THE FLOW OF POLYCRYSTALLINE METALS UNDER SIMPLE SHEAR STRESS

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ABSTRACT

A method for studying the flow of metals under conditions of simple shear was described by Andrade and Jolliffe (Proc. Roy. Soc. A, 213, 1952, 3 and A, 245, 1960, 291) and used by them to investigate the shear creep of pure lead and cadmium. A simplification of their method has been designed, and it has been found that the results given by the new method bear a simple relation to those given by the original method. The general creep behaviour described by Andrade and Jolliffe has been verified with the new method, the three forward and the four reverse stages of lead have been found to apply, with differences in the constants, and the absence of the first linear reverse stage in the case of cadmium has been verified.

The new method was then used, in conjunction with the original method, to investigate in greater detail the creep characteristics of pure lead, and, briefly, cadmium.

Two new forward creep laws have been established, a $t^{2/3}$ law for strains less than 0.015, followed by a $t^{1/2}$ law for strains between 0.015 and 0.04, which leads in turn to the well established $t^{1/3}$ law, applying for strains above 0.04. Recrystallisation terminates the $t^{1/3}$ law, at a strain of 0.09 in the case of the lead studied here. A series of photomicrographs taken during a typical creep experiment covers all the forward stages.

The laws of the reverse flow have been verified, but the new method gives a reverse flow which has lower coefficients than that of the original method for equivalent forward coefficients.

Repeated reversal experiments point to the possibility of using the method for fatigue investigations.

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INTRODUCTION - I

Creep may be defined as the slow progressive change of strain that takes place under stress. The majority of creep measurements have been made on the extension of wires or rods under tensile stress, as in the pioneer work of Andrade[1], who demonstrated that the creep under constant stress had characteristic features which were common to all the pure metals he studied. One effect of creep, of engineering significance, was realised in 1921 when Chevenard and Dickenson[2] showed that if a stress were sustained for a sufficiently long time, fracture could occur although the stress was very much lower than that required to cause fracture in a short time tensile test.

Since then the study of creep has developed along two largely separate paths.

1. The measurement of the creep properties of various industrial alloys, largely at constant load.

2. Work aimed at understanding the mechanisms of creep, in particular the behaviour of the grain structure at the different stages.

Only the second approach will be considered here.

The general result of the earlier experiments on tensile creep, was that the creep at constant stress could be expressed by the Andrade Law,

$$l = l_0(1 + \beta t^{1/3}) e^{Kt}$$

where l is the length of the specimen at time t, l_0, β and K are constants. The exponential form of the term in K is merely a consequence of the increase in length, since. $\frac{1}{l}\frac{dl}{dt} = K.$

The law accounts for the three parts of the strain-time curve commonly observed, the initial extension, primary or transient creep at a decreasing rate and secondary or quasi-viscous creep at an approximately constant rate. /a

Andrade further suggested that β flow is associated with glide and rotation of the crystallites and K flow with bodily movements of crystals past one another. The first point was later confirmed by the work of Andrade and Chalmers[3] on the change in resistivity of metals undergoing deformation. The rotation of glide planes during deformation would be expected to change the resistivity of face-centred cubic and hexagonal metals, but not that of body-centred cubic metals. The experiments confirmed this and Ramlal and Gibbs[4] were able to measure the rotation of the planes during deformation by using X-rays.

The relative importance of the two processes is

governed by Θ, the ratio of the absolute temperature of the test to the absolute melting point, so that iron at 450°C has similar creep properties to lead at 0°C.

The Andrade Law has been shown to apply also to zinc single crystals by Cottrell and Aytekin[5], to iron and certain steels by Feltham[6], and to lead over extremely long periods of some hundreds of hours by Hopkins[7].

Wyatt[8] investigated the creep of pure copper, aluminium and cadmium over a range of temperatures and stresses and found that at higher temperatures and stresses a $t^{1/3}$ law was valid, but at low temperatures and small stresses he found a logarithmic law, which held when the total strain was less than 0·5%.

A fourth stage of the creep curve, so called tertiary creep, a region of rapidly increasing creep rate, is a common feature of creep curves. In many of the early experiments, apparent tertiary creep was due to stress intensification which takes place under conditions of constant load, owing to the decrease in cross sectional area of the specimen as its length increases. Real tertiary creep has, however, been demonstrated by, among others, Sully, Cale and Willoughby[9] and by Tapsell[10], who, working on certain steels found accelerating creep at extensions of less than 1%, where the thinning of the specimen could have little effect. Andrade[11] has attributed this stage to recrystallisation during the process

of creep.

