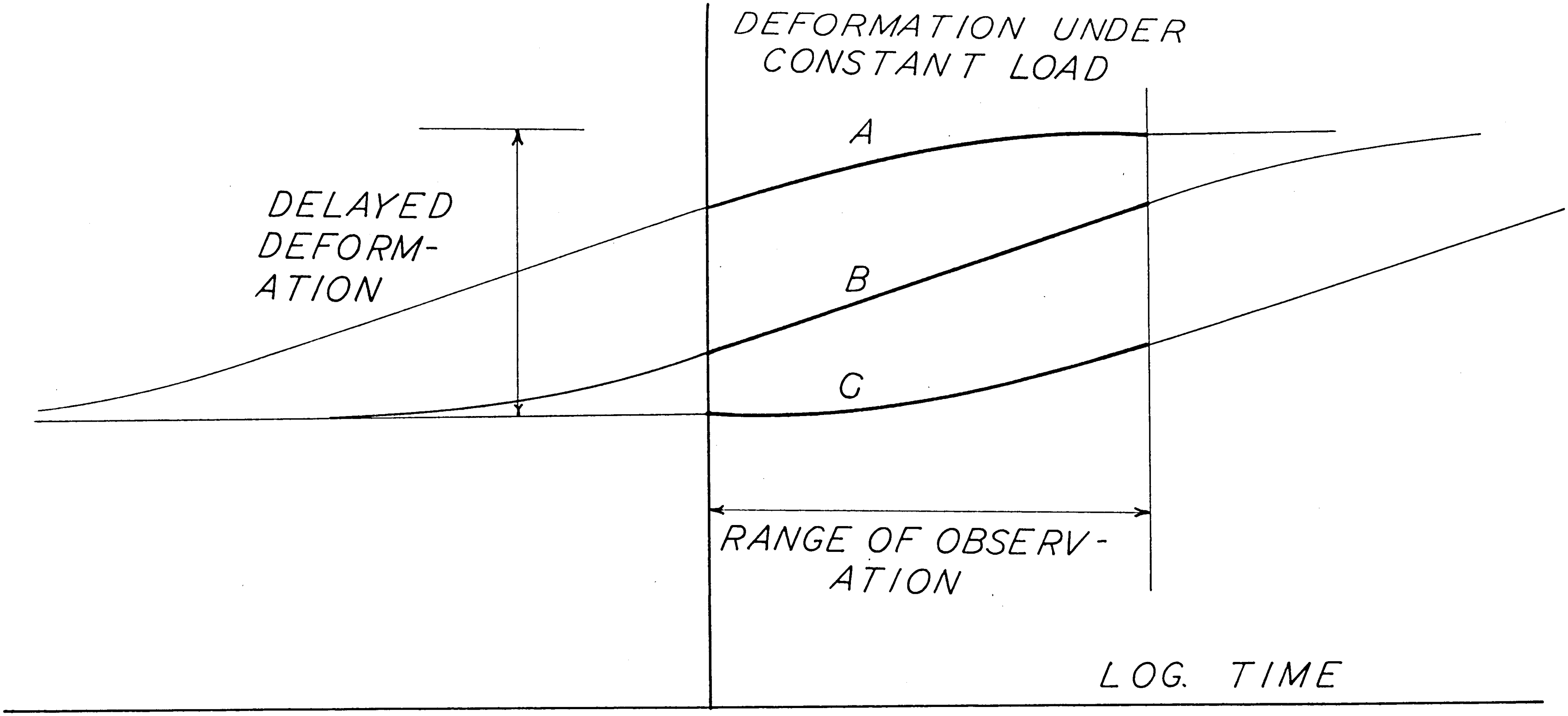
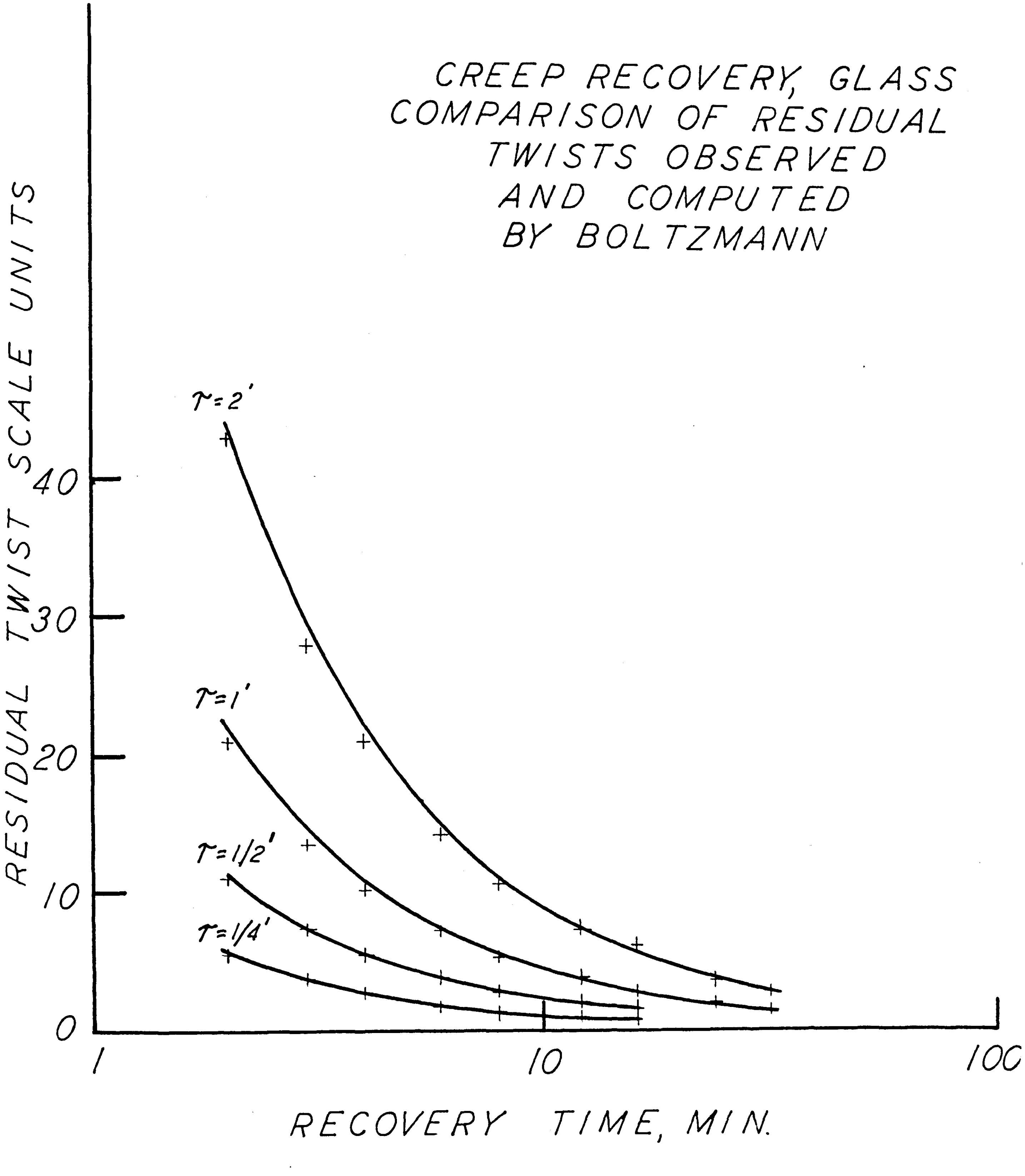


FIG. 18

POSSIBLE CREEP BEHAVIOR OF GLASS

FIG. 19



CREEP RECOVERY, GLASS
COMPARISON OF RESIDUAL
TWISTS OBSERVED
AND COMPUTED
BY BOLTZMANN
RESIDUAL TWIST SCALE UNITS
RECOVERY TIME, MIN.
0
10
20
30
40
1
10
100
$\tau = 2'$
$\tau = 1'$
$\tau = 1/2'$
$\tau = 1/4'$

FIG. 20

TORSION CREEP RECOVERY
IN GLASS

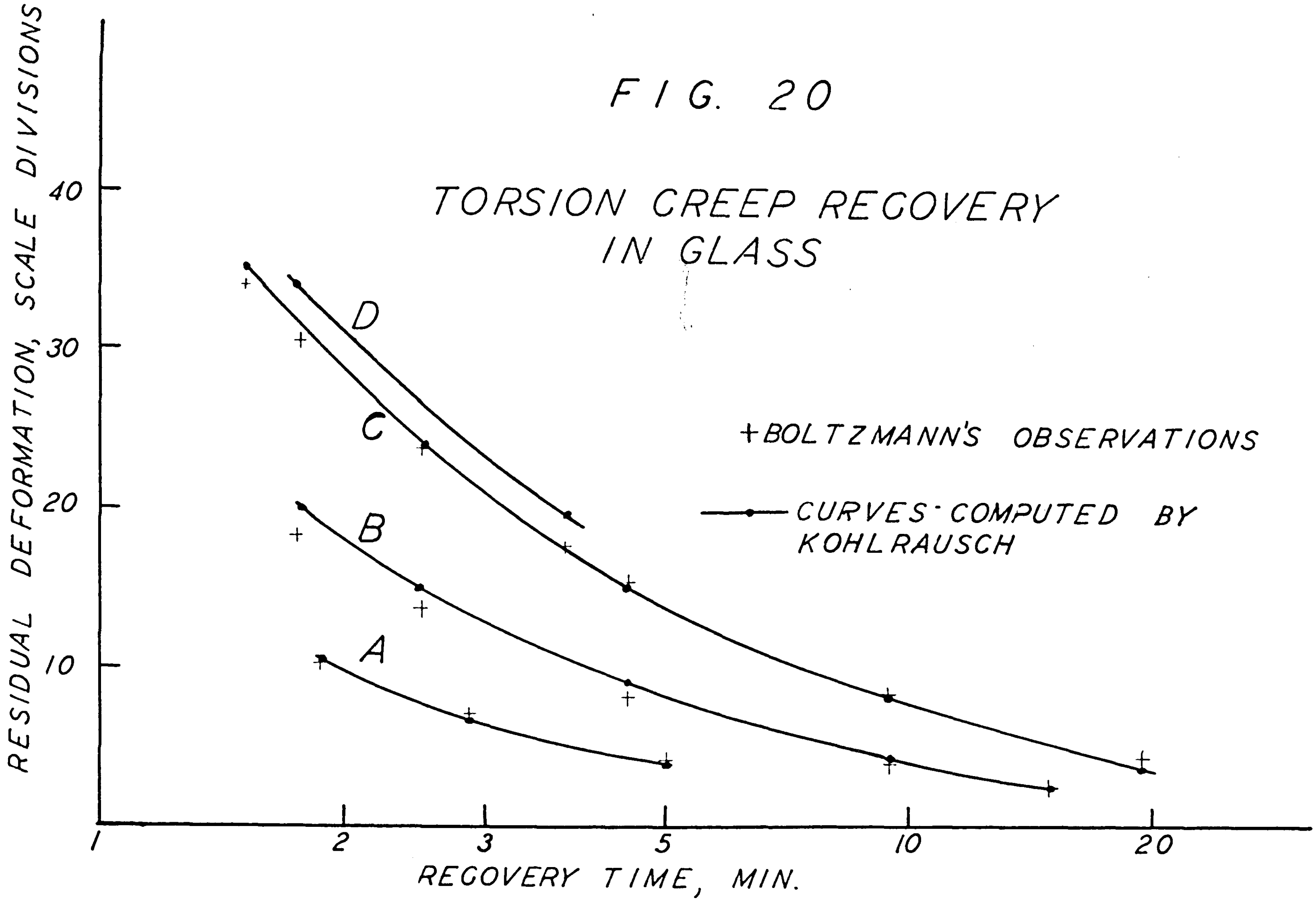
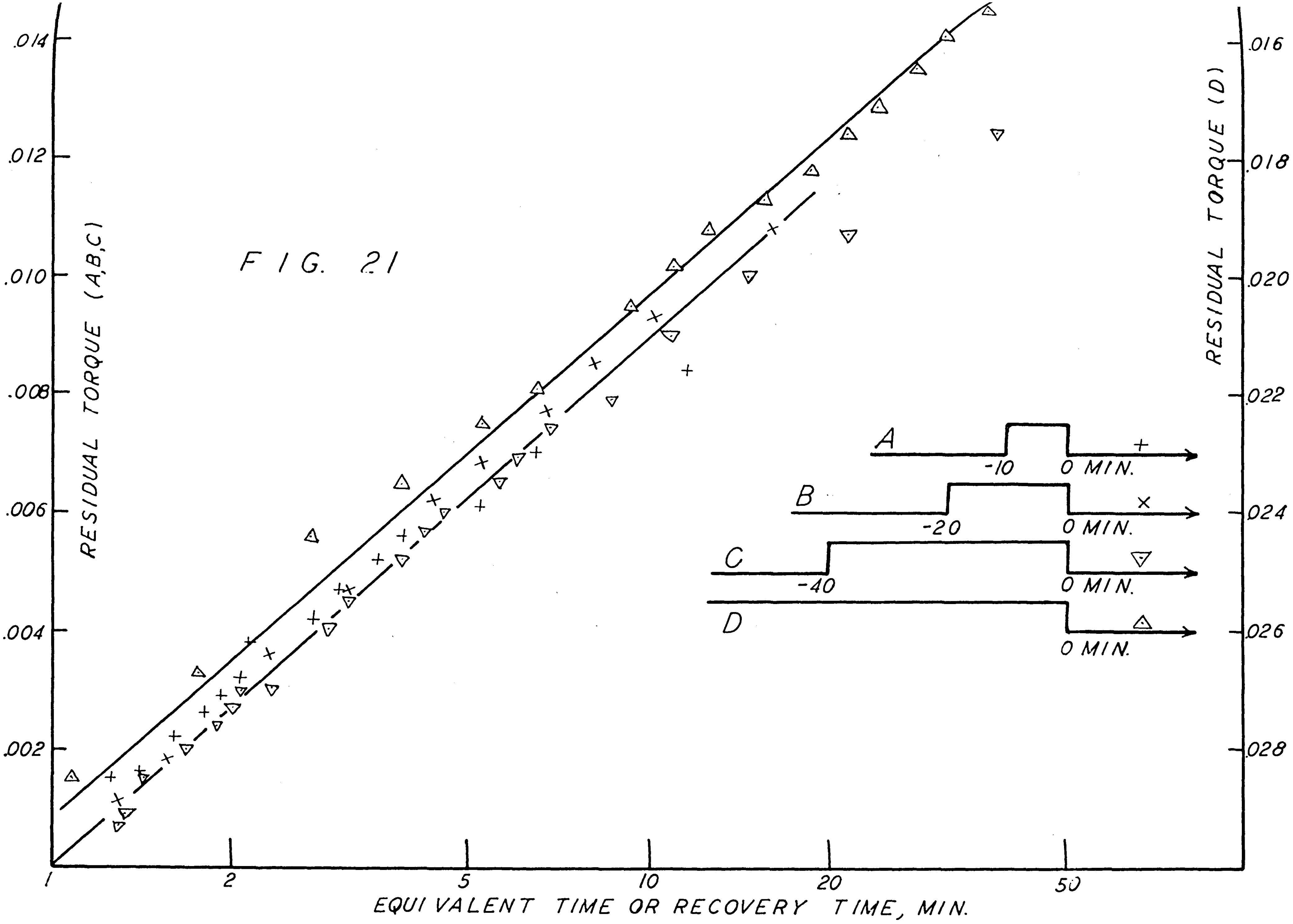


FIG. 21



RESIDUAL TORQUE (A,B,C)
.014
.012
.010
.008
.006
.004
.002
RESIDUAL TORQUE (D)
.016
.018
.020
.022
.024
.026
.028
1
2
5
10
20
50
EQUIVALENT TIME OR RECOVERY TIME, MIN.
A
-10
0 MIN.
+
B
-20
0 MIN.
×
C
-40
0 MIN.
▽
D
0 MIN.
△

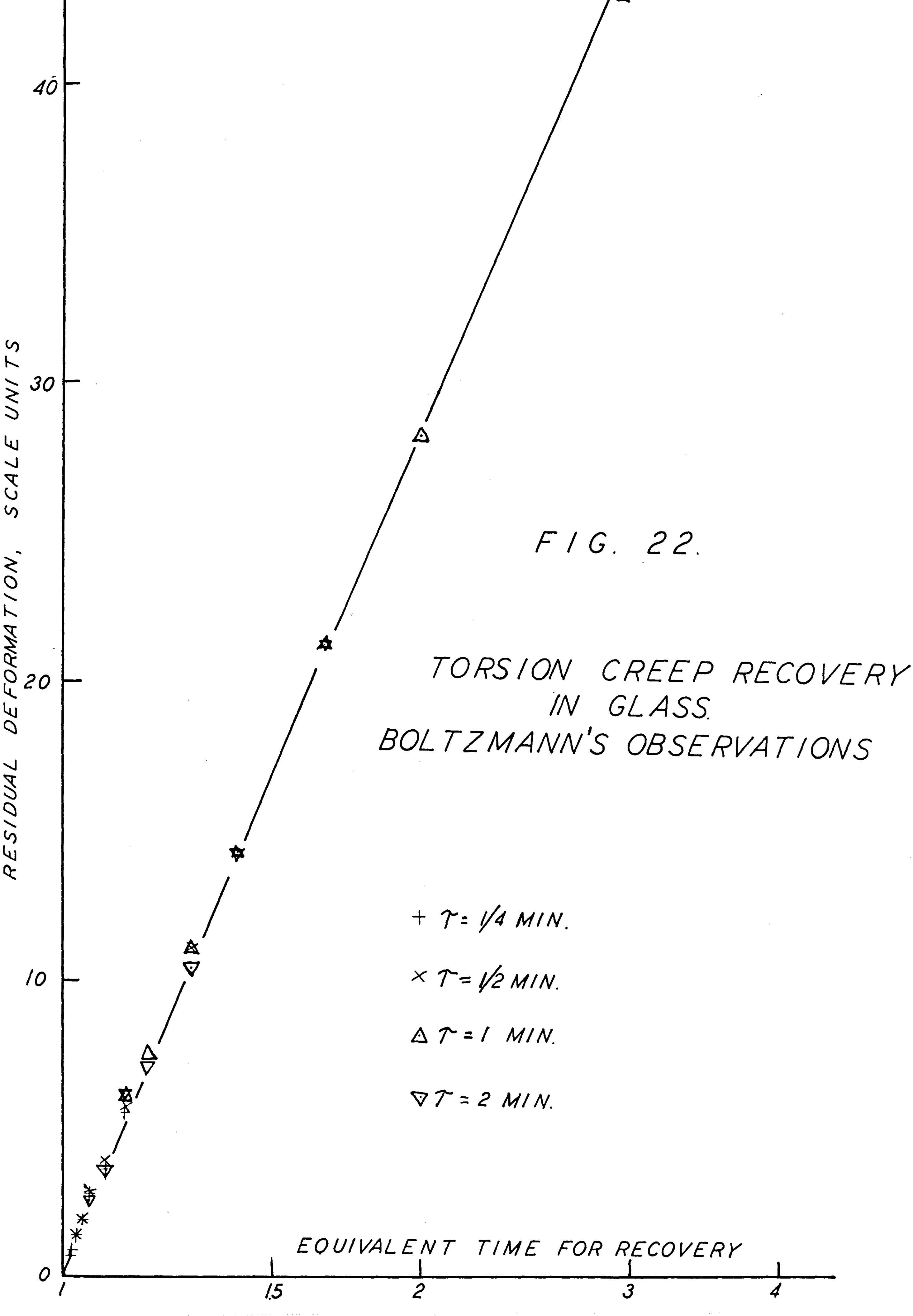


FIG. 22.

TORSION CREEP RECOVERY IN GLASS. BOLTZMANN'S OBSERVATIONS

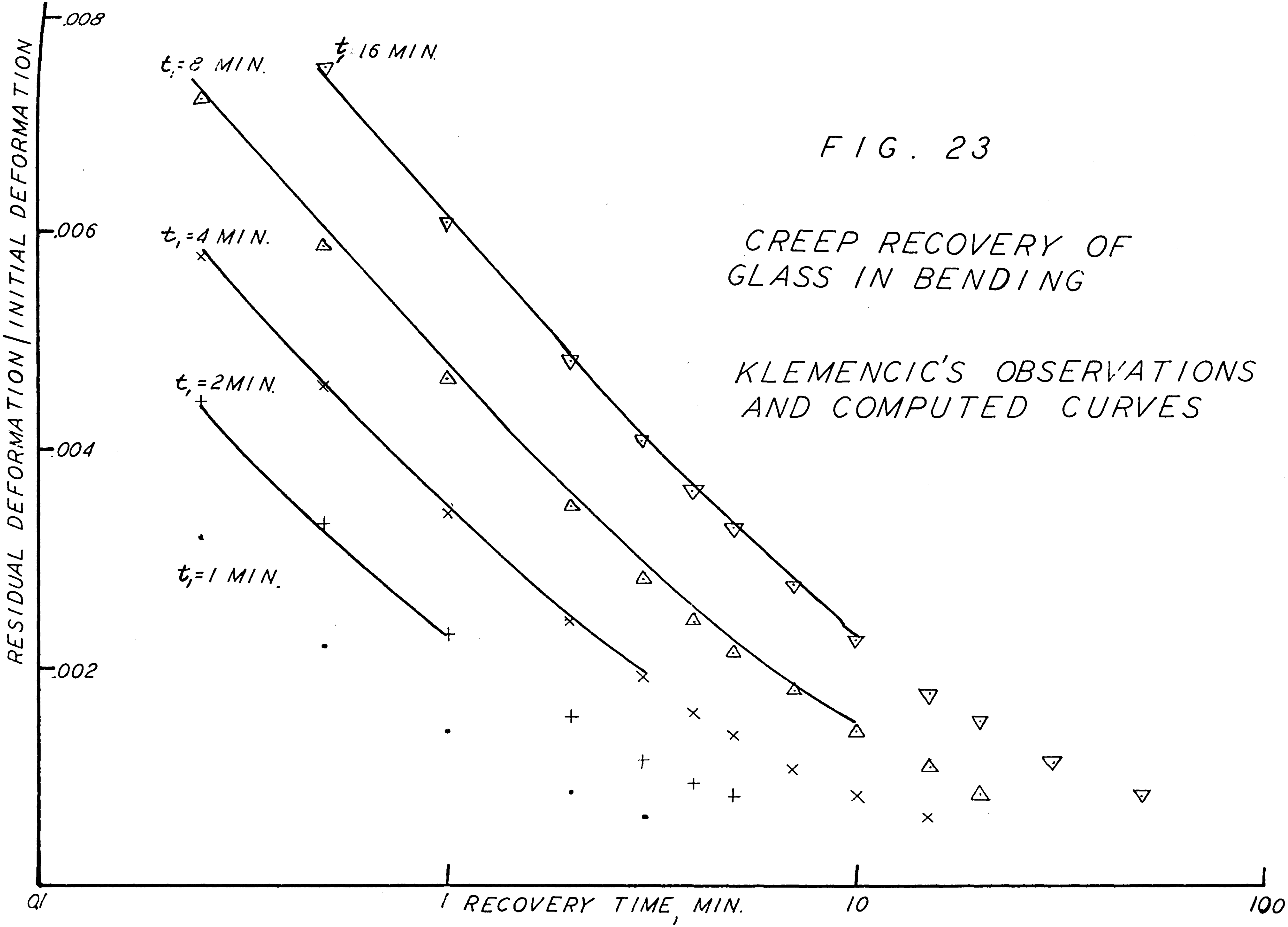


FIG. 23

CREEP RECOVERY OF GLASS IN BENDING

KLEMENCIC'S OBSERVATIONS AND COMPUTED CURVES

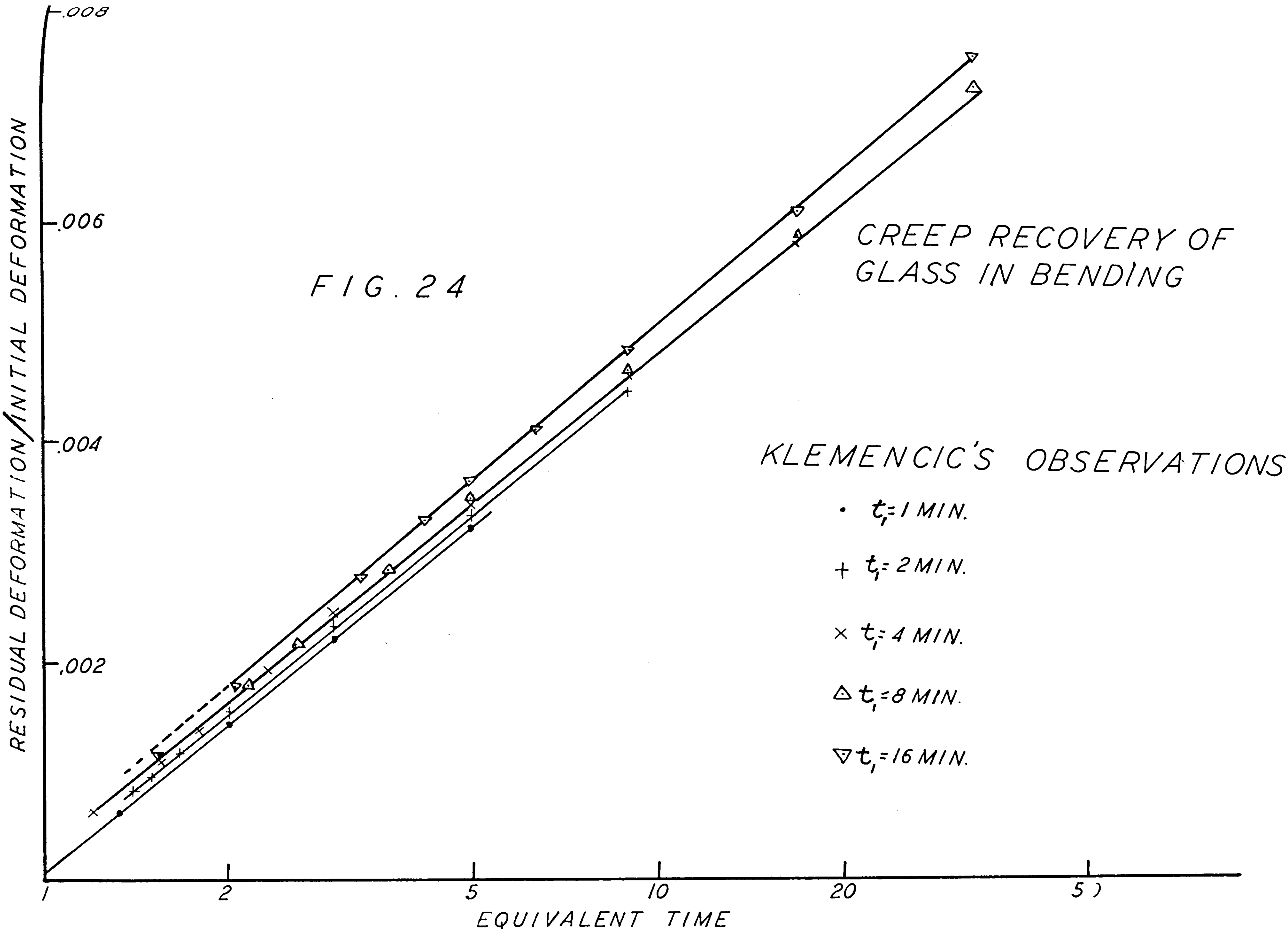


FIG. 24

CREEP RECOVERY OF GLASS IN BENDING

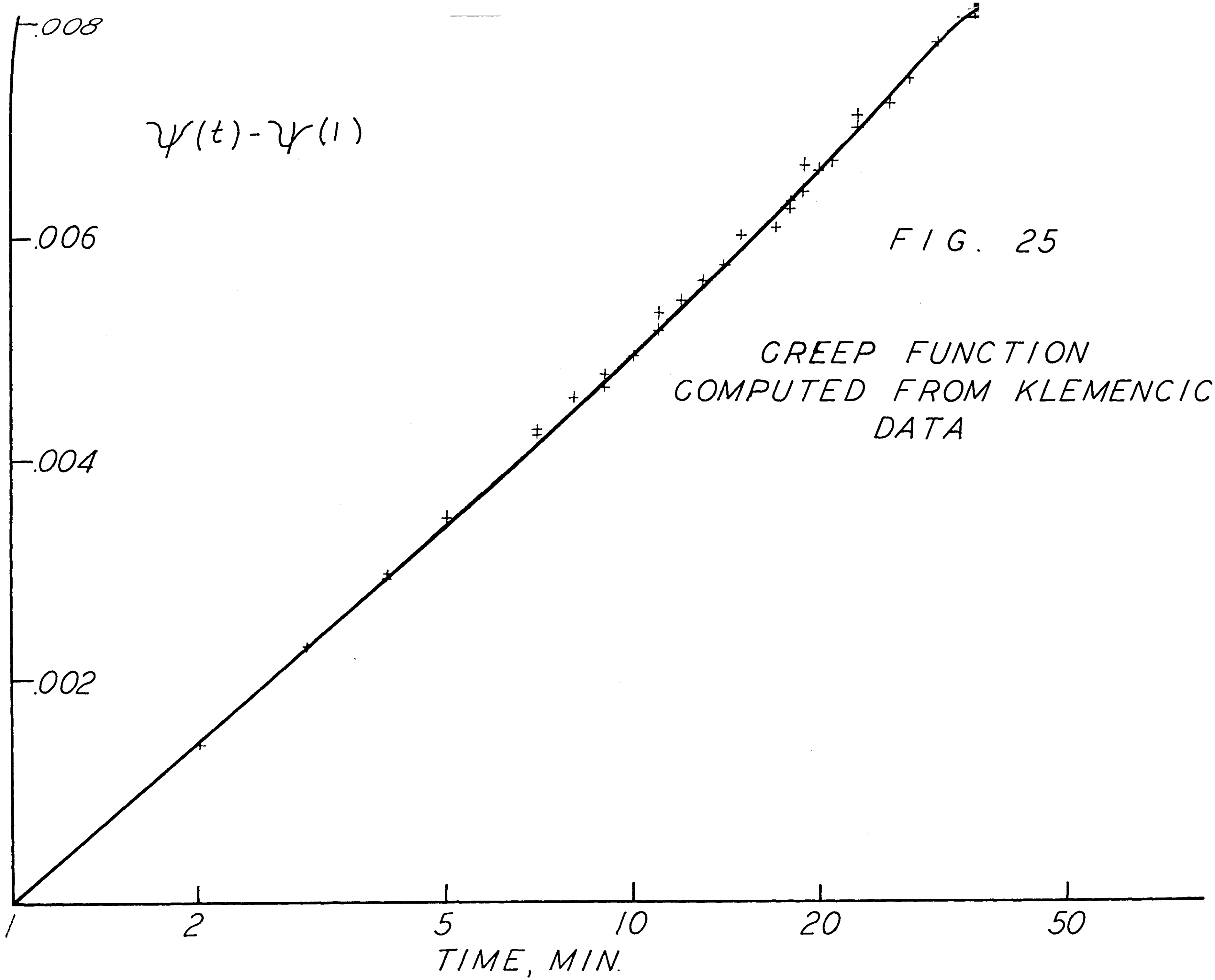


FIG. 25

CREEP FUNCTION
COMPUTED FROM KLEMENCIC'S
DATA

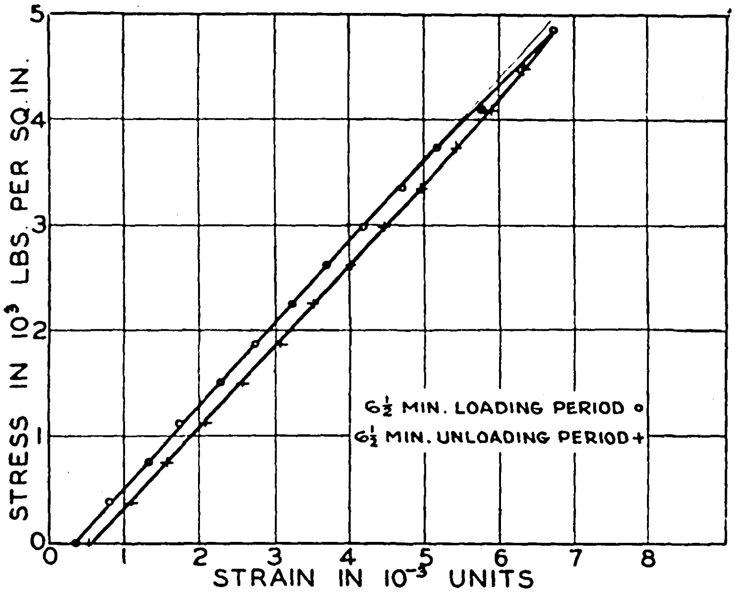


Fig. 26

Stress-Strain Loop in Bakelite (Weibel)

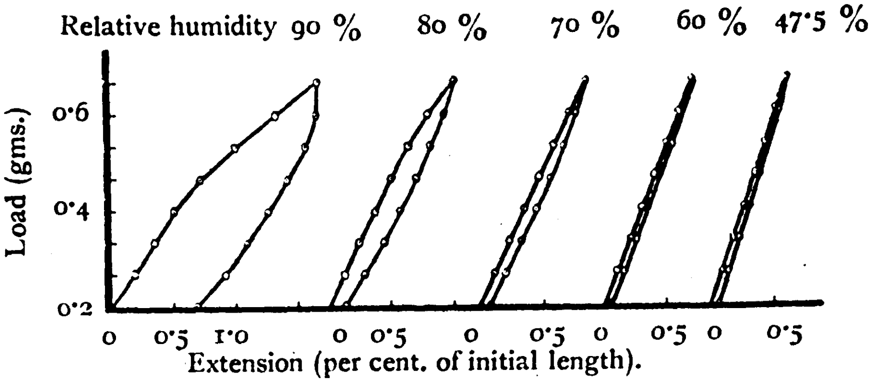


Fig. 27

Load-Extension Loops in Silk

(Denham and Lonsdale)