The problem of creep under conditions of tensile stress is complicated by the fact that the mechanical conditions of the tests are very complex. The surface of the specimen must continually increase in area and there is a radial velocity gradient. The surface stresses are abnormal and the behaviour of the surface grains is not representative of the grains in the body of the material (Andrade and Kennedy[12], and Rachinger[13]). It is not surprising therefore that attempts to formulate mathematical laws of creep have only succeeded in accounting for creep under special conditions and have only limited applicability.

Furthermore, the work of Andrade and Kennedy and of Rachinger constitutes a serious criticism of much of the photomicrographic evidence of creep presented in the literature, particularly that at low strain rates and high temperatures, since most of the photographs are of grains at the surface of a tensile specimen. Attempts at understanding the basic mechanisms of the deformation of metals are only made more difficult by the complexities of the tensile method.

A novel approach is that of Andrade and Jolliffe[14], where the metal is subjected to a homogeneous shear stress. This method has certain advantages over the normal tensile method. The mechanical conditions are

very much simpler and since there is no change in surface area of the specimen during straining, the behaviour of the grains at the surface of a shear specimen cannot be very different from that of the grains in the interior of the metal. A further advantage is that the stress may easily be reversed.

Important results of these investigations on lead and cadmium are that under the conditions of simple shear stress, the flow from the start is of a transient type, obeying a simple cube root law

$$\gamma = A + Bt^{\frac{1}{3}}$$

that is, the "permanent" component of the creep of tensile specimens is absent, a striking simplification of the creep law.

The reverse creep behaviour has been analysed into certain definite stages rather similar to those of the forward creep, though at a greater rate. The first stage of the reverse creep of lead is, however, a linear stage not represented in the forward creep.

Photomicrographs and X-ray photographs showed that the transient $t^{\frac{1}{3}}$ flow is accompanied by progressive slip and local rotation of the lattice.

Though the simple shear stress method has obvious advantages, it has been little used in the study of metal deformation. The subject of this investigation is a

simplification of the Andrade and Jolliffe method of studying the creep of polycrystalline metals. The specimen used is simpler in form, easier to machine and requires less material. A disadvantage is that the geometry of the specimen will affect the creep behaviour. An assessment of the effect of this geometry, and further investigations into the creep properties of metals under simple shear stress will be described in this thesis.

SPECIMENS - II

The specimen used by Andrade and Jolliffe was in the form of a disc of metal in which a circular groove was cut, the part of the disc exterior to this groove being gripped, and the part interior being subjected to a constant torque. The shear force applied to the thin annulus varies inversely as the radius. The annulus is therefore cut so that the thickness varies as $1/r^2$, where r is the distance from the centre of the disc, and the shear stress applied to it is then constant over the range of radii involved. The specimens are therefore difficult to prepare, requiring special techniques.

To surmount this difficulty, the form of the specimen used in this investigation is much simpler.[20] Two uniform parallel grooves each 1 cm. wide are cut in a rectangular slab of metal, Fig. 1. The outer parts of the original thickness are gripped, and the central thick part subjected to a constant load, applied parallel to the edges of the grooves, so that, in the grooves, the thin parts of the metal, 1 mm. thick, are subjected to a constant shear stress. Fig. 2 shows a lead specimen after 0.4 strain. The advantages enjoyed by the Andrade and Jolliffe method are

retained, but the free ends of the thin parts, or webs have an effect on the creep behaviour.

The problem of the elastic stress distribution in a rectangular plate undergoing shear strain was considered by Inglis[16], following earlier work by Andrade[17] on the distribution of slide in a right six face subjected to pure shear.

Their analyses show that the distribution of stress along the central section of the plate, parallel to the two shearing forces, rises from zero at the ends of the section to two maxima, one near each end of the section, falling slightly to a lower value along the central part of the section. The maxima are less strongly marked on the sections nearer to the edge of the plate.

Part of the web is subjected to little or no stress and will not deform. This stress-free area remains constant whatever the length of the specimen and the effect will therefore be greater for shorter specimens. The creep rate of the shorter specimens would be expected to be higher than that of longer specimens for constant load per unit length.

Inglis's analysis further led him to predict that the failure of the plate would occur as a tearing at the corners.

The lead used in this investigation is a pure lead conforming to BSS 1085 (1946), and was called lead III by Andrade and Jolliffe.