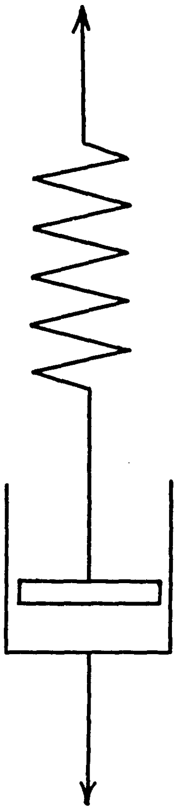


FIG. 28

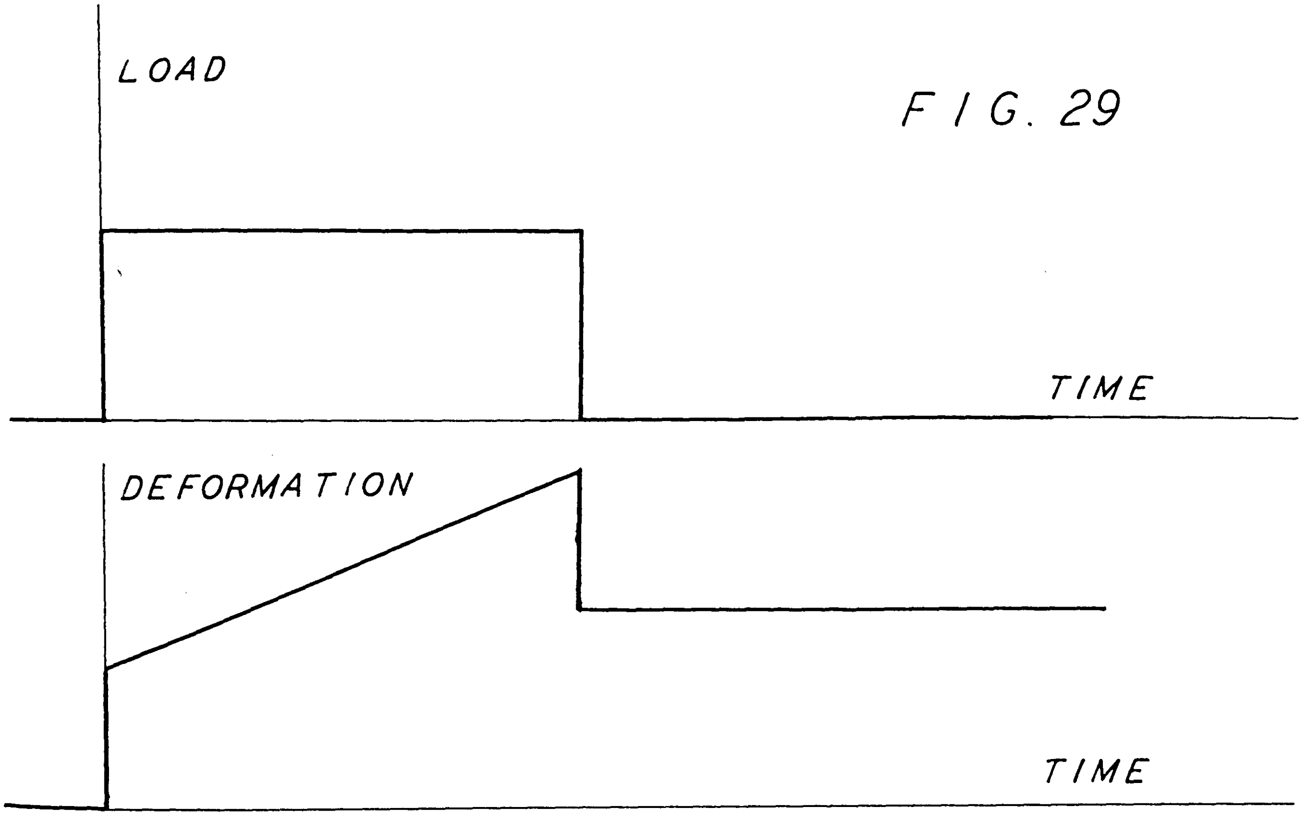


FIG. 29

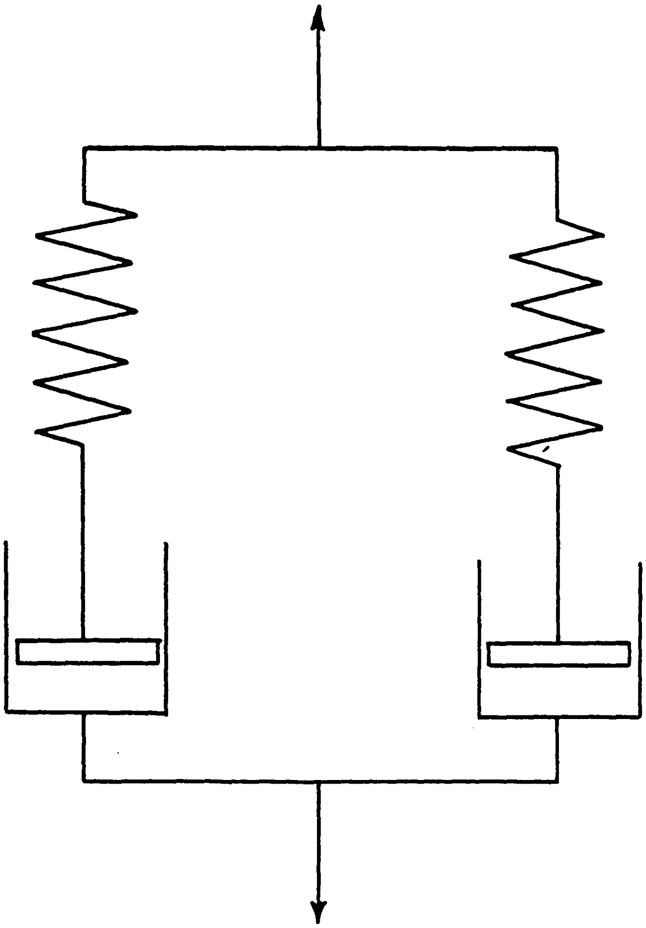


FIG. 30

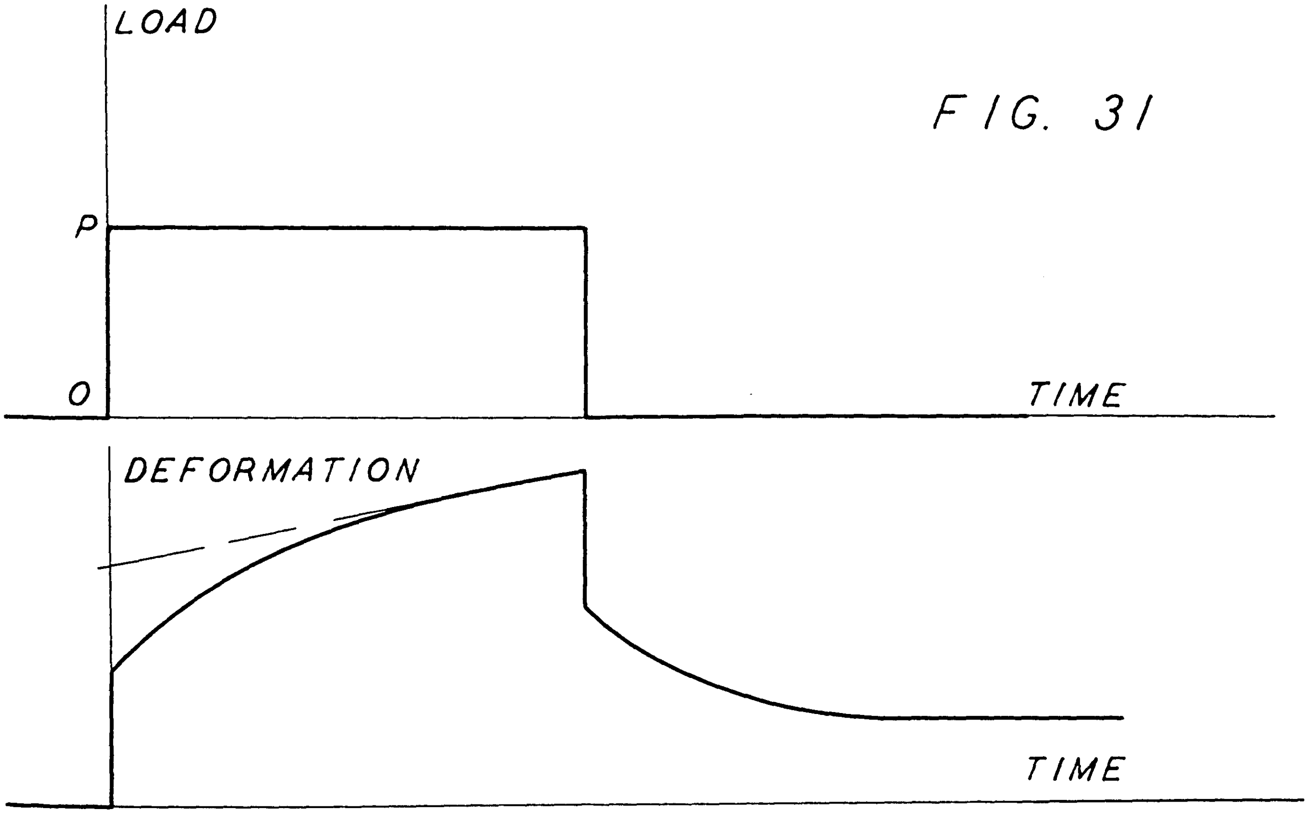


FIG. 31

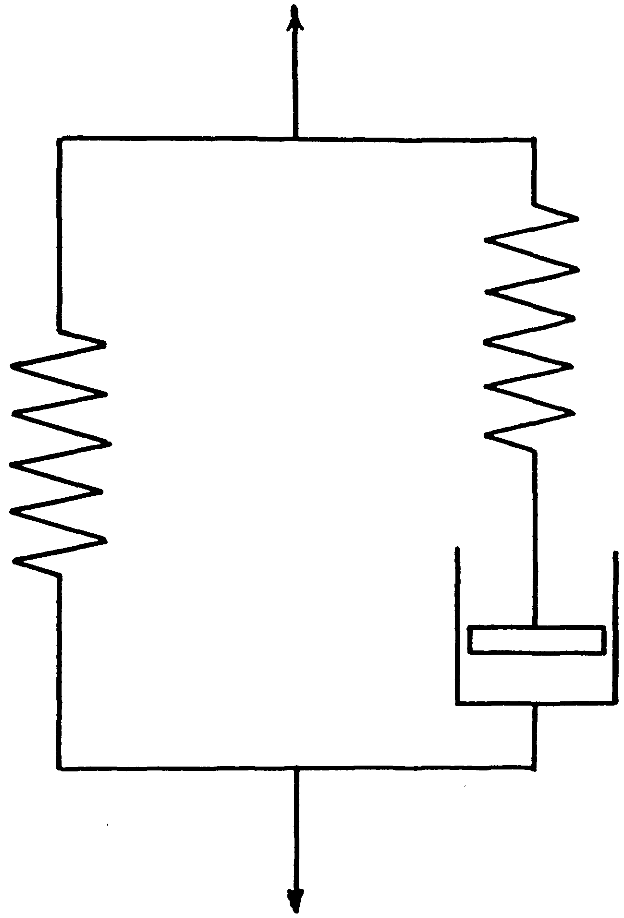


FIG. 32

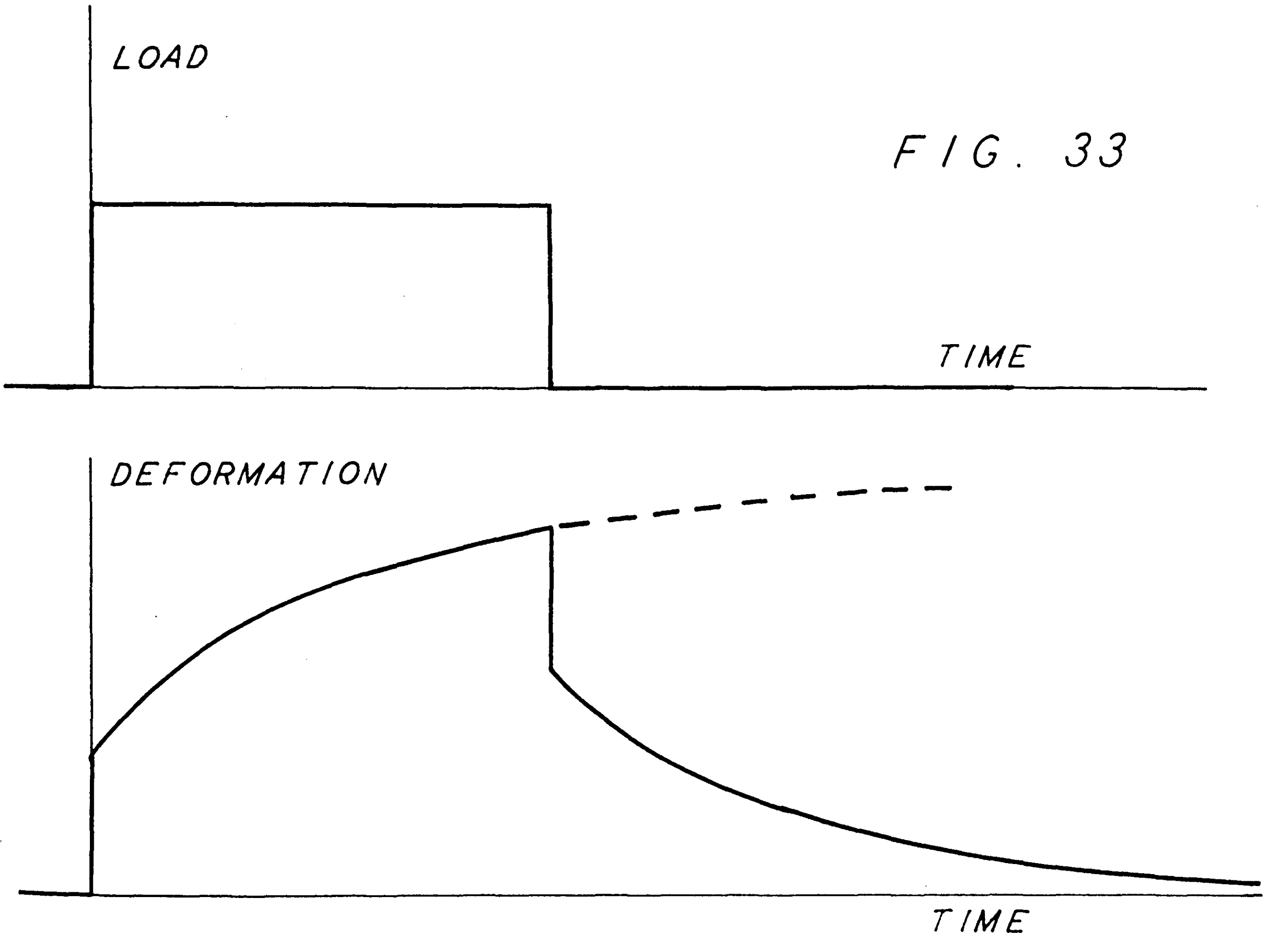


FIG. 33

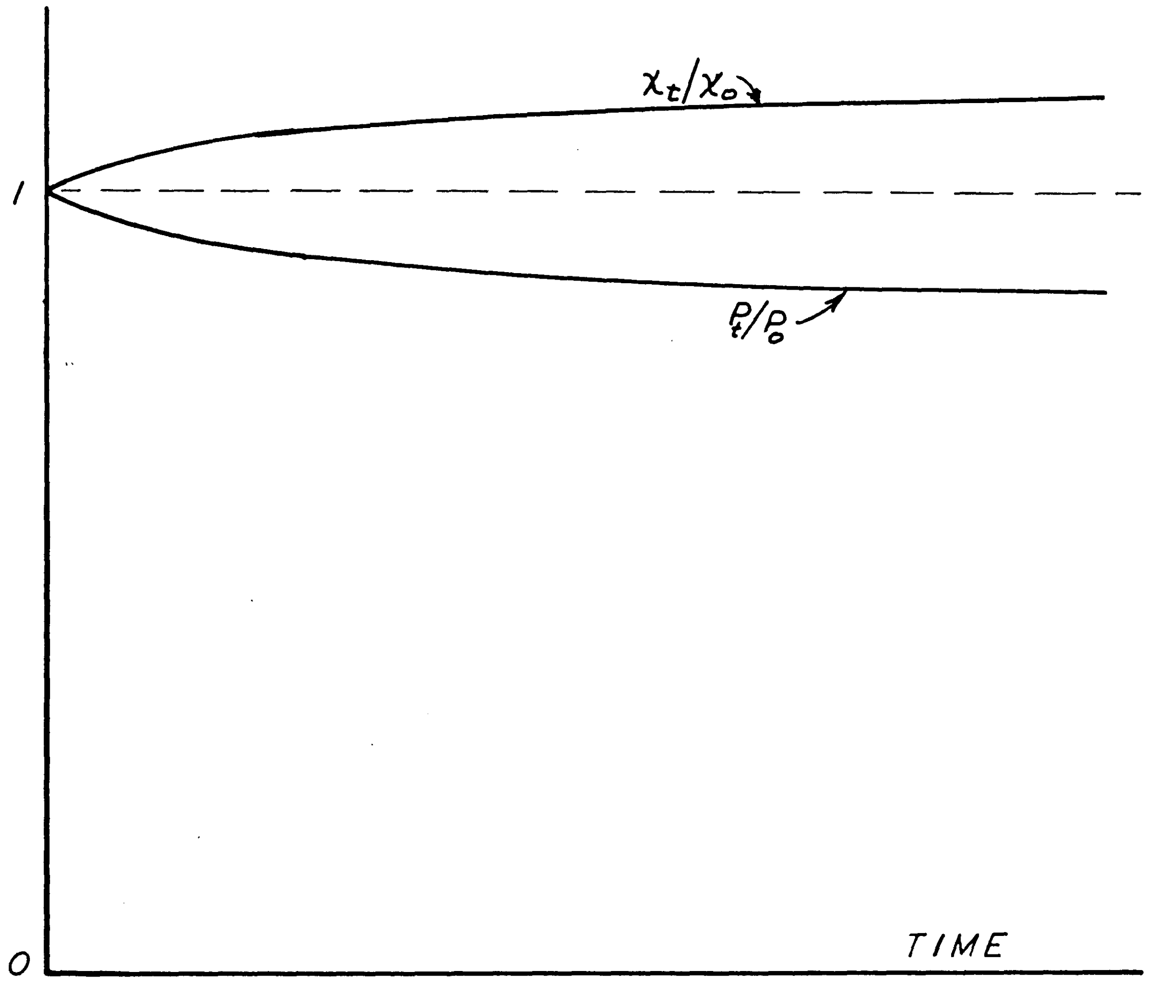


FIG. 34

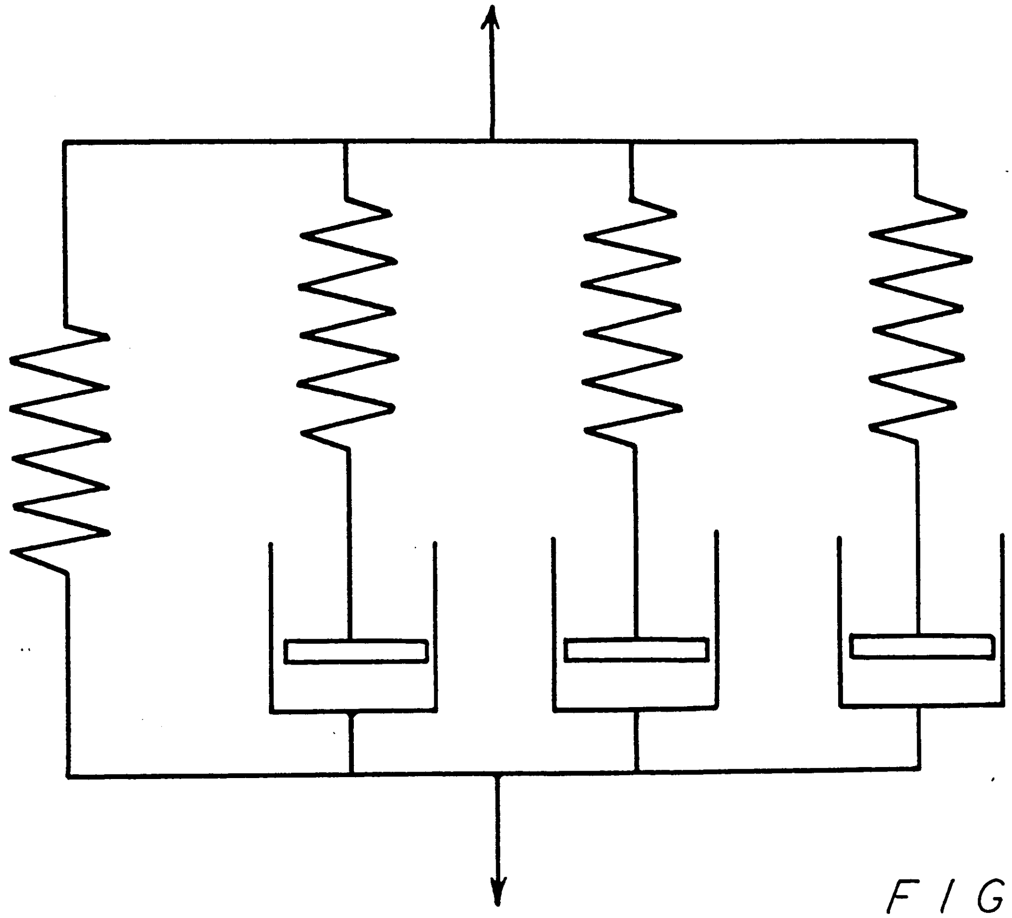


FIG. 35

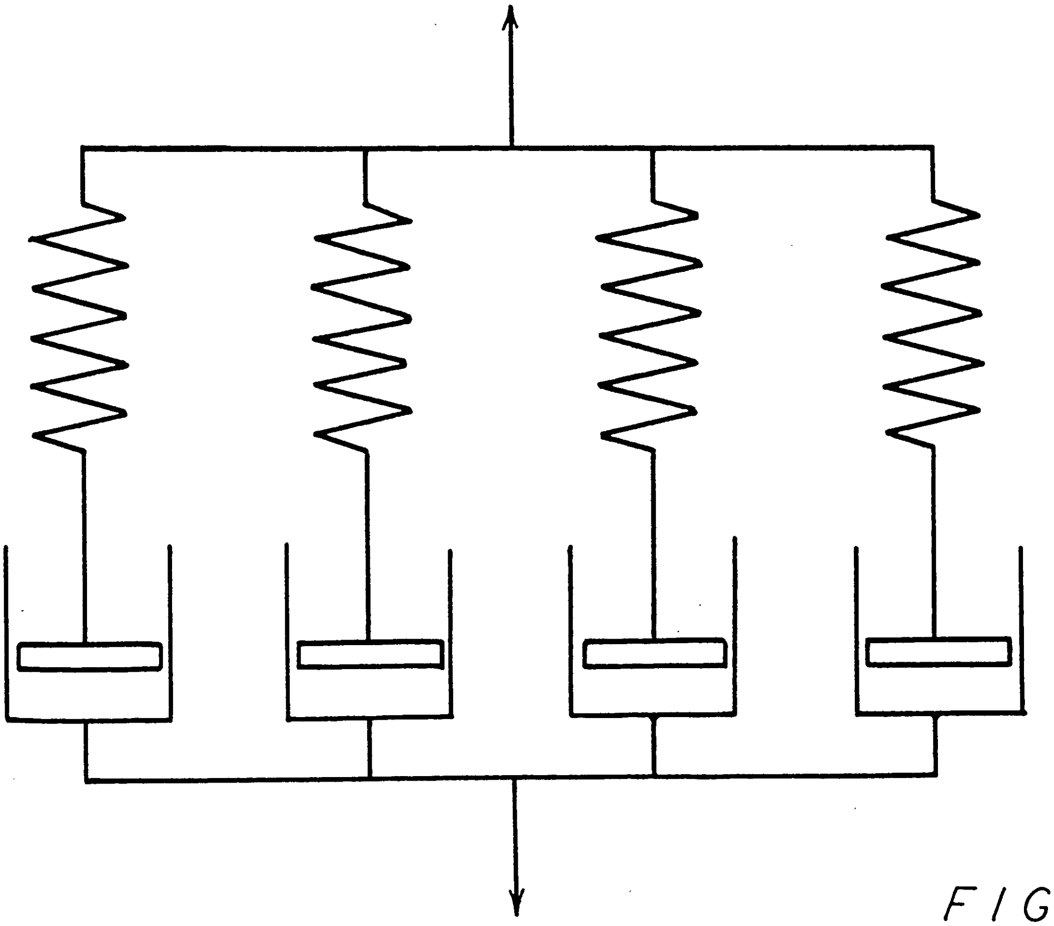


FIG. 36

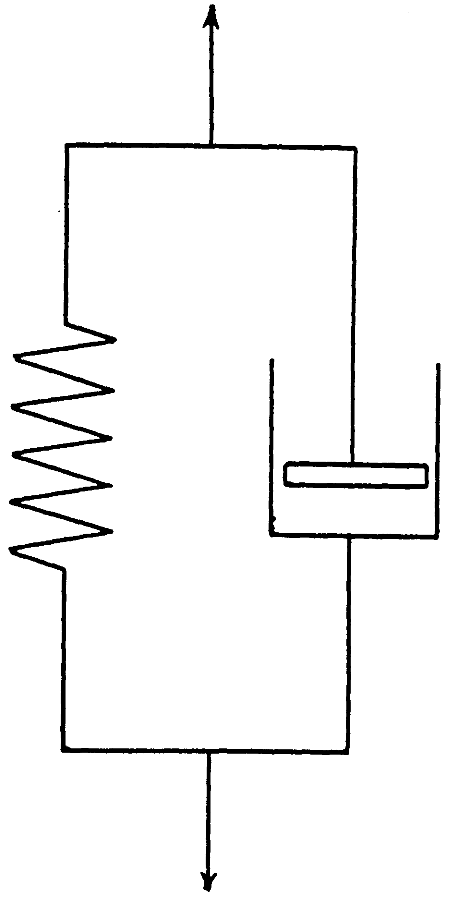


FIG. 37

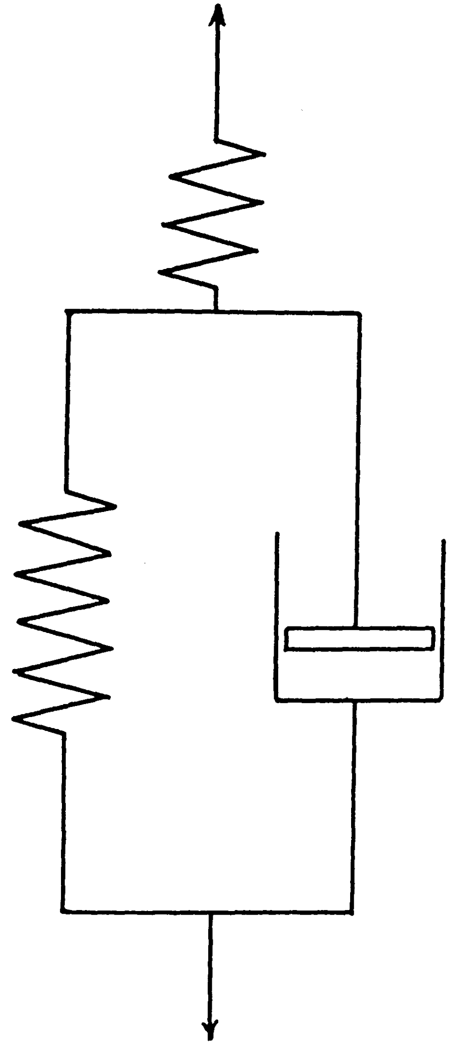


FIG. 38

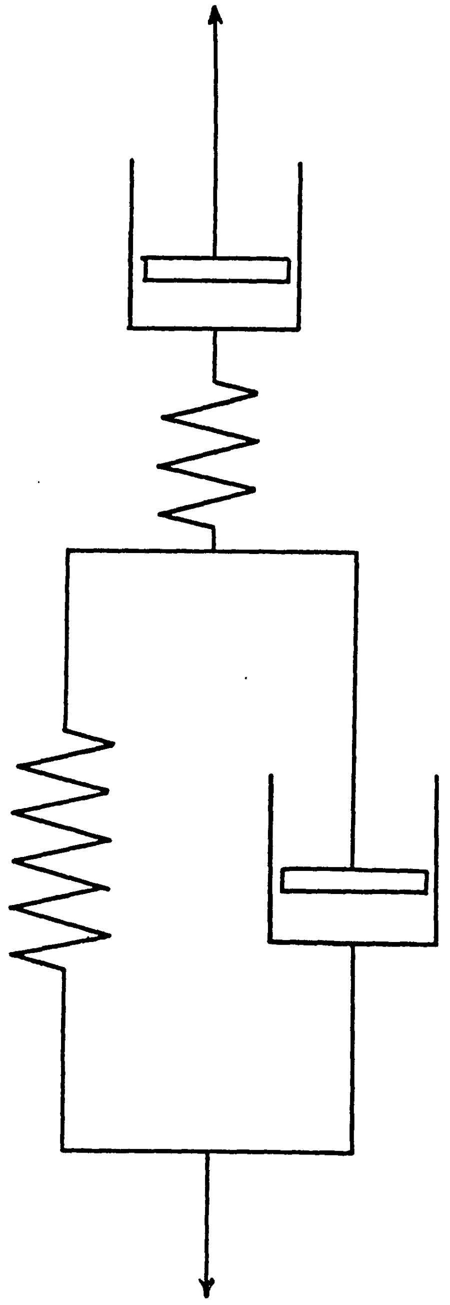


FIG. 39

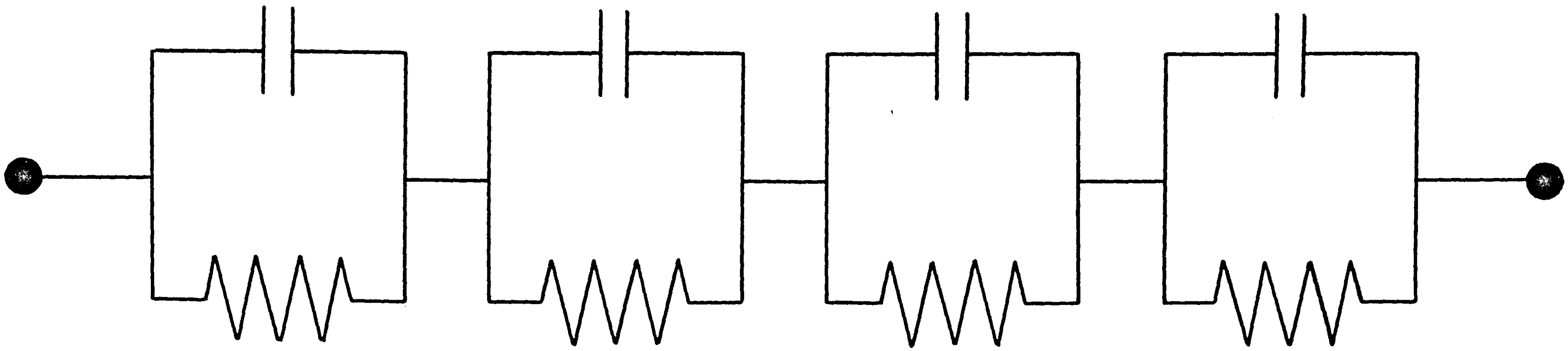


FIG. 40

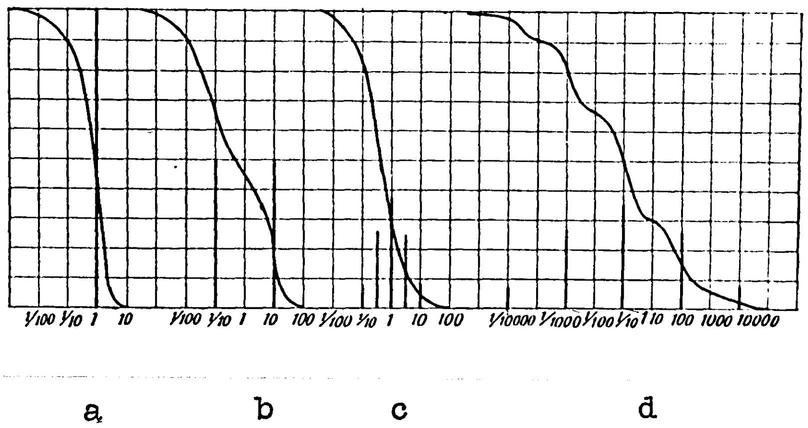


Fig. 41

Computed Relaxation Functions (Wiechert)

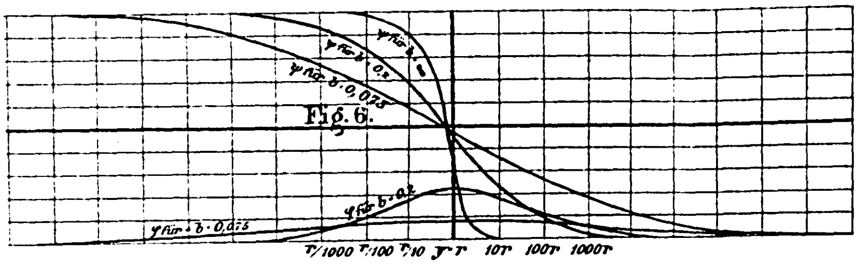


Fig. 42

Decay of Epibolic Stress (Wiechert)

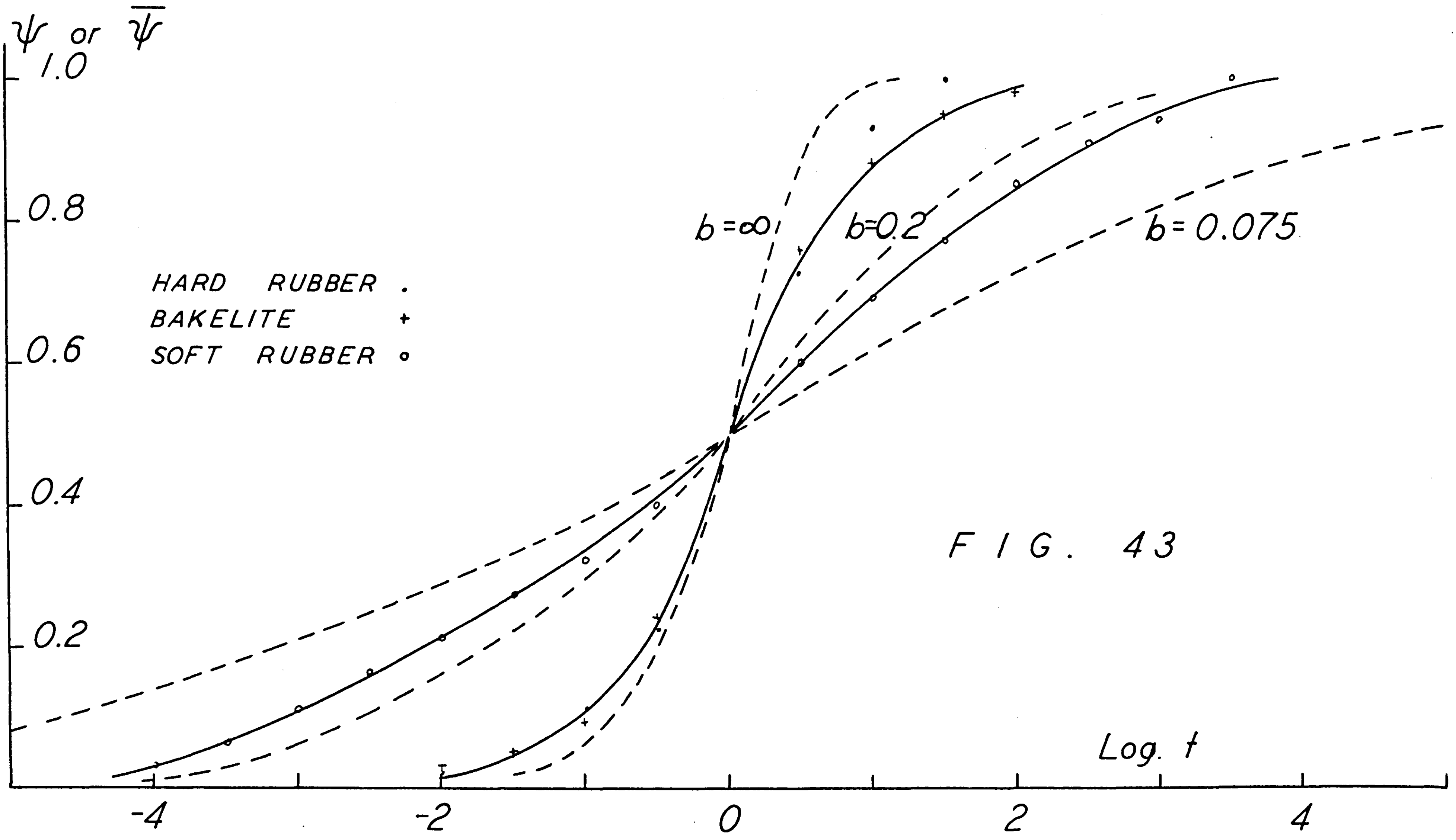

ψ or $\overline{\psi}$
1.0
0.8
0.6
0.4
0.2
HARD RUBBER .
BAKELITE +
SOFT RUBBER o
b = ∞
b = 0.2
b = 0.075
Log. t
-4
-2
0
2
4

FIG. 43

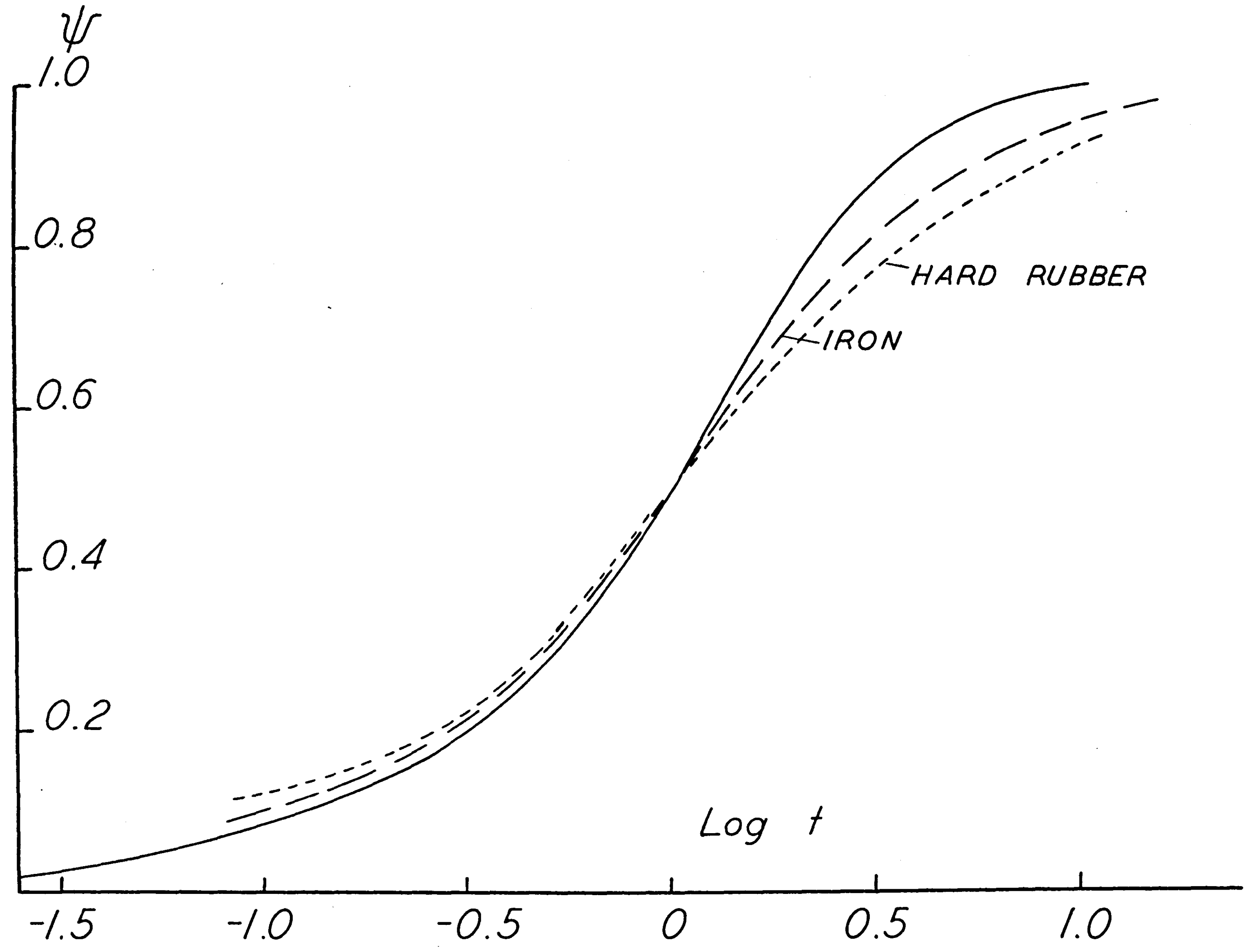


FIG. 44

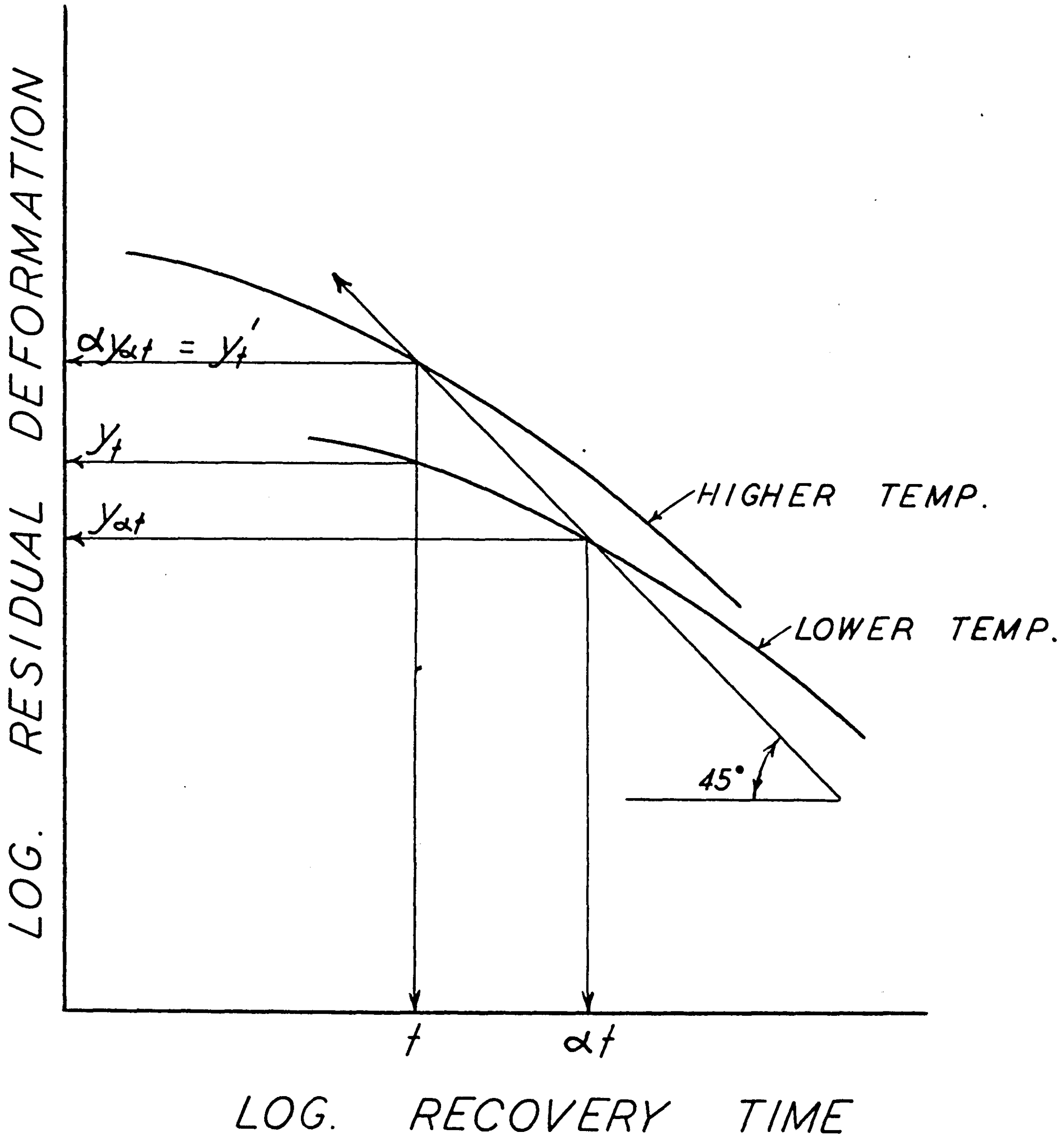

LOG. RESIDUAL DEFORMATION
$\alpha y_{\alpha t} = y_t'$
y_t
$y_{\alpha t}$
HIGHER TEMP.
LOWER TEMP.
45°
t
αt
LOG. RECOVERY TIME

FIG. 45

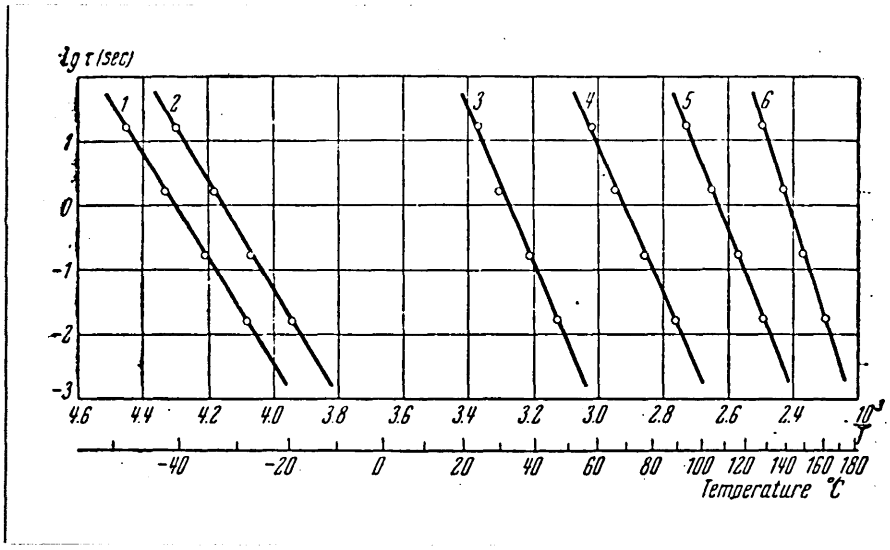


Fig. 46

Energy of Activation from Dynamic
Tests (Alexandrov and Lazurkin)

1. Rubber
2. Chloroprene
3. Partly Vulcanised Ebonite
4. Methyl Methacrylate with 30% plasticizer
5. ditto with 10% plasticizer
6. ditto without plasticizer

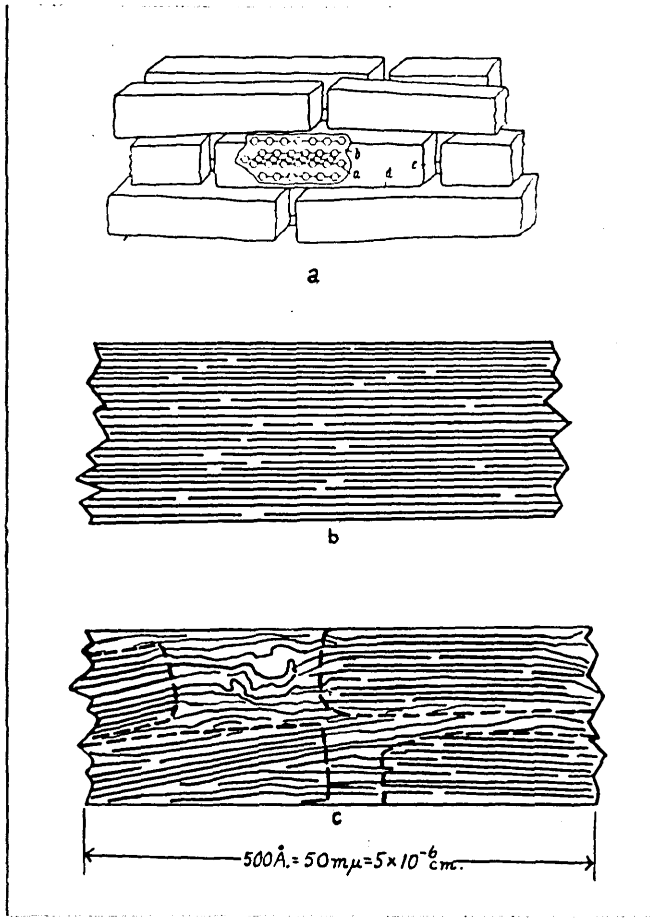


Fig. 47

Theories of Structure (Mark)

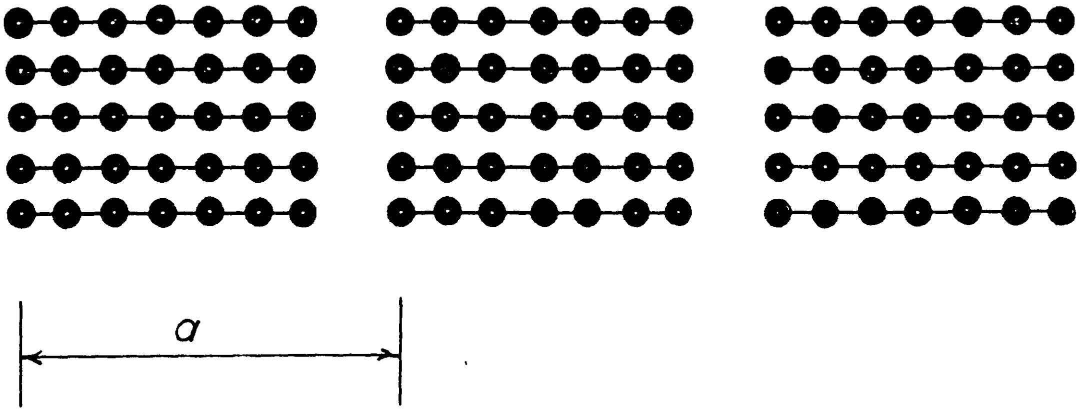


FIG. 48

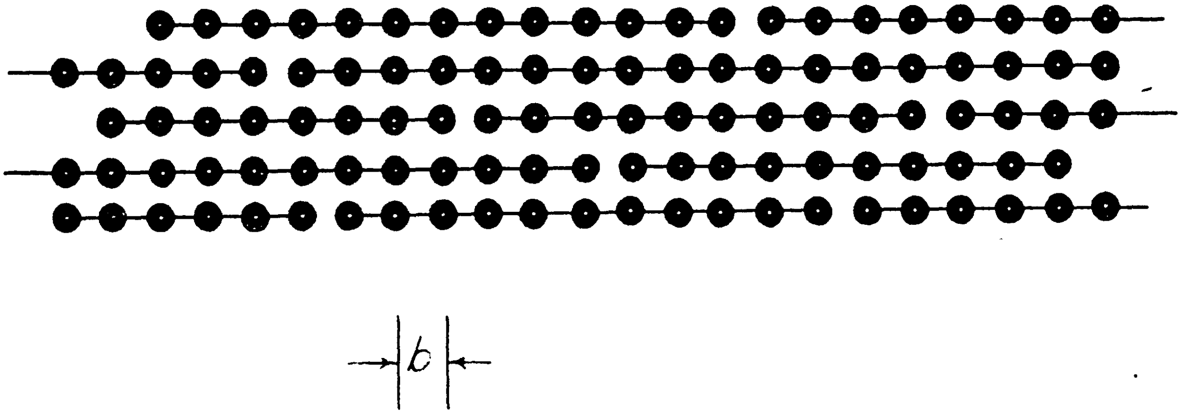


FIG. 49

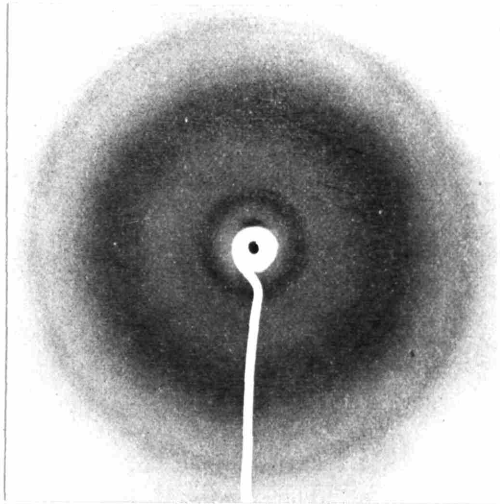


Fig. 50

X-Ray Diagram of Unstretched
Air-Dry Gelatin

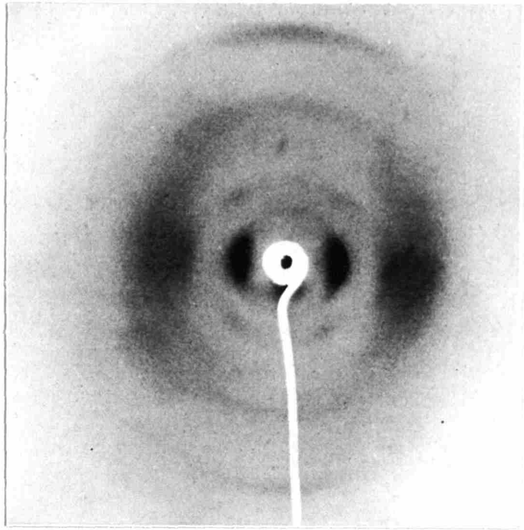


Fig. 51

X-Ray Diagram of Collagen (Sinew)

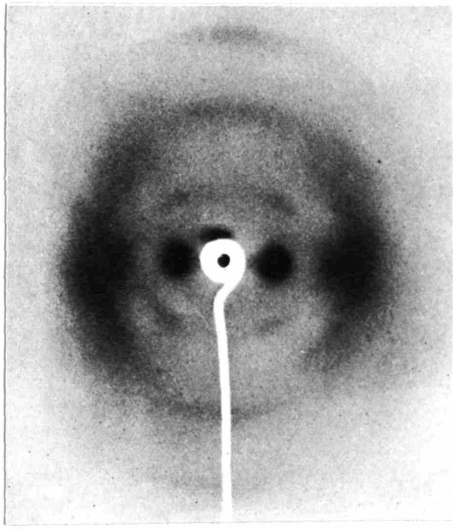


Fig. 52

X-Ray Diagram of Stretched Gelatin

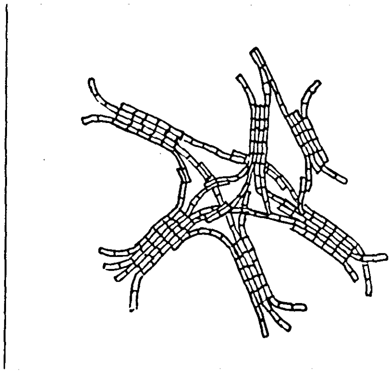


Fig. 53

Unoriented Fringed Micelles

(Herrmann and Gerngross)

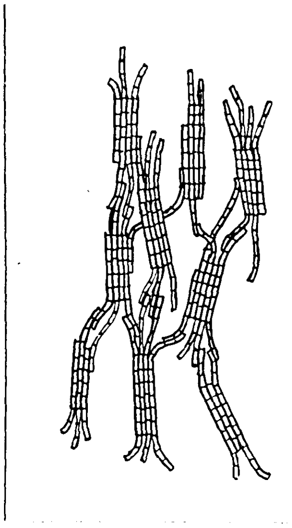
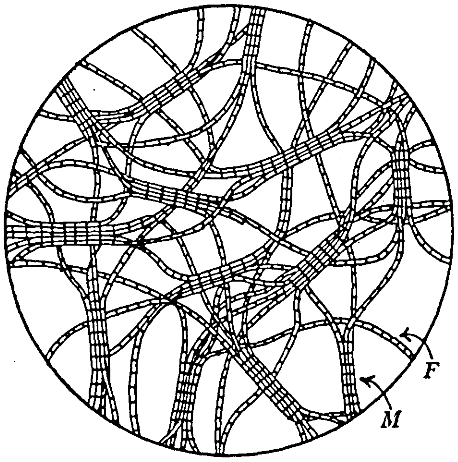


Fig. 54

Oriented Fringed Micelles

(Herrmann and Gerngross)



Fringe structure of rubber after Herrmann and Gerngross.
F, fringes; *M*, micelles (crystallites).

Fig. 55

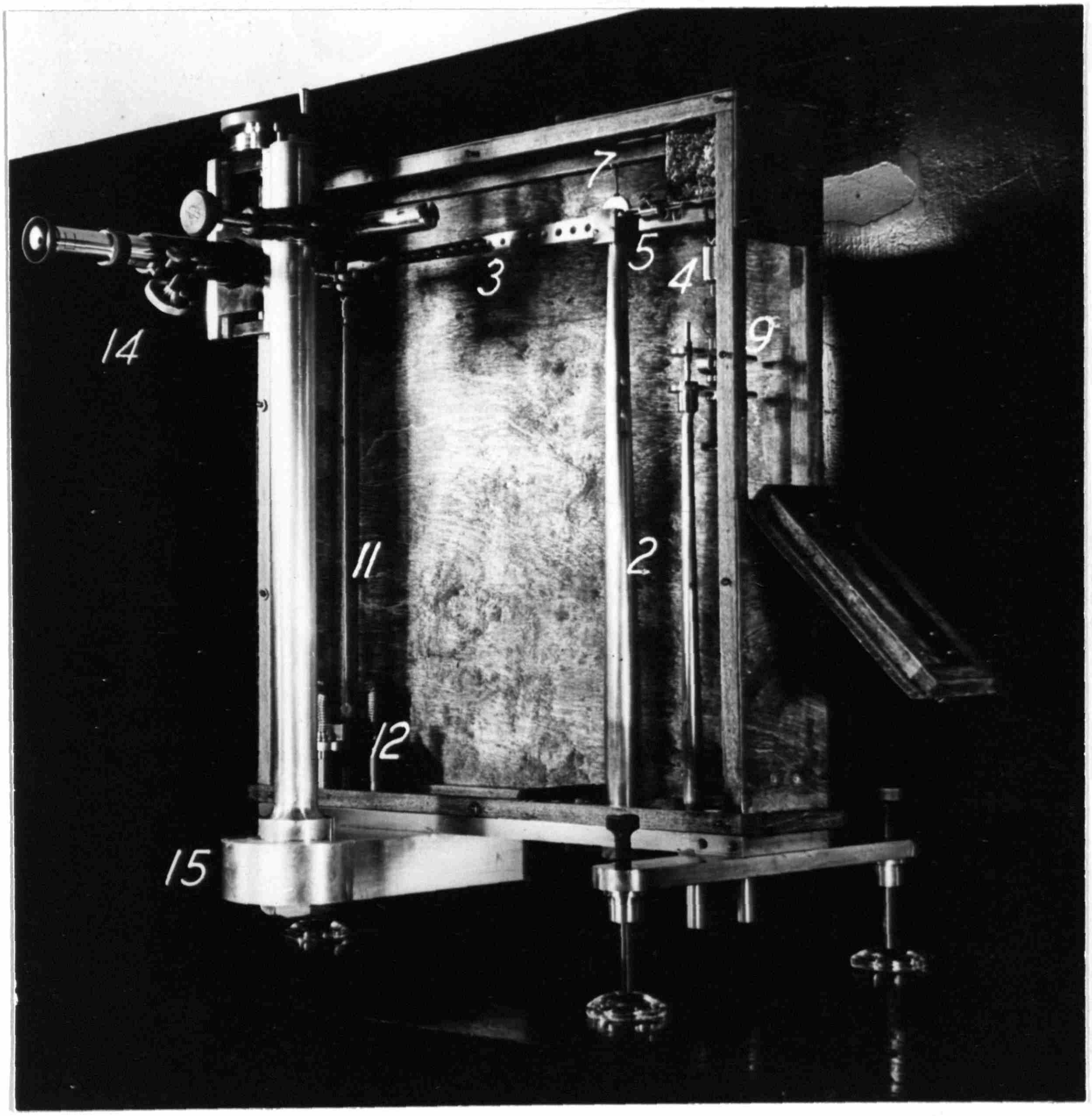


Fig. 56

Creep Balance, Front View

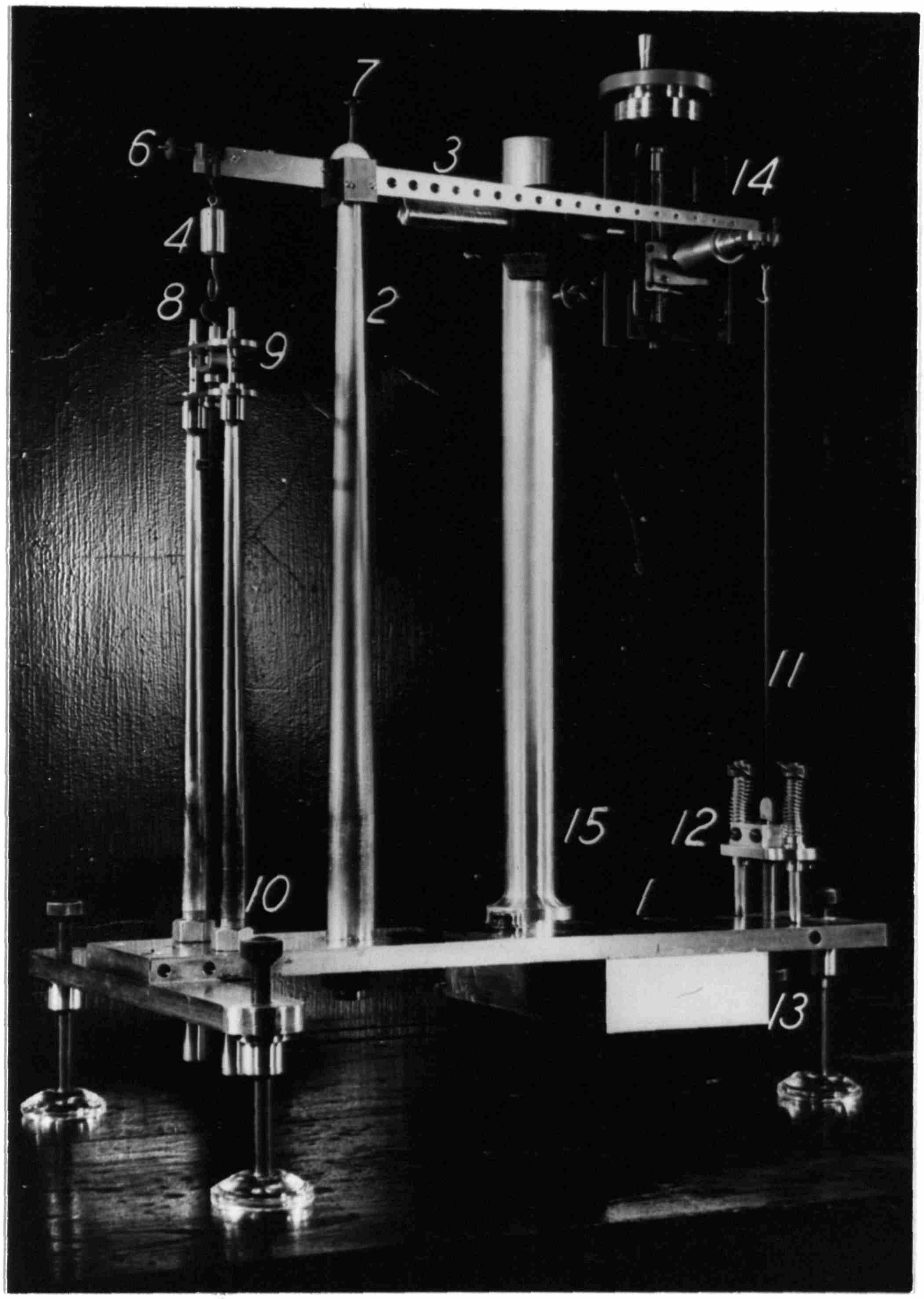


Fig. 57

Creep Balance, Rear View

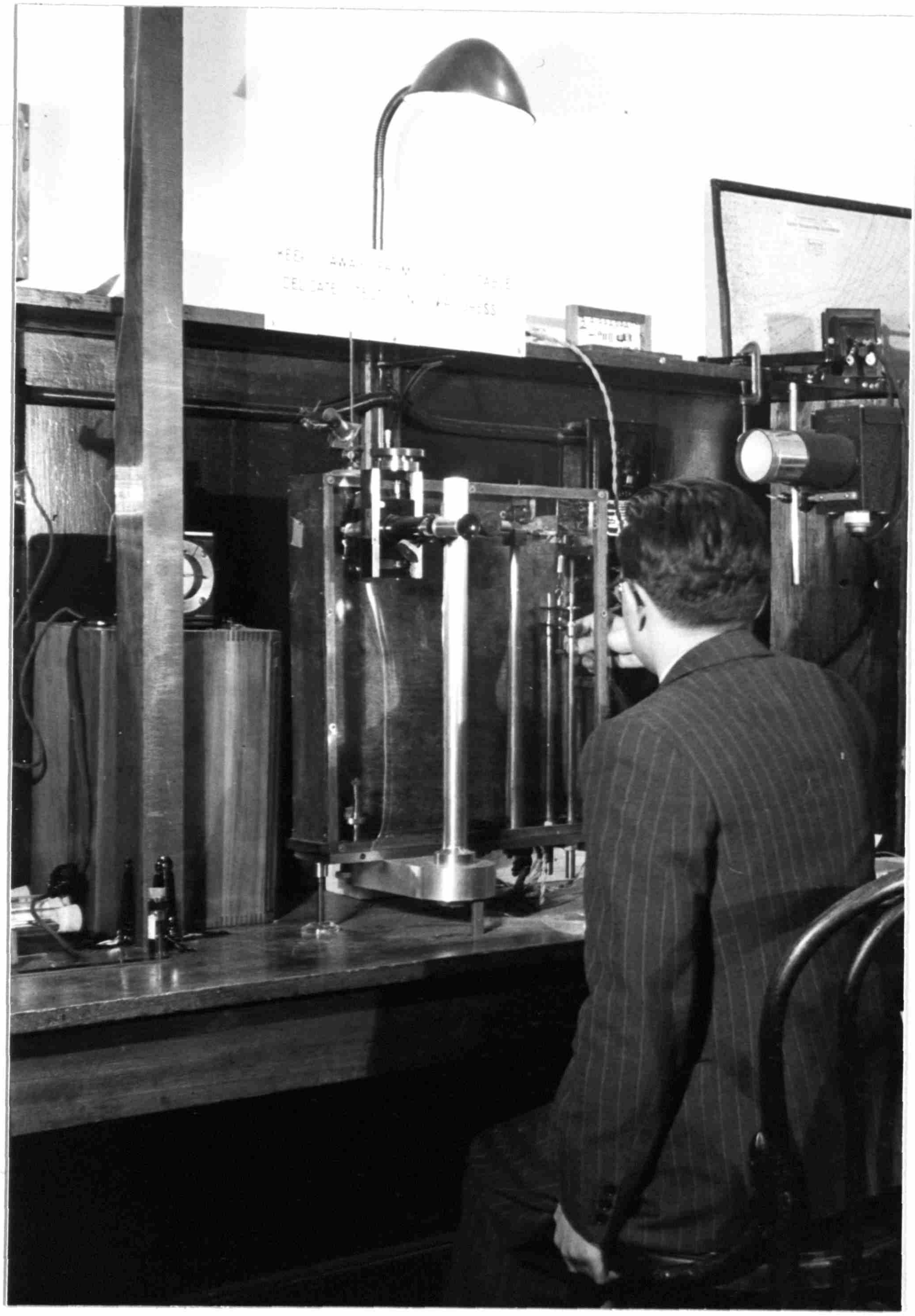


Fig. 58

Creep Apparatus

Fig. 59

Aural Timer

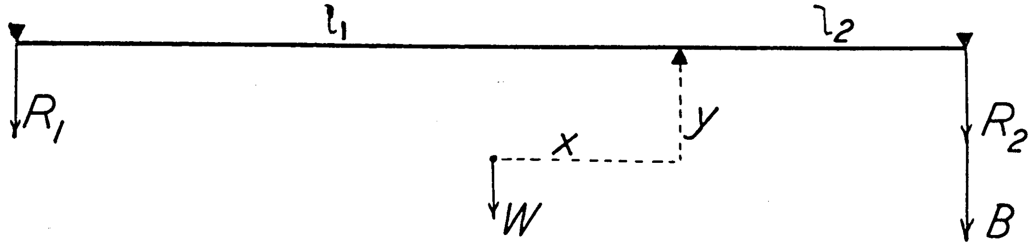


FIG. 60

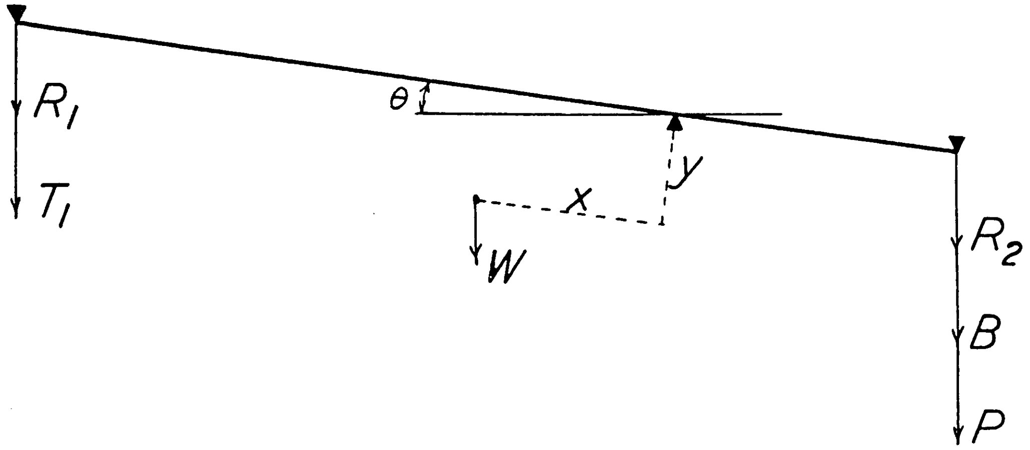
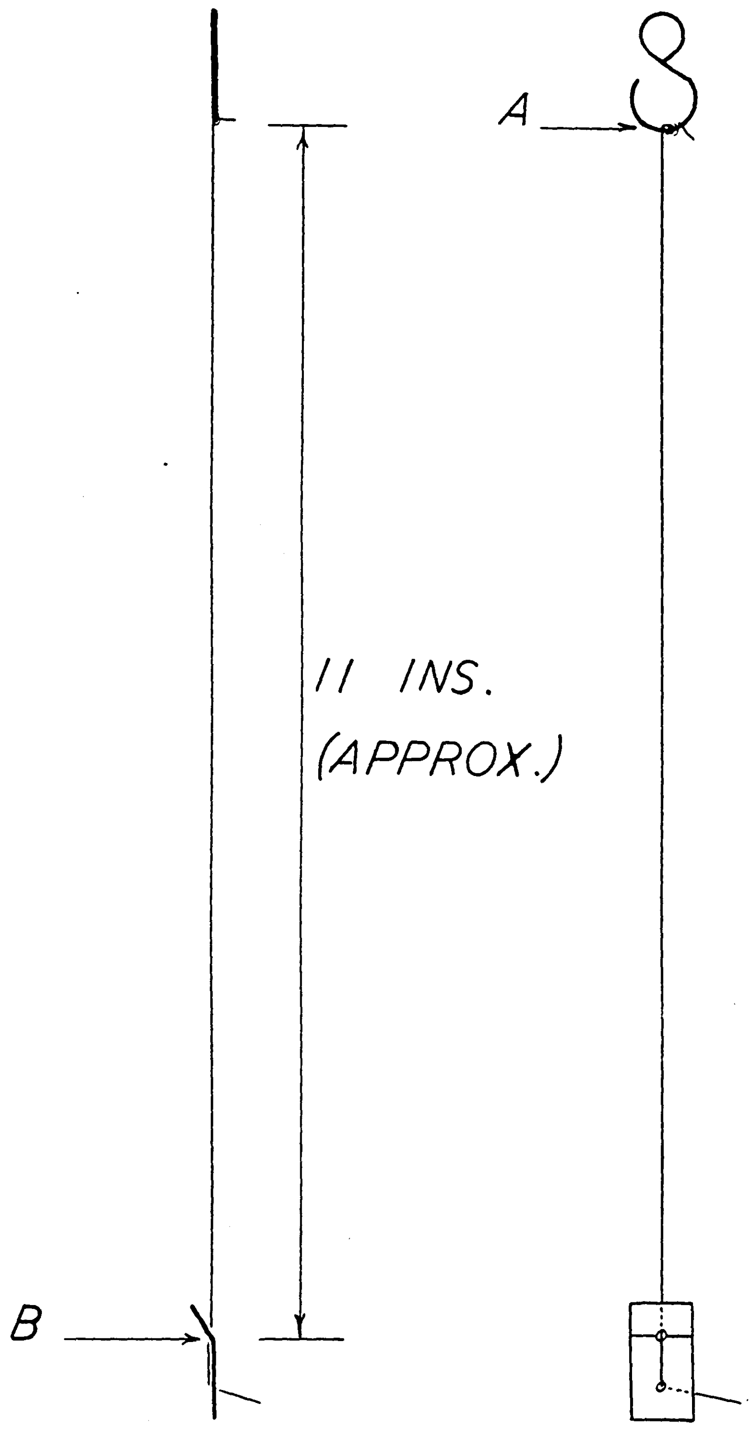


FIG. 61

Fig. 62

Filament Preparation Apparatus



F I G. 63

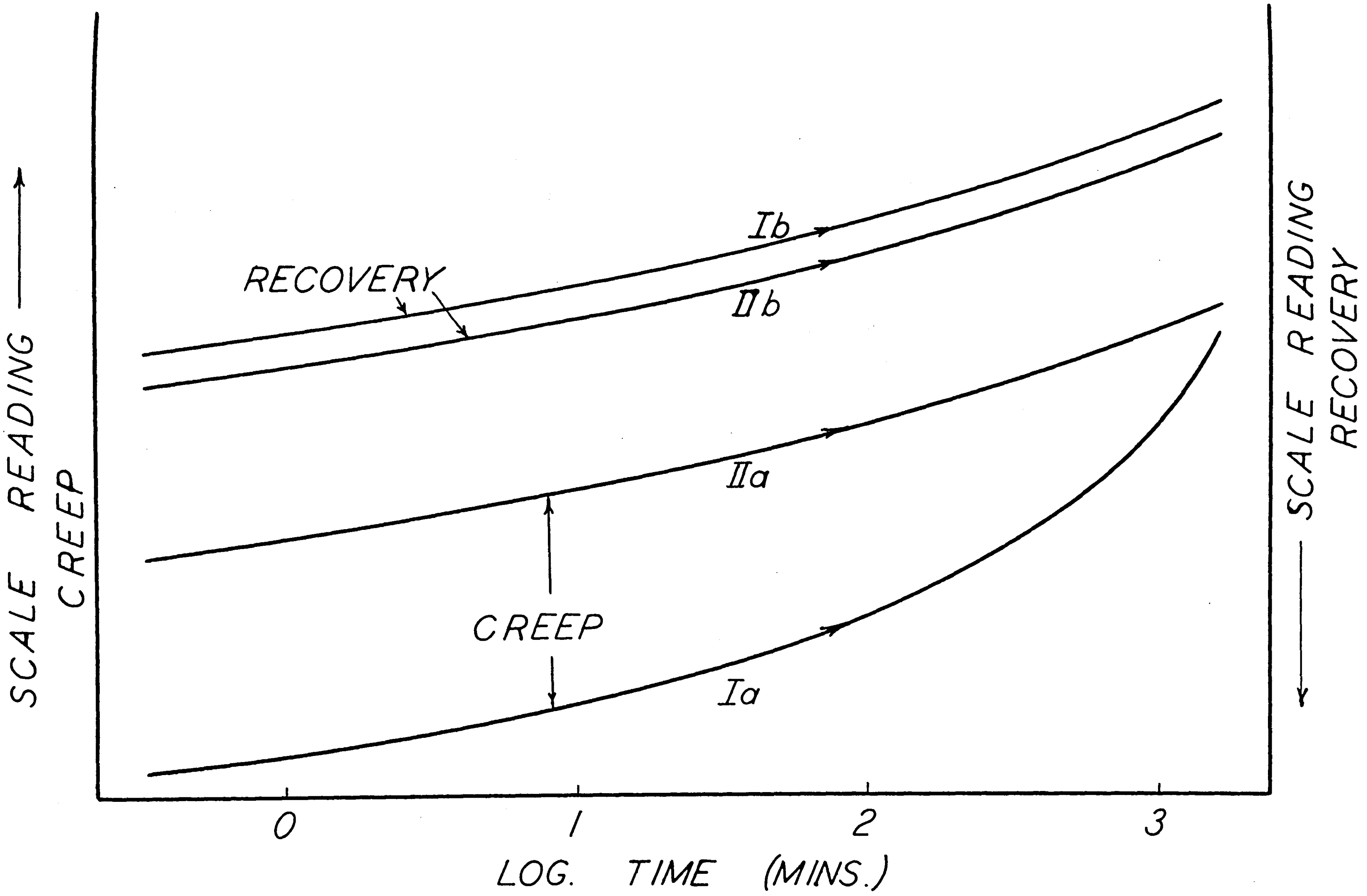
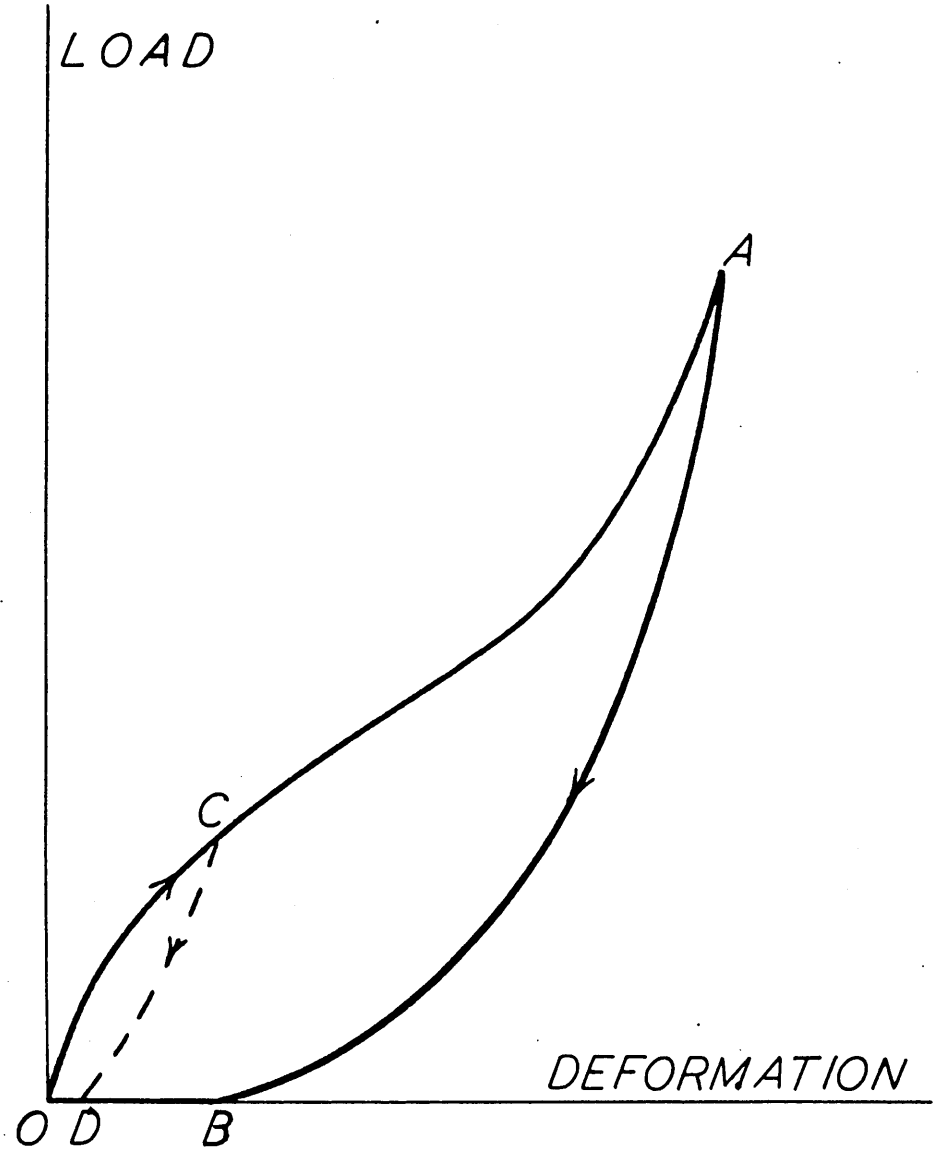

SCALE READING → CREEP
SCALE READING ← RECOVERY
RECOVERY
Ib
IIb
IIa
CREEP
Ia
0
1
2
3
LOG. TIME (MINS.)

FIG. 64



F I G. 65

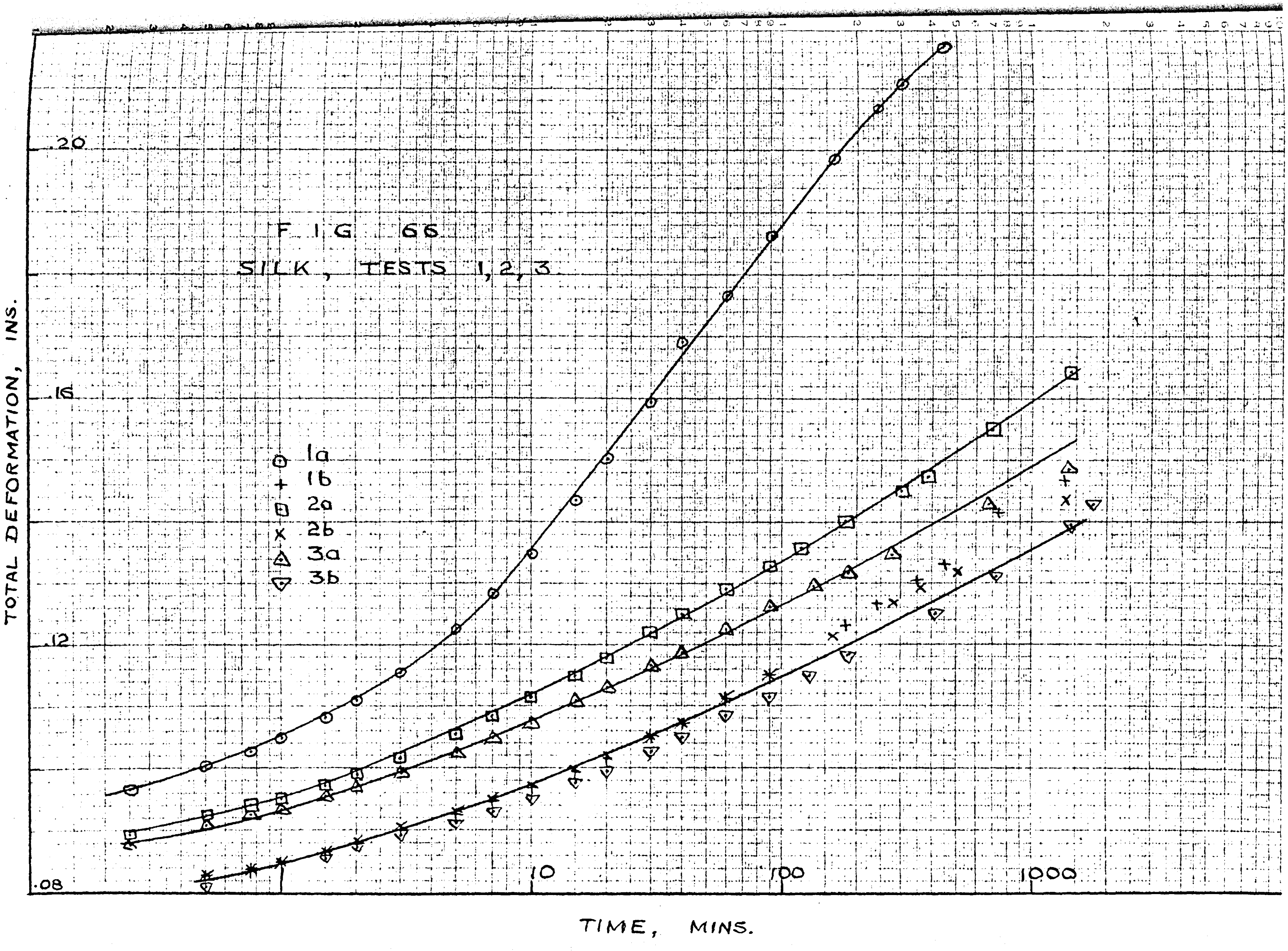


FIG 66

SILK, TESTS 1, 2, 3

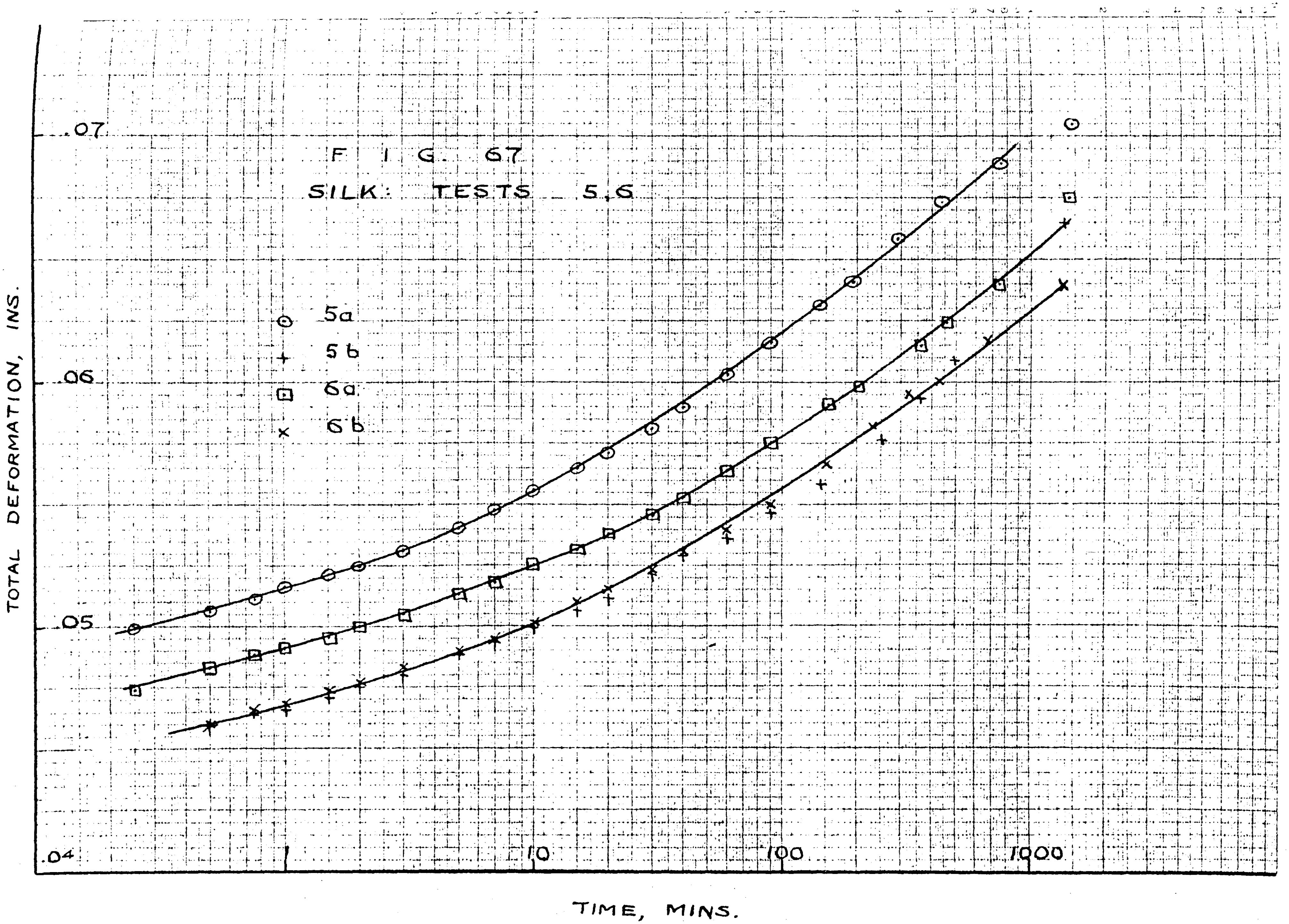


FIG. 67

SILK: TESTS 5,6

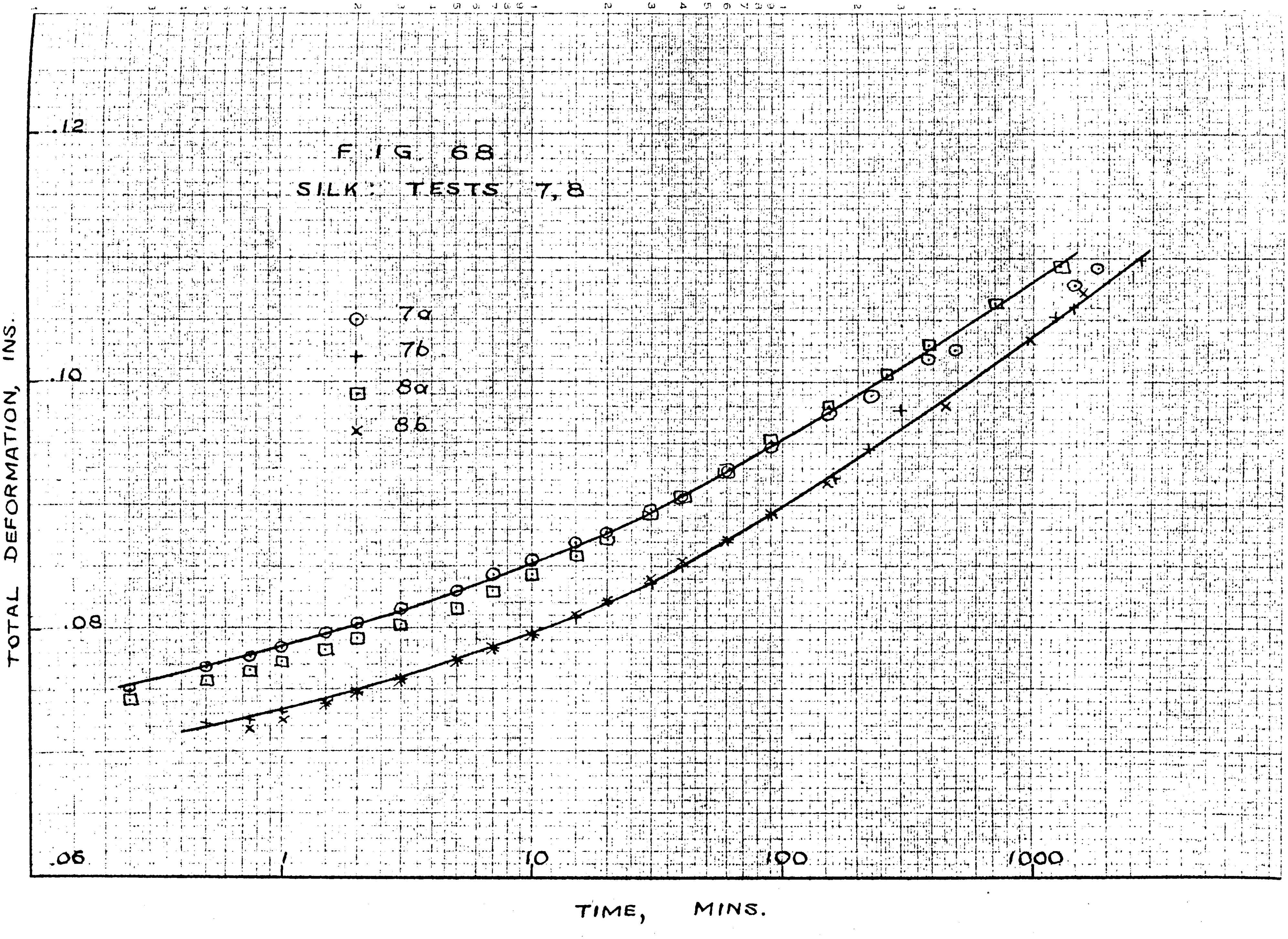


FIG 68

SILK: TESTS 7,8

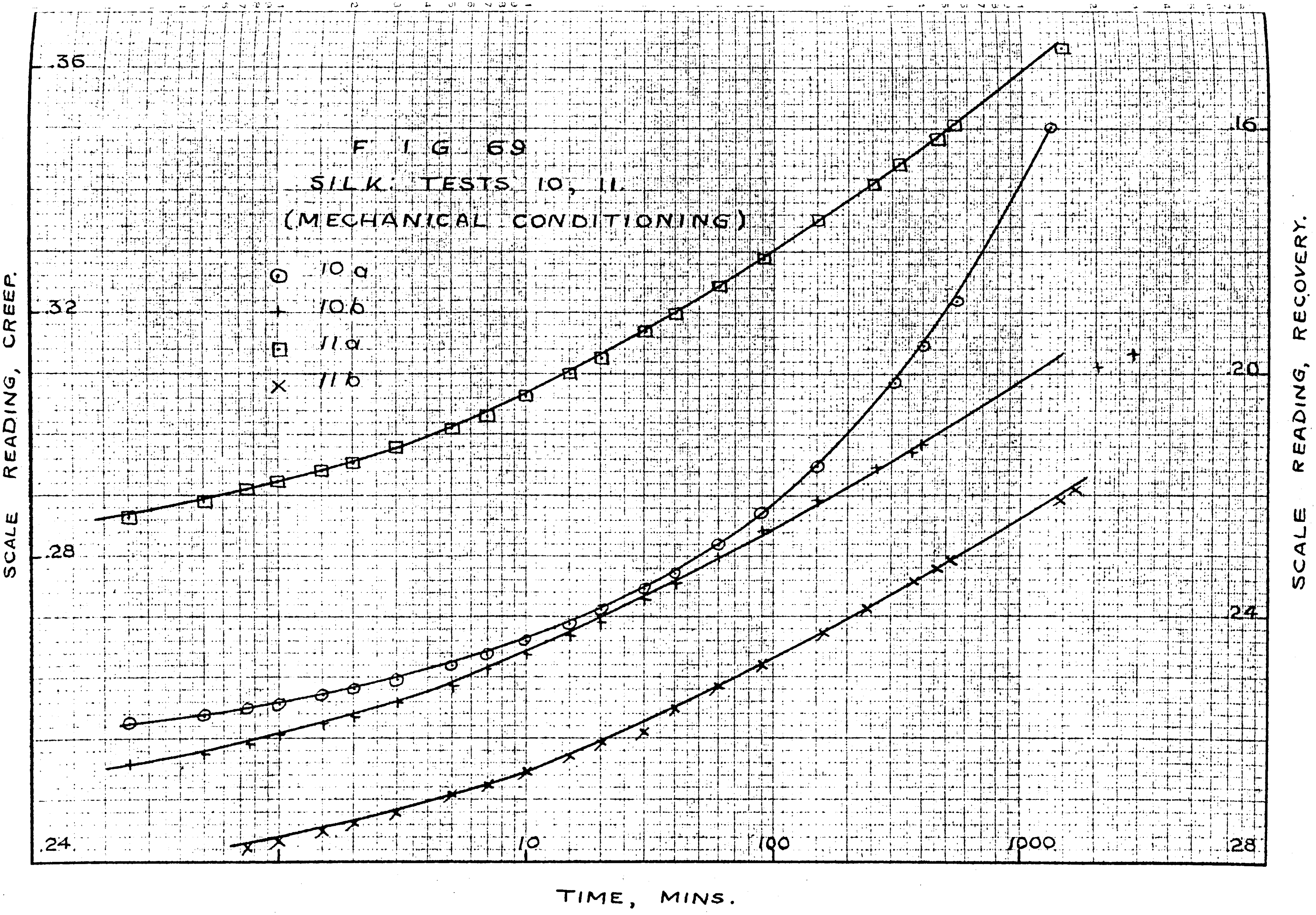


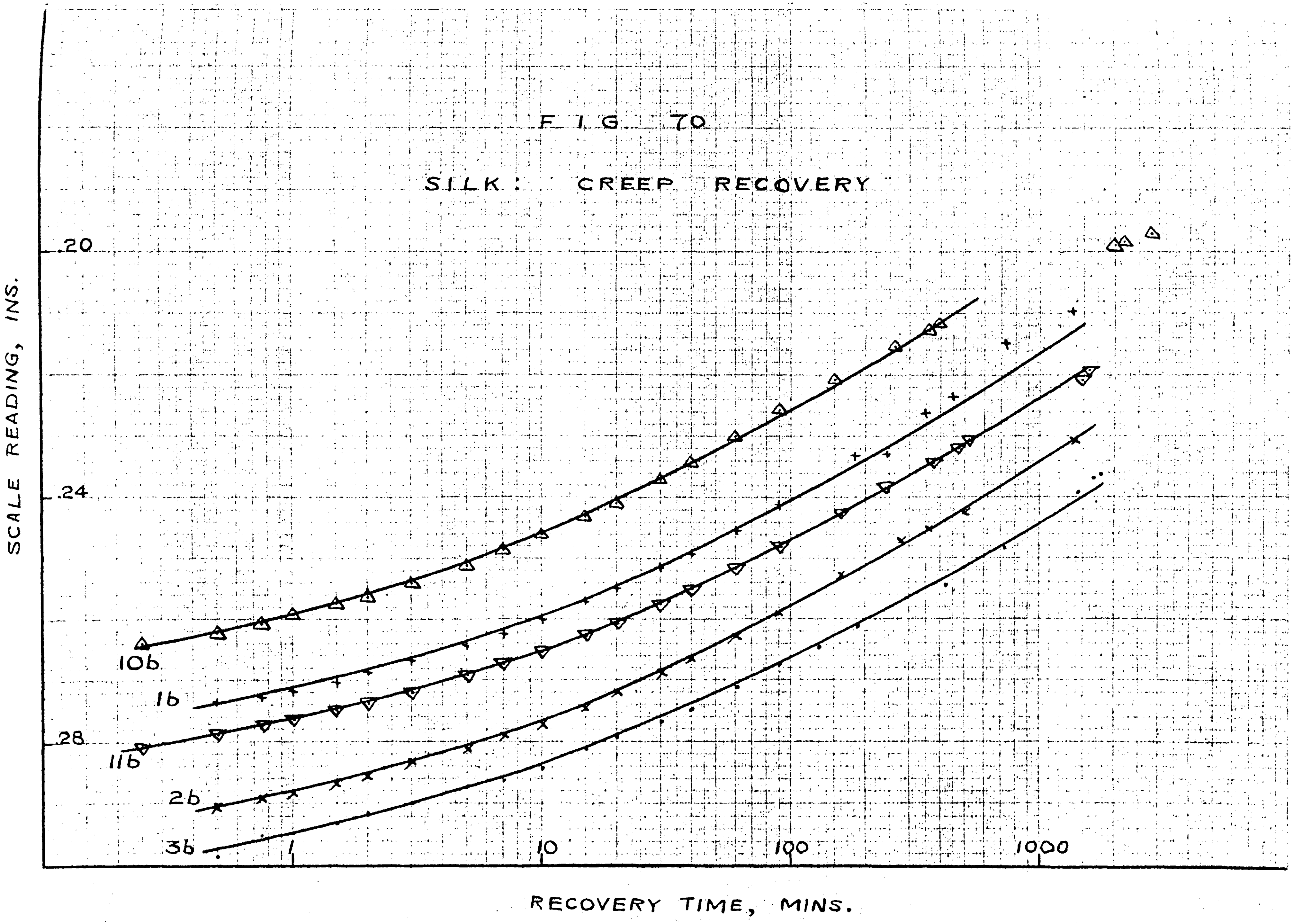
FIG 69

SILK: TESTS 10, 11.

(MECHANICAL CONDITIONING)

FIG 70

SILK: CREEP RECOVERY



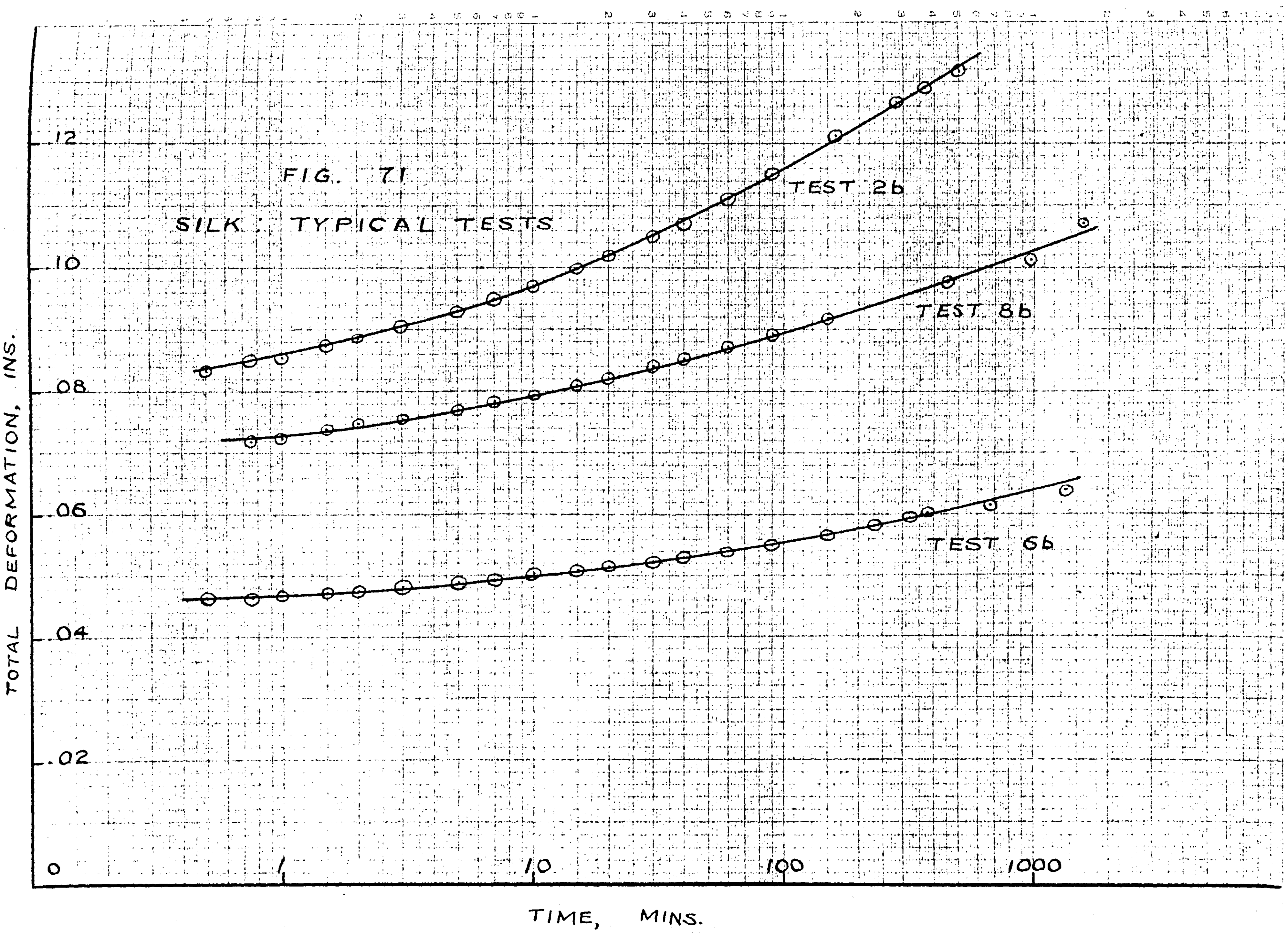


FIG. 71

SILK : TYPICAL TESTS

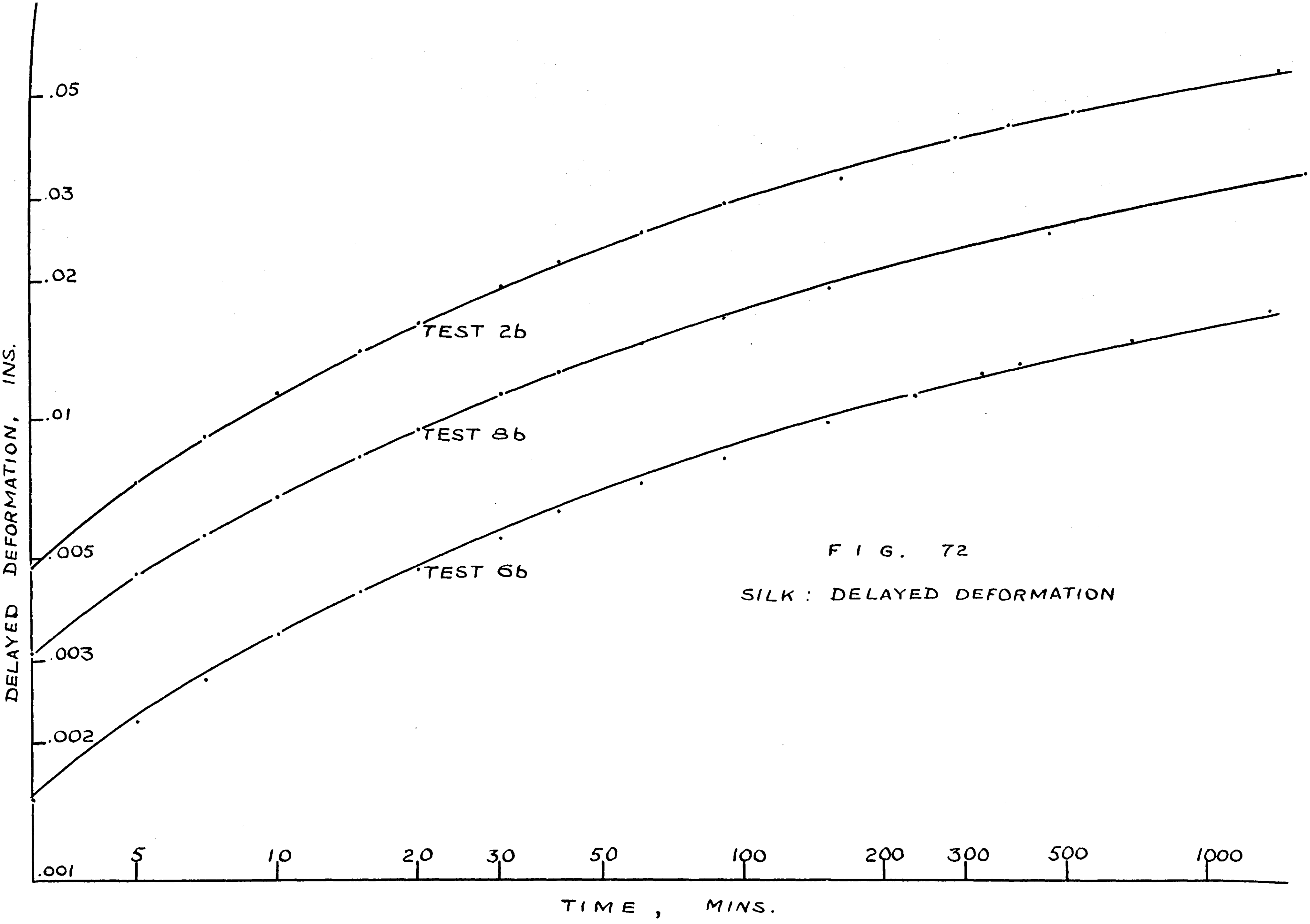
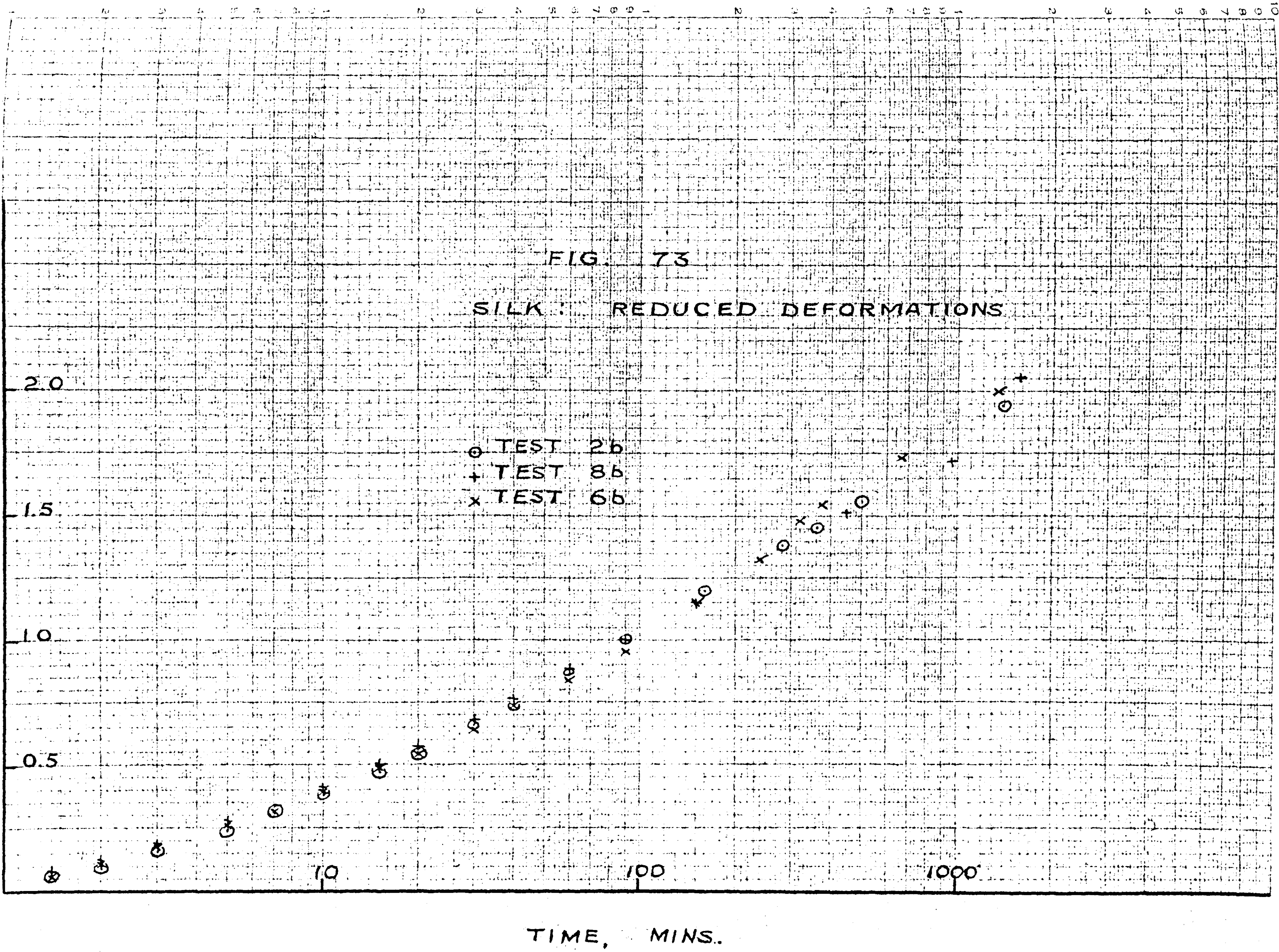


FIG. 72

SILK: DELAYED DEFORMATION

FIG. 73

SILK: REDUCED DEFORMATIONS



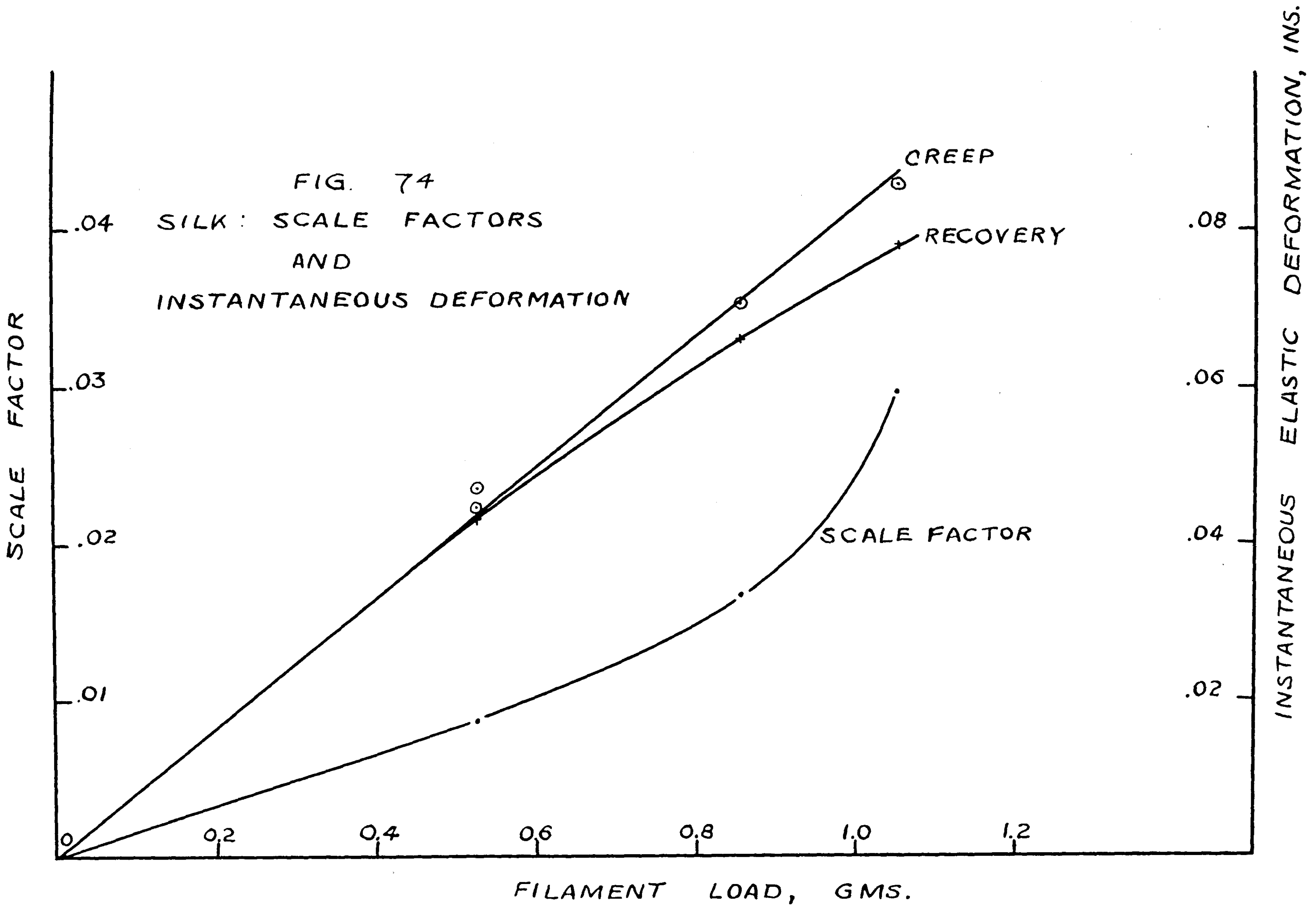


FIG. 74

SILK: SCALE FACTORS AND INSTANTANEOUS DEFORMATION

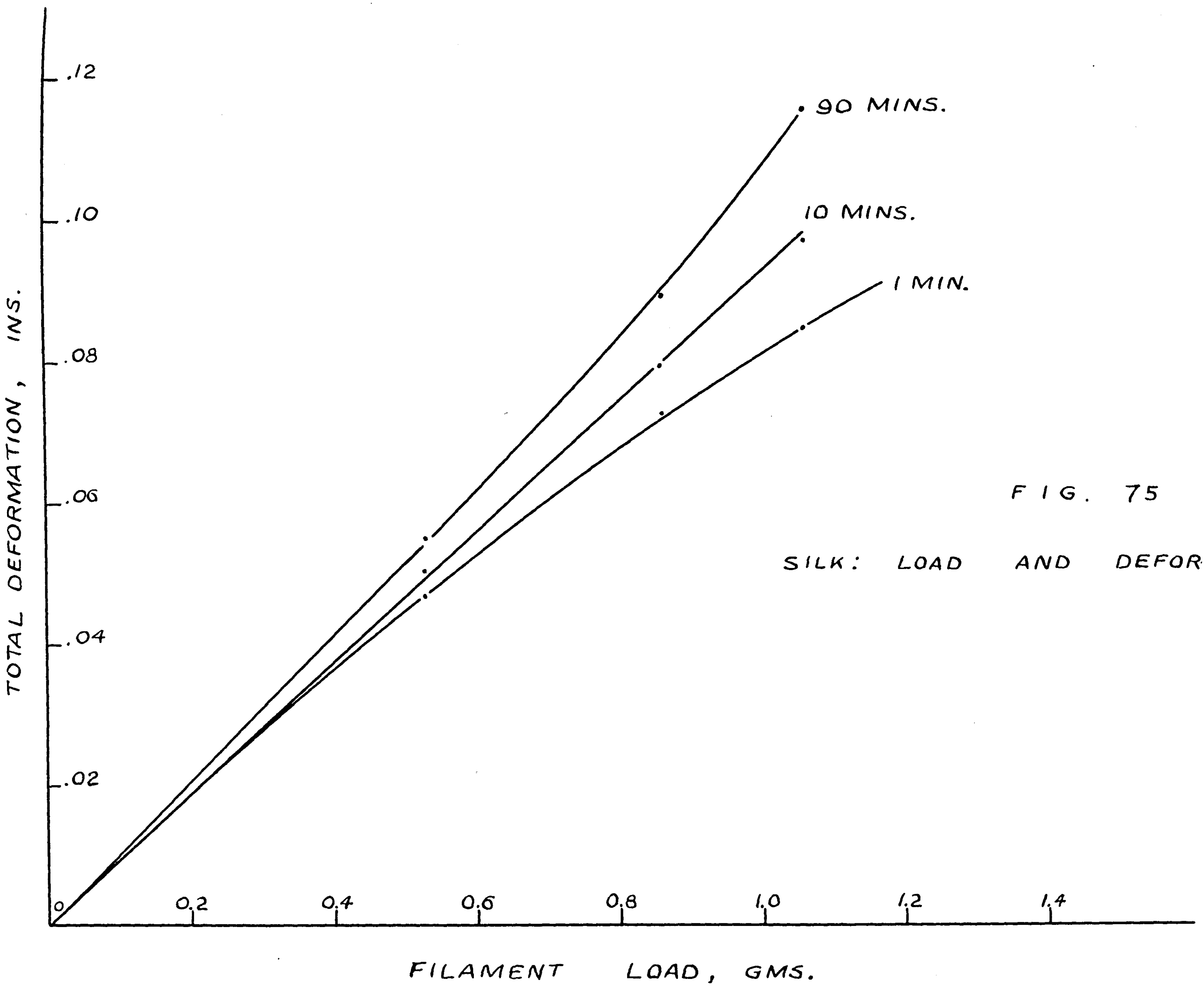
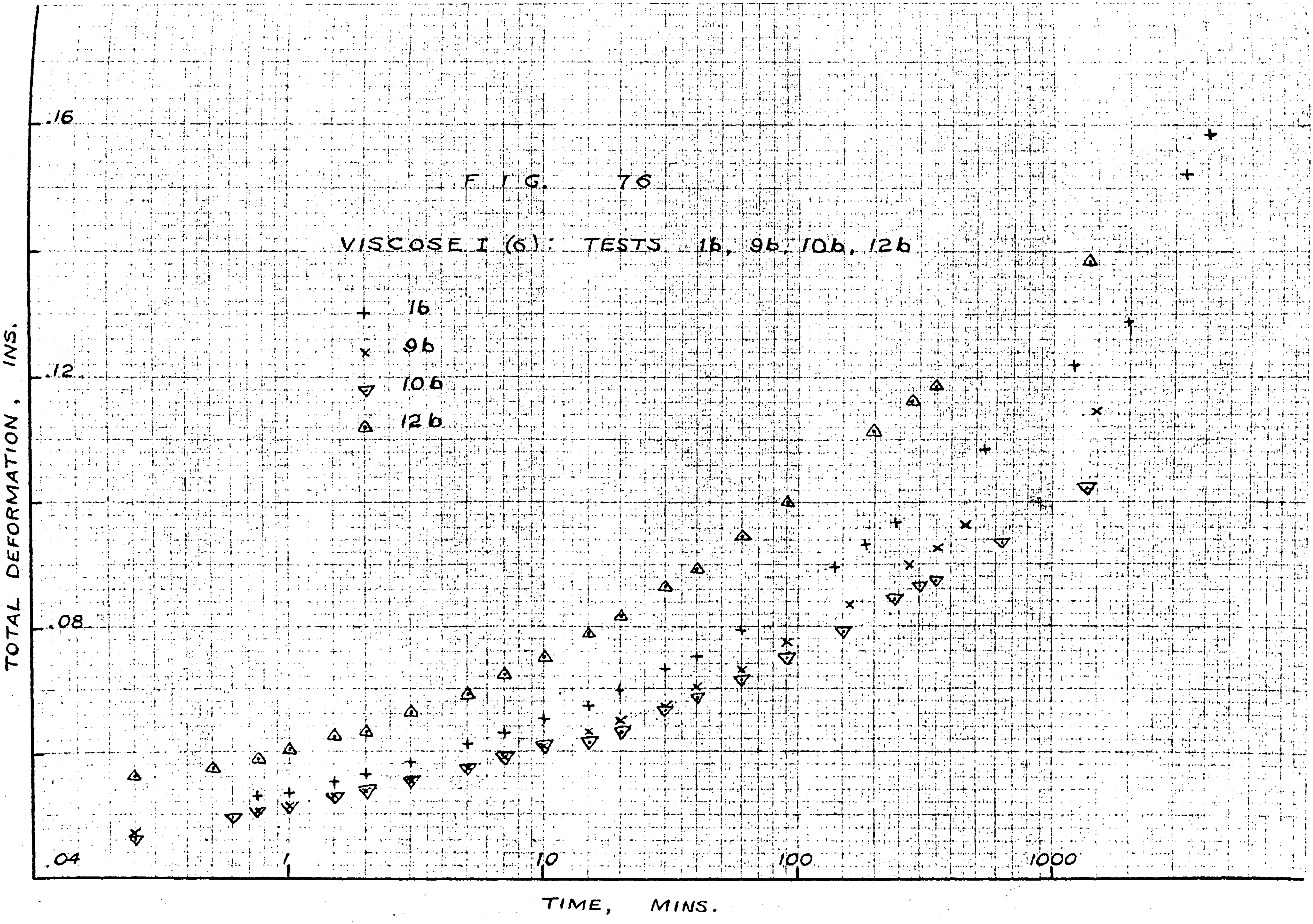


FIG. 75

SILK: LOAD AND DEFORMATION.