EXPERIMENTAL - III

1. Apparatus

a) Method of Stressing

A special apparatus has been built to apply the shearing stress. It is represented in Fig. 3. The apparatus, which will be described in detail later, is firmly mounted on a massive 'I' section frame. The outer, thick parts of the specimen are gripped rigidly by the fitting, and the shearing loads applied to the central thick part of the specimen.

The downward shearing load is applied directly to the central part of the specimen, and the upward shearing load is applied by means of a flexible steel tape passing over a 20" diameter pulley wheel. The pulley wheel is pivoted on an accurate pair of knife edges and grooves which are mounted at the top of the I section frame.

The shearing apparatus is represented in more detail in Fig. 4. A "yoke" fitting, A, has been constructed to take the specimen, the outer thick parts of the specimen XX being firmly bolted to the fitting. In order to apply the loads, mild steel strips BB are bolted, one at the back and one at the front of the central part of the specimen Y, and the downward load is carried by a

mild steel dowel C joining these strips at their lower ends. The load is applied by means of weights carried in a bucket which is attached to the dowel C by a wire device. The bucket stands on a hydraulic jack which is driven by an electric motor and the load is applied and relieved by lowering or raising the jack at a constant rate. The upward pull is applied by means of the flexible steel tape which passes over the pulley wheel and is attached to the dowel C^1 by a wire device. The load for the upward pull is carried in a bucket which stands on a motor driven hydraulic jack which is exactly similar to that used for applying the downward load. The upward and downward loads are therefore applied and relieved at exactly the same constant rate.

The moment of application of the load is controlled by setting the jacks at pre-determined heights and starting the motor at pre-determined times, a few seconds, before the start of the experiment.

One of the essential conditions of a creep experiment is that the loads should be applied axially. A procedure was devised to check that this was so, and the check repeated from time to time. A small steel slab was made, of the same dimensions as a specimen but without the grooves. This steel blank could be bolted into the fitting in the usual way and the loads could be applied to it

without it deforming in any way, other than very small elastic deformations.

The loading strips BB, and the wire devices are attached to the steel blank and it is hung freely from the flexible steel tape passing over the pulley wheel. To take out any slack in the linkages the forward bucket is loaded with about 50 kg. and supported by a load of about 70 kg. in the reverse bucket. The loading line is then truly vertical.

The nature of the wire devices in the loading links is such that the system is self-aligning about the vertical axis.

Deflections out of this vertical axis about the two principal horizontal axes can be indicated by the movement of beams of light reflected from two suitably placed mirrors attached to the strips BB.

The steel blank is bolted into the fitting and the lack of alignment in the vertical axis is indicated as described above. The four adjustable legs of the massive 'I' section frame are then set so that the positions of the two optical images are unchanged with the steel blank bolted into the fitting or hanging freely. The line of application of the shearing loads is then axial.

The mass balancing of the system is carried out in two parts. The pulley wheel is first mass balanced about

its fulcrum, the knife edges. The loading links and buckets are then hung from the wheel and balanced by the addition of small weights to the reverse side. In this way it is ensured that the loads applied in the forward and reverse directions are exactly the same.

b) Temperature Control

To maintain the specimen at a fixed temperature two 75 watt domestic iron heating elements are clamped between a thin aluminium plate and a thin sheet of Sindanyo, an asbestos compound prepared for heat insulation, of the same size. The aluminium plate is bolted in contact with the back of the fitting holding the specimen. A large box made of Sindanyo sheet encloses the heater and fitting and the temperature of the specimen is raised to a value controlled by a mercury contact thermometer and relay. The thermometer bulb sits in a hole drilled in a small block of metal which is bolted to the heating plate, the hole being filled with mercury to ensure good thermal contact between controller and heater.

Thermocouples are pressed onto the specimen when it is being bolted into position, and the temperature of the specimen measured in the usual way. This system has been found to control a temperature setting of 27.5°C to within about 0.2°C with a constant temperature difference along

the longest specimen of less than 0.5°C.

c) Strain Recording

The roller and mirror method of strain measuring is used, as described by Henderson[18]. It is represented in Fig. 5. A silver steel cylindrical rod D of diameter 2.54 mm. or 5.08 mm. is placed between the long thin mild steel strip B, which is an extension of one of the steel strips gripping the central part of the specimen, and the flat face of the block E. This block is attached to a rod, which is supported at its upper end on a simple knife edge and "Vee" assembly in such a way that small weights fastened to the counter-balance arm F apply a force on the roller just sufficient to retain it without slipping, between the two vertical surfaces. The mirror, a plane front silvered mirror, is fixed to the roller so that the plane of the mirror is coincident with the axis of the roller.

A beam of light, from a narrow slit, reflected at the mirror is focussed onto a scale. Strain of the specimen results in a vertical movement of the steel strip B, relative to the block E, causing a rotation of the roller and a deflection of the light beam. The position of the light beam and hence the rotation of the roller is registered photographically. In Fig. 6 H is a light-proof

box carrying a perspex strip G on which is engraved an accurate metre scale.

Small, split wooden dowels in the inside faces of the box constrain the scale into an arc, the centre of curvature of which is at the plane mirror fixed to the roller, some 1.27 metres from the scale. This distance was calculated to allow a simple and direct conversion of scale readings into strain.

The beam of light from a narrow slit J, mounted on top of the box, is turned onto the roller mirror by a plane mirror K which reflects it onto the scale. Focussing is effected by the lens L. Ilford 35 mm. recording paper, attached to rollers in boxes M and N, is held firmly against the perspex scale. A Sangamo Short Interval Timer is connected in the electrical circuit so as to cause the lamp I to light for 5 seconds at a time, at intervals which can be set by the Timer. In this way the strain is recorded automatically. The engraved scale is formed on the paper as a shadow image by flashing a small pea lamp mounted in the mouth of the box adjacent to the roller. In this way any shrinkage of the recording paper during developing and fixing does not affect the accuracy of strain measurements.

Exposed recording paper is wound up out of the recording box into a 35 mm. cassette in box M. New paper

is fed into the recording box from a roll of paper carried in box N on the bottom edge of the recording box.

The range of strain that can be recorded using a 5.08 mm. roller, is 0.2 and the sensitivity is 0.00004.

c) Photography

A microscope P, with camera R, Fig. 7, is mounted so that it can follow the vertical movement of a given small area of the specimen surface during strain. The brass plate T is firmly bolted to the I section frame which supports the specimen. The microscope projects through a hole in the front face of the Sindanyo box U, so as to focus on the specimen, the specimen being illuminated normally by means of the vertical illuminator S, which reflects the beam of a 36 watt Tenslite Lamp.

2. Experimental Procedure.

a) Preparation of Specimen

(i) Machining. The metal was received in large plates, measuring 8"x 8"x $\frac{3}{8}$" in the case of lead. These are cut down into smaller blocks of the required size and one face of the block made plane by progressive fly-cutting, the worked layer being kept as thin as possible by the technique of taking progressively smaller cuts.

The small blocks are then bolted, plane face down, into a specially made jig, and two grooves, each 1 cm. wide are cut by the milling machine. The first cut is a deep one, and leaves the web about 5 mms. thick. This thickness is reduced to about 1.0 mm. by cuts varying progressively from about 1 mm. to about 0.1 mm,, again keeping the worked layer as thin as possible.

(ii) Annealing. The object of the pre-testing heat treatment is to establish a standard specimen state. E. J. Hooker[19] has reported some significent experiments on the ageing of lead following annealing treatments. He found that specimens which had been annealed and then either quenched or slow cooled showed progressive changes in their hardness value over several days. Hooker's work has been repeated on the lead used in these investigations and a similar ageing behaviour was found, as illustrated in Fig. 8 where hardness, as measured with the Vickers machine is plotted against time after slow cooling. The period which elapses between annealing and testing is, then, of importance when standard conditions are essential. This effect has been controlled by taking hardness measurements before setting up a creep experiment, and rejecting those specimens with hardness values which varied by more than about 2% from an accepted standard figure, 4.20 on the Brinell scale in the case of this lead.

The normal annealing treatment for lead has been 17 hours at 100°C. This gives a uniform grain size of about 27 grains to the $mm.^3$., as shown in Fig. 9. Fig. 10 shows a specimen annealed at 150°C for 17 hours and indicates marked grain growth.

The annealing treatment for cadmium was 17 hours at 150°C. The X-ray photographs, Fig. 11 and Fig. 12, of a specimen before and after annealing show the grain growth, and the absence of asterism in Fig. 12 indicates that the material is stress relieved. The annealing produced a grain size of about 350 grains to the mm^3.