FIG. 76

VISCOSE I (6): TESTS 1b, 9b, 10b, 12b



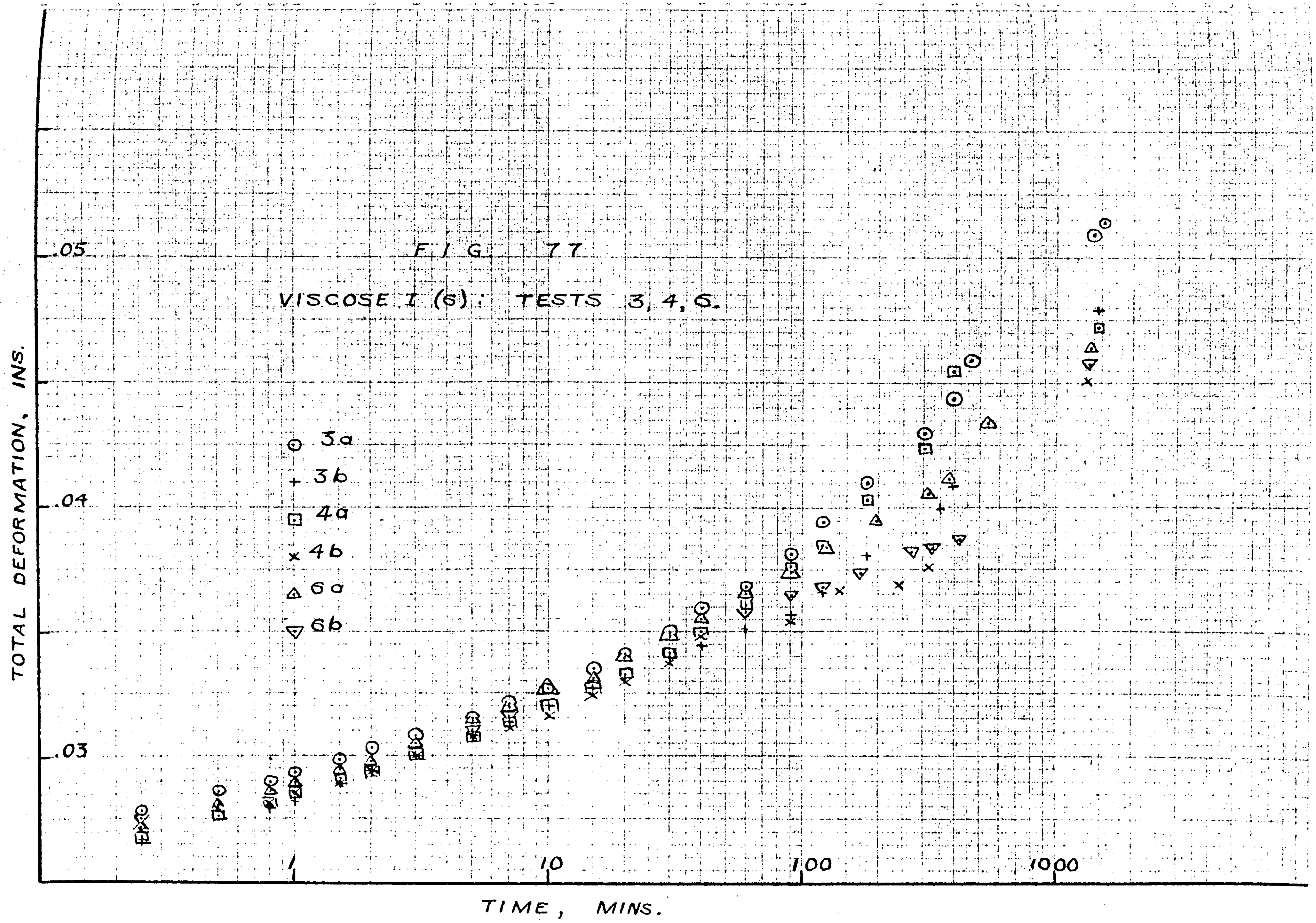


FIG. 77

VISCOSE I (6): TESTS 3, 4, 6.

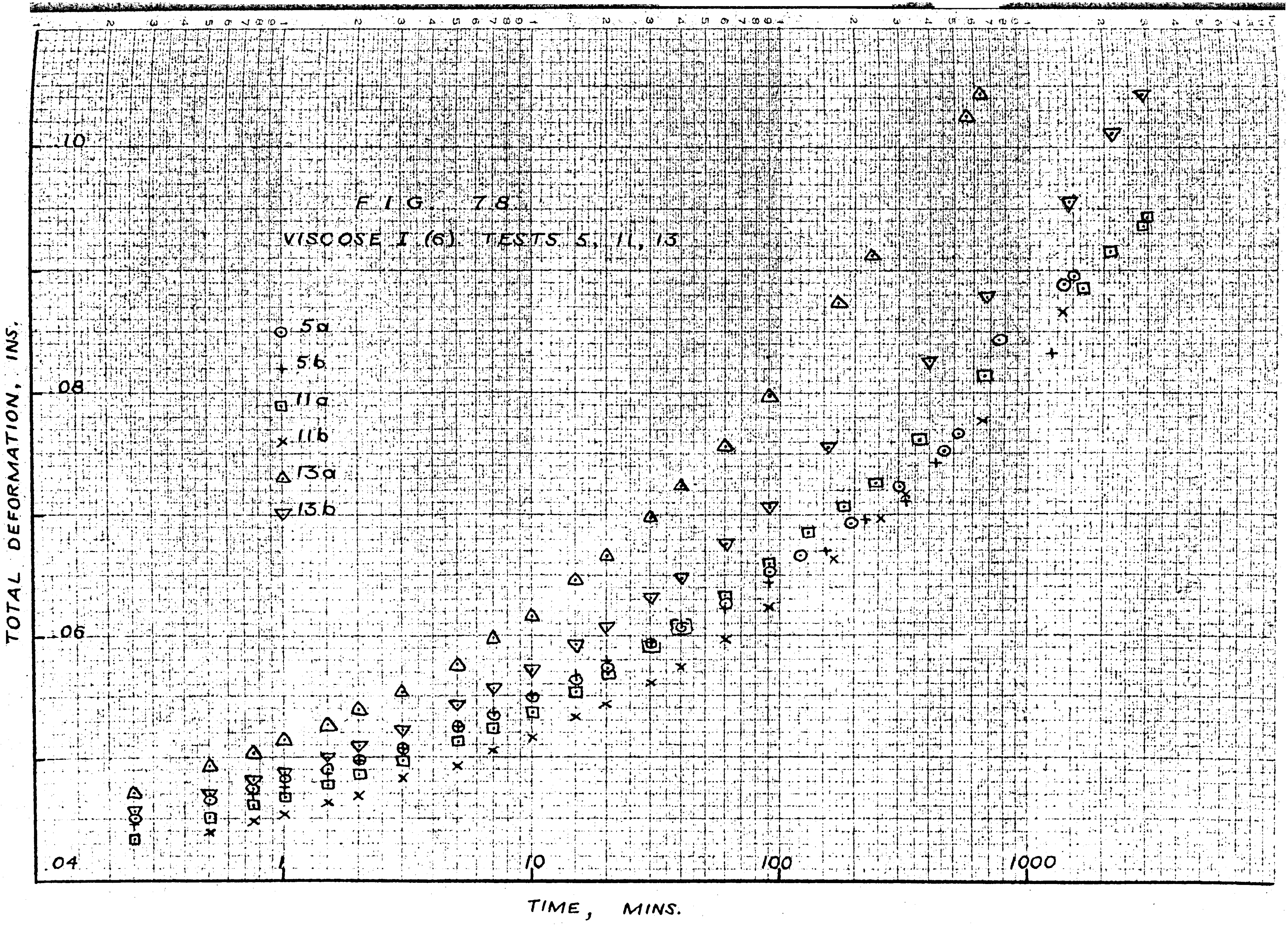


FIG. 78

VISCOSE I (6) TESTS 5, 11, 13

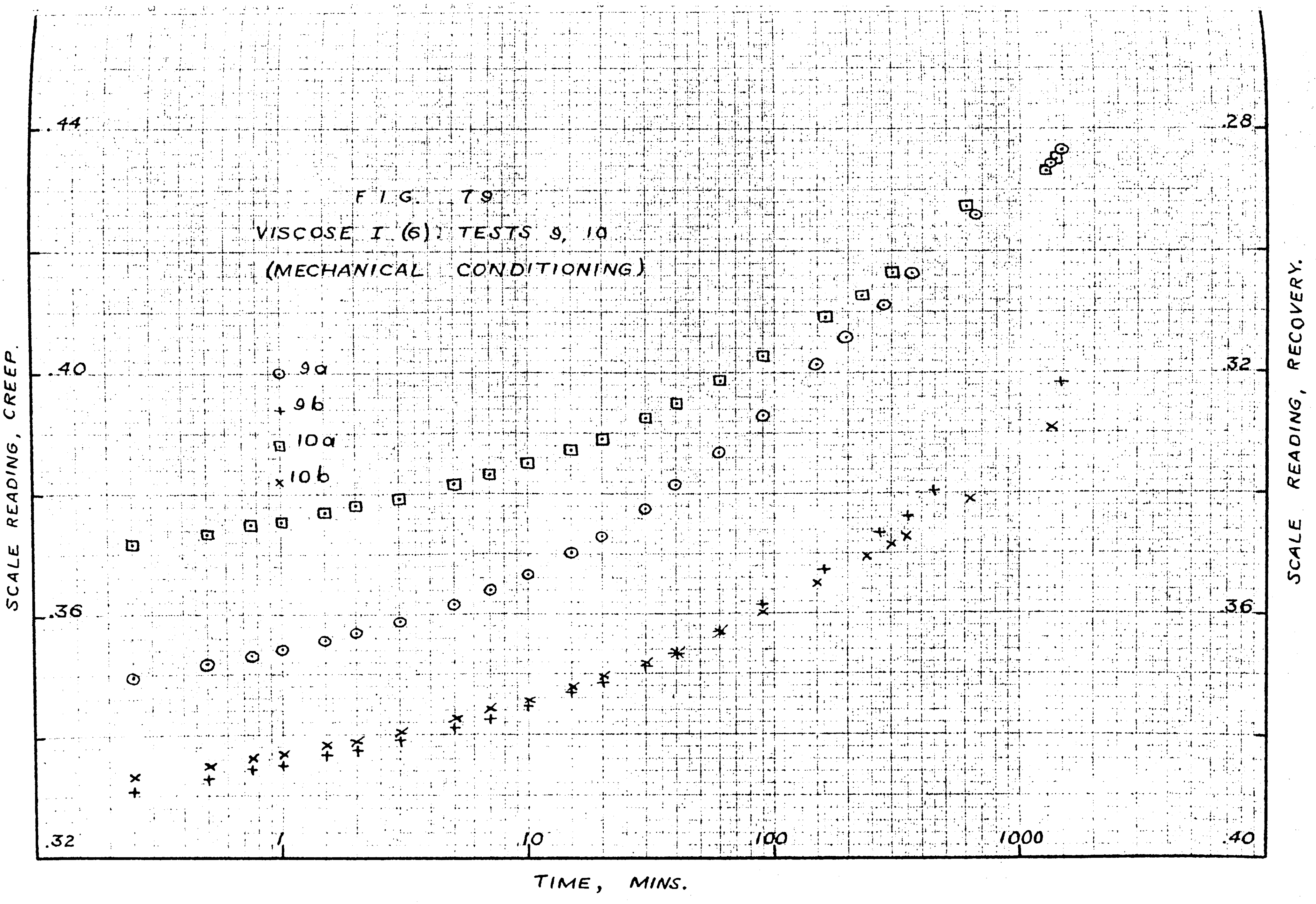


FIG. 79

VISCOSE I (6): TESTS 9, 10

(MECHANICAL CONDITIONING)

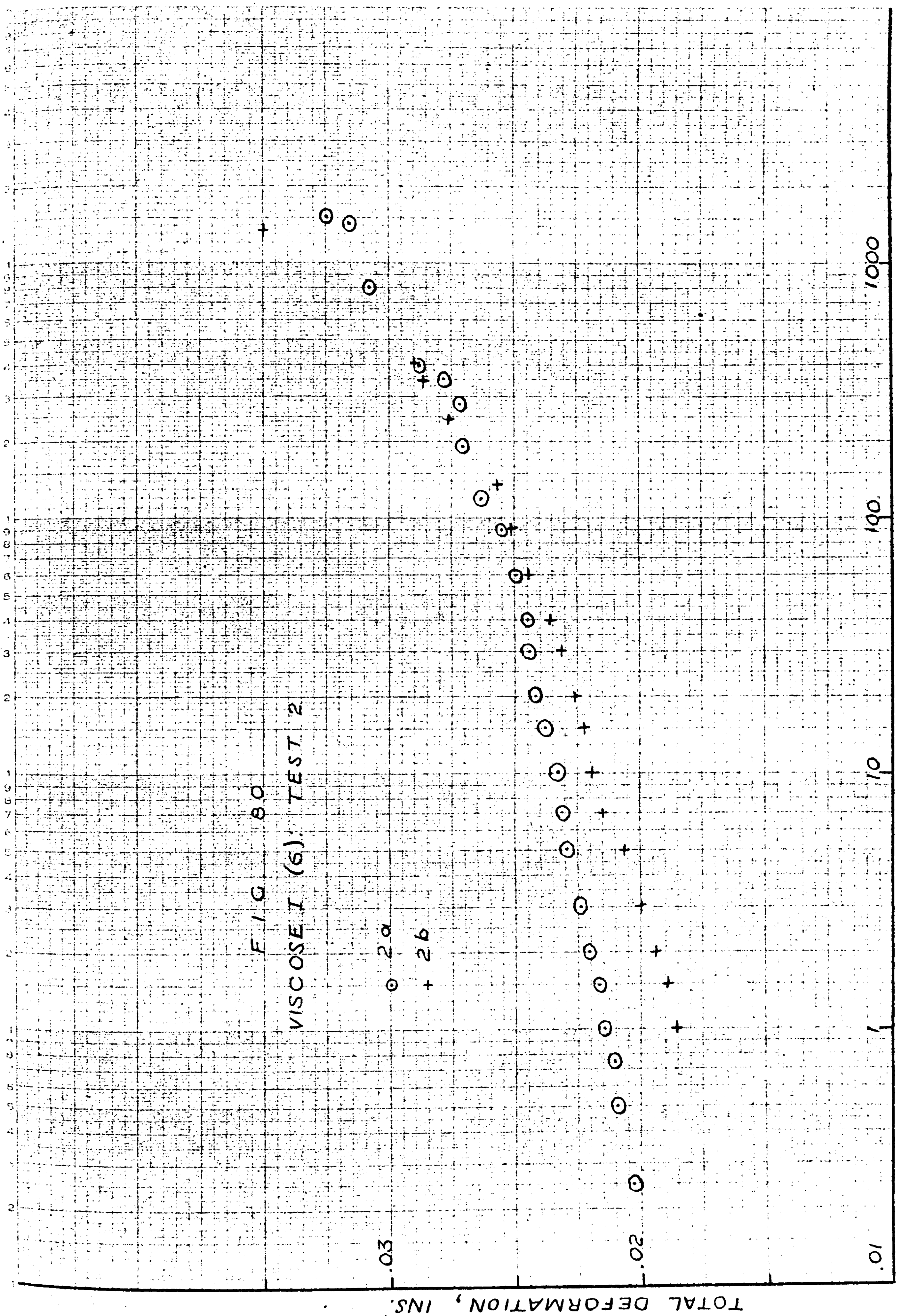


FIG 80

VISCOSE I (6) TEST 2

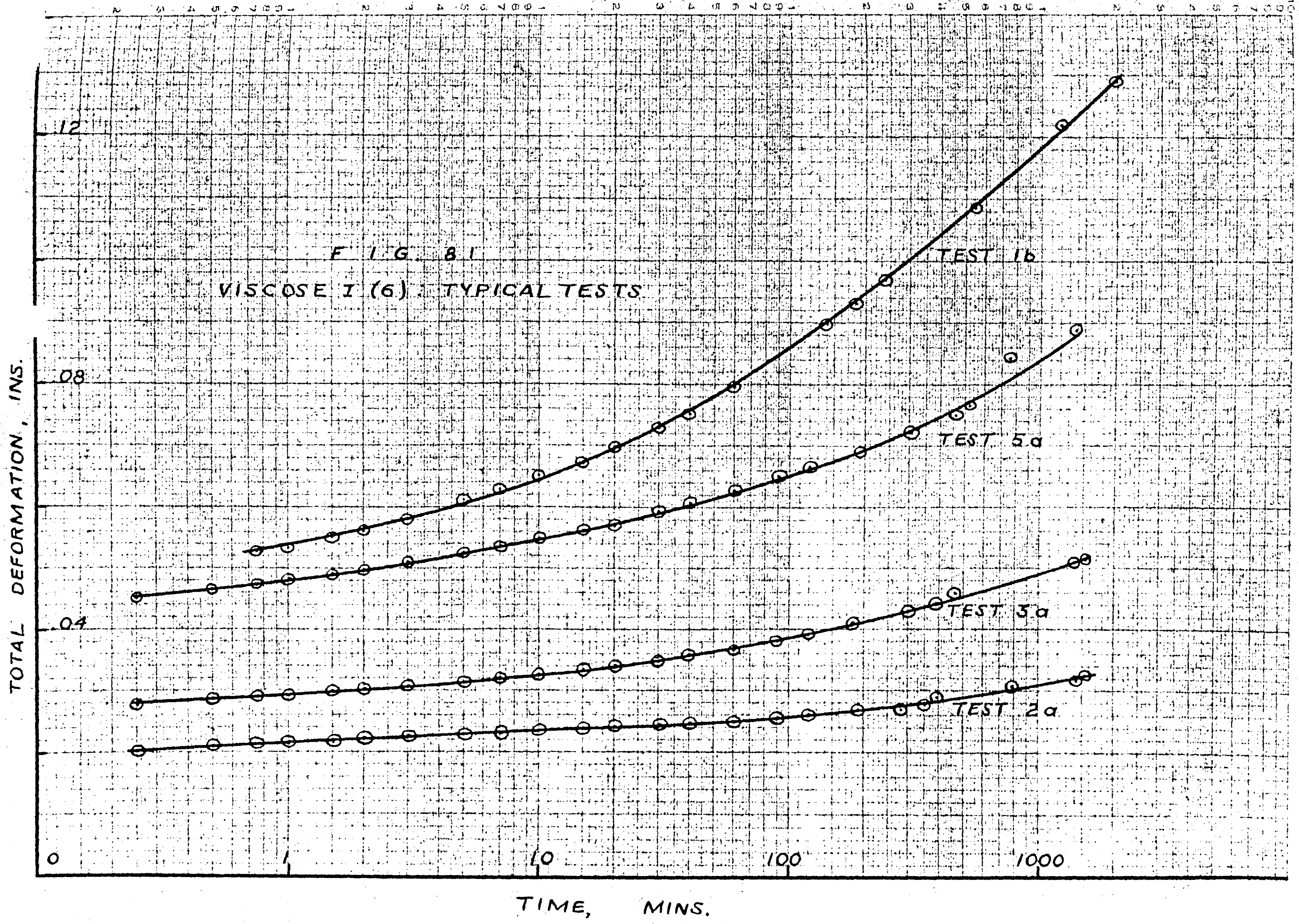


FIG. 81
VISCOSE I (6): TYPICAL TESTS

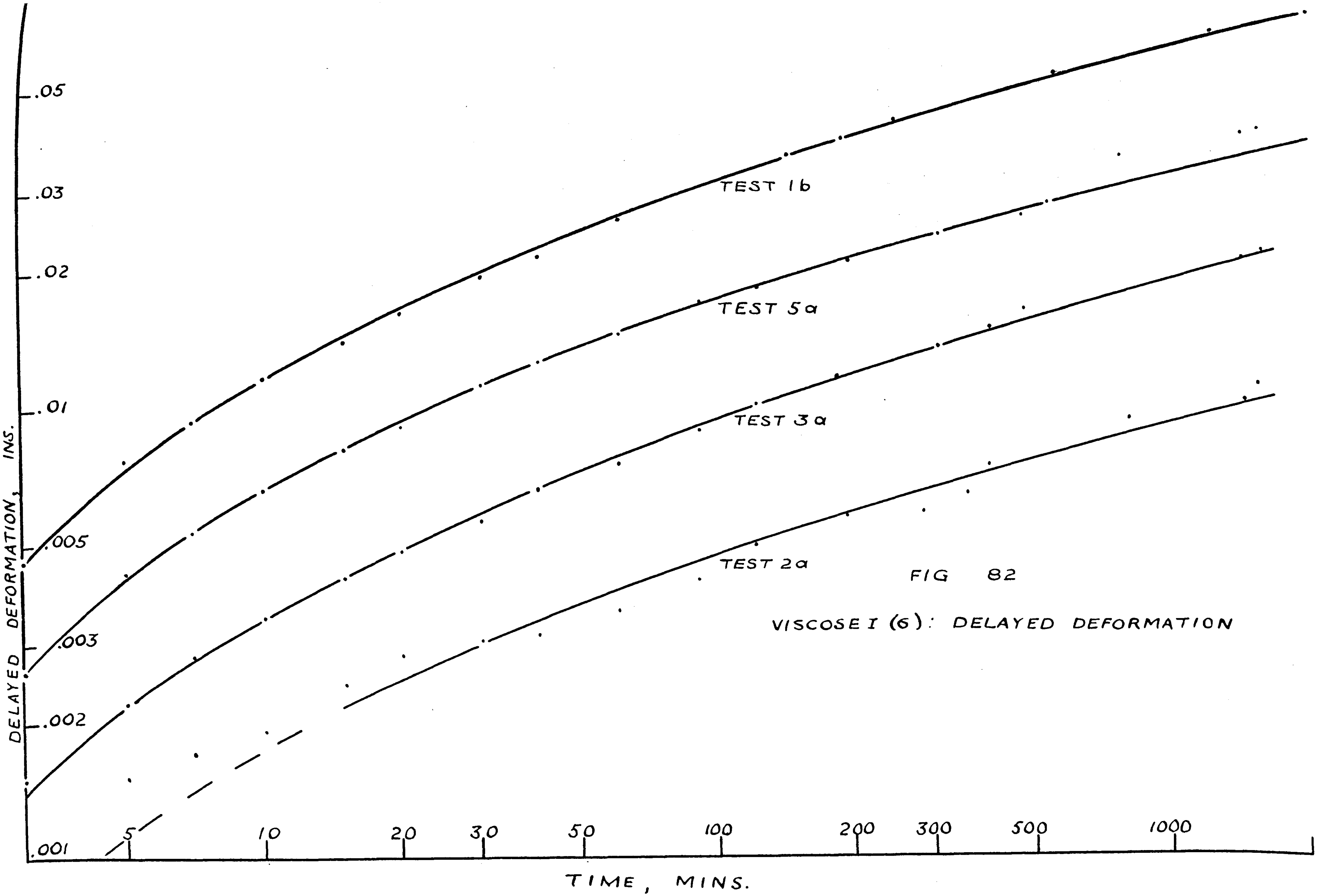


FIG 82

VISCOSE I (6): DELAYED DEFORMATION

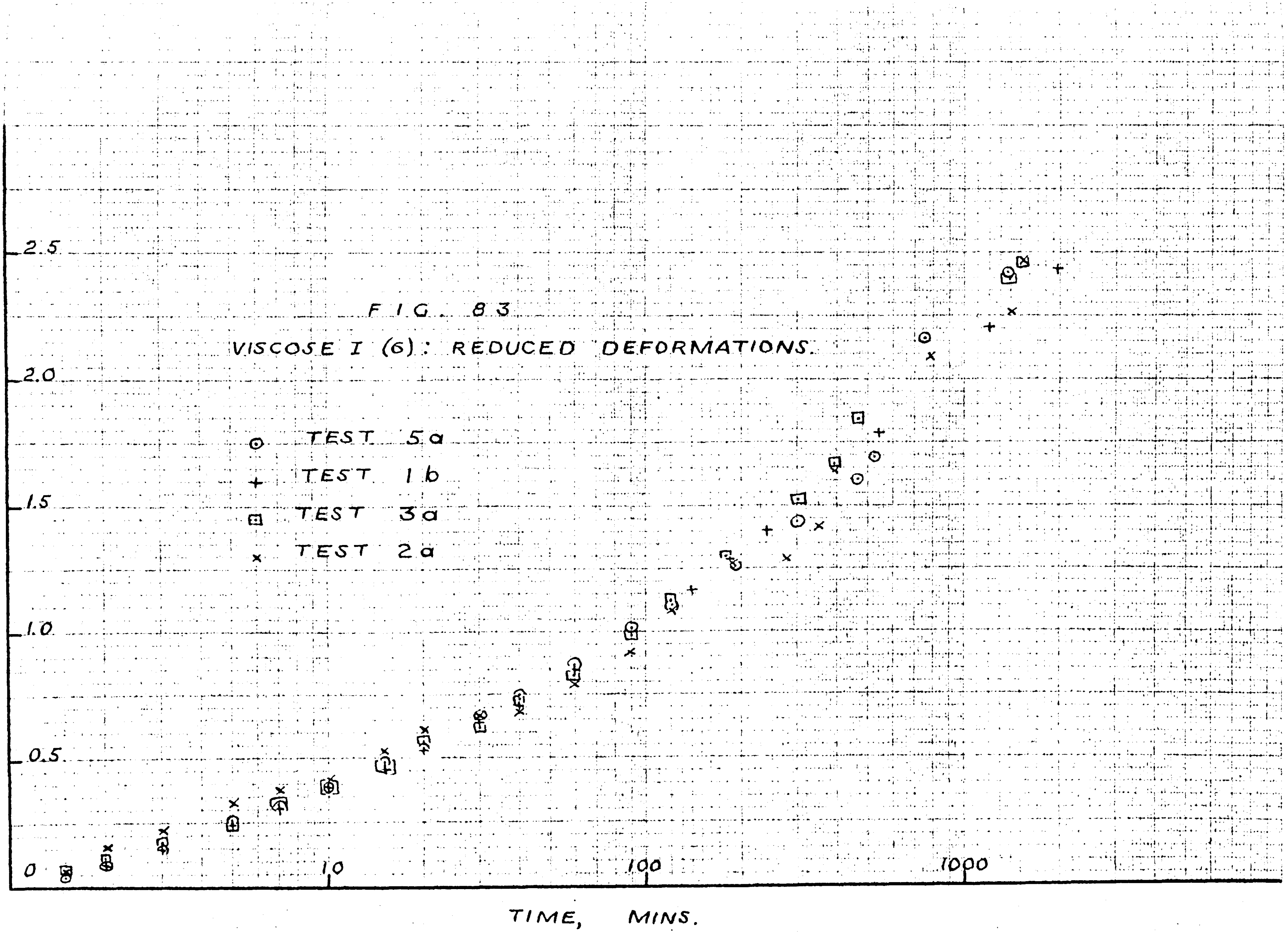
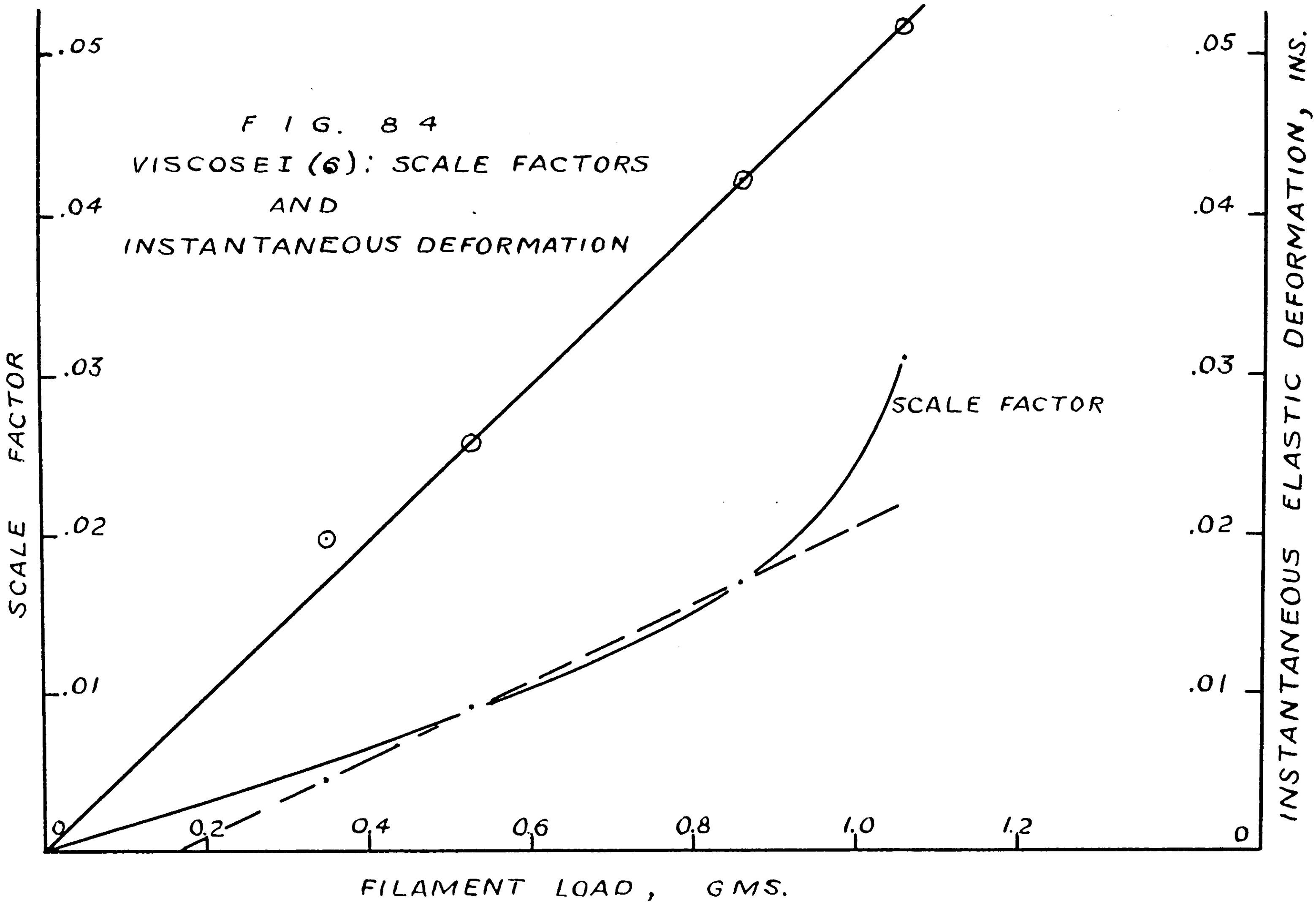


FIG. 83

VISCOSE I (6): REDUCED DEFORMATIONS.



F I G. 8 4

VISCOSE I (6): SCALE FACTORS
AND
INSTANTANEOUS DEFORMATION

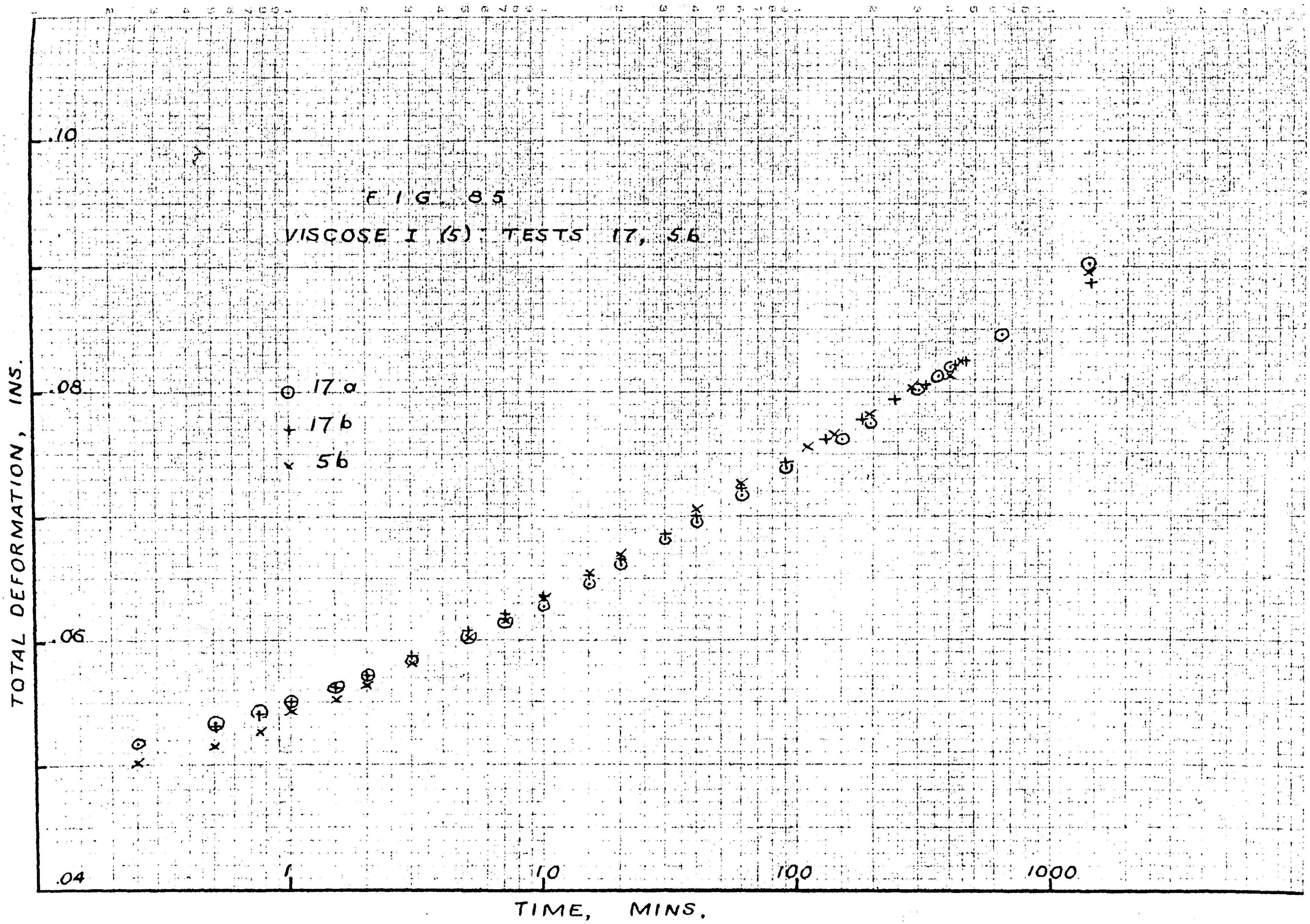


FIG. 85

VISCOSE I (5) TESTS 17, 56

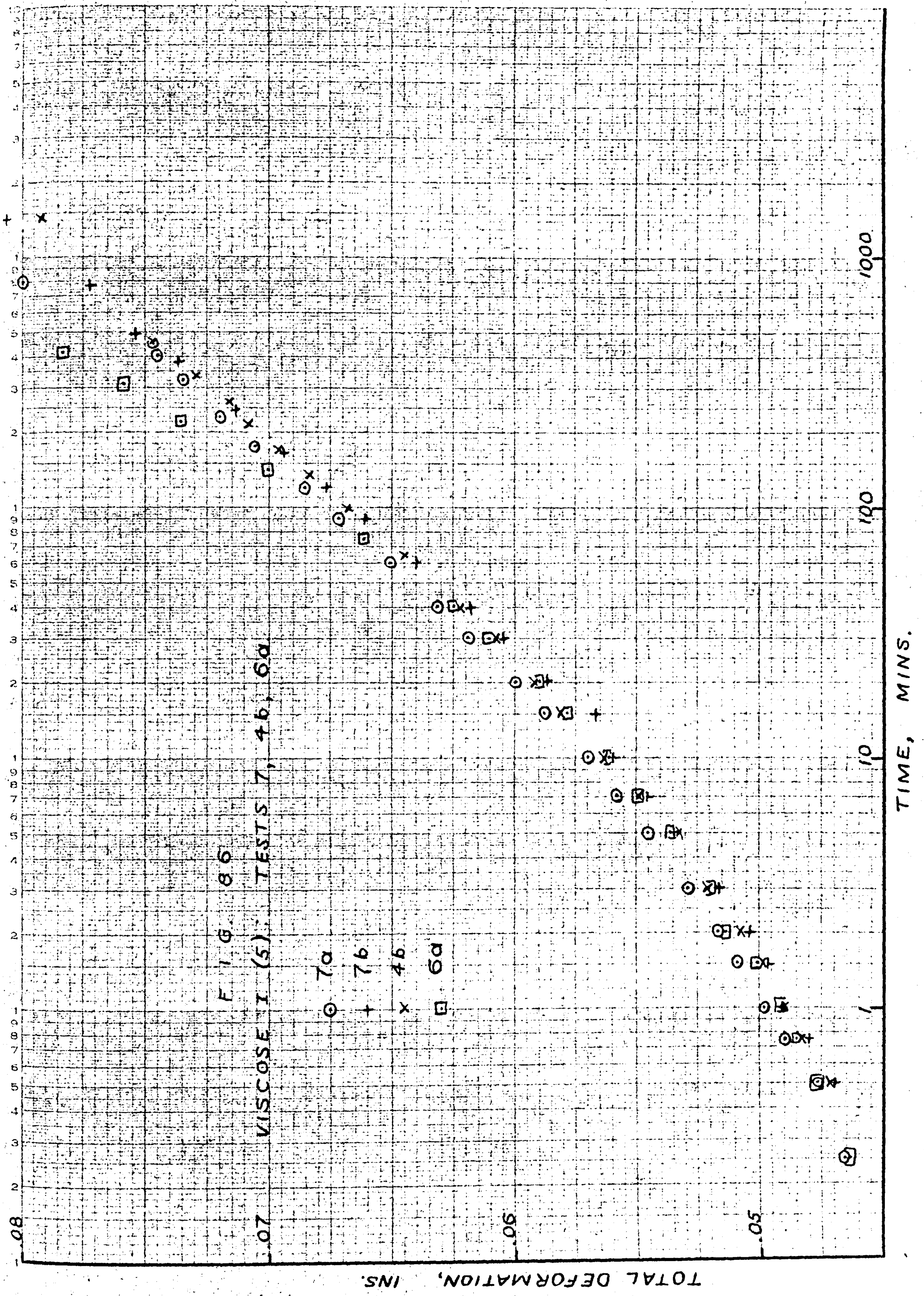


FIG 86 VISCOSE I (5) TESTS 7, 4b, 6a

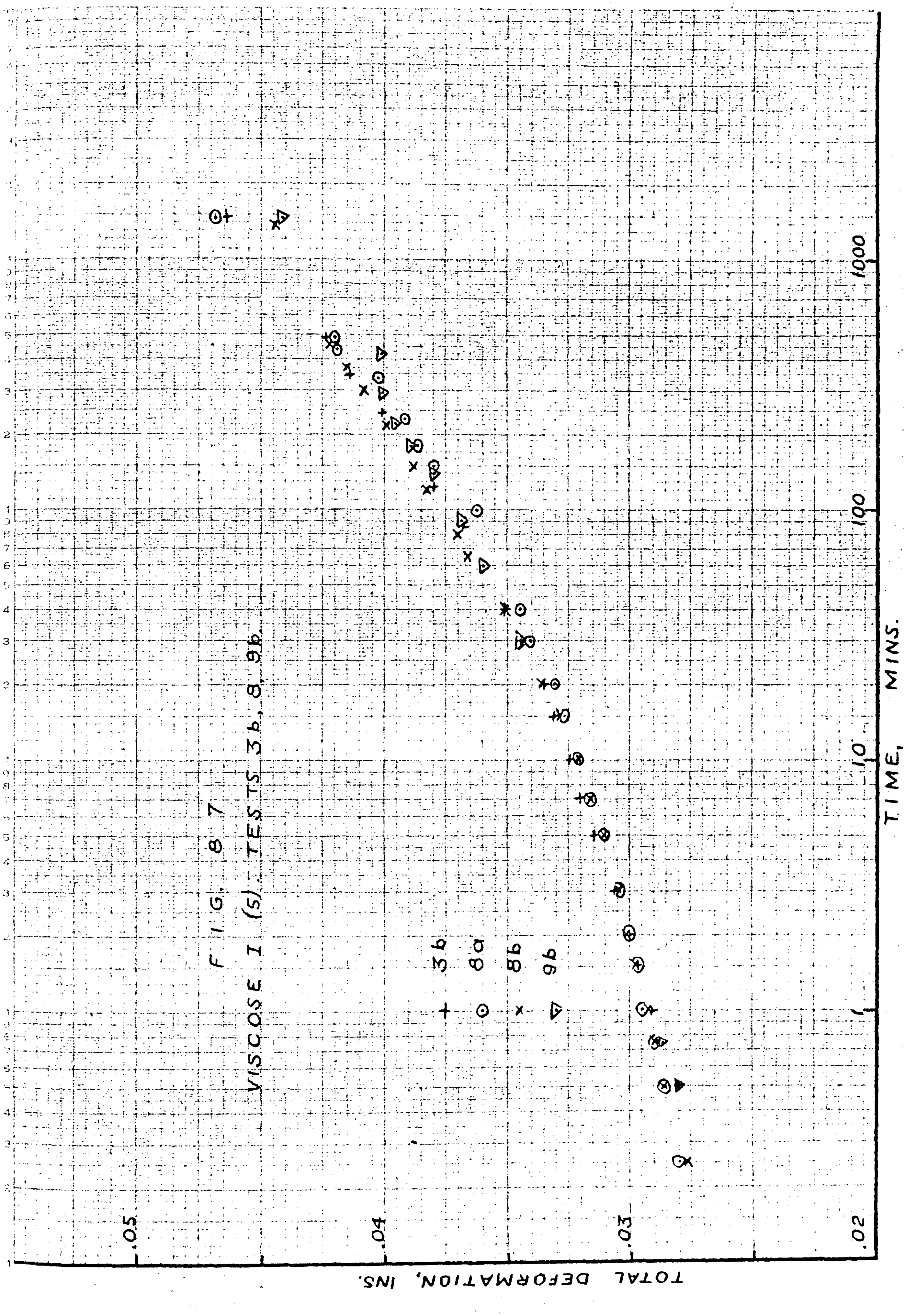


FIG. 87

VISCOSE I (5) TESTS 3b, 8, 9b

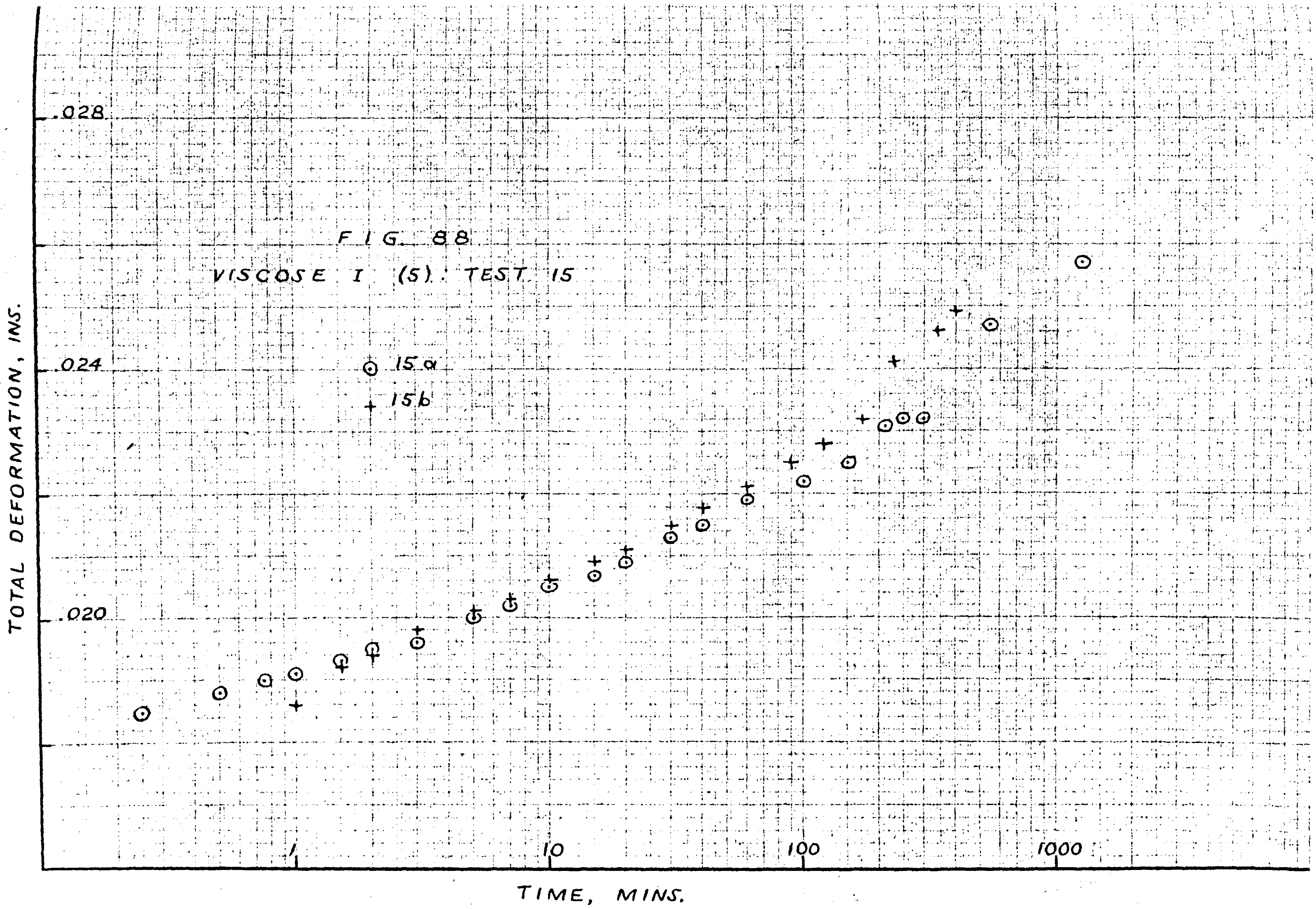


FIG. 88

VISCOSE I (5). TEST 15

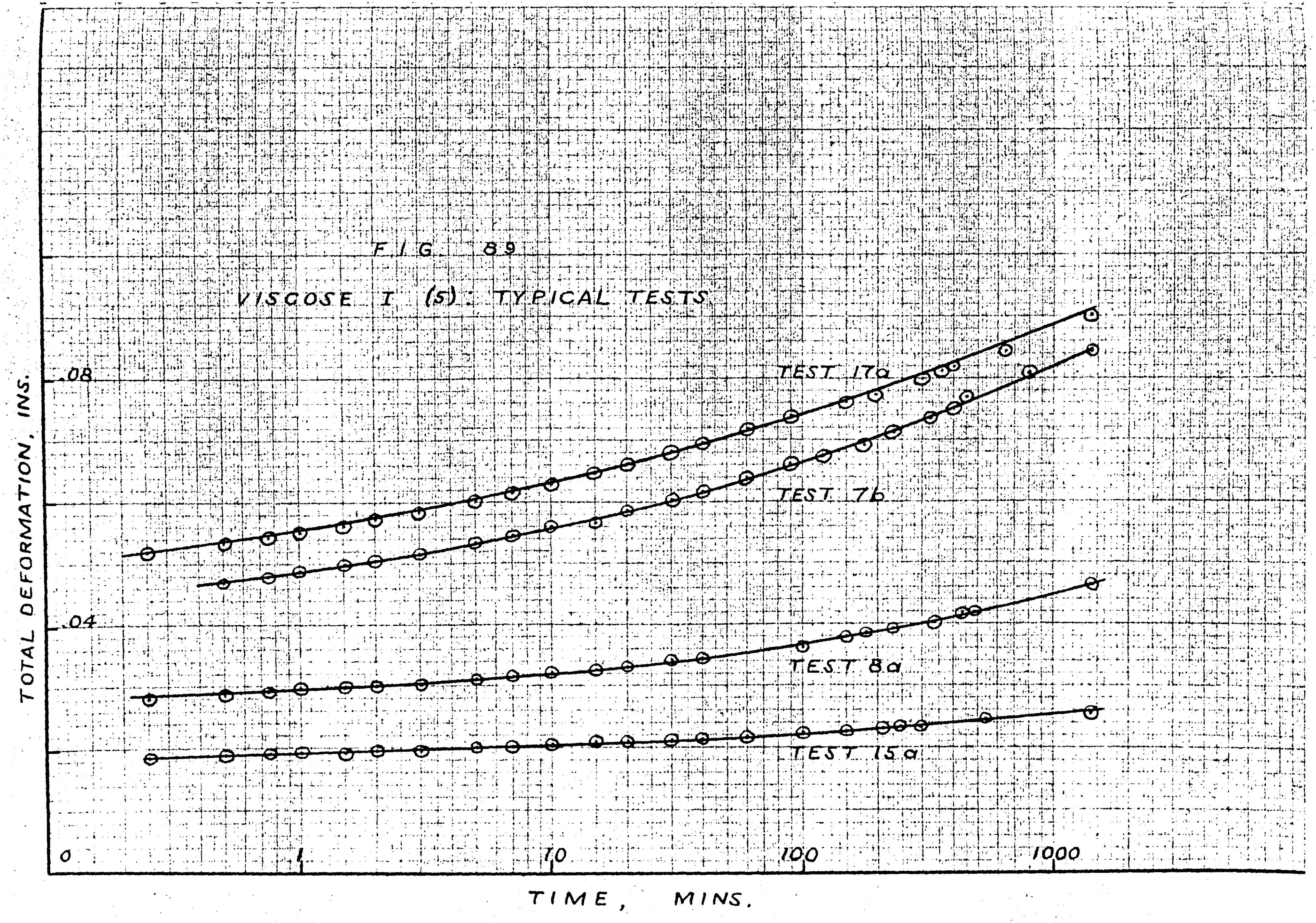


FIG. 89

VISCOSE I (5): TYPICAL TESTS

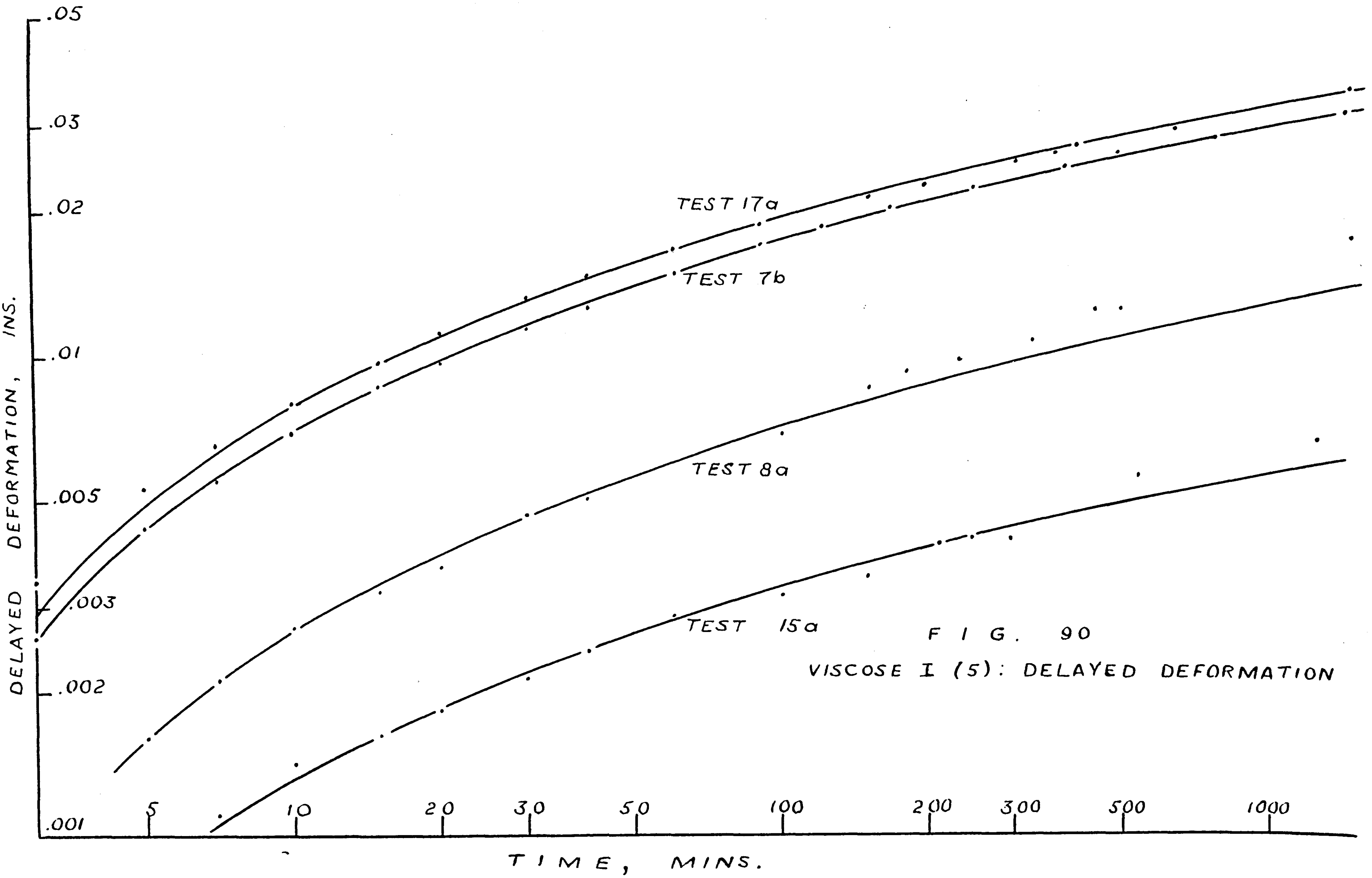


FIG. 90

VISCOSE I (5): DELAYED DEFORMATION

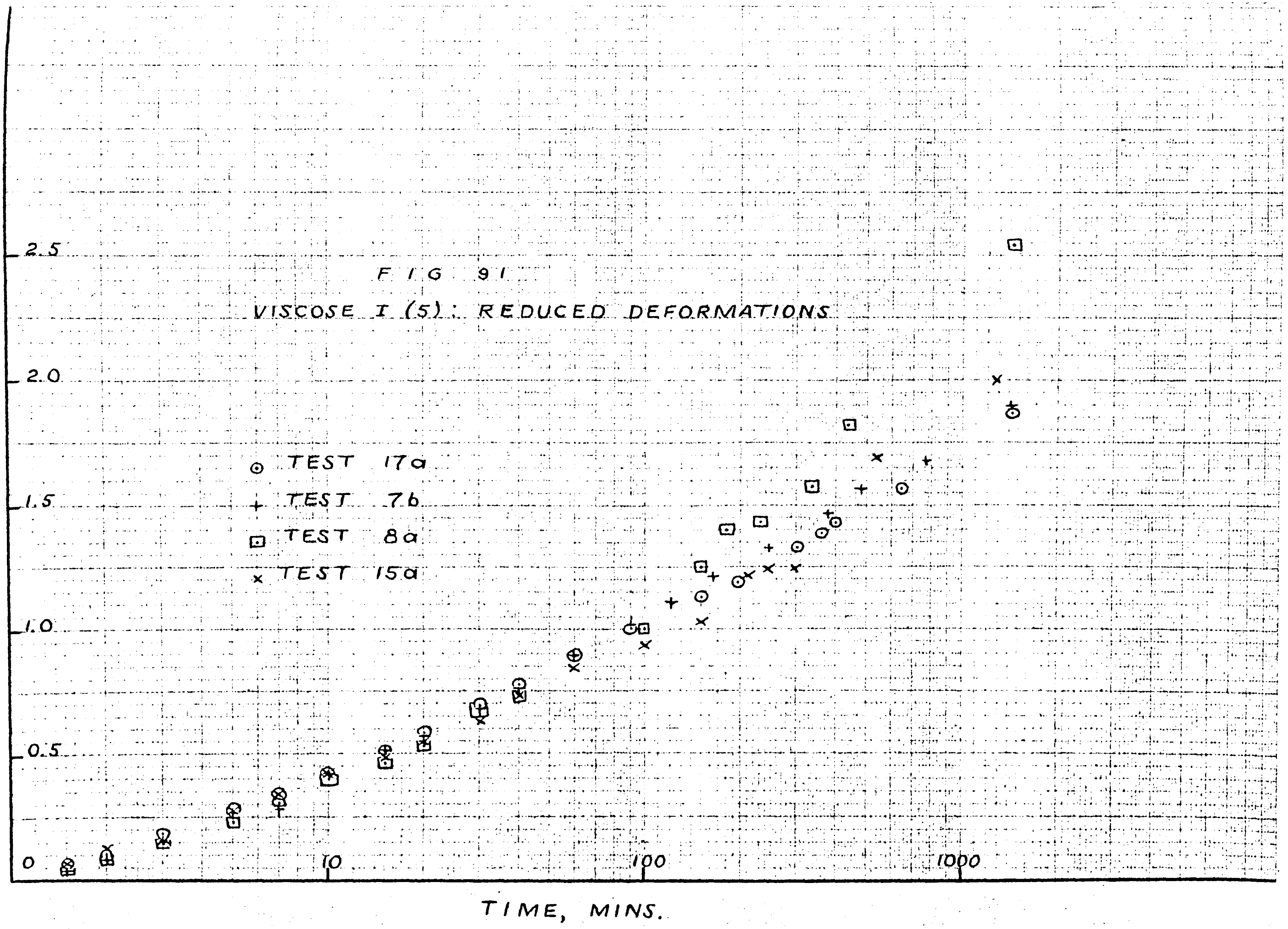


FIG 91

VISCOSE I (5): REDUCED DEFORMATIONS

FIG. 92

VISCOSE I (5): SCALE FACTORS AND INSTANTANEOUS DEFORMATION

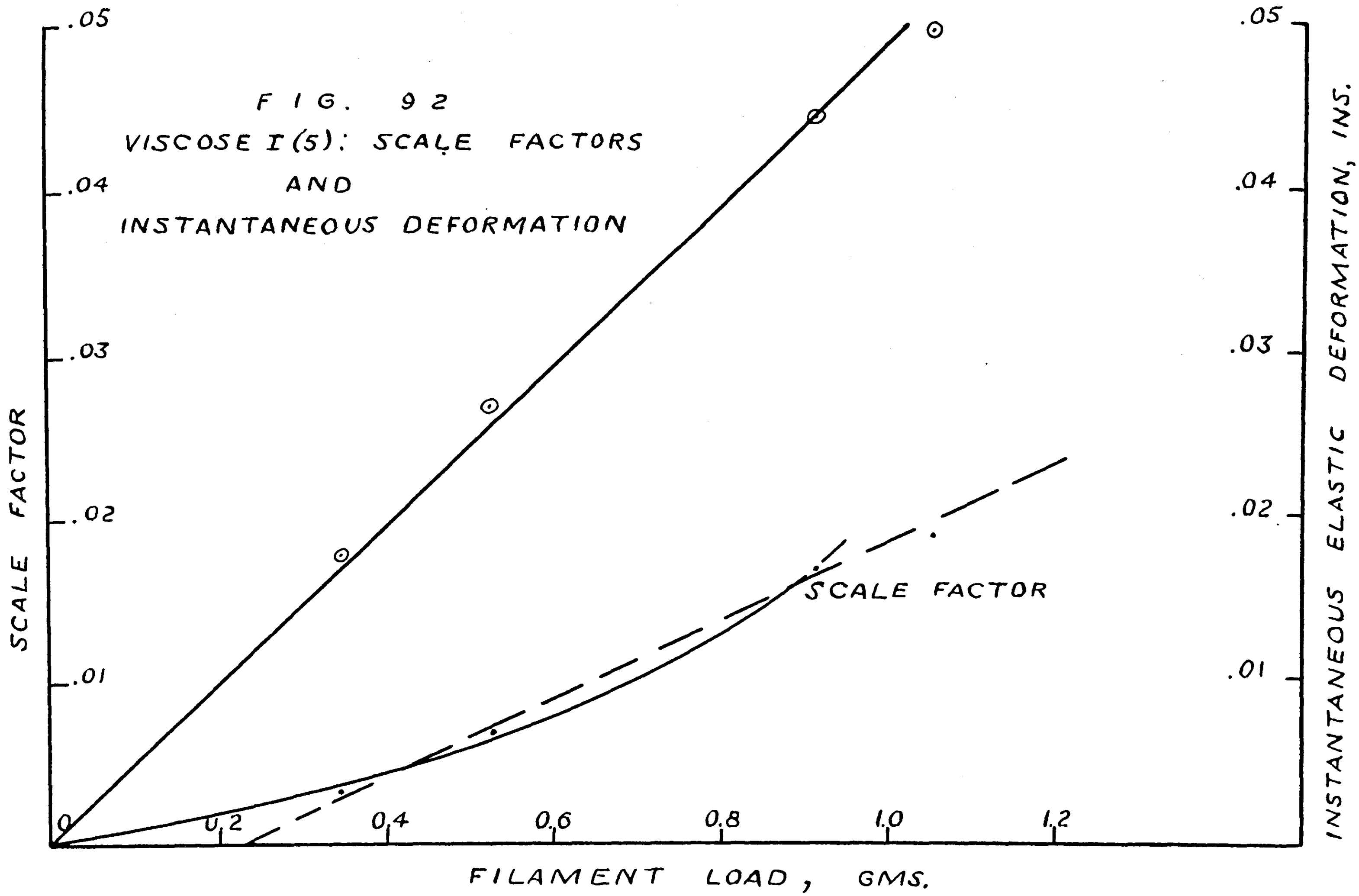


FIG 93

NYLON II: TESTS 3, 4

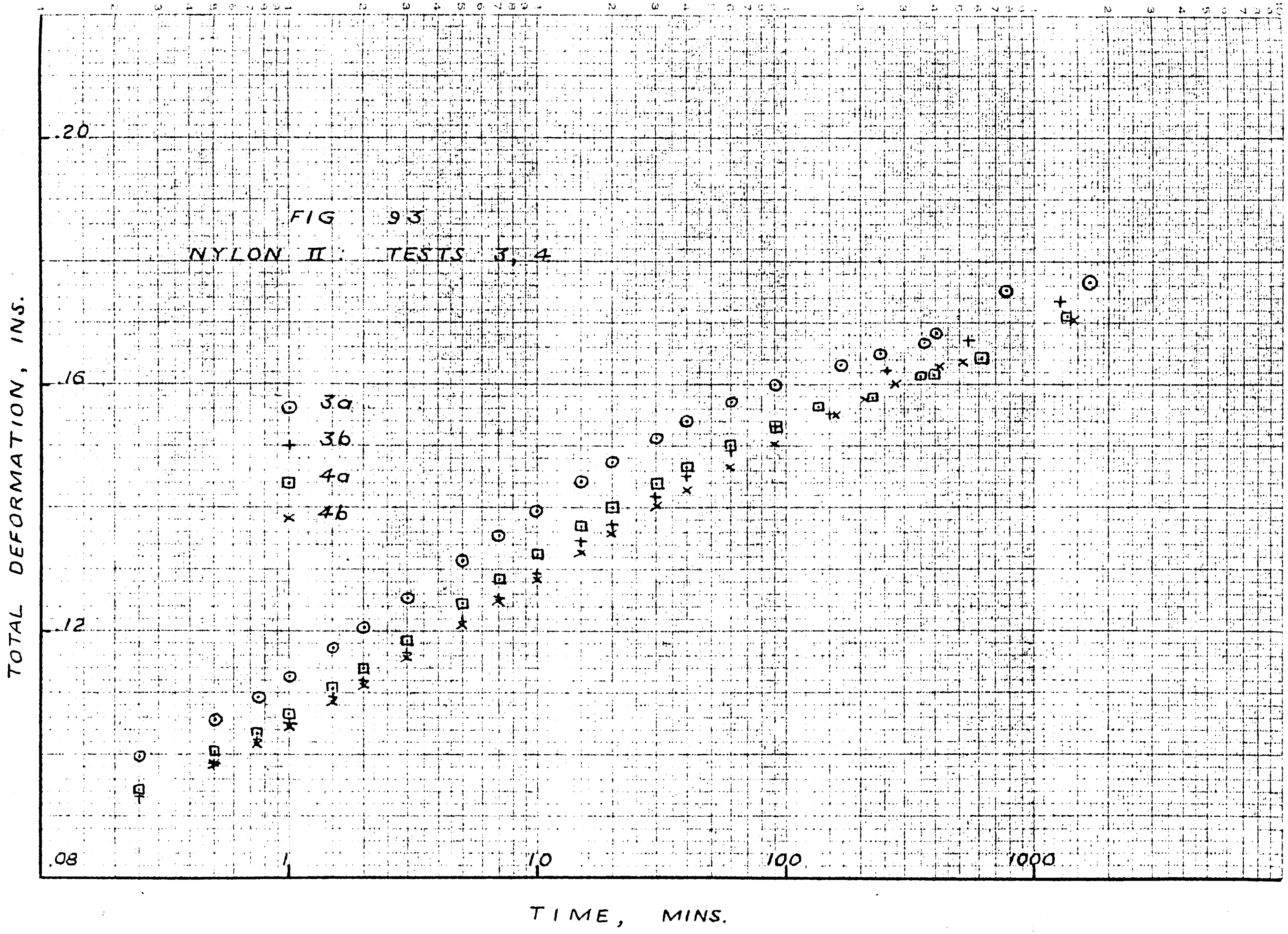
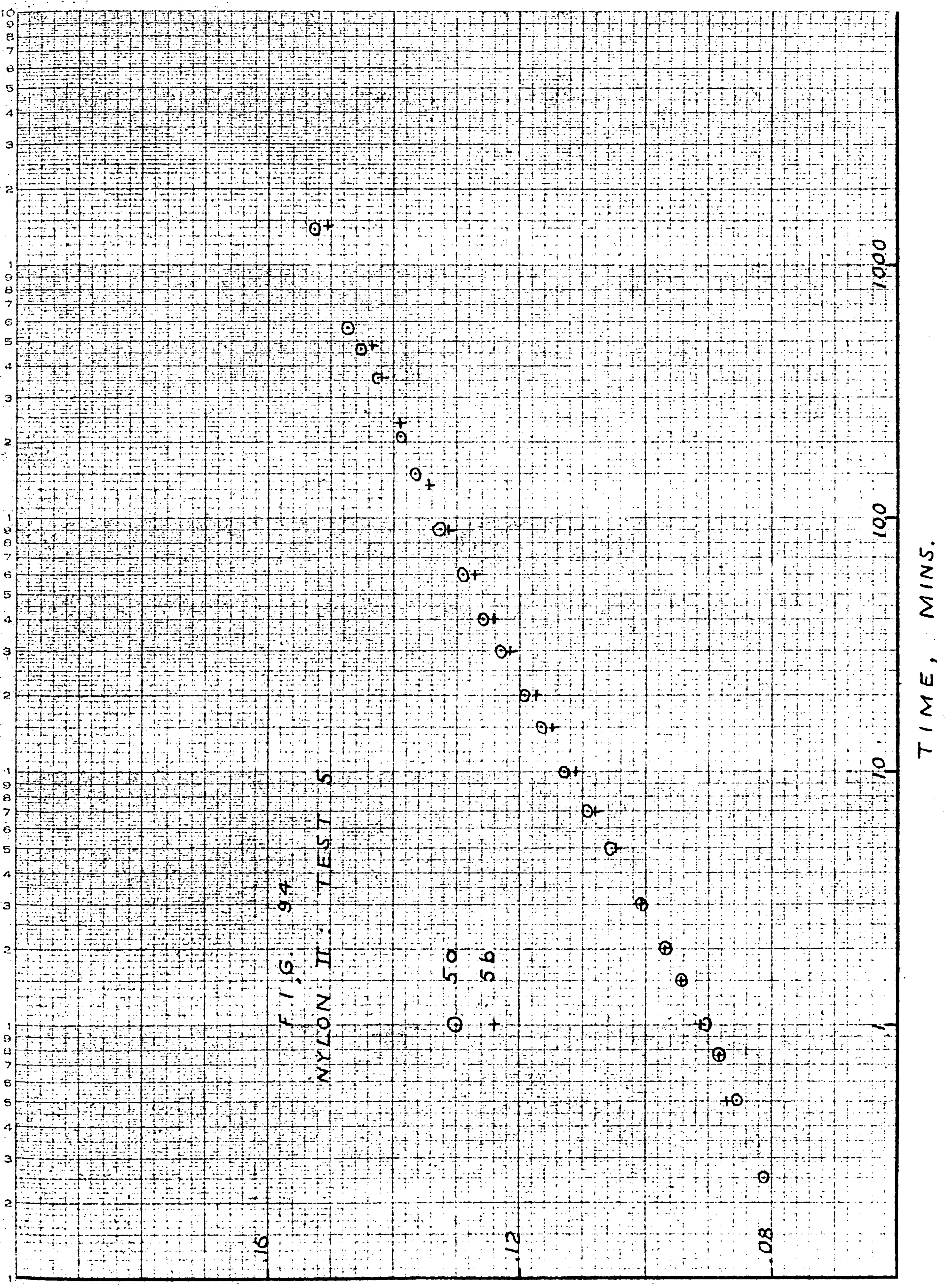


FIG. 94 NYLON II TEST 5



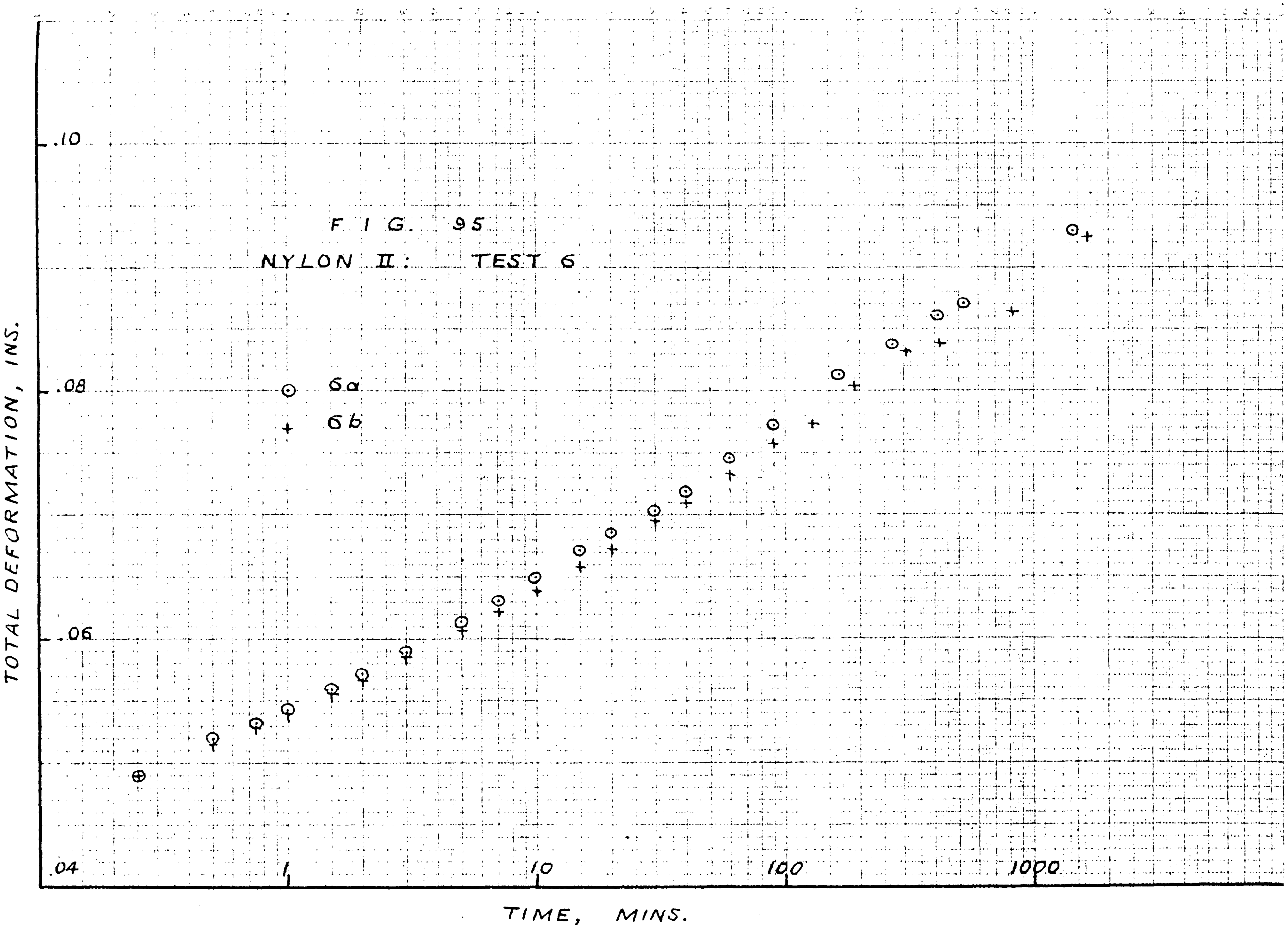


FIG. 95

NYLON II: TEST 6

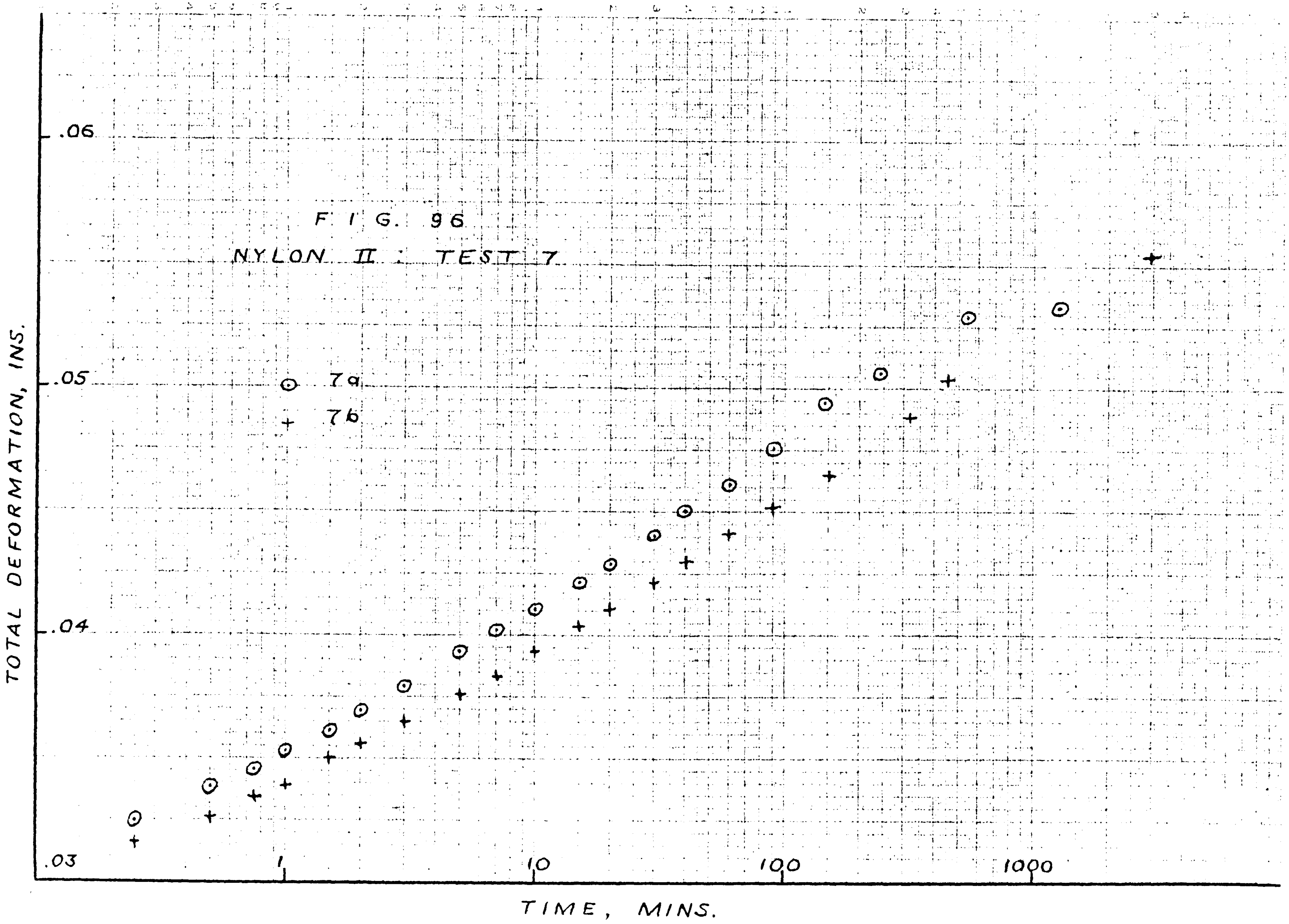


FIG. 96

NYLON II : TEST 7

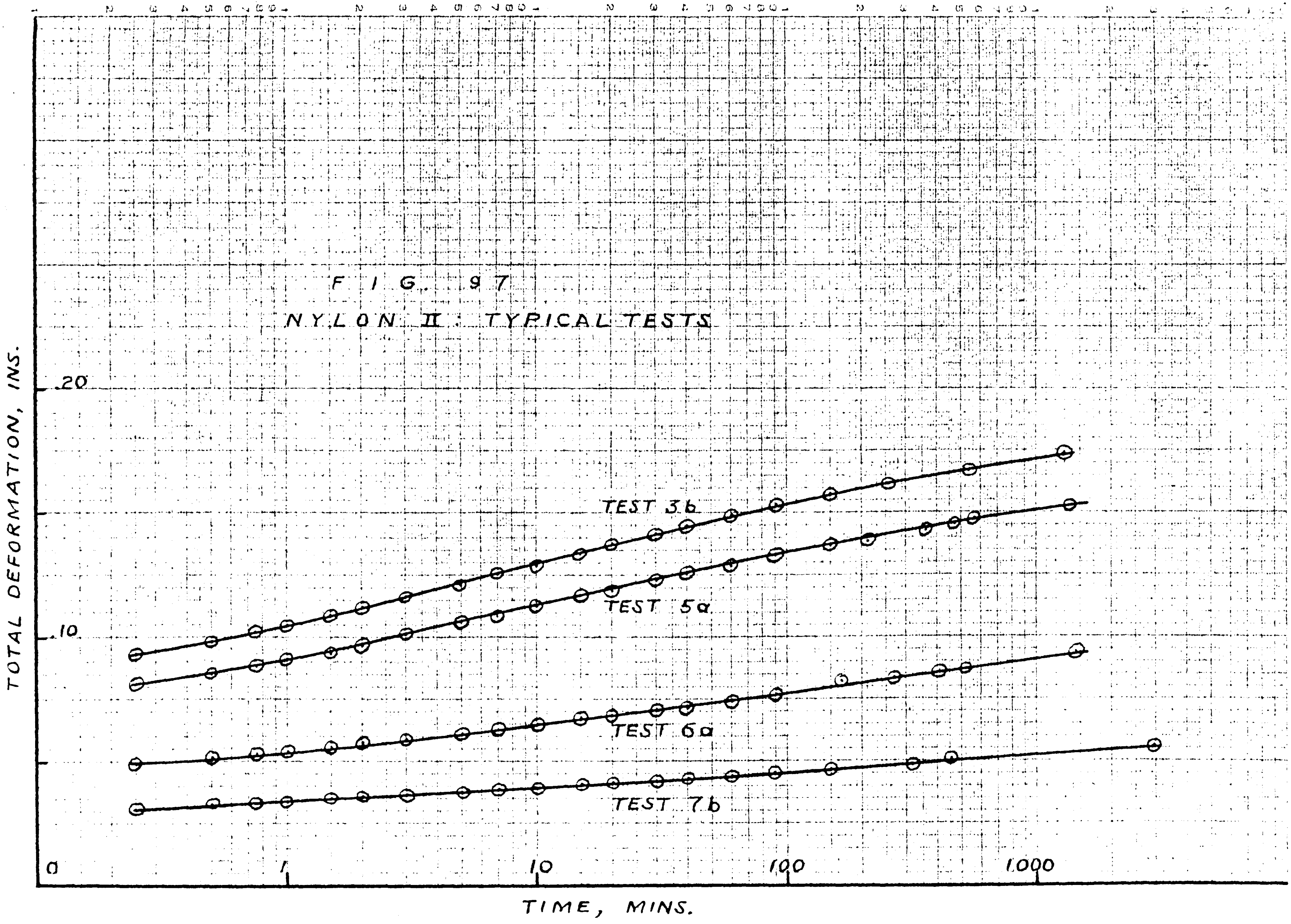


FIG. 97

NYLON II: TYPICAL TESTS

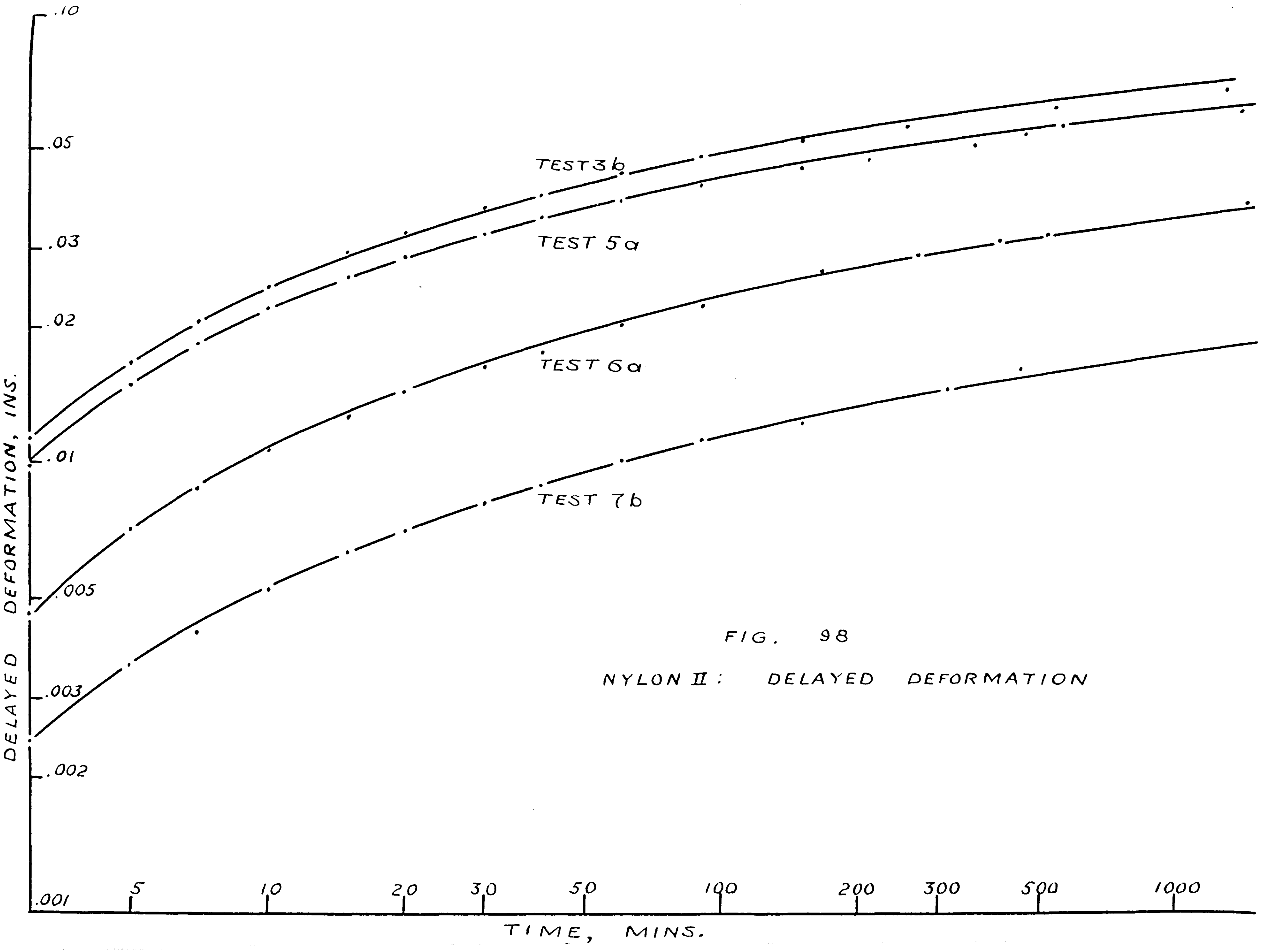


FIG. 98

NYLON II: DELAYED DEFORMATION

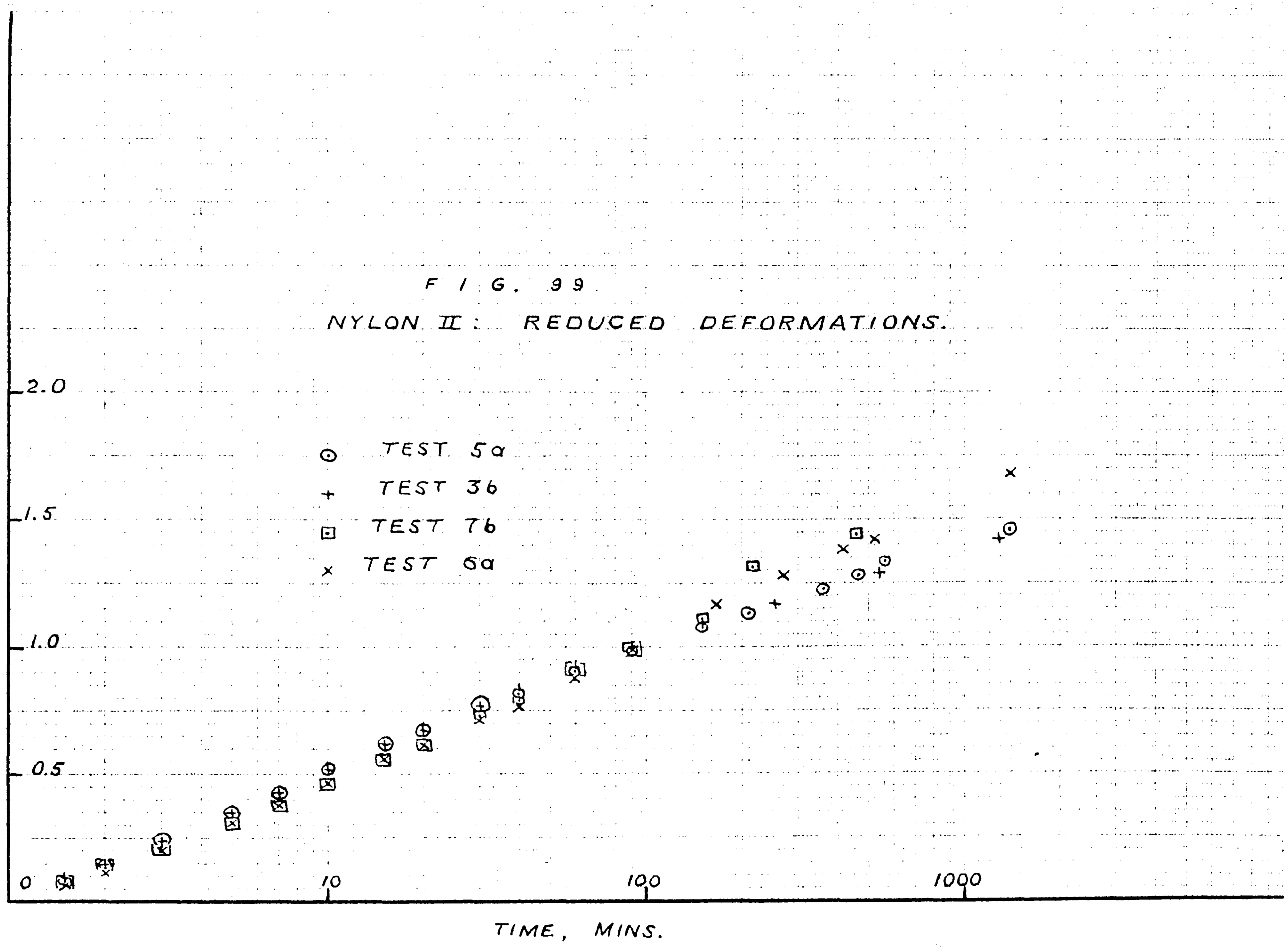
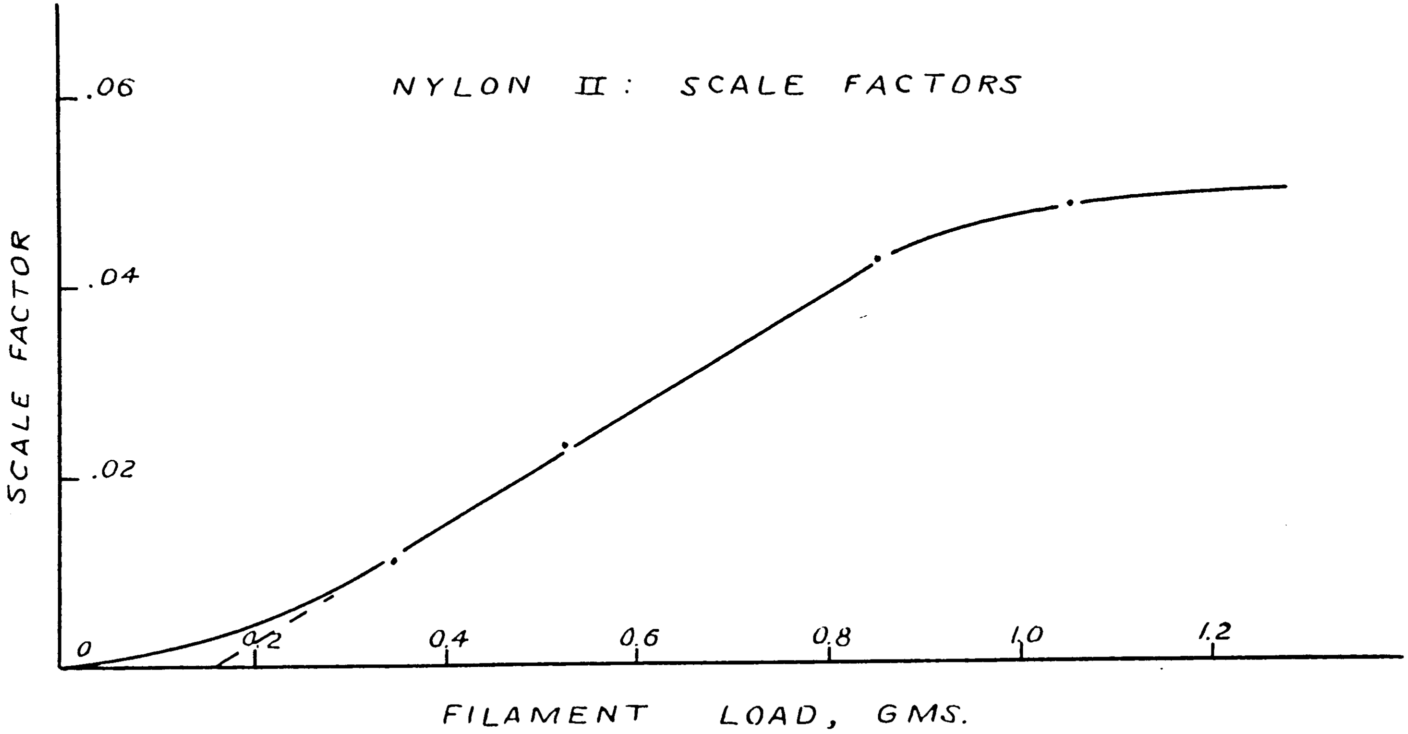


FIG. 99

NYLON II: REDUCED DEFORMATIONS.

FIG. 100

NYLON II: SCALE FACTORS



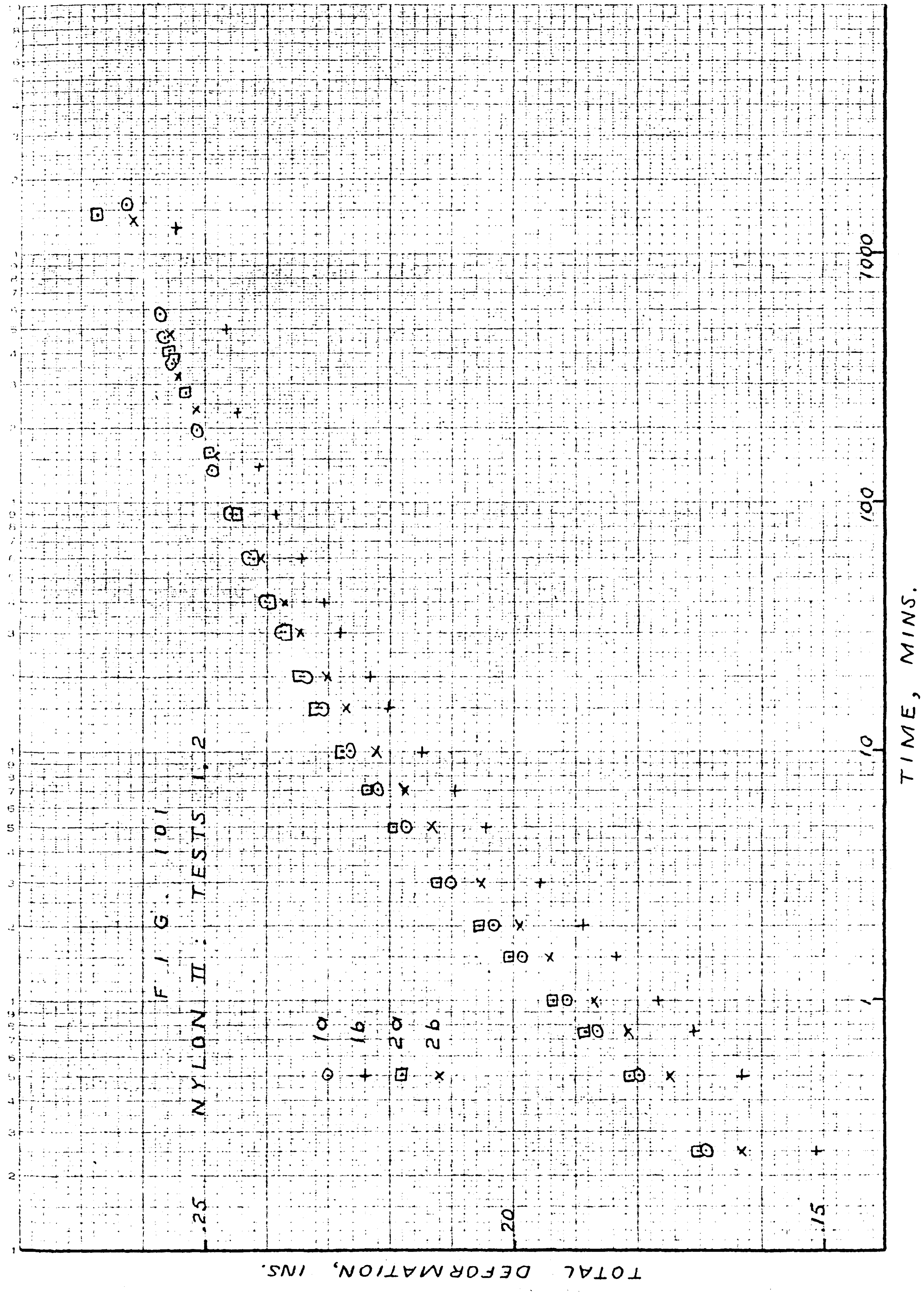


FIG. 101

NYLON II: TESTS 1, 2

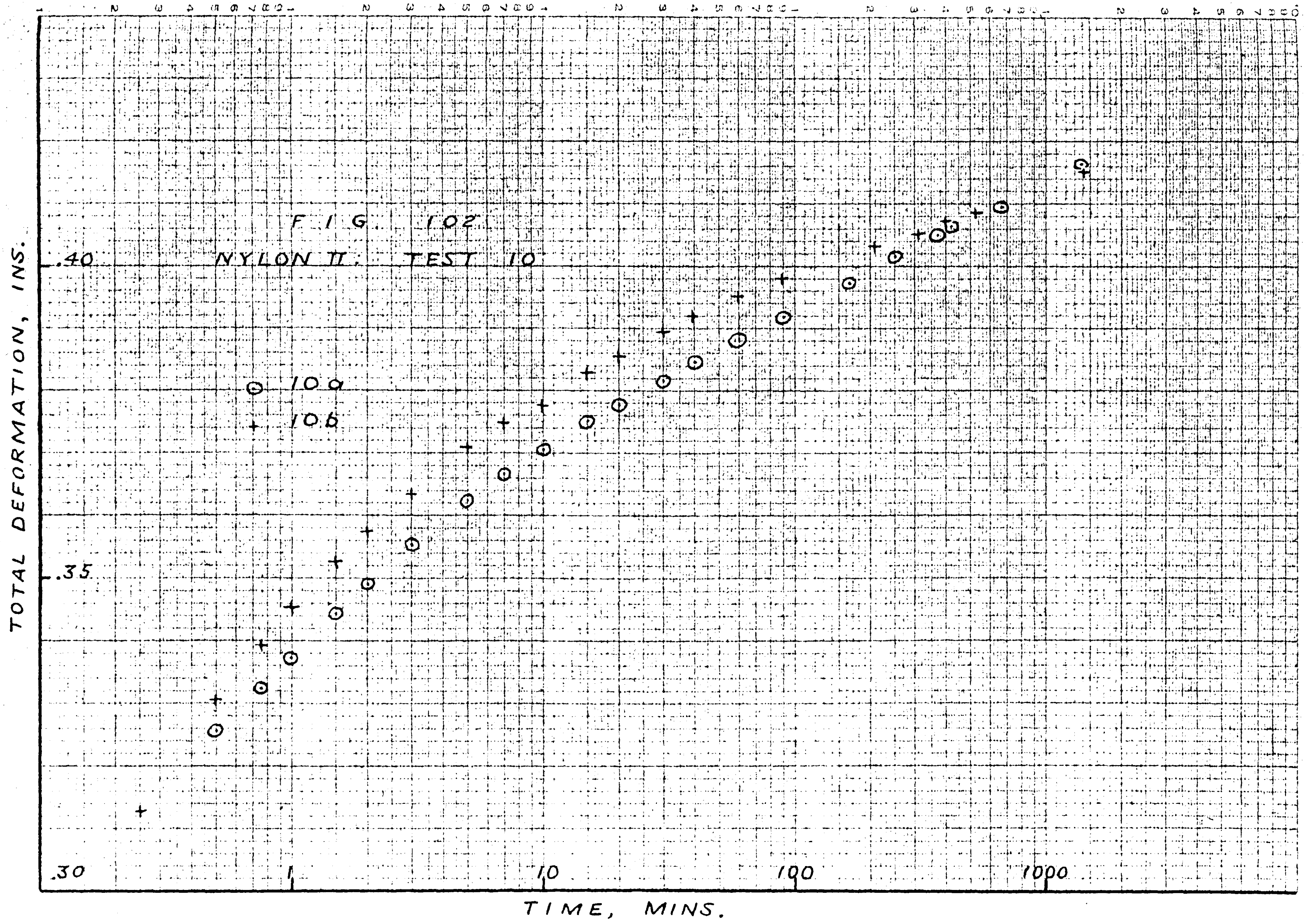


FIG. 102

NYLON II. TEST 10

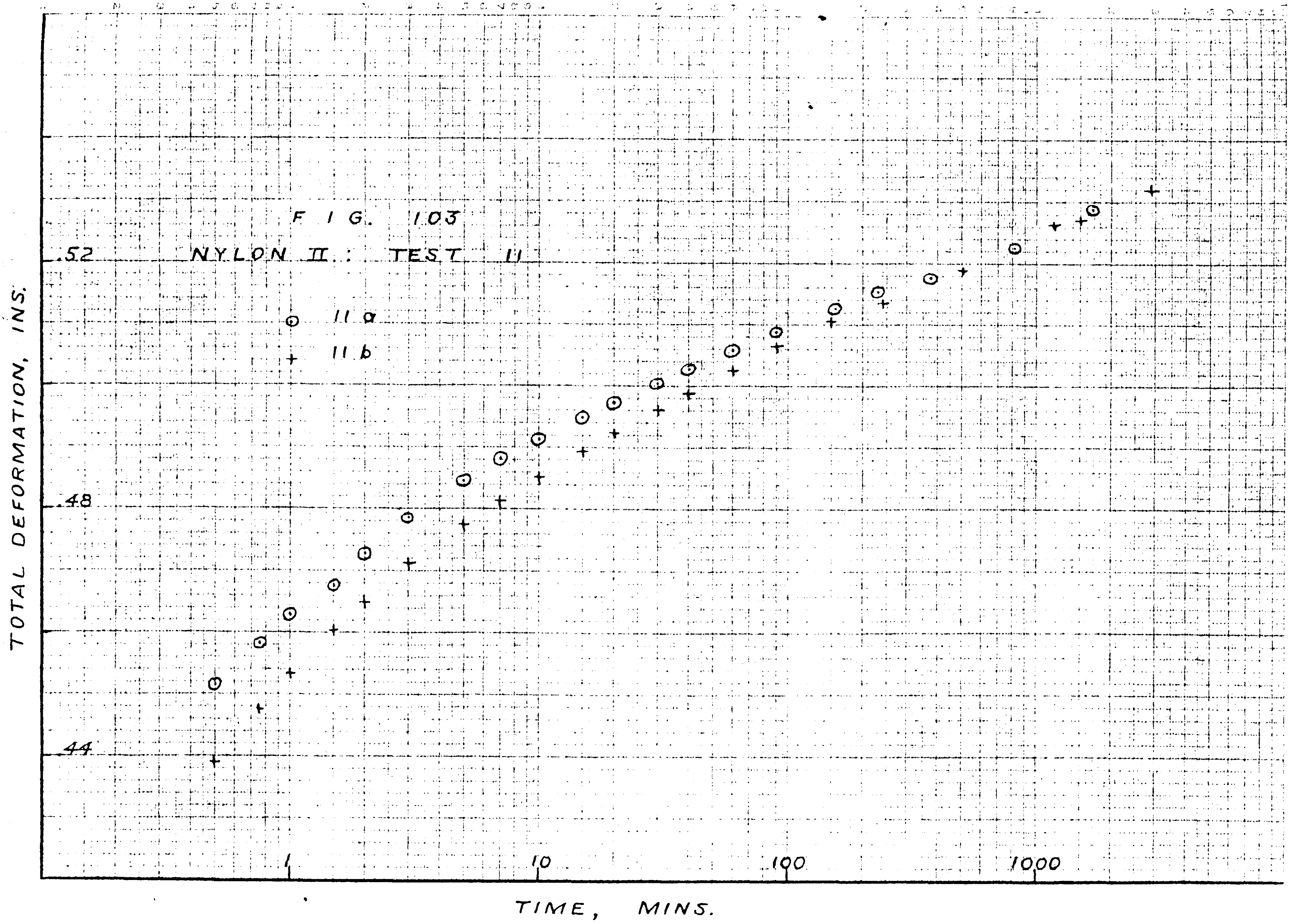
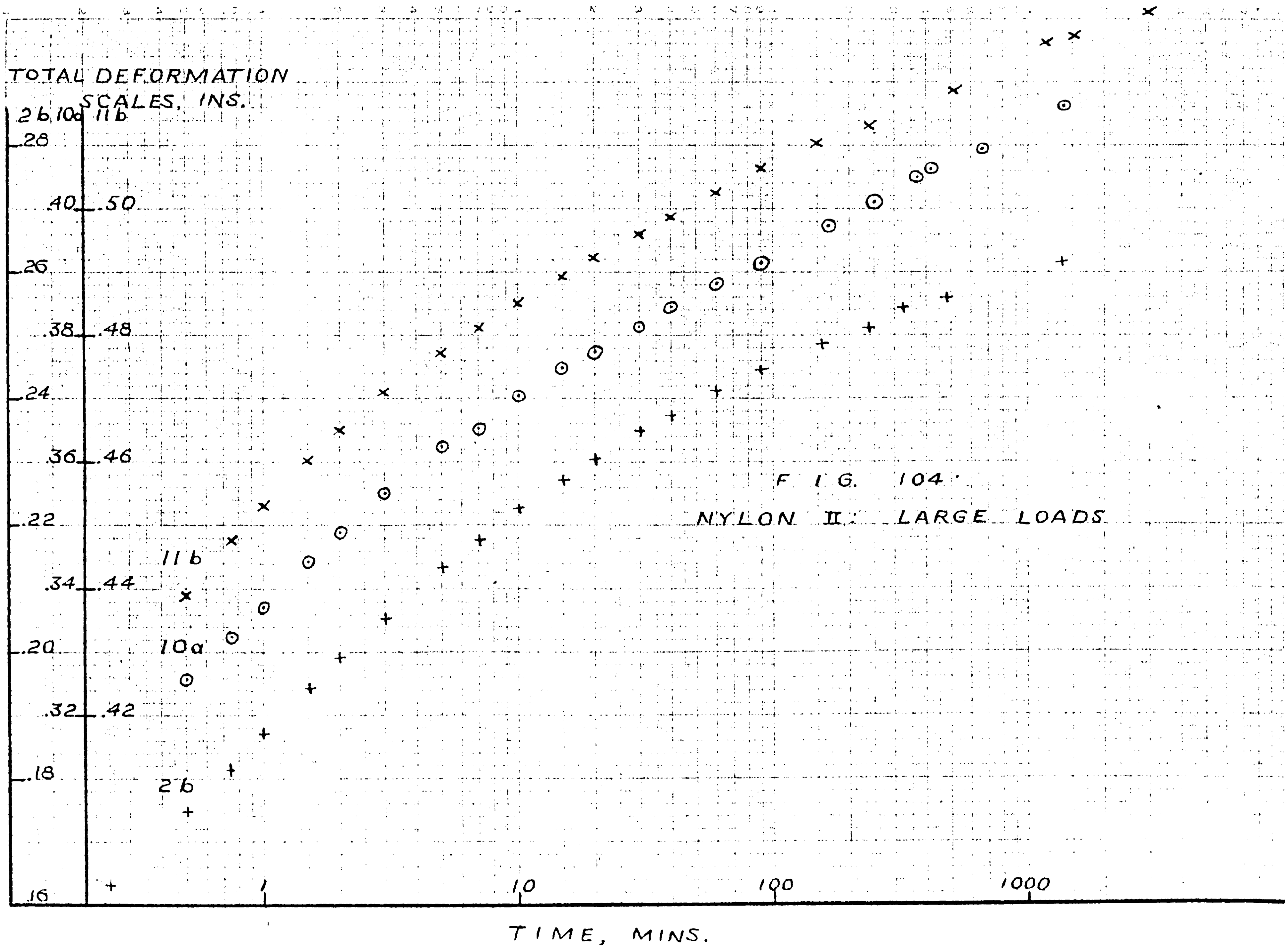