(iii) Stress Calculation. The length of the finished specimen is measured by a micrometer screw gauge, and the thickness of the webs by a clock gauge, reading to 0.002 mms., mounted on a solid steel bed, the thickness being given by the separation of the gauge plunger and a reference dowel, protruding above the surface of the bed, when the web is inserted between them. This procedure allows the load-bearing area to be calculated to within about 0.2%.

(iv) Metallography. The surface of one of the webs is prepared for photography by etching, with concentrated nitric acid in the case of cadmium, and with

Russell's solution, followed by Worner and Worner solution, in the case of lead. These treatments give a field of view in the microscope of even brightness, the crystal boundaries showing as fine dark lines.

b) Creep Testing

The surface of one of the webs of an annealed specimen is etched as described above, and the specimen is then bolted into the fitting with its thermocouples, loading strips and dowels attached to it. The Sindanyo box is closed by screwing home the front face and the microscope and camera unit mounted in front of it, with the microscope projecting through a hole in this front face

The temperature control unit is switched on and the specimen left to come up to the set temperature. A small weight is permanently hung from the pulley wheel to give a small upward pull on the specimen to compensate for the weight of the loading strips attached to its central thick part.

The roller and mirror system is set up so that the image of the slit, focussed on the scale gives a suitable reading for the start of the experiment and the recording box is sealed. Recording paper is fed into the box, a zero mark made by flashing the lamp, the timing mechanism is started and the load applied.

The strain is recorded every minute for the first few minutes, during which time the strain rate is high, by flashing the lamp manually. It is subsequently recorded automatically at suitable intervals, set on the Sangamo Interval Timer.

A complete forward and reverse run can be recorded on one length of recording paper, without confusing the marks, by using a half-slit for the forward run and a full slit for the reverse run. This dispenses with the necessity of changing the recording paper at the reversal of the stress, and so allows the rest period between forward and reverse straining to be kept short.

A rest period of 1 minute was the normal practice.

The microstructure of the specimen is examined periodically throughout a test, and photographs taken when desired.

RESULTS - IV

A. LEAD

1. General Form of the Forward Creep Curves

The general form of the forward creep curves, for shear stress, obtained with the apparatus to which reference has been made, was described by Andrade and Jolliffe, part II[15]. They divided the process into three stages:

Stage F_I, in which the flow obeys a $t^{1/3}$ law,

Stage F_{II} a stage of accelerating creep, and

Stage F_{III}, a linear, quasi-viscous stage that continues until rupture of the metal begins.

The limits of the stages are defined by characteristic strains. In the case of pure lead, stage F_I holds up to a strain of 0.09, when stage F_{II} begins. During the F_I stage the flow obeys the equation

$$\gamma = A + Bt^{\frac{1}{3}}$$

where γ is the strain at time t, A and B are constants.

Specimens of the new form already described, having various lengths, were tested at constant stress and temperature, the stress being defined as the load divided by the length x web thickness. In Fig. 13 are shown the results for the different lengths indicated.

The laws as described by Andrade and Jolliffe were found to apply. The creep curve for the shortest

specimen passed through the forward stages earlier than the longer specimens and in fact is the only one to show any acceleration of strain rate.

The results in these three cases are plotted against the cube root of time in Fig. 14. The validity of the law with the new form of specimen is evident. As described by Andrade and Jolliffe, the law is obeyed between certain limits of strain, the immediate jump of the shortest specimen being so large that the law was obeyed from the start.

Comparison of the creep characteristics of the three specimens can be made conveniently by applying the $t^{1/3}$ law to obtain the coefficient B, the slope of the straight lines drawn in Fig. 14. The coefficient B, which gives the creep rate at a particular time is higher for the shortest specimen at the same stress and temperature, a result to be expected, as already explained.

2. The "End-Effect"

The effect of the free ends of the parts of the specimen subjected to shear stress, the "end-effect", was investigated by measuring the creep curves of specimens of various lengths between 2.5 and 12.5 cms., all at the same stress and temperature. The coefficients A and B of stage F_I were calculated for each length from plots similar to those in Fig. 14.

The "end-effect" is made clear in Fig 15, where B is plotted against the length of the specimen, l. For lengths greater than about 6.5 cms., the coefficient B stays roughly constant, but as l is decreased from 6.5 cms. B rises rapidly, increasing by about 60% for a specimen 2.5 cms in length.