FIG. 1.03

NYLON II : TEST 11

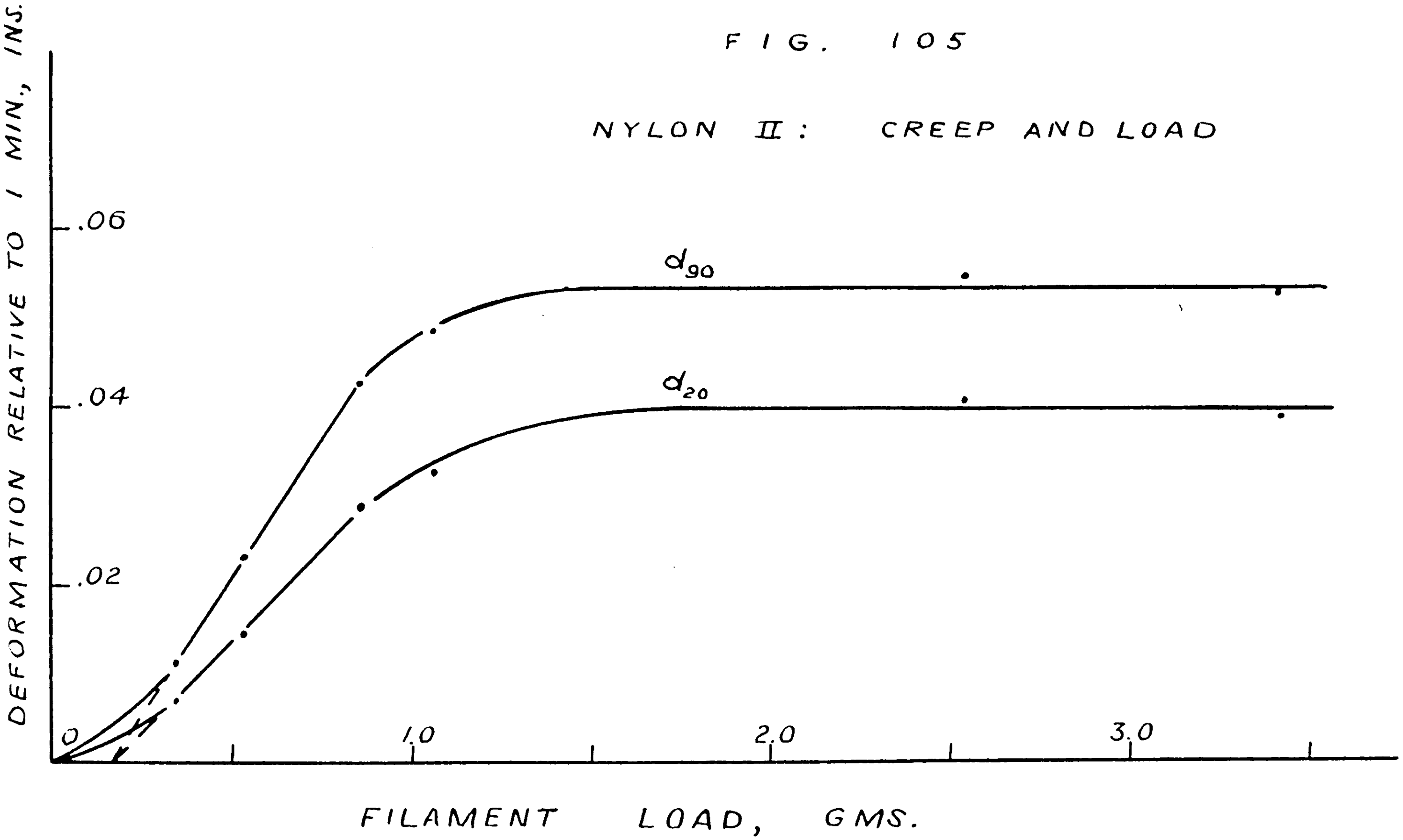


F I G. 104

NYLON II: LARGE LOADS

FIG. 105

NYLON II: CREEP AND LOAD



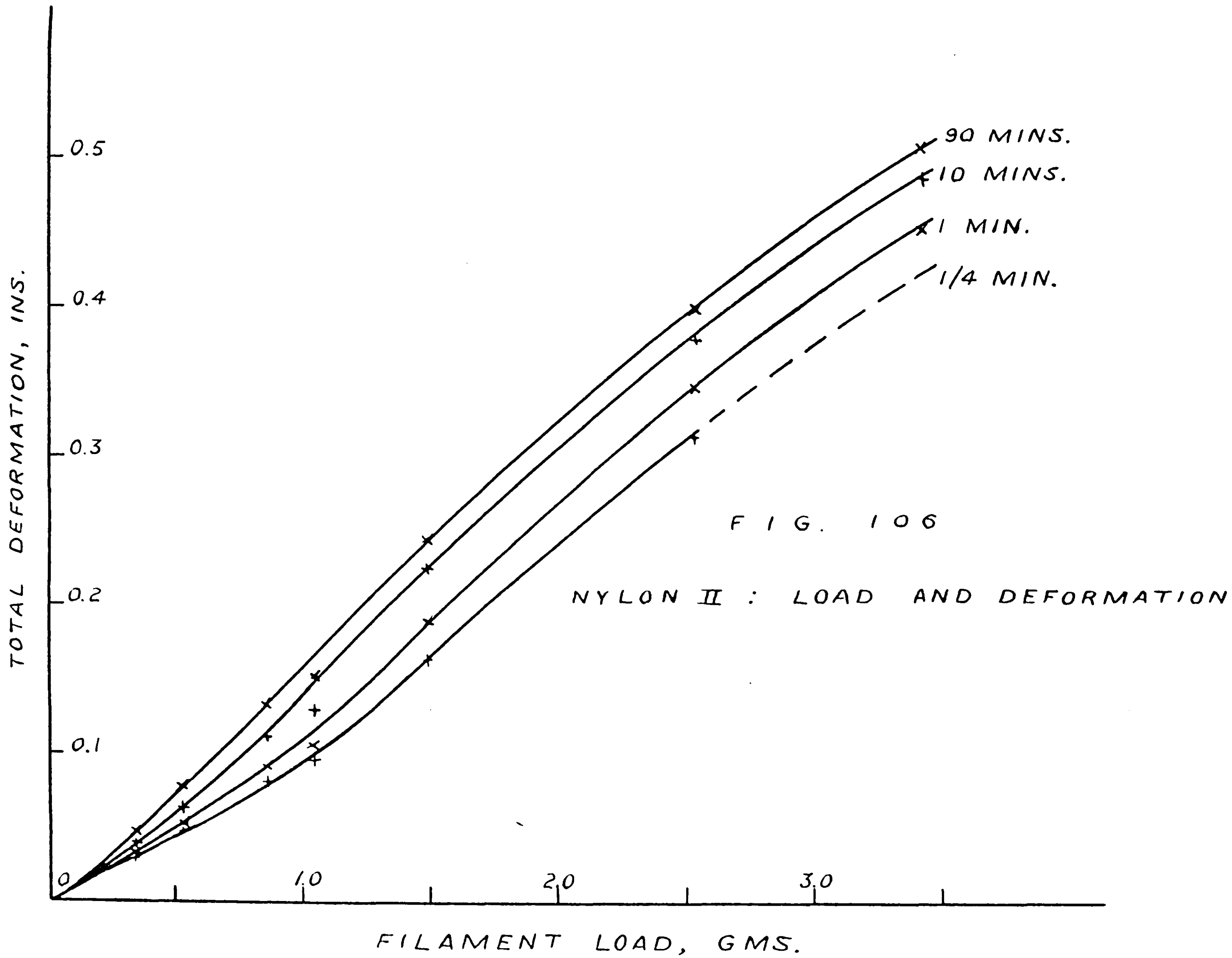


FIG. 106

NYLON II : LOAD AND DEFORMATION

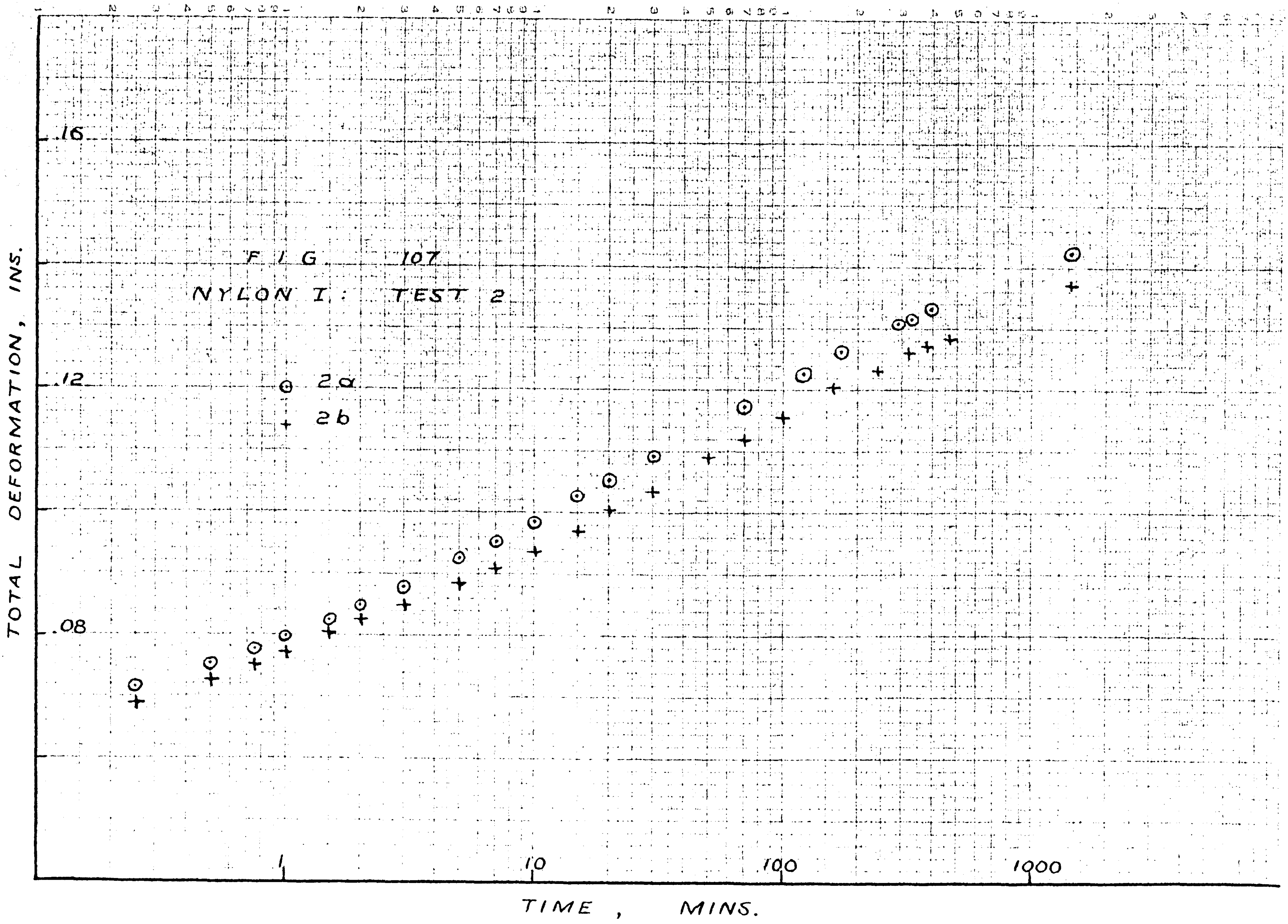


FIG 107

NYLON I: TEST 2

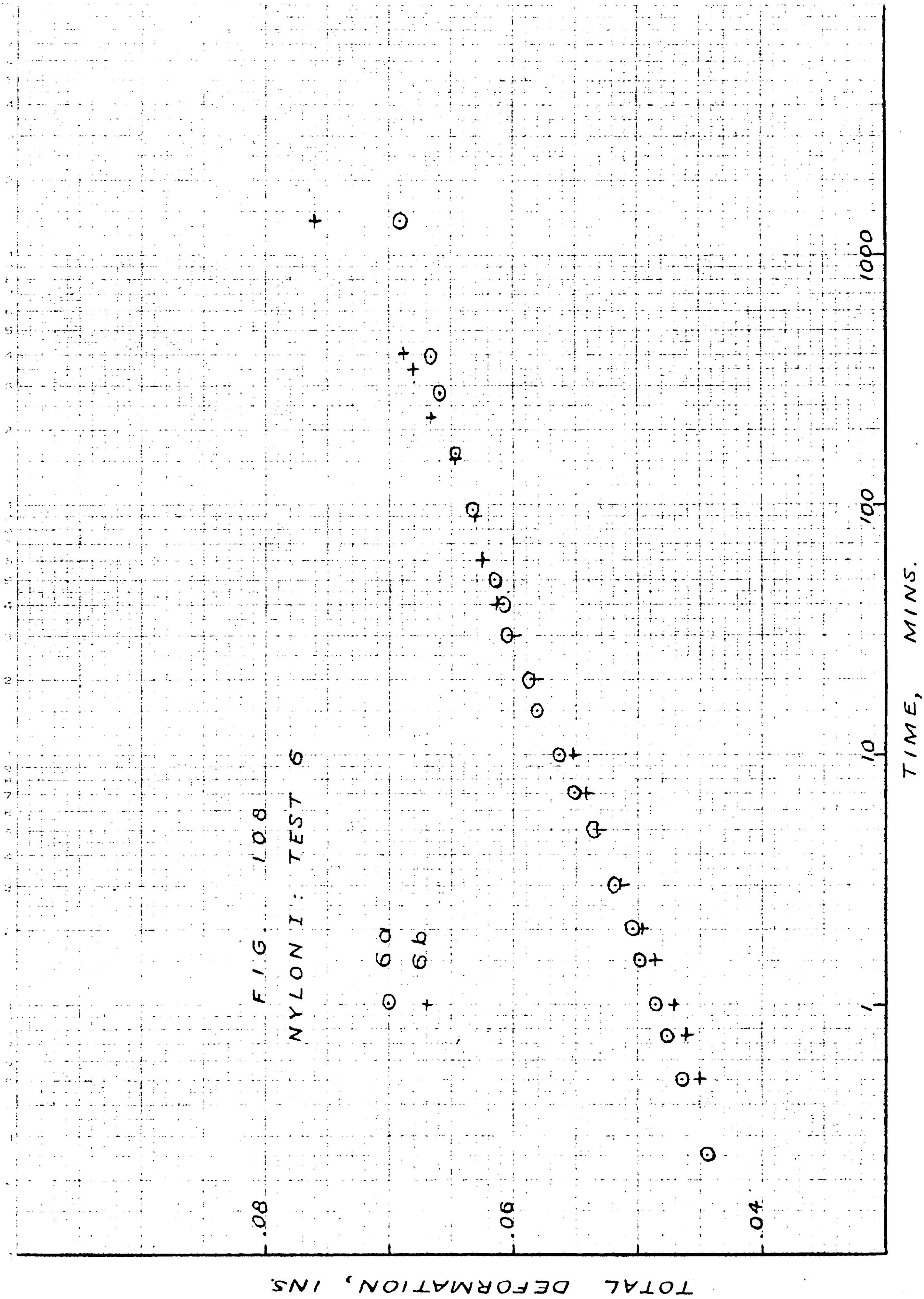


FIG. 108

NYLON I: TEST 6

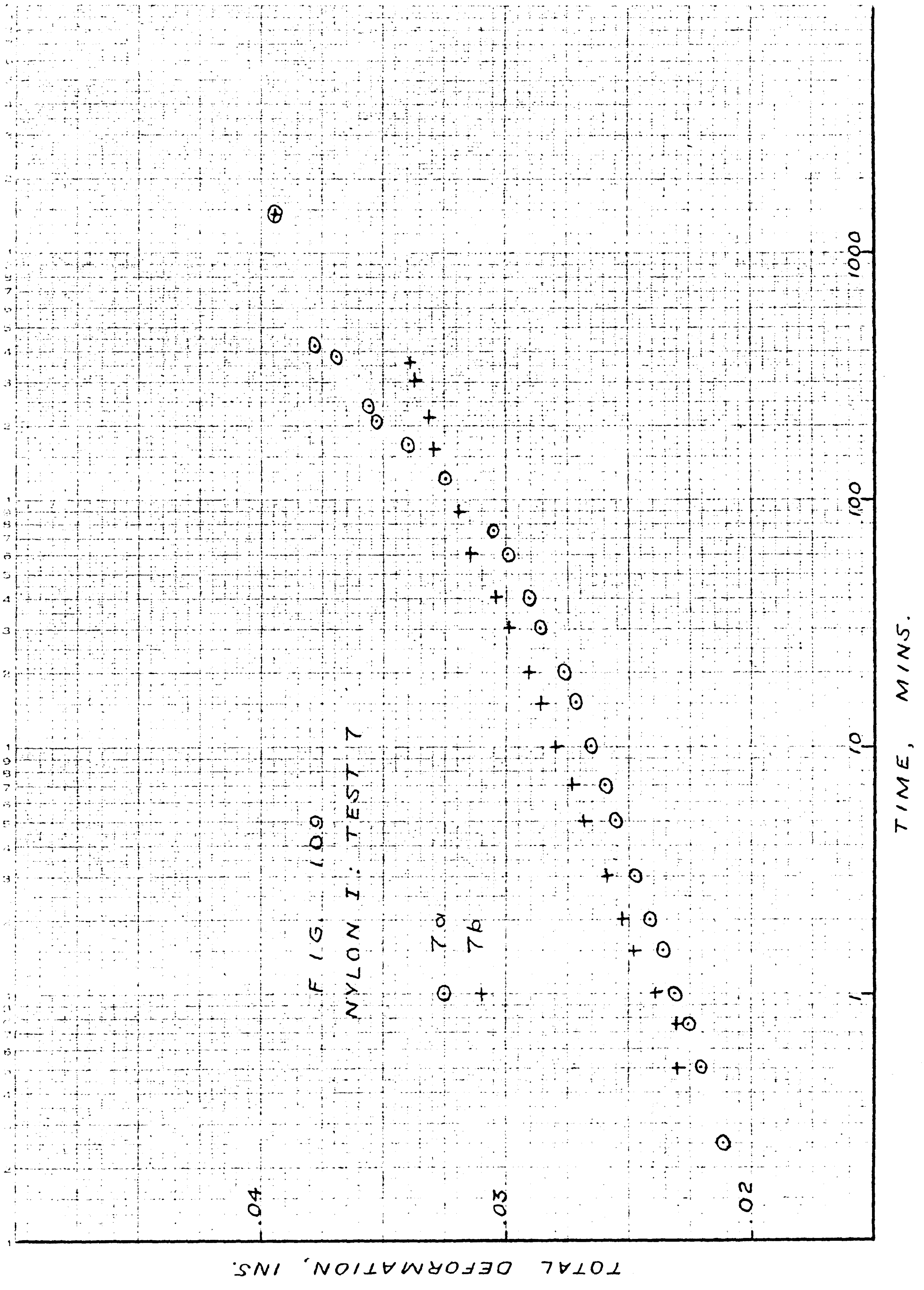


FIG. 109

NYLON I: TEST 7

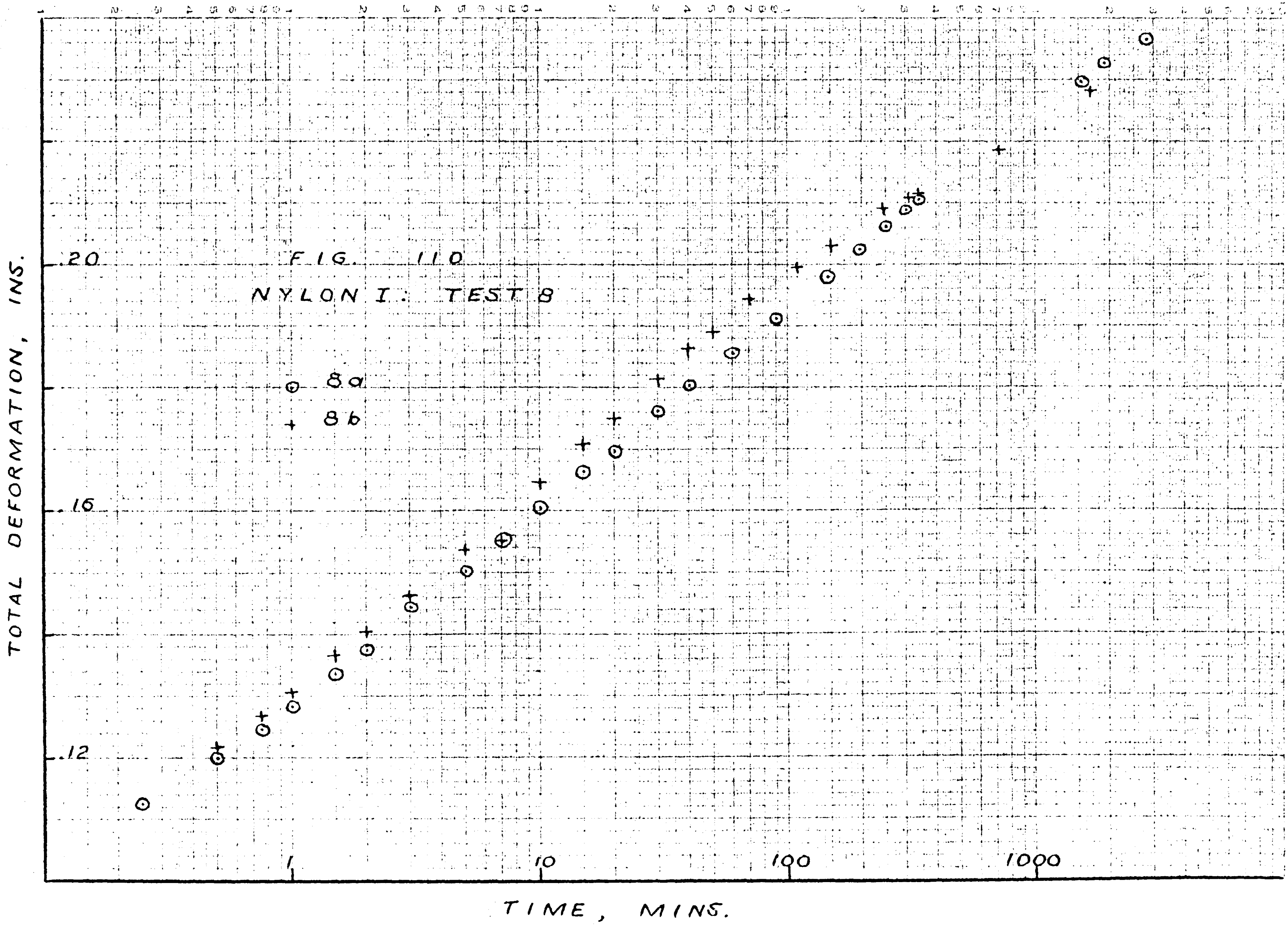


FIG. 110

NYLON I. TEST 8

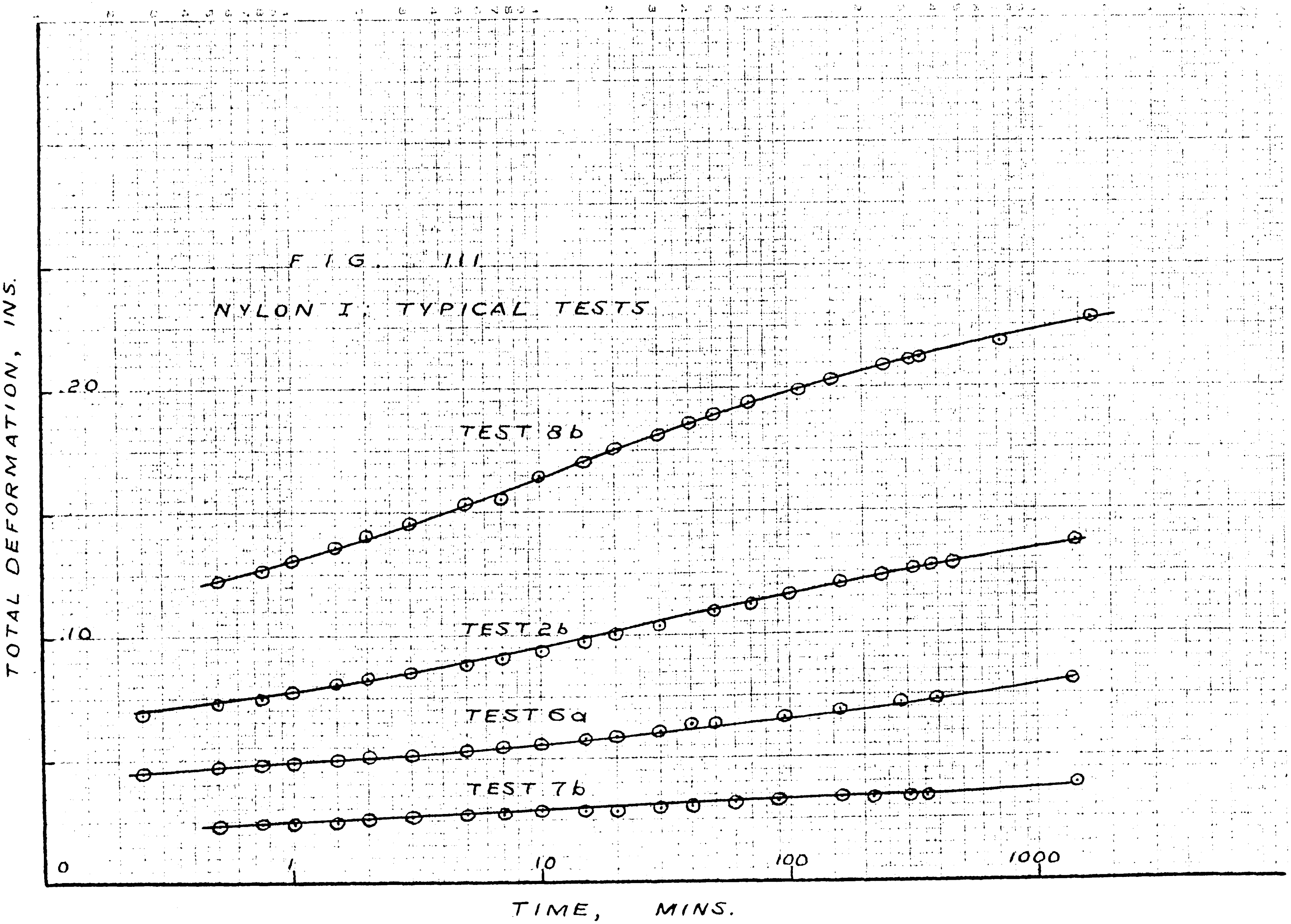


FIG. III

NYLON I: TYPICAL TESTS

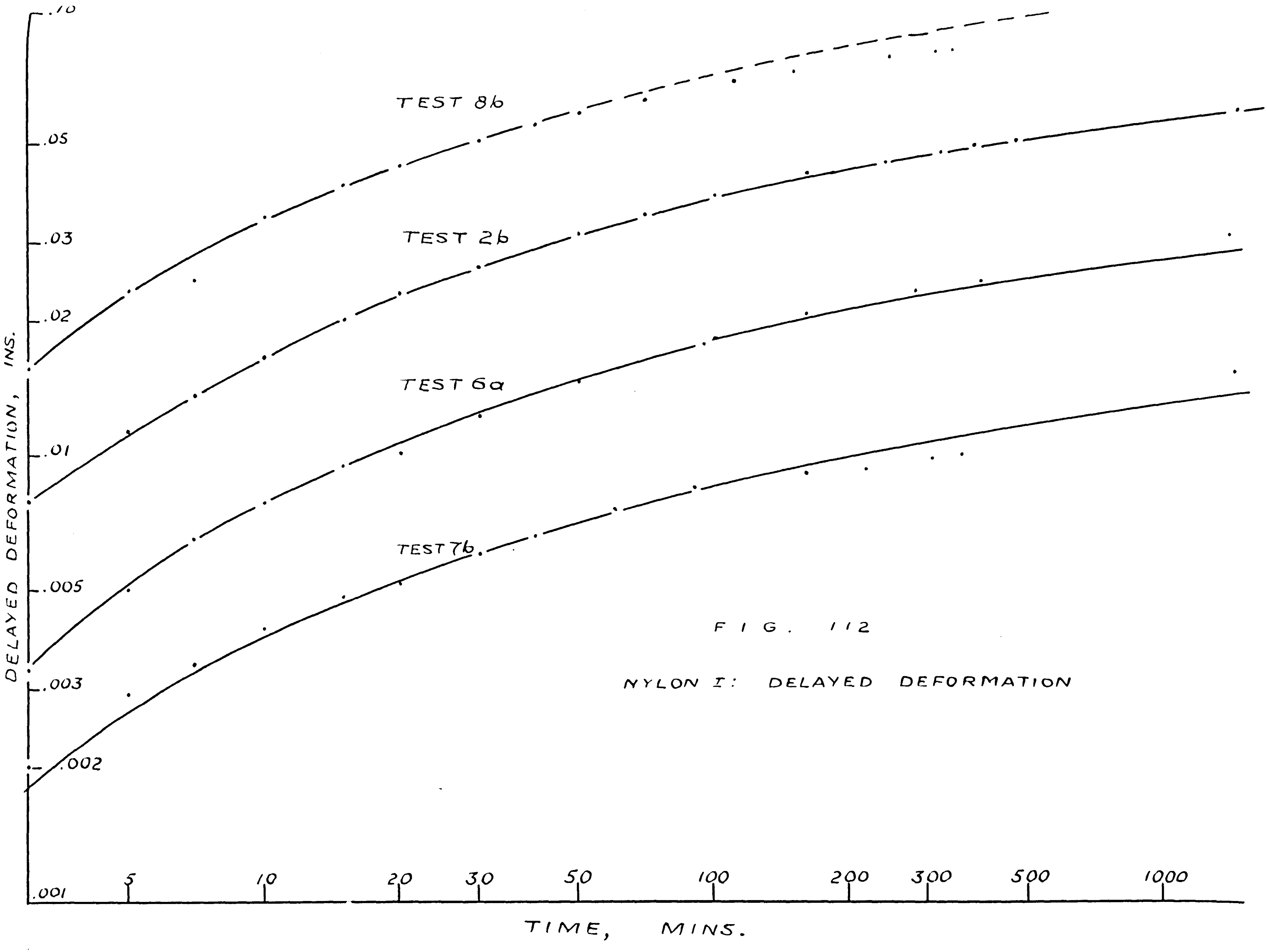


FIG. 112

NYLON I: DELAYED DEFORMATION

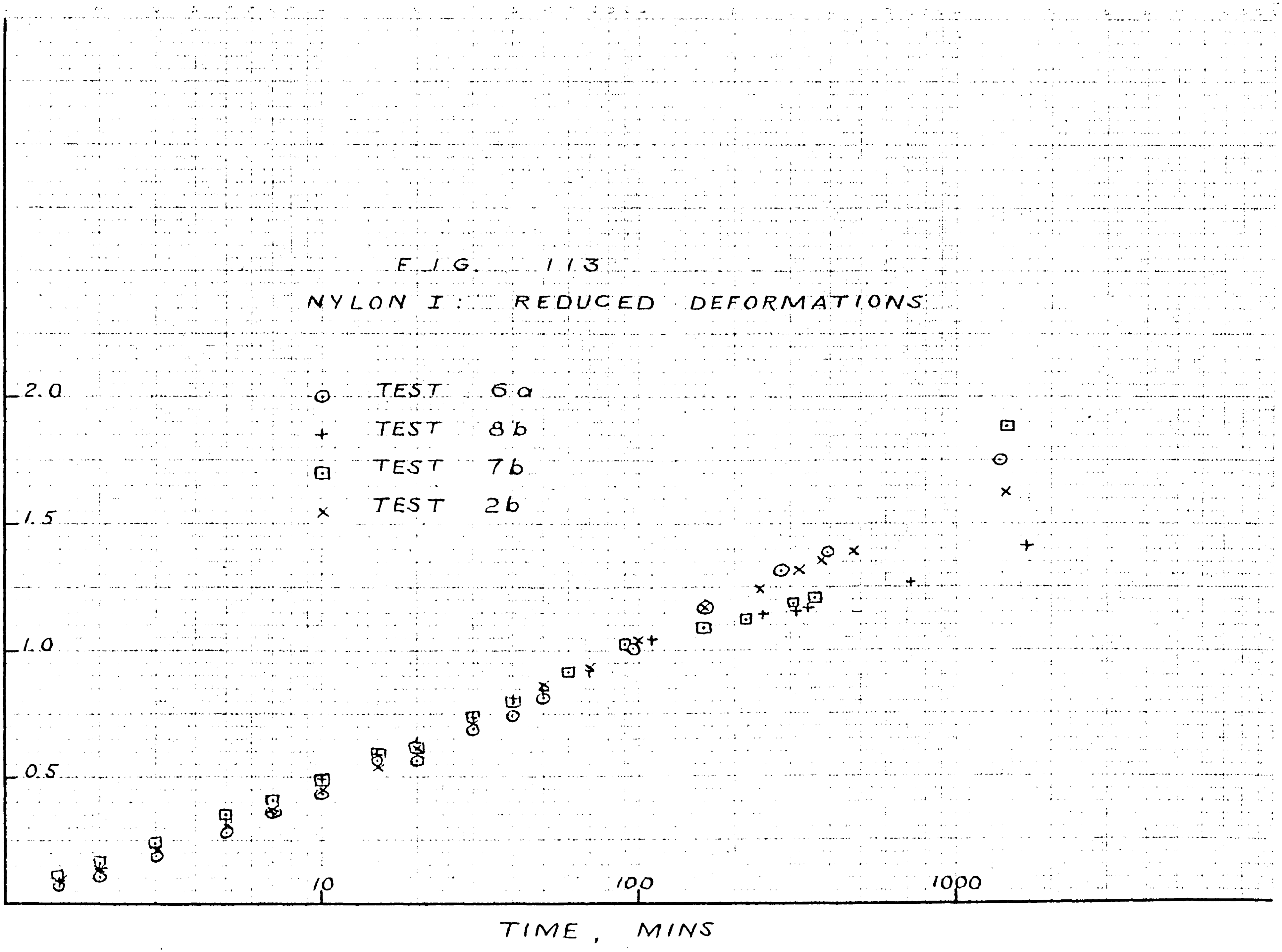


FIG. 113

NYLON I: REDUCED DEFORMATIONS

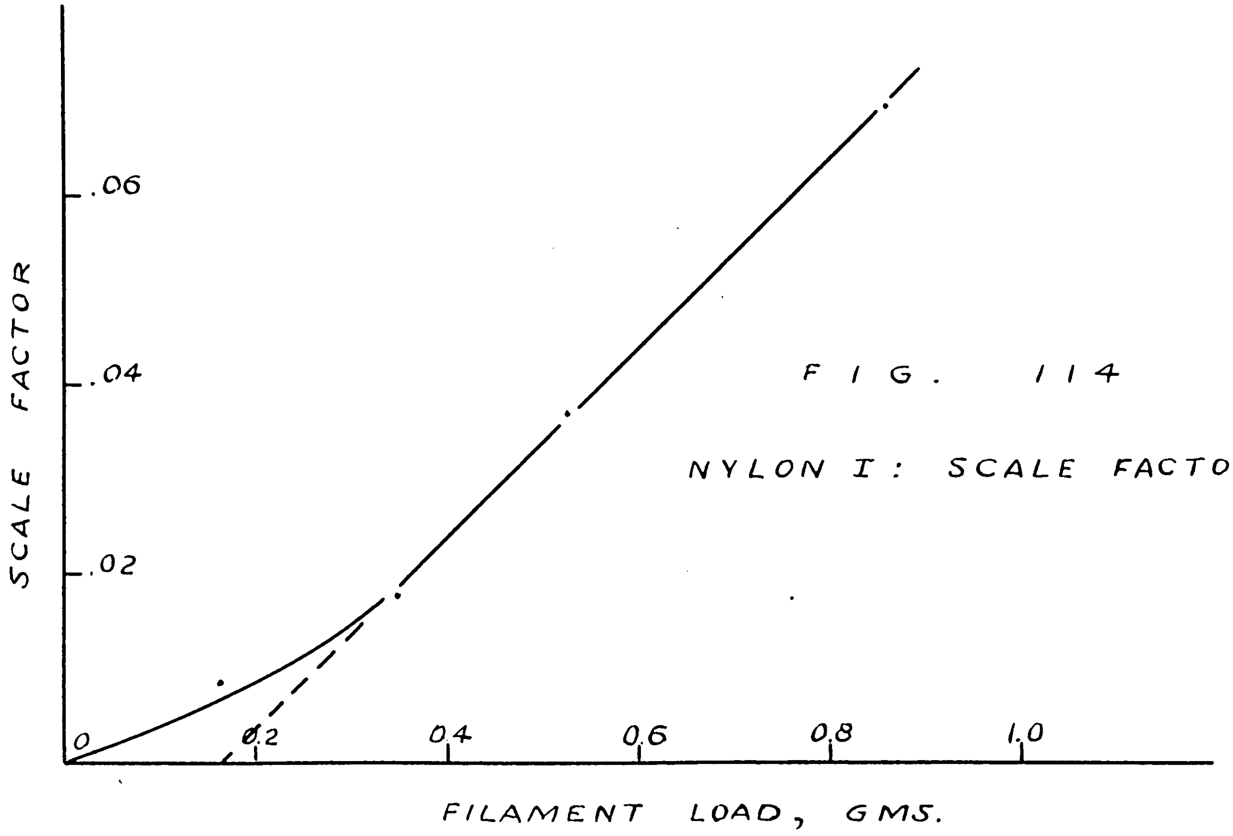


FIG. 114

NYLON I: SCALE FACTORS

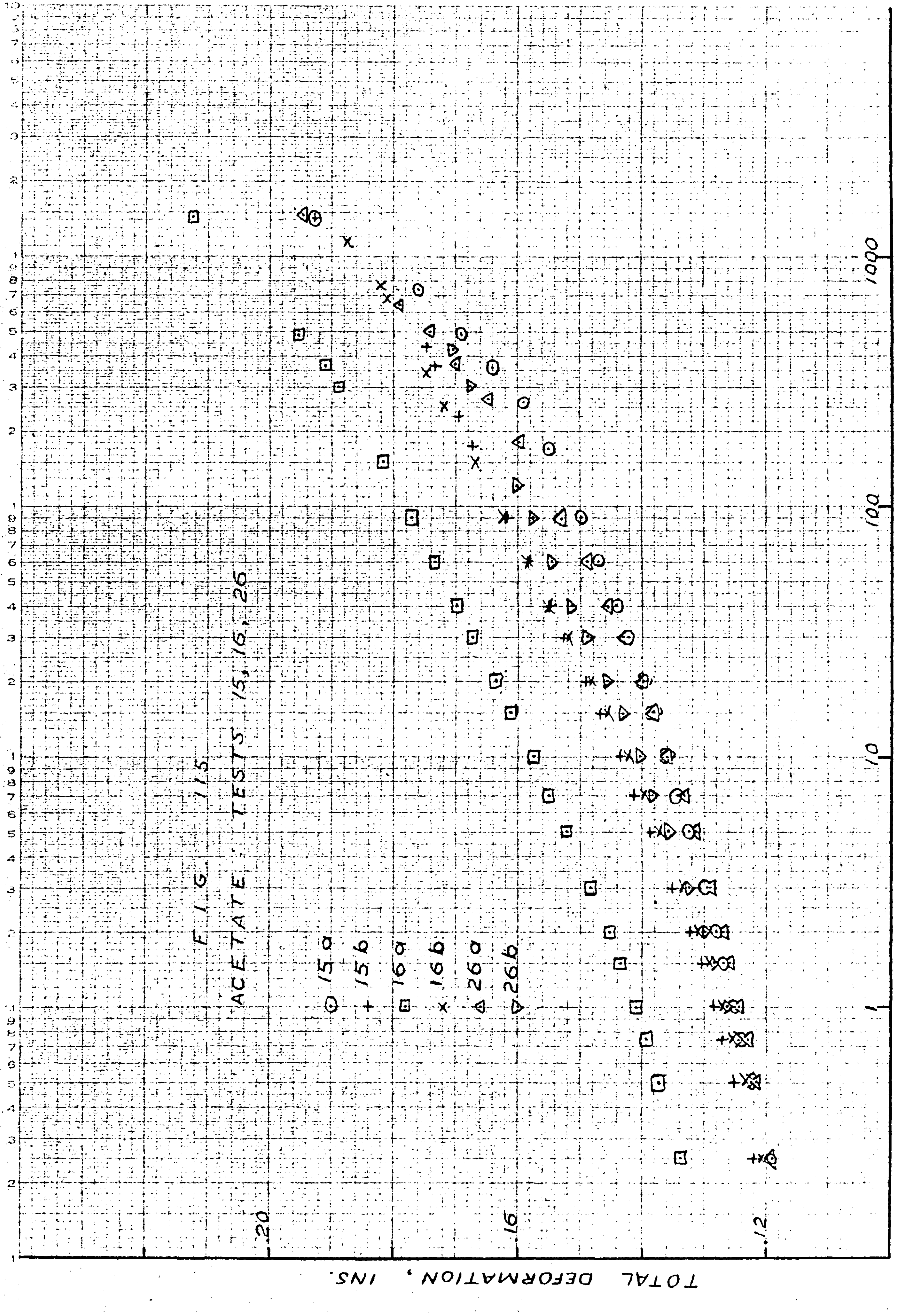


FIG 115

ACETATE TESTS 15, 16, 26

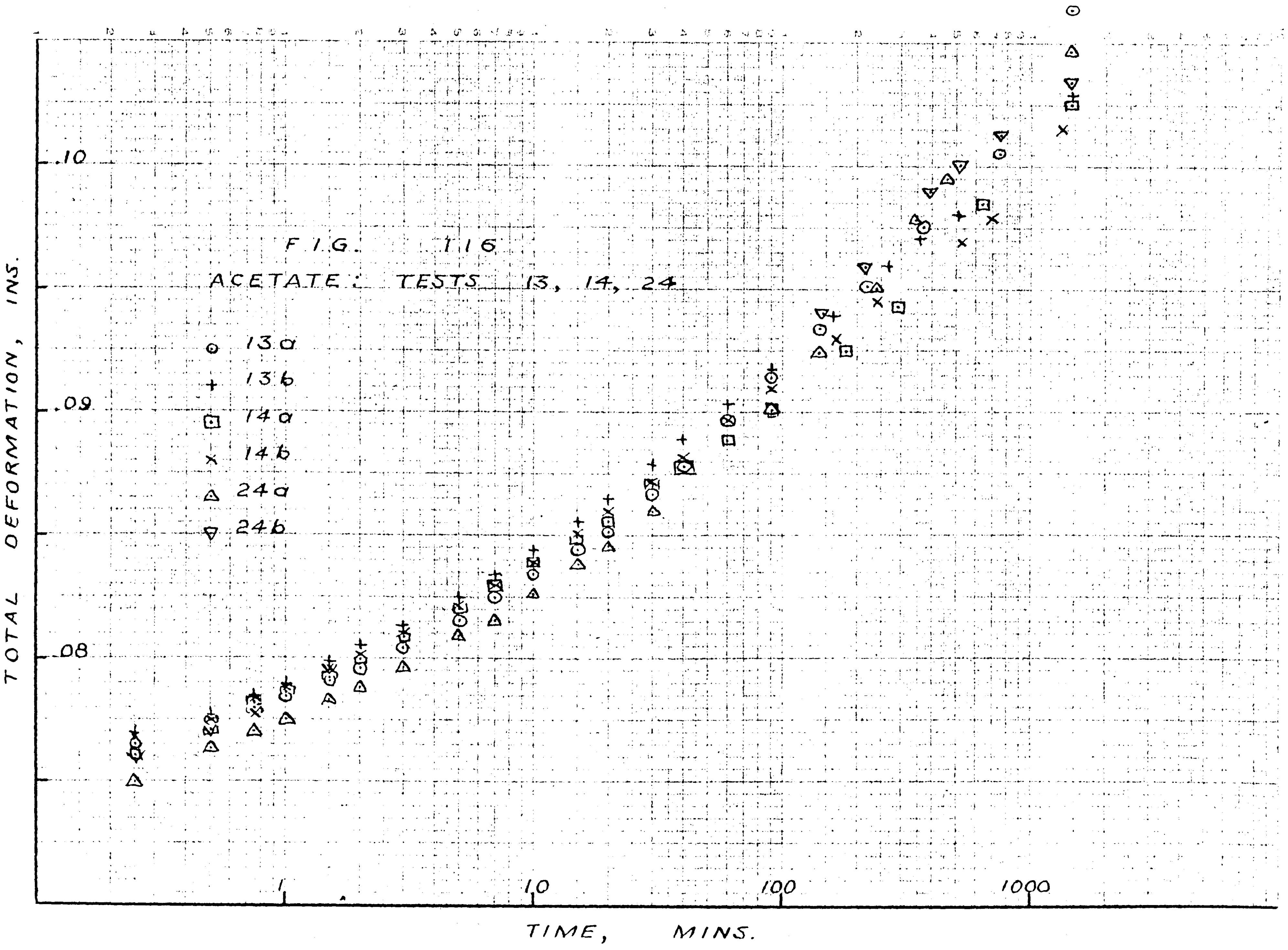


FIG. 116

ACETATE: TESTS 13, 14, 24

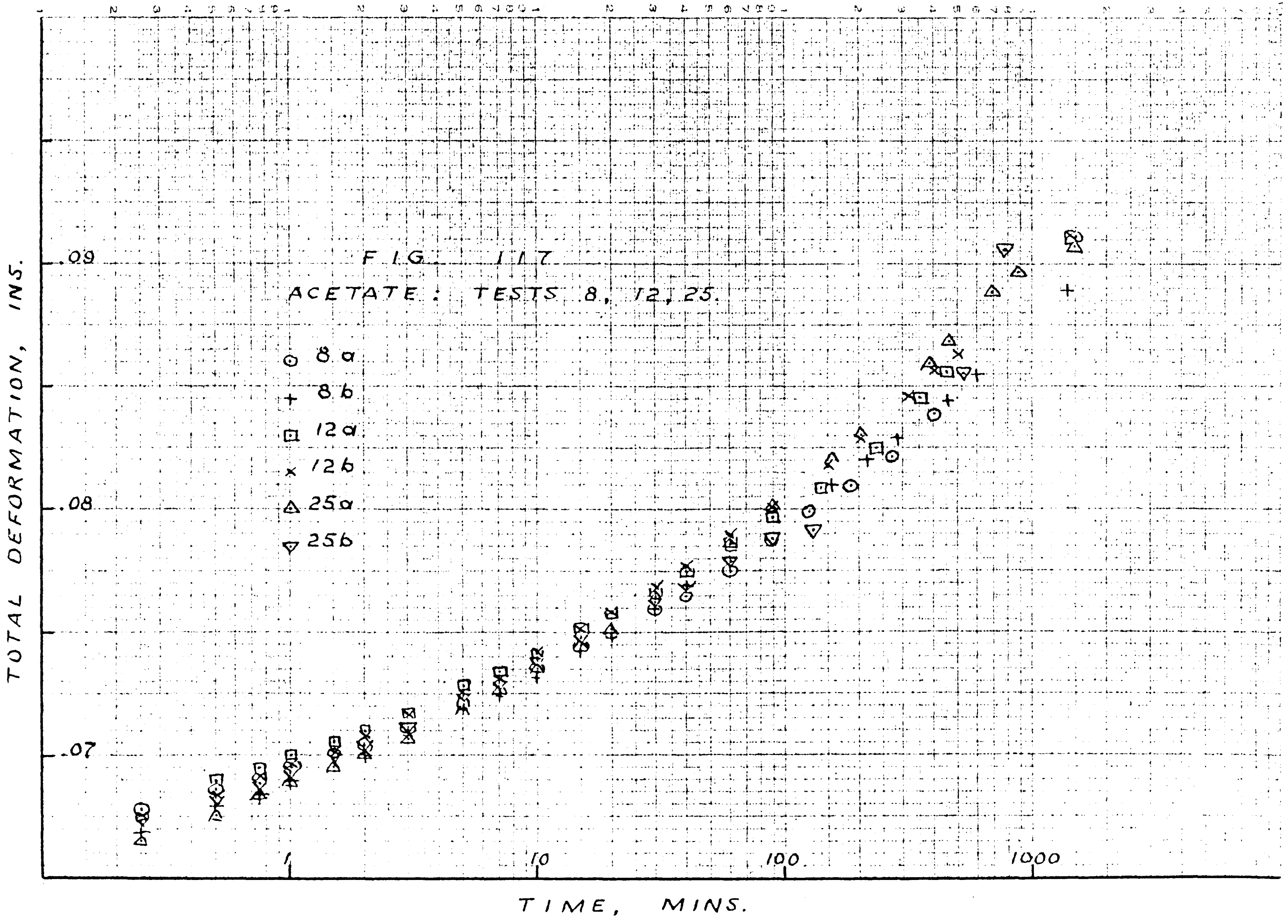


FIG. 117

ACETATE: TESTS 8, 12, 25.

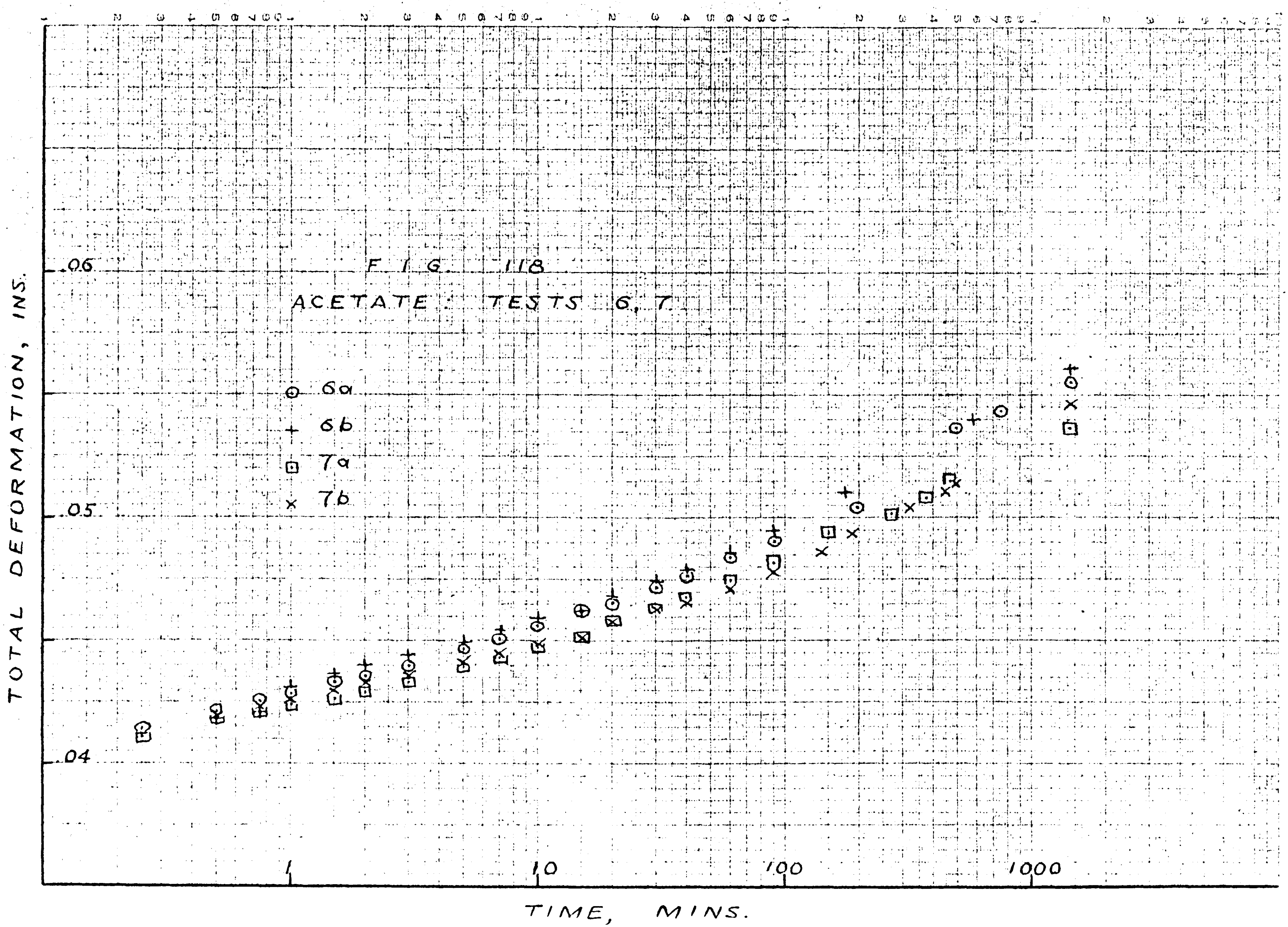


FIG. 118

ACETATE: TESTS 6, 7

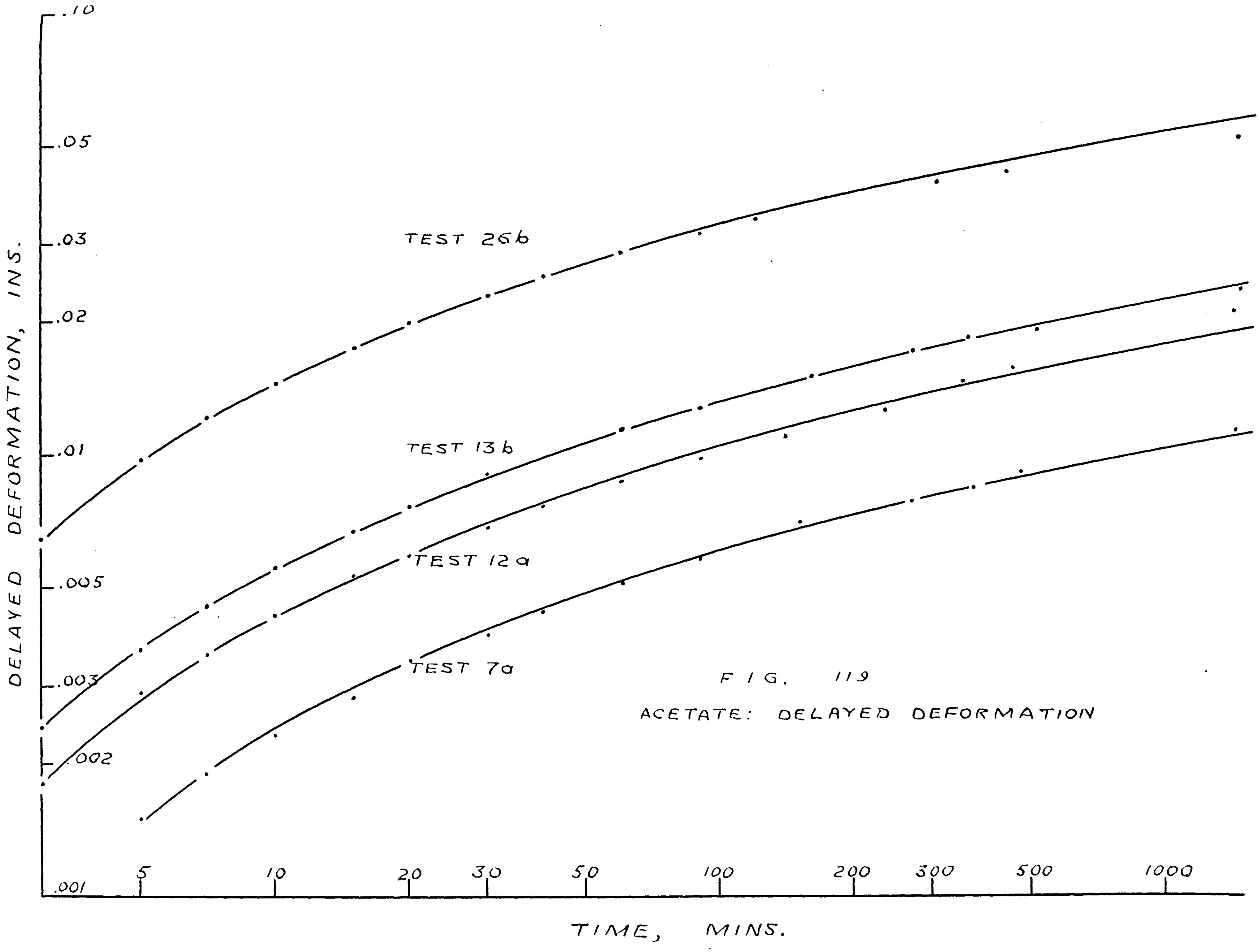


FIG. 119

ACETATE: DELAYED DEFORMATION

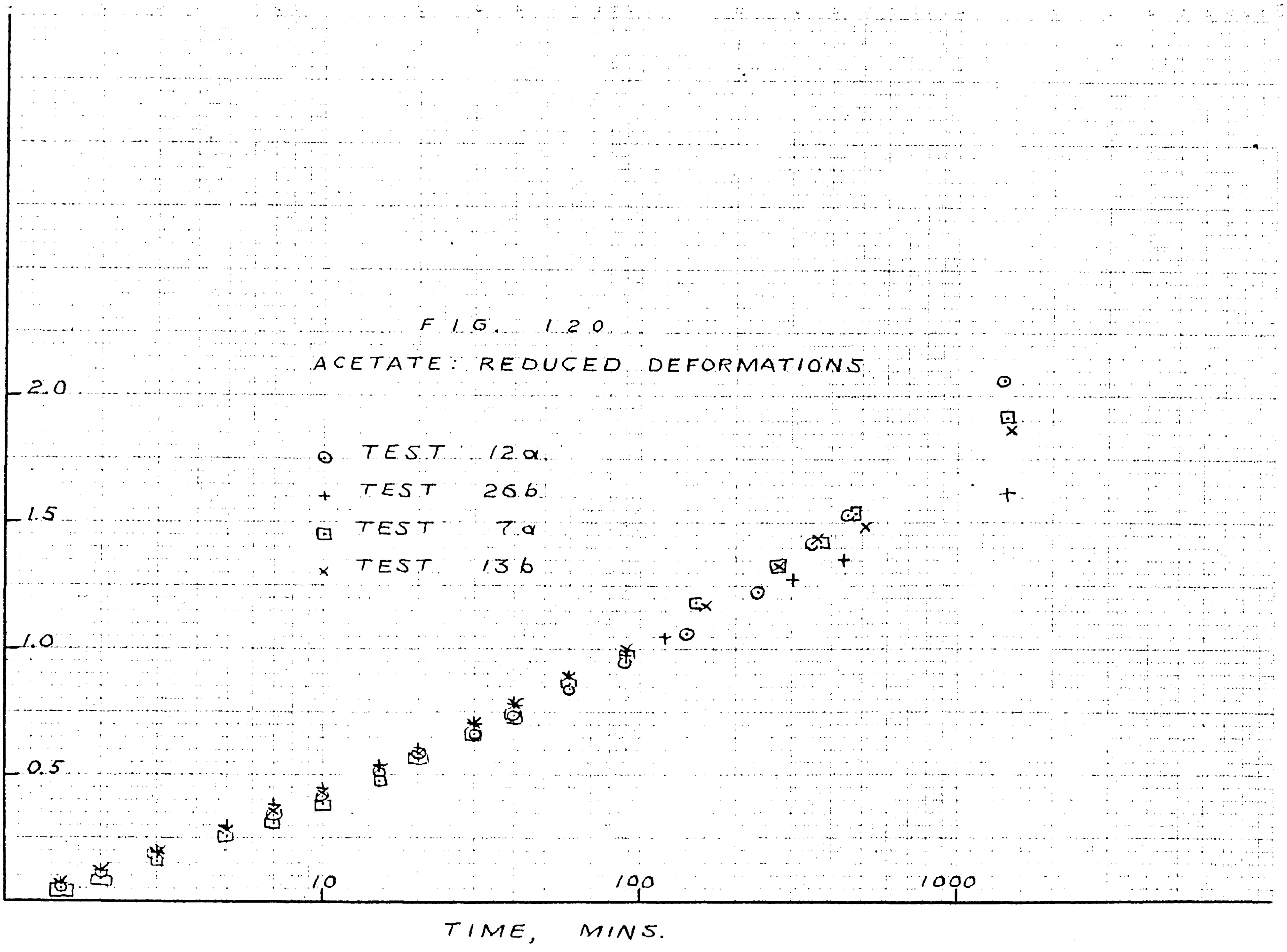


FIG. 1.20

ACETATE: REDUCED DEFORMATIONS

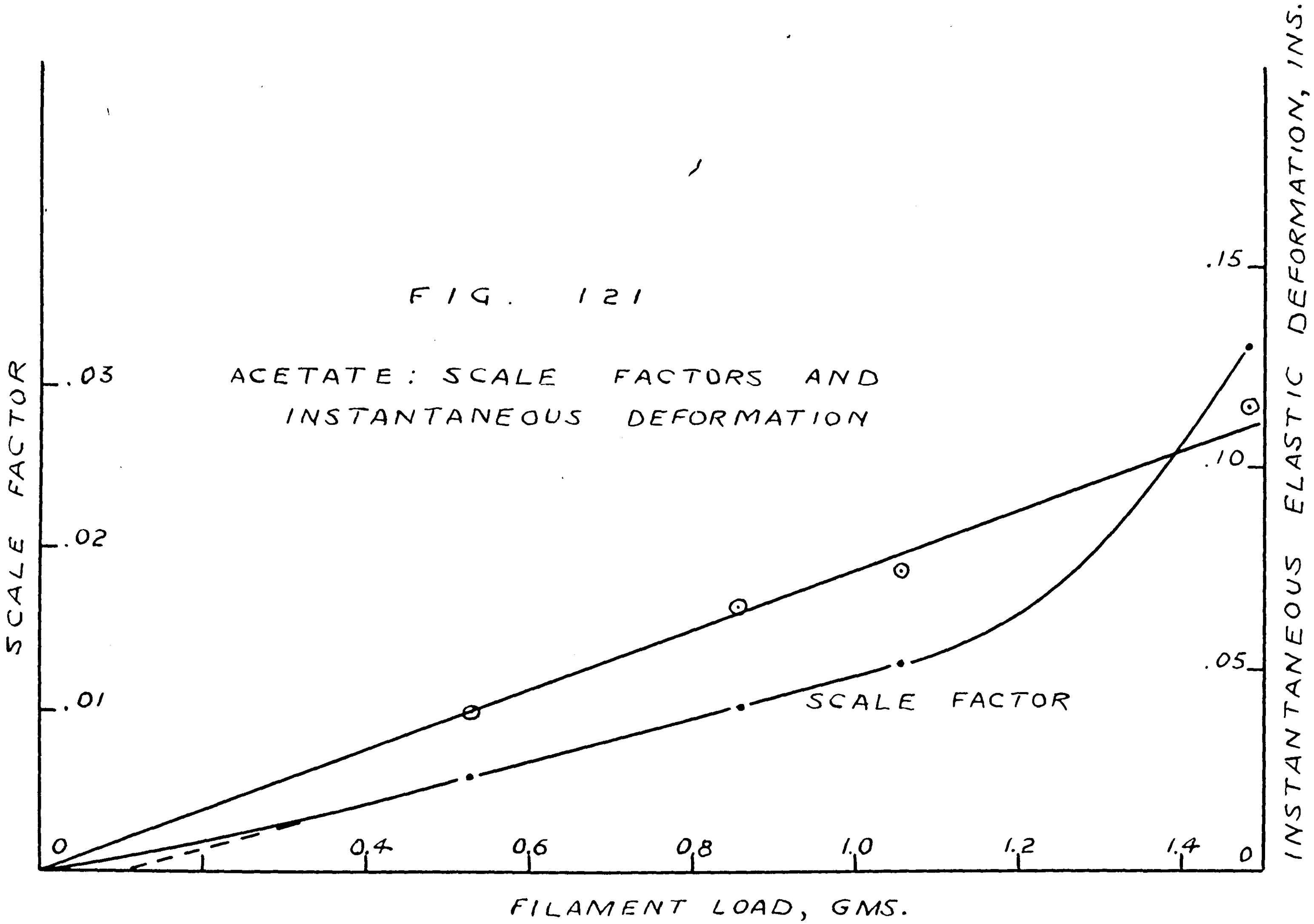


FIG. 121

ACETATE: SCALE FACTORS AND INSTANTANEOUS DEFORMATION

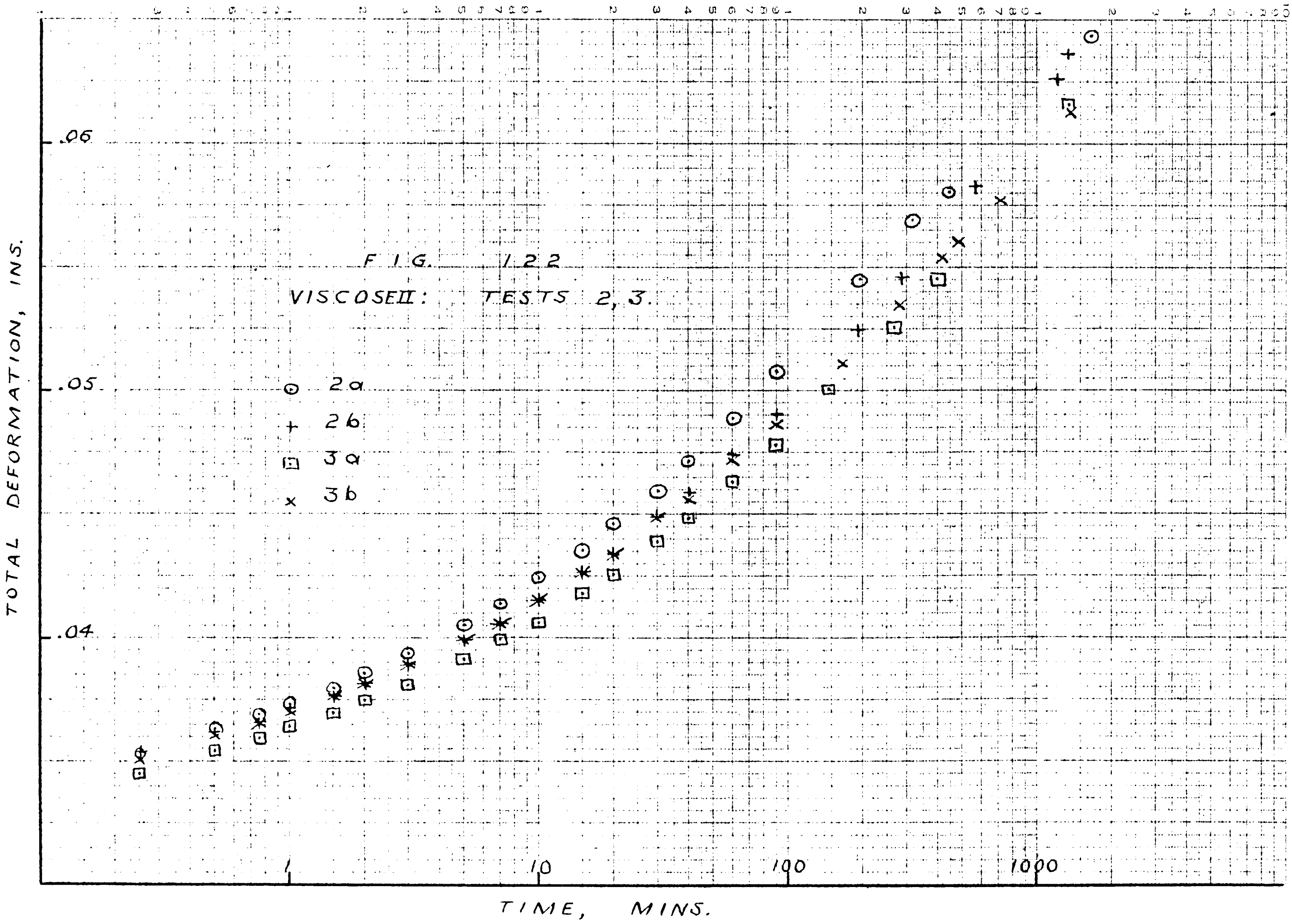


FIG. 122

VISCOSE II: TESTS 2, 3.

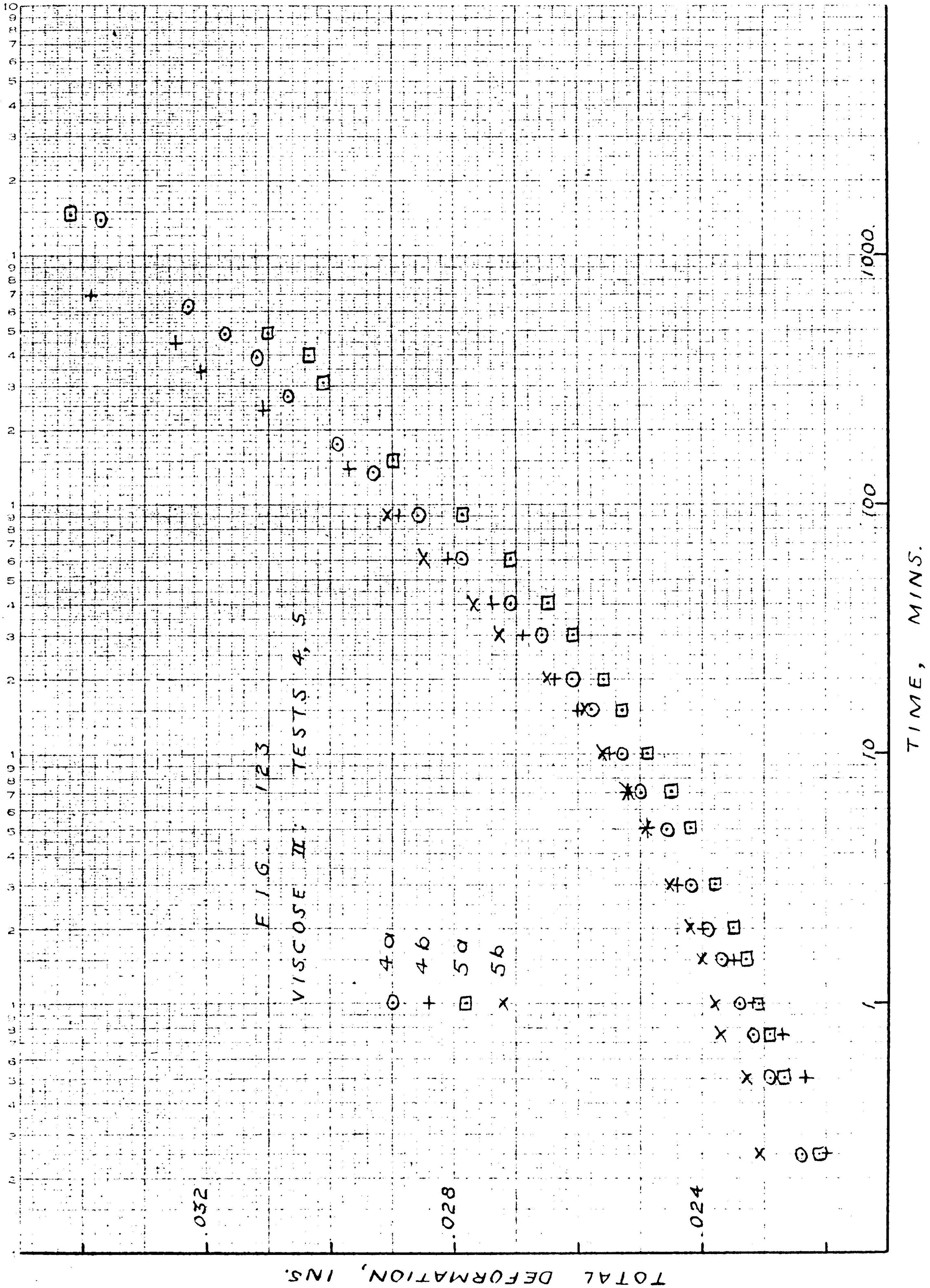


FIG. 123

VISCOSE II, TESTS 4, 5

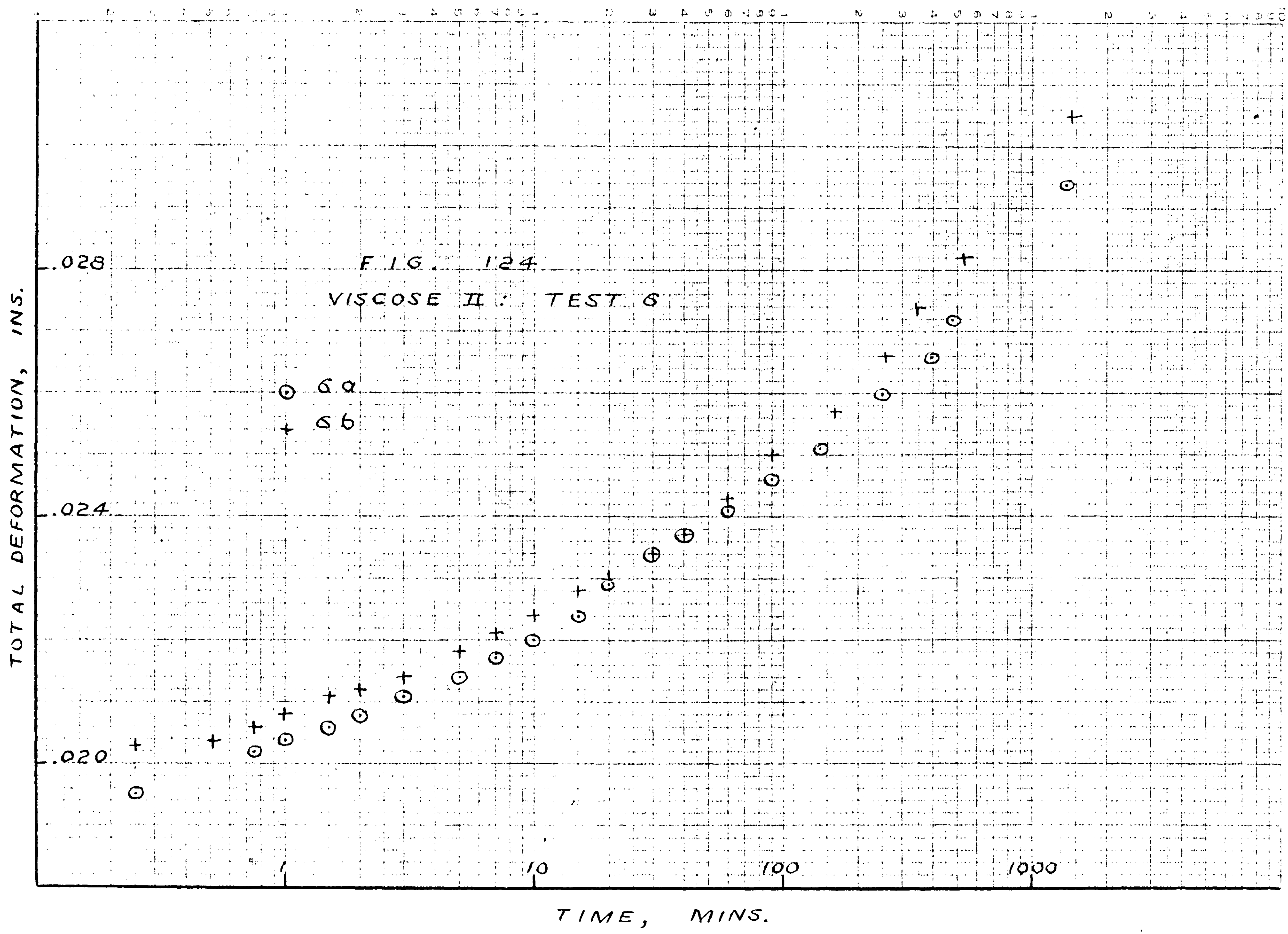


FIG. 124

VISCOSE II : TEST 6

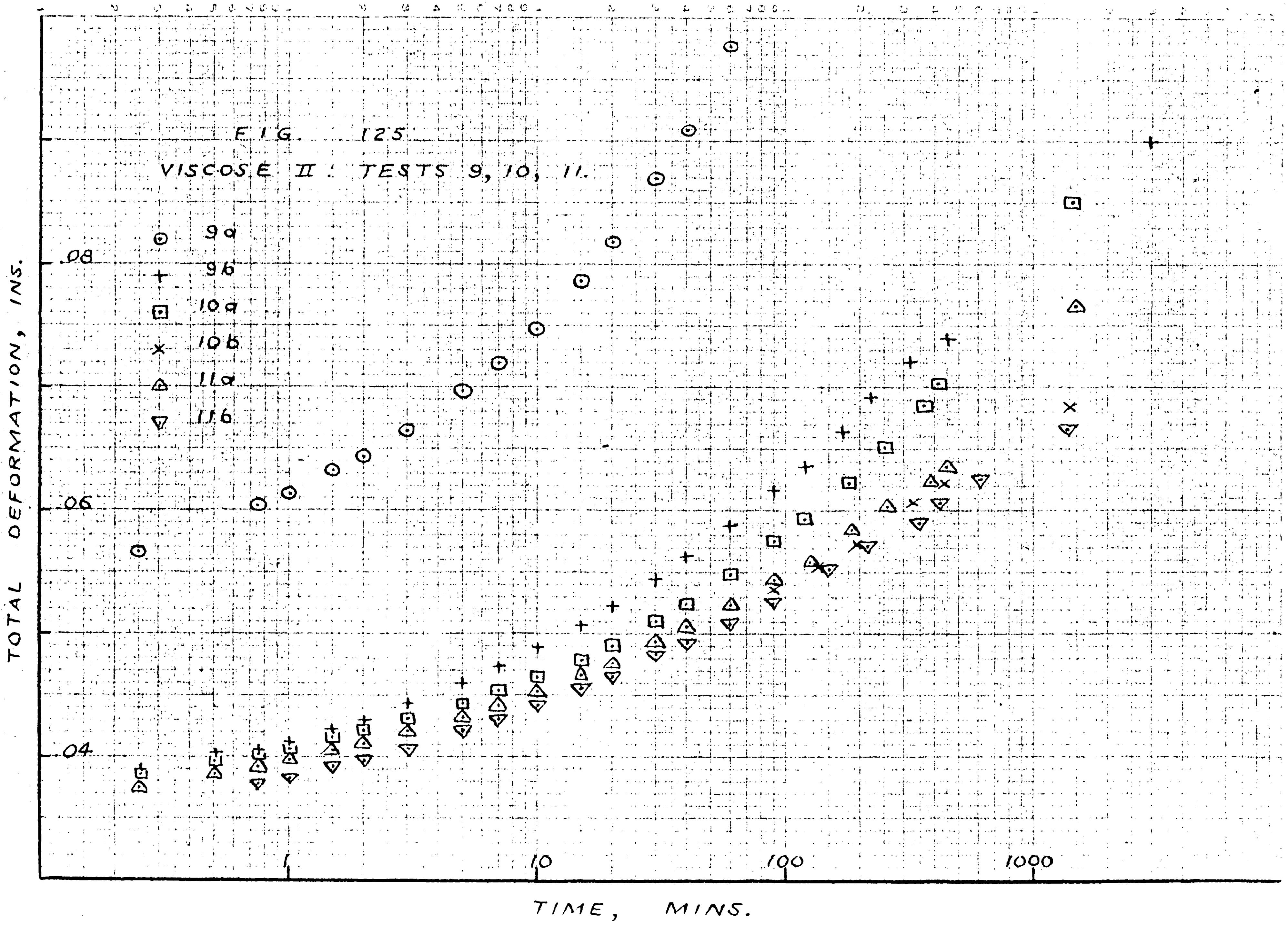


FIG. 125

VISCOSE II : TESTS 9, 10, 11.

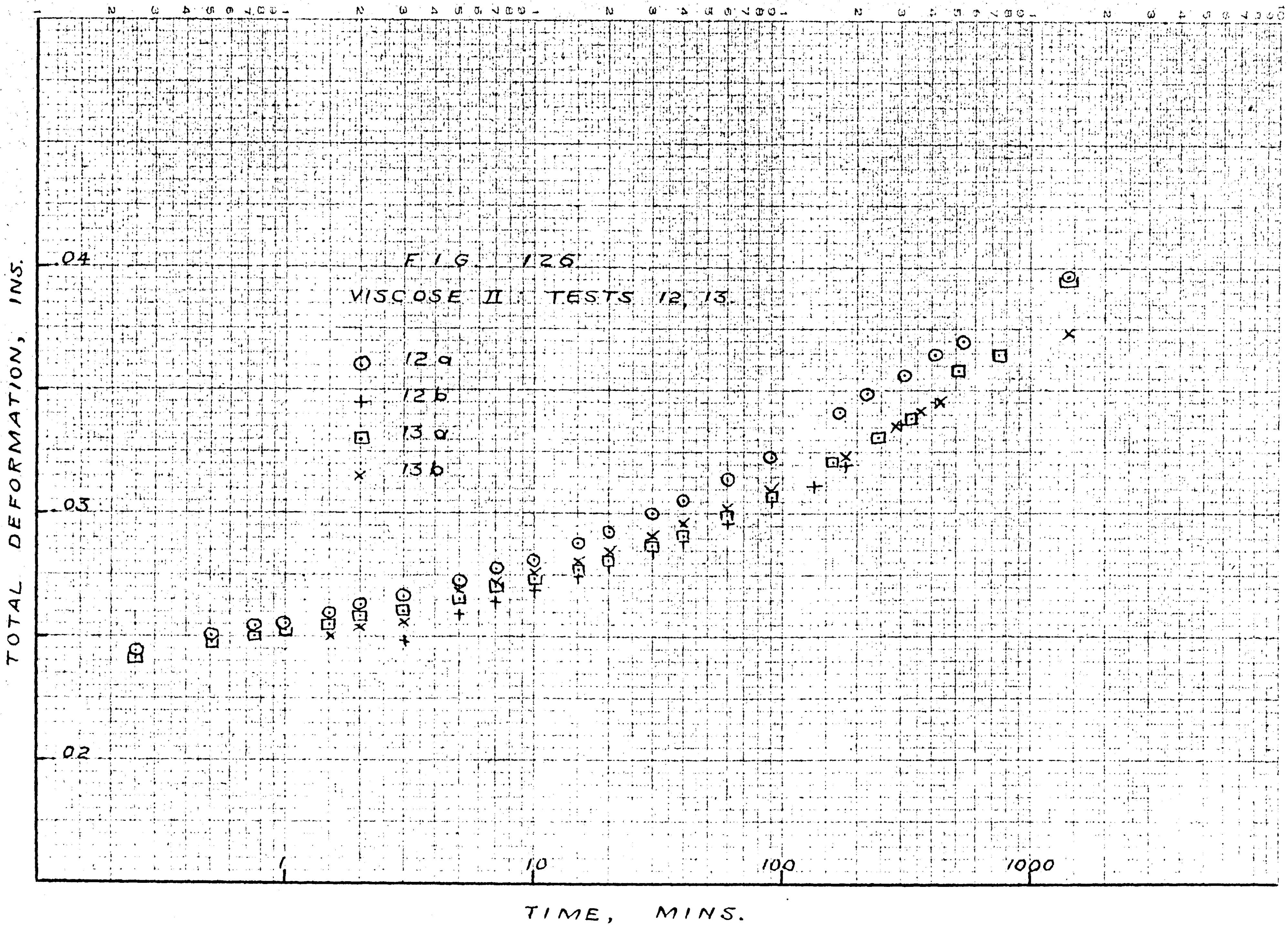


FIG 126

VISCOSE II : TESTS 12, 13

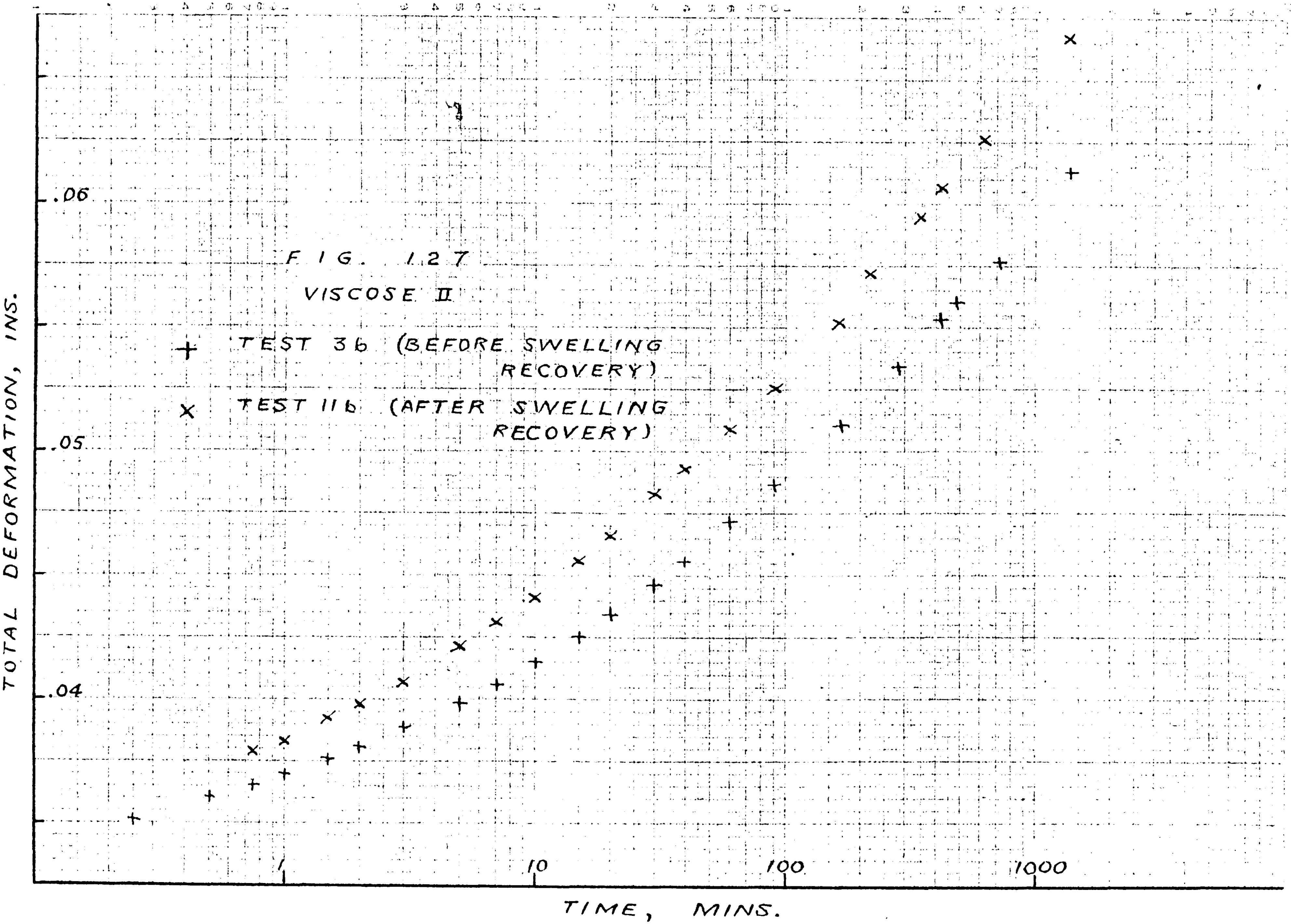
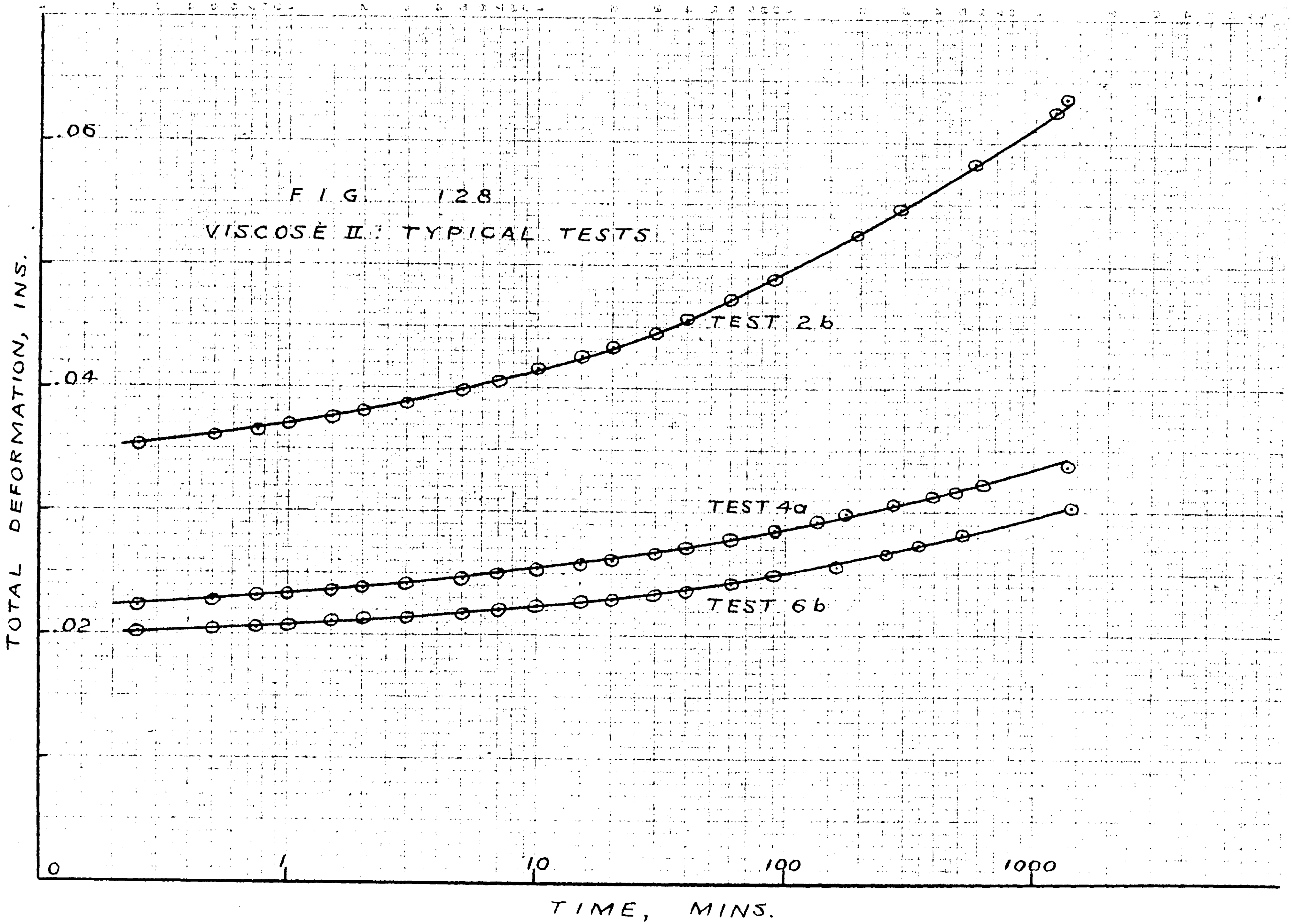


FIG. 127

VISCOSE II

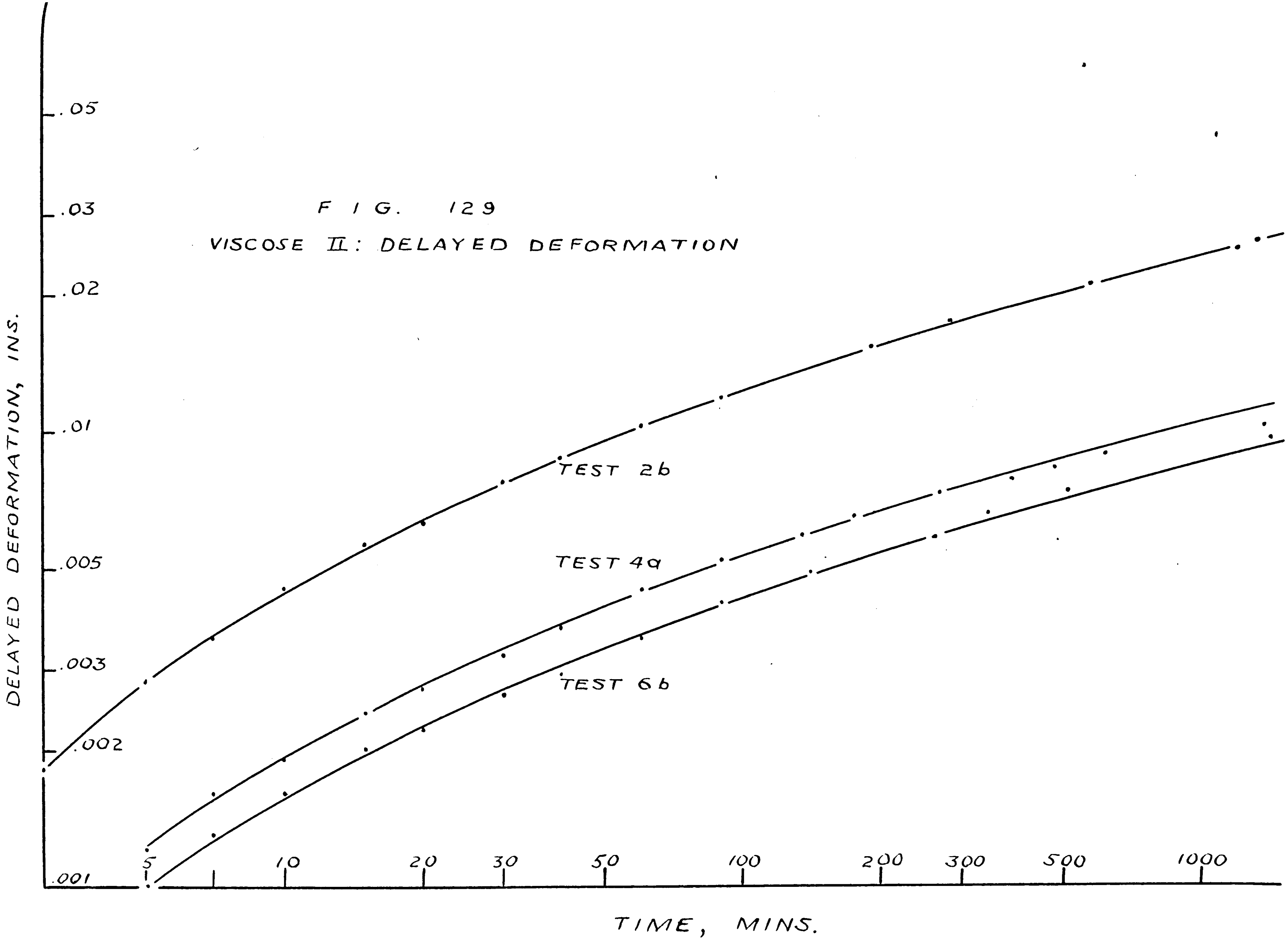


F I G. 128

VISCOSE II: TYPICAL TESTS

FIG. 129

VISCOSE II: DELAYED DEFORMATION



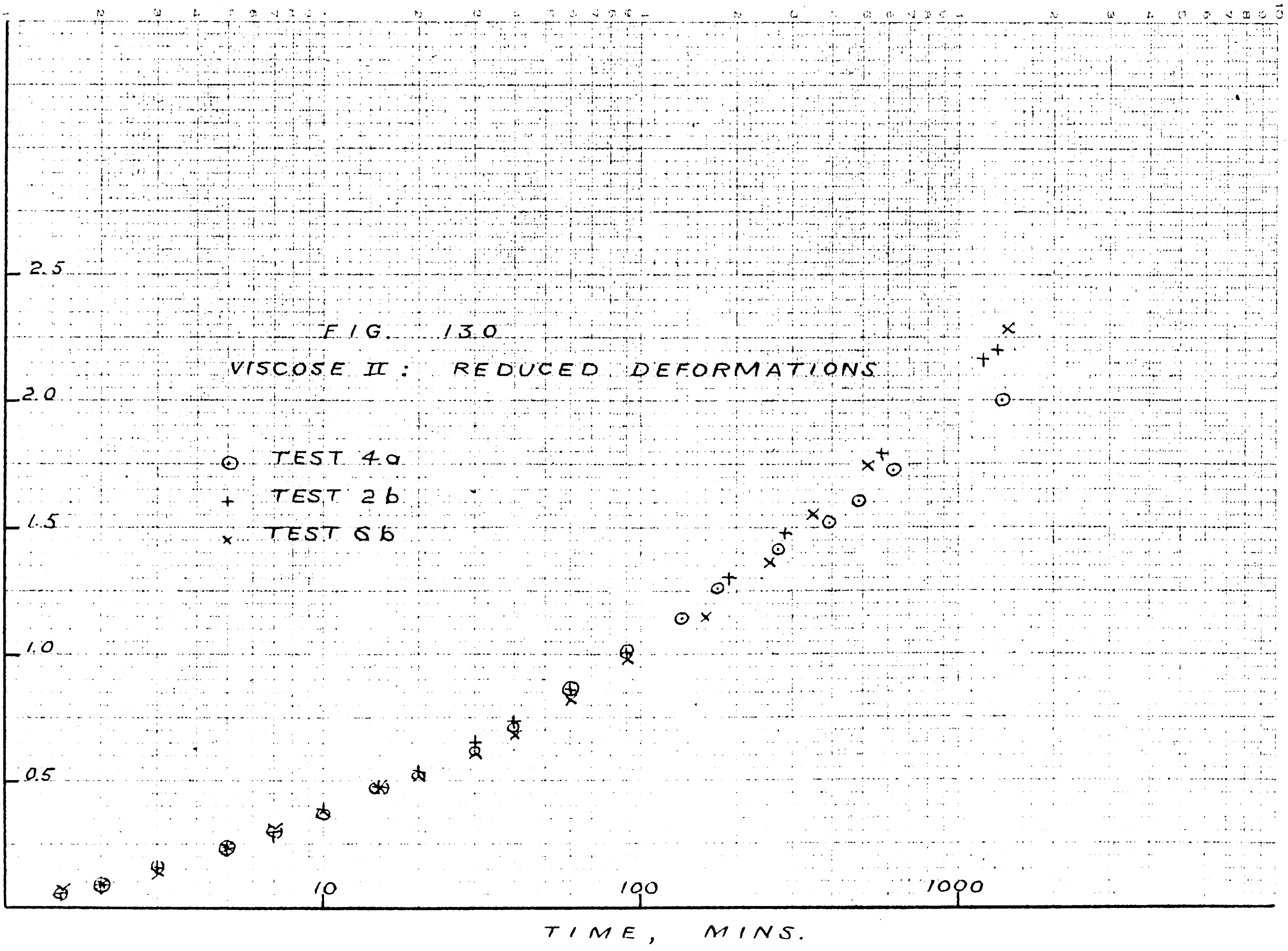


FIG. 130

VISCOSE II: REDUCED DEFORMATIONS

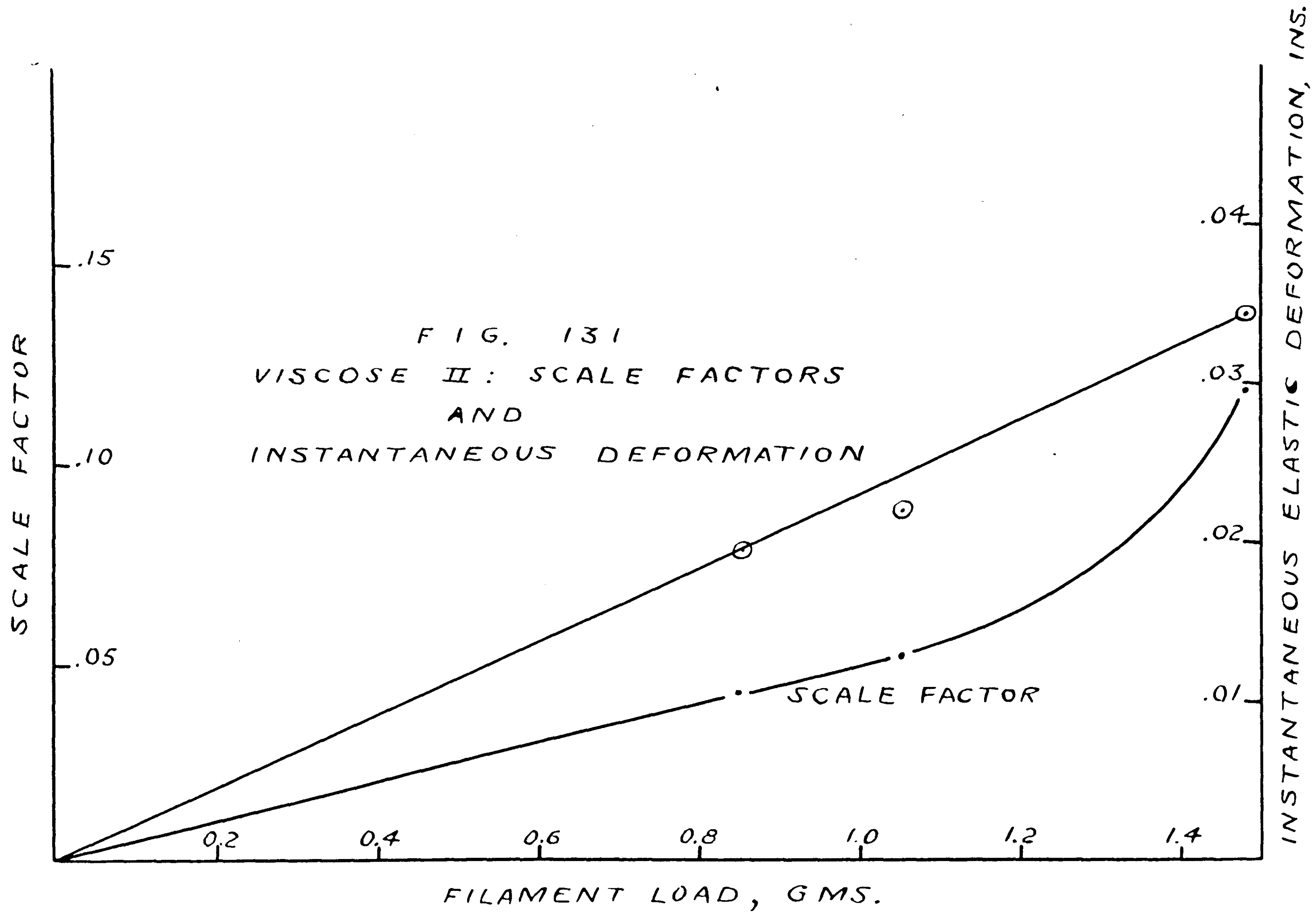


FIG. 131

VISCOSE II: SCALE FACTORS
AND
INSTANTANEOUS DEFORMATION

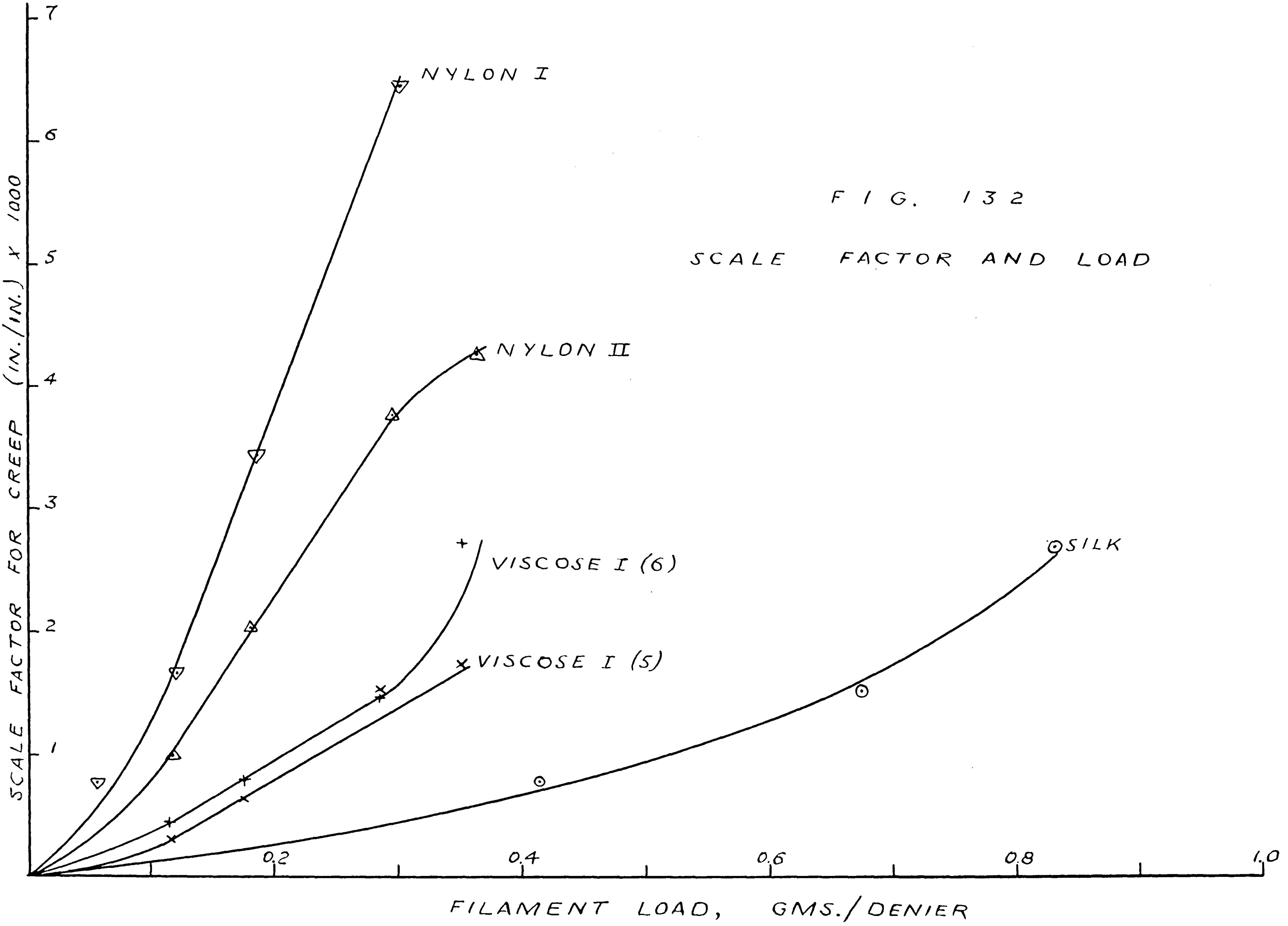


FIG. 132

SCALE FACTOR AND LOAD

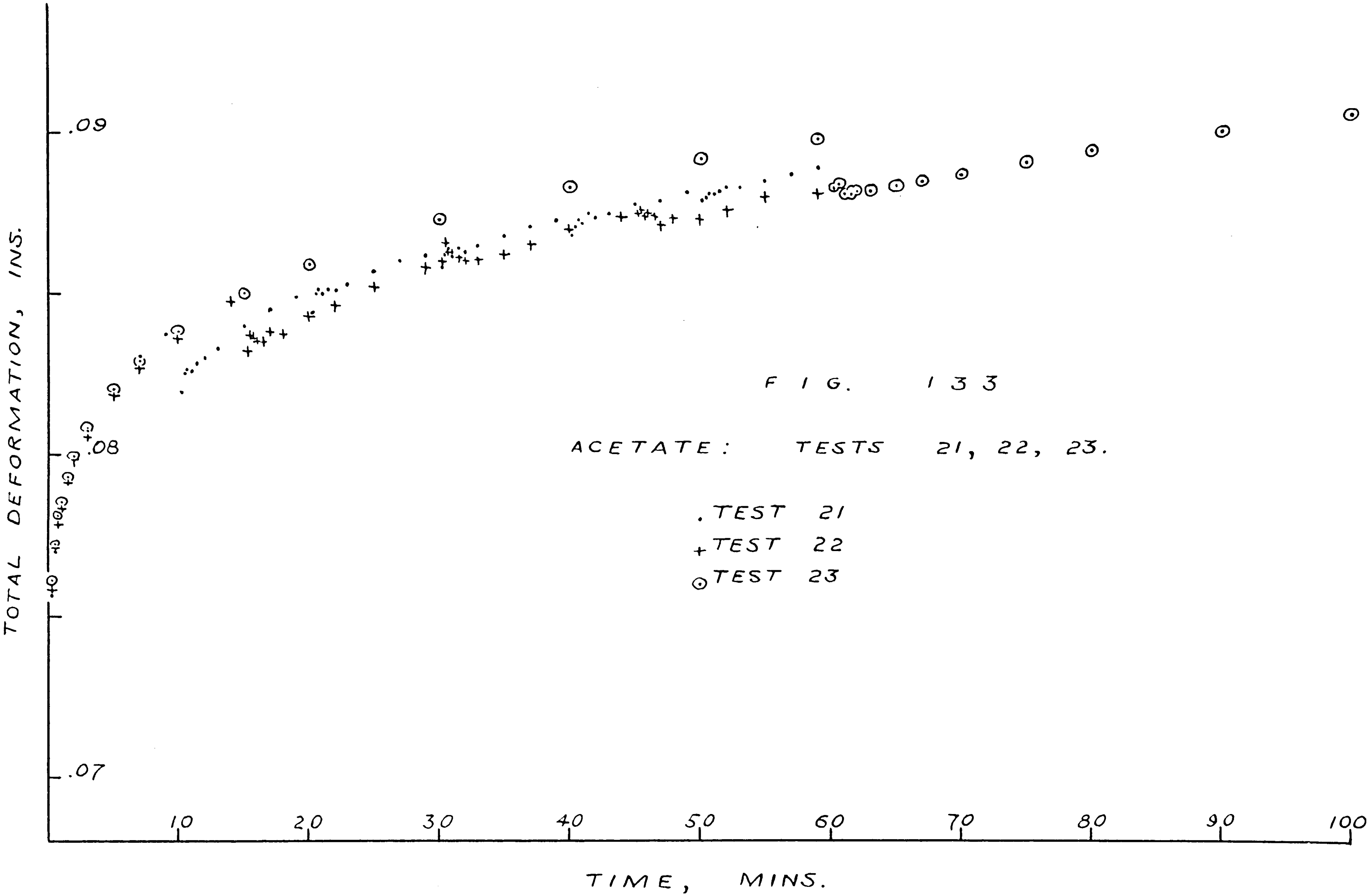


FIG. 133

ACETATE: TESTS 21, 22, 23.

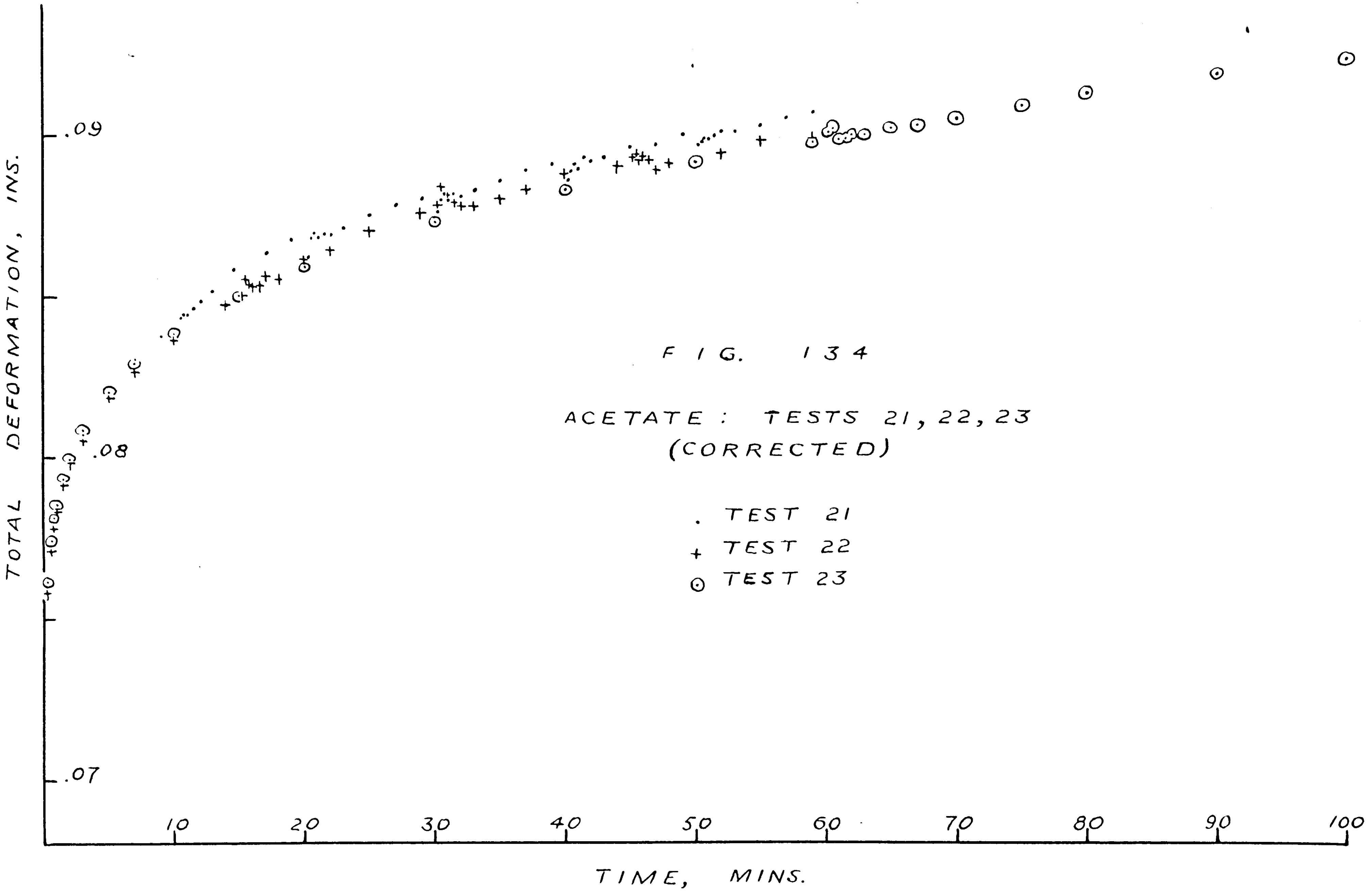


FIG. 134

ACETATE: TESTS 21, 22, 23 (CORRECTED)

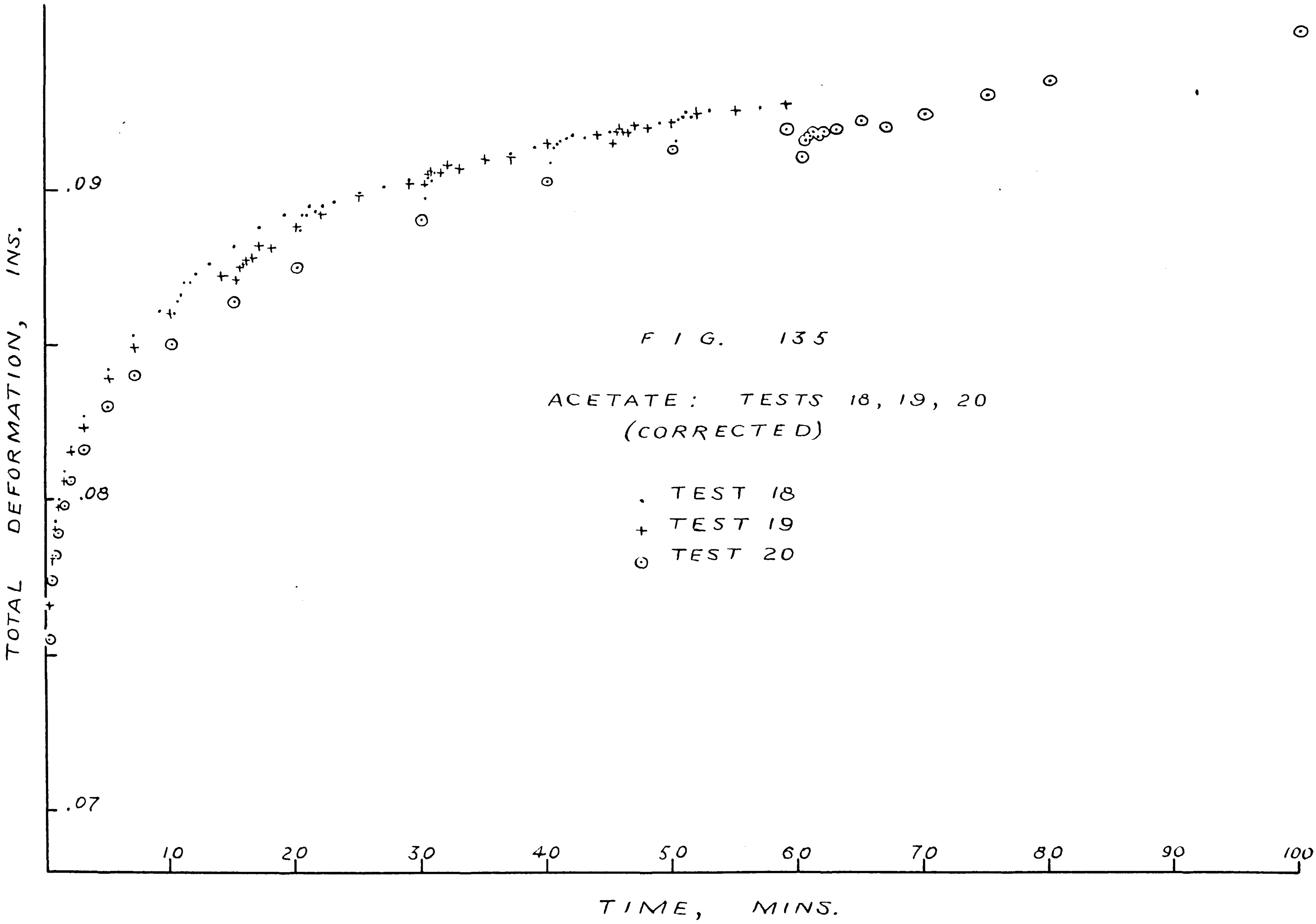


FIG. 135

ACETATE: TESTS 18, 19, 20 (CORRECTED)

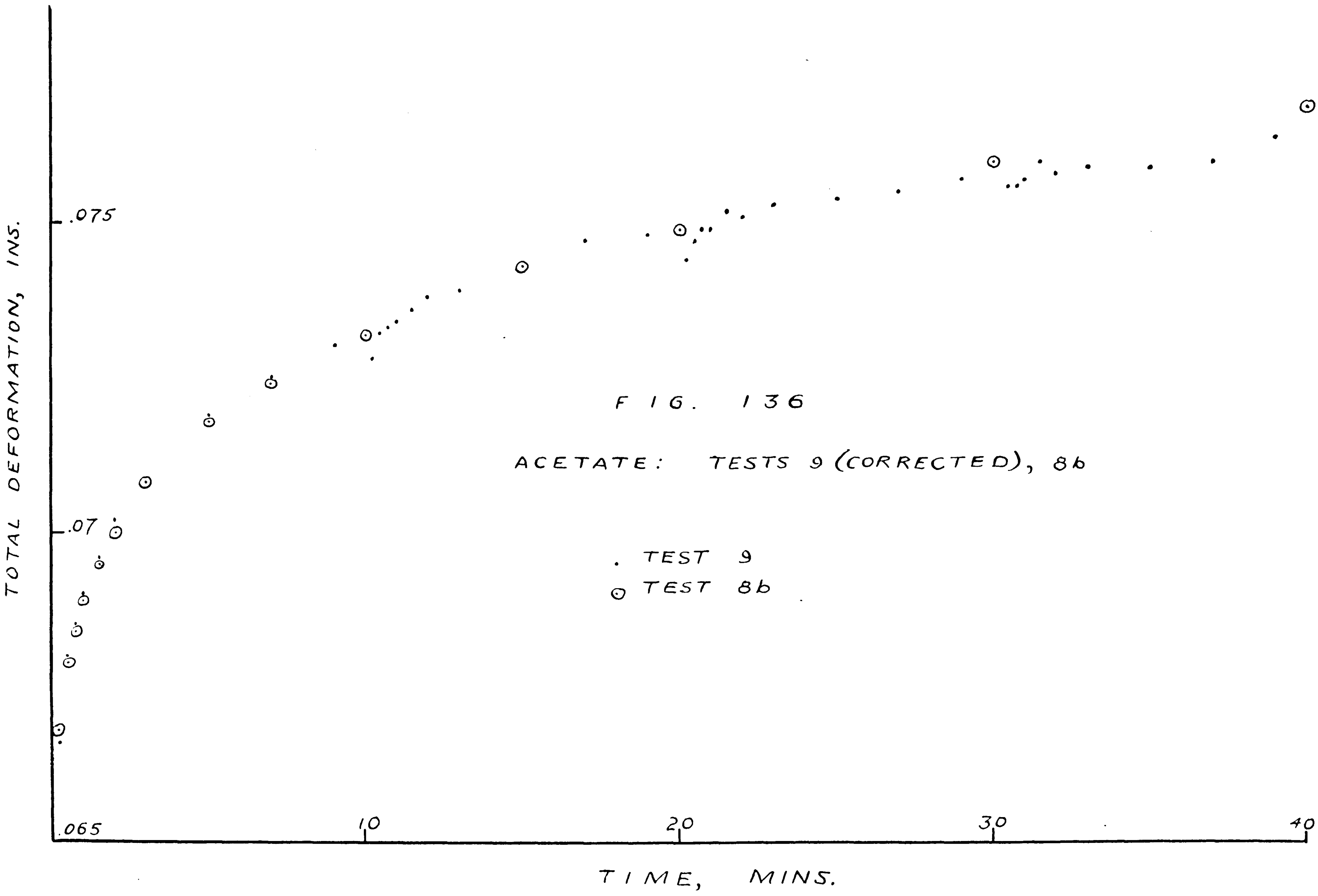


FIG. 136

ACETATE: TESTS 9 (CORRECTED), 8b

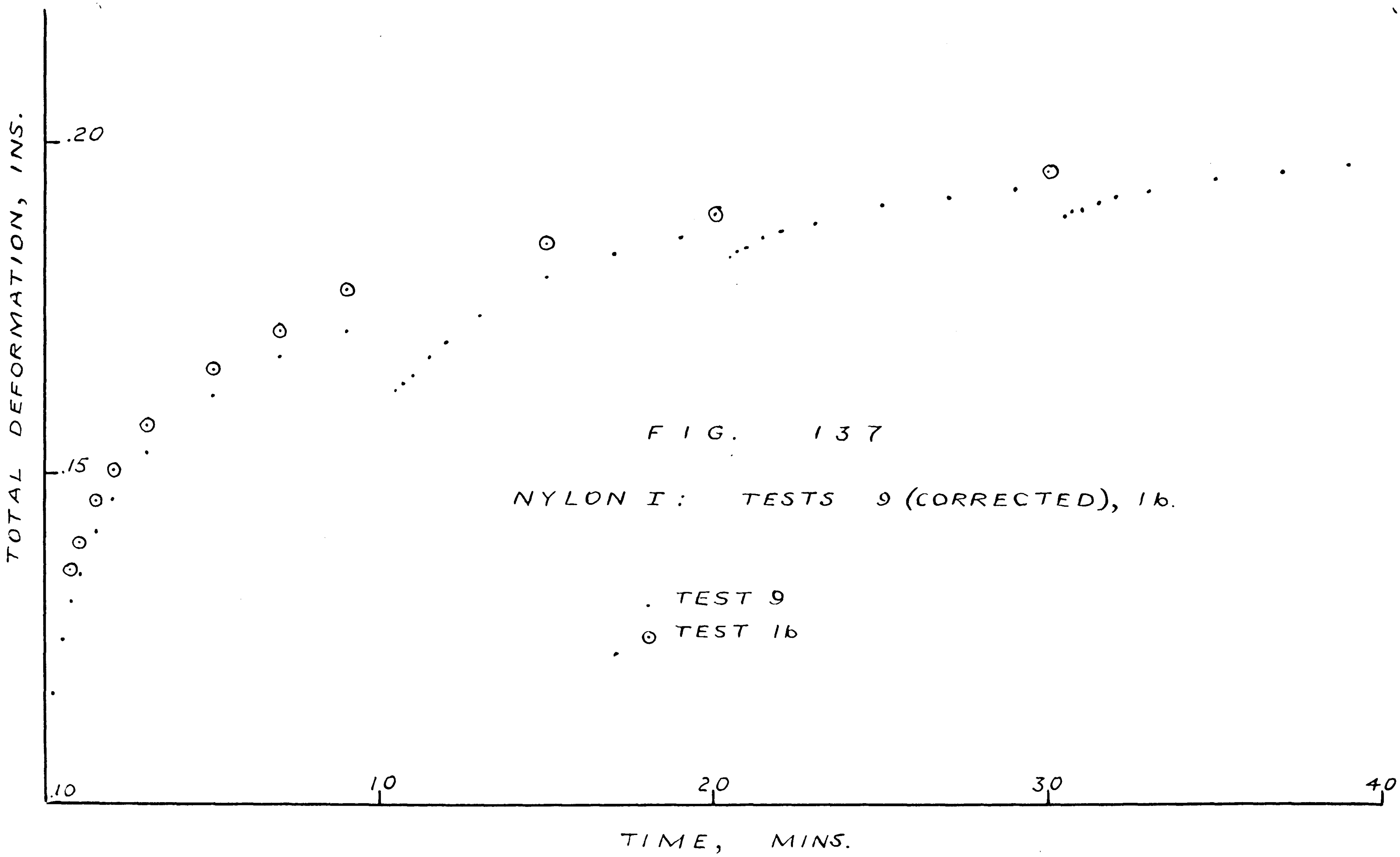


FIG. 137

NYLON I: TESTS 9 (CORRECTED), 1b.

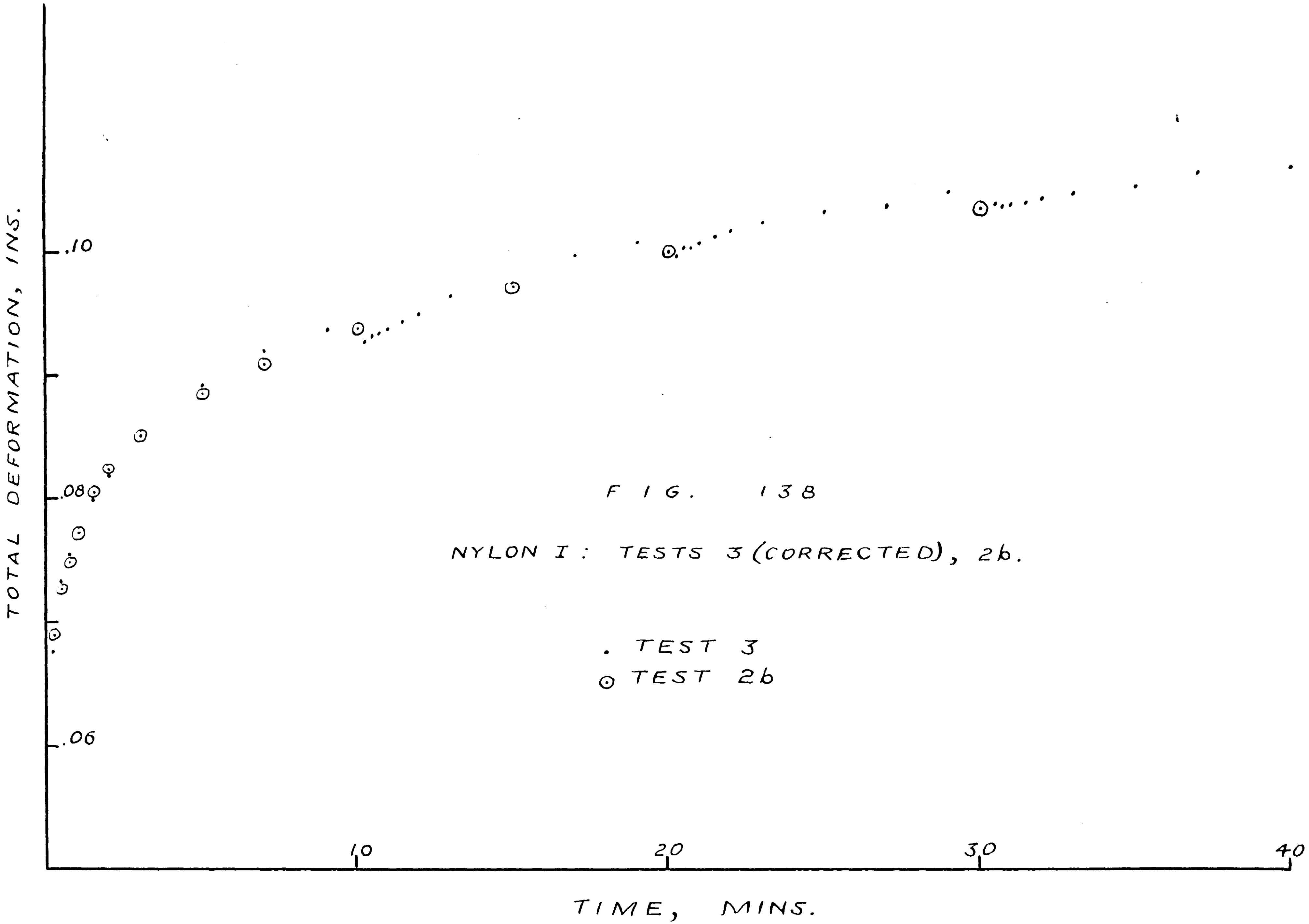


FIG. 138

NYLON I: TESTS 3 (CORRECTED), 2b.

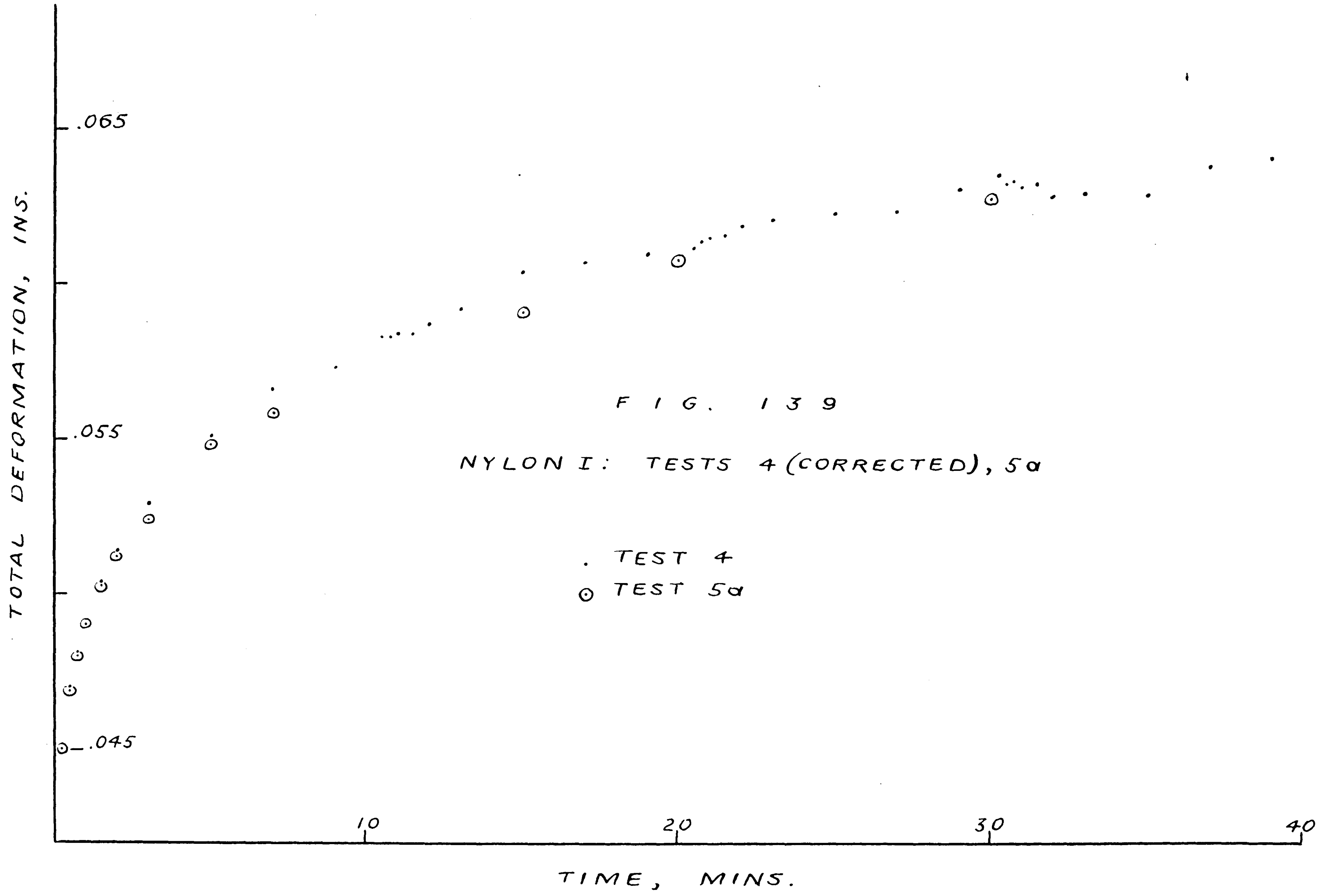


FIG. 139

NYLON I: TESTS 4 (CORRECTED), 5a

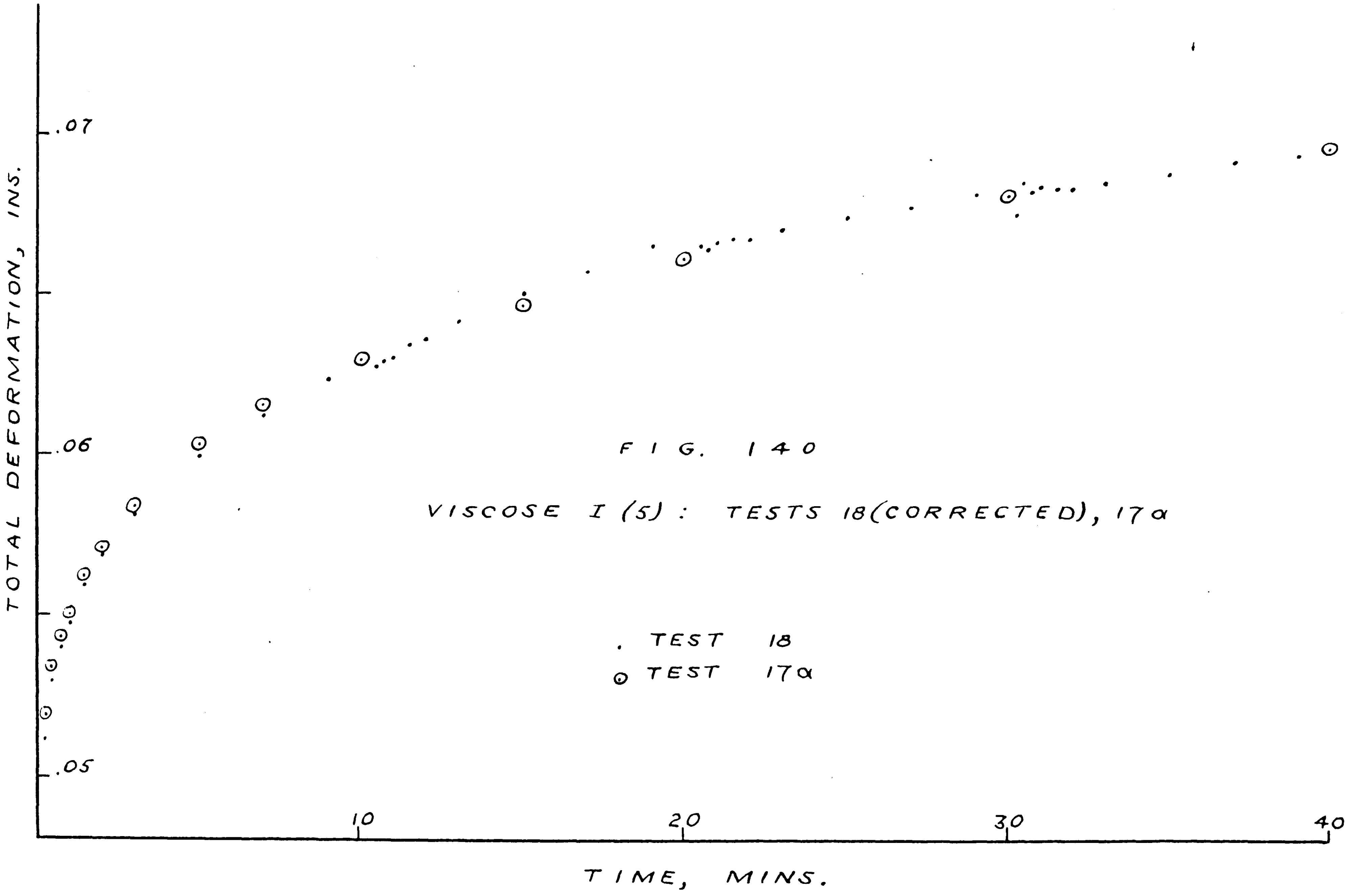


FIG. 140

VISCOSE I (5) : TESTS 18(CORRECTED), 17α

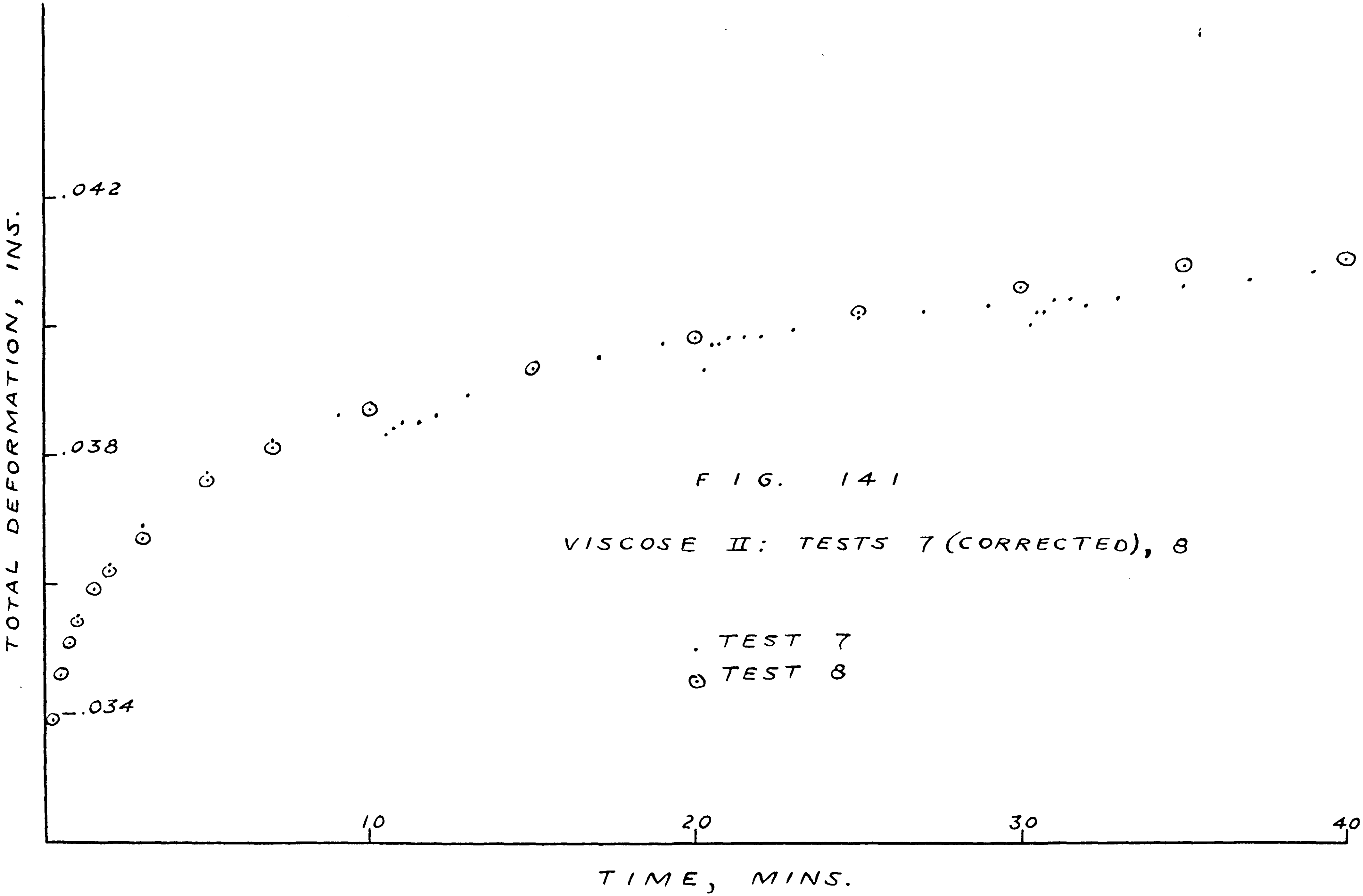


FIG. 141

VISCOSE II: TESTS 7 (CORRECTED), 8

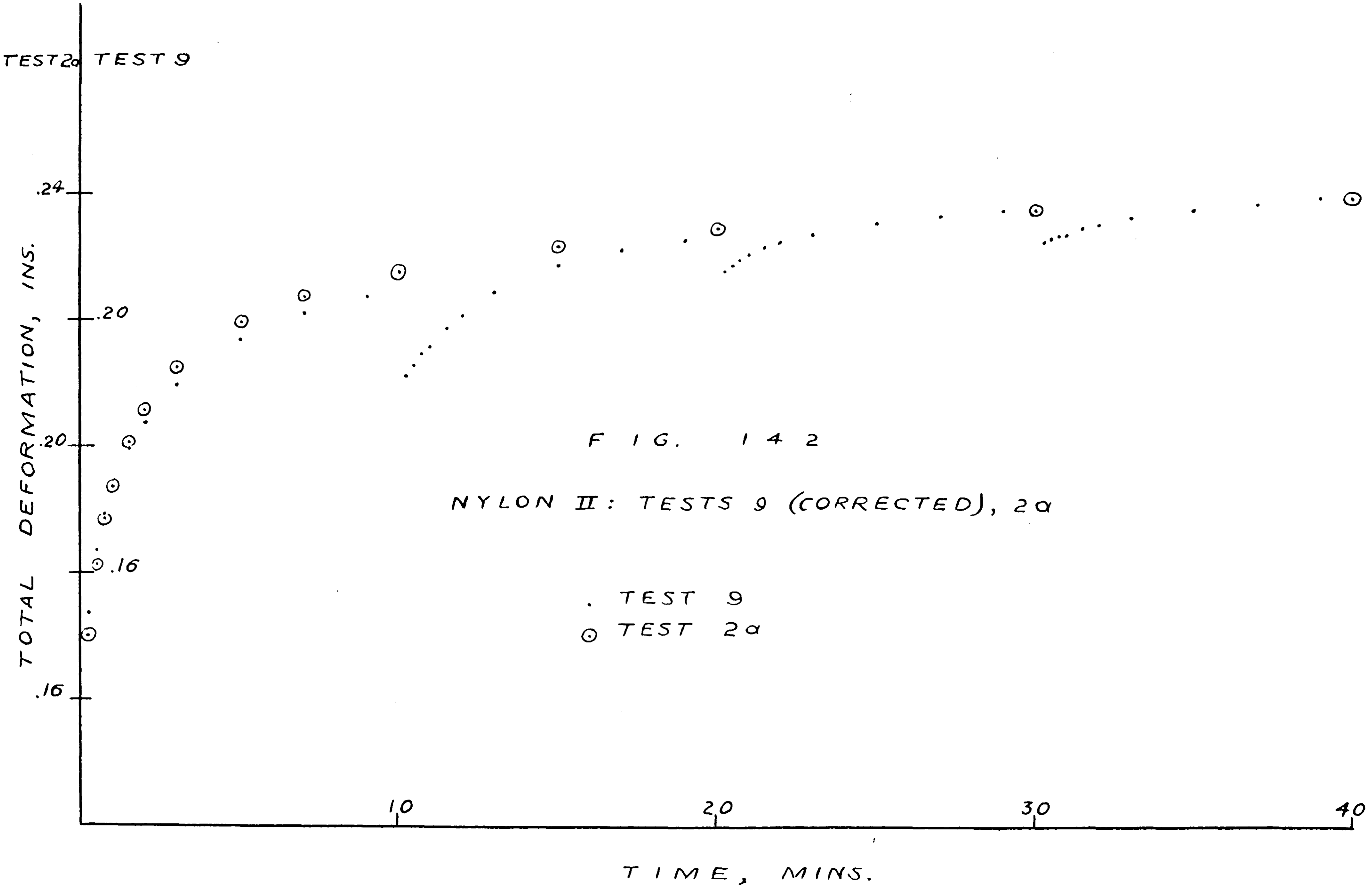


FIG. 142

NYLON II: TESTS 9 (CORRECTED), 2a

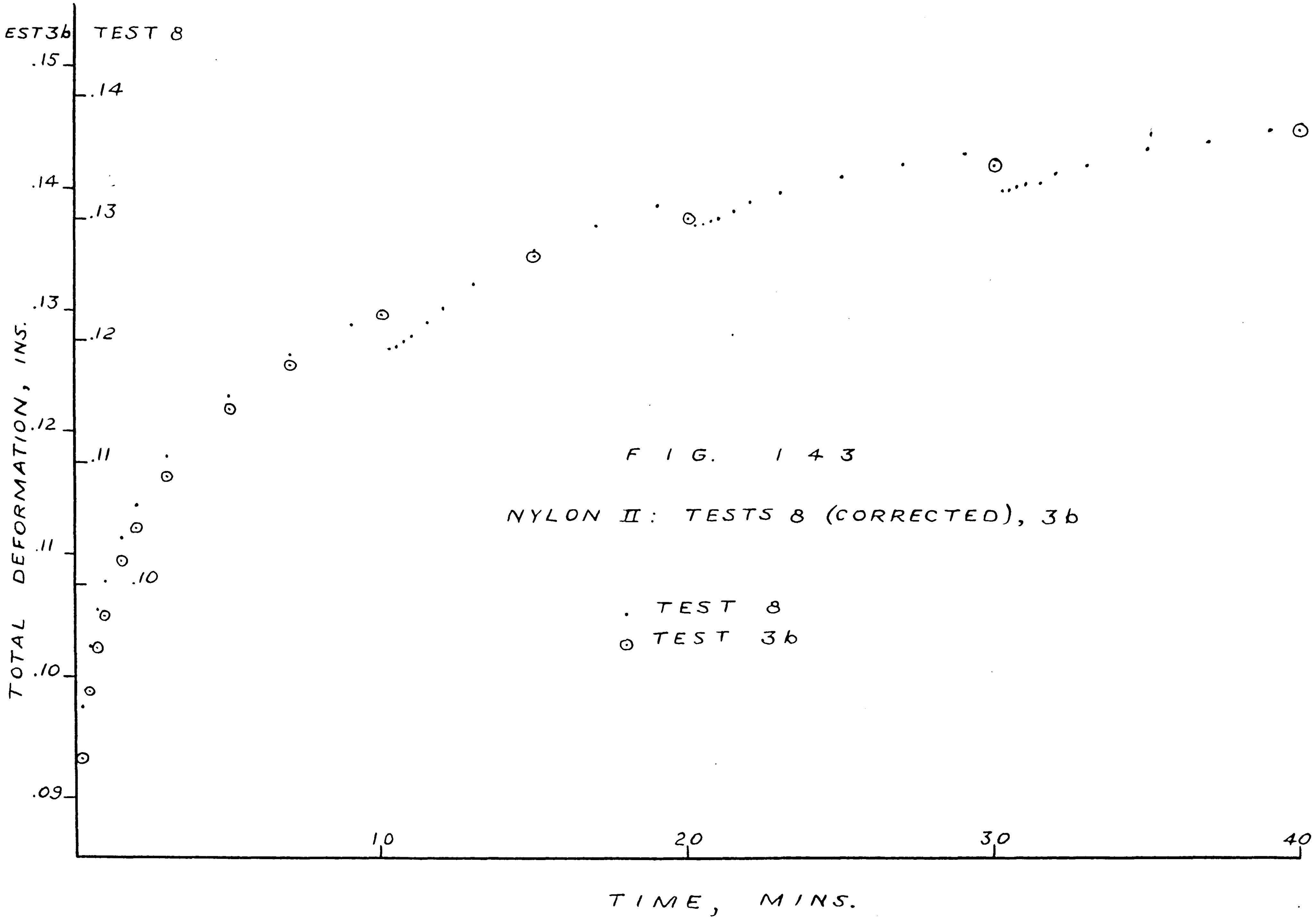


FIG. 143

NYLON II: TESTS 8 (CORRECTED), 3b