An interesting confirmation of this relationship was given by an experiment on a specimen 9 cms in length whose thin parts or webs had been divided into three equal lengths of just under 3 cms, by two narrow cuts across each web. The 9 cm. specimen had thus been made into a composite specimen, consisting of three 3 cm. specimens in series. This composite specimen, and an uncut 9 cm. specimen were tested at the same stress and temperature and the results are shown in Fig. 15 as the black spots. A striking difference in the creep rate of the two specimens was observed. The composite specimen was found to creep some 30% faster than the uncut specimen at any time, a result that conforms very well with the general form of the B-l relationship of Fig. 15.

Since B stays roughly constant for lengths greater than 6.5 cms, a length of 7.0 cms was chosen for subsequent investigations.

The distribution of strain over the webs has been investigated. A rectangular grid of very fine scratch

marks was inscribed on the surface of a web before straining. A fine steel needle, mounted in a milling machine head was used as the scribing tool, the specimen being bolted to the table of the milling machine. In this way a very accurate grid could be inscribed. The specimen was then strained in the usual way, and after straining photographs of the web were taken. These photographs showed that the strain was uniform over most of the web, but as to be expected, was non-uniform at each end of the web.

A photograph of one end is shown in Fig. 16. The strain at various points on the web was estimated by measuring the angle between the grid lines, and in this way a map of the strain distribution over the end of the web has been drawn up, Fig. 17. The strain over the main body of the web is 0.40, and it falls off towards the end of the web, being zero over a small area right at the end of the web. This small area does not shear as the rest of the specimen does, but rather turns about an axis normal to the web. This causes extra metal to accumulate at the top right hand corner of the web in Fig. 16, and material to be withdrawn at the top left hand corner. As strain proceeds, this is obviously going to result in a tearing at the top left hand corner of the web, leading to a complete failure of the specimen. Fig. 18 shows a

short specimen, 2.5 cms long, after 1.00 strain, and the tearing is well developed. The character of the failure agrees with that predicted by Inglis[16].

3. Forward Creep Characteristics.

a) The F_I Stage

With a specimen of the selected length of 7.0 cms at a temperature of 27.5°C the forward creep behaviour of lead at different stresses was investigated.

In Fig. 19 are plotted three experiments, all at 27.5°C but with different stresses. The range of strain is higher than in Fig. 13 and the creep curves of Fig. 19 show all the features described by Andrade and Jolliffe for forward flow; stages F_I, F_{II} and F_{III}, F_{III} being the final linear stage evidenced by the curve for the highest stress.

The strain is plotted against $t^{1/3}$ in Fig. 20 and again shows the range of validity of $t^{1/3}$ creep, which is for values of γ from about 0.04 to 0.09. Between these limits of strain the $t^{1/3}$ law is obeyed very accurately as is demonstrated in Table 1 where the experimental values of strain are compared with those calculated from the coefficients A and B obtained by the method of least squares. The differences in the values of strain are very small for values of strain between 0.04 and 0.085

The variation of creep behaviour with regard to stress is shown in Fig. 21, where the coefficient B is plotted against stress. The open circles represent experimental results, and the line through them is the line given by the equation

$$B = 0.0672 \times \exp.\ (0.0739.\ \sigma)$$

where σ is the stress.

As can be seen from Fig. 21, the experimental fit to the exponential law is very good over the whole stress range. The upper limit of this range is determined by the fact that recrystallisation begins at a strain of about 0.09, so that as the stress is increased the duration of the F_I stage decreases until it becomes too short to measure with the existing apparatus. The limit occurs at a stress of about 52 kg/cm^2. The lower limit of strain for $t^{1/3}$ creep is about 0.04 and so, as the stress is decreased, the onset of F_I takes place at greater and greater times from the application of stress. At the lower stresses the rate of increase of strain is so small that to reach the critical strain at which the validity of its $t^{1/3}$ law begins would require very long times, over a week. The range of the stresses used in this investigation is, then, the whole of the convenient laboratory range, and over this range, the relationship between B and stress is accurately exponential.

The lower line on Fig. 21 gives the relationship between B and stress found by Andrade and Jolliffe with the original specimen form for a different lead, lead I. Again the law is an exponential one, holding accurately over a wide range of stress, but failing at very high stresses. Higher stresses are possible for lead I since it recrystallises at a higher strain than does lead III. The falling away of B at the higher stresses is similar to the "sigmoid" relation of tensile creep rate with stress reported by some workers.

Specimens of the new form have been made from lead I and have been tested so as to make a direct comparison between the two shear methods. The black spots on Fig. 21 represent the experimental results on lead I. For a given stress, the constant B is higher for the new rectangular specimen than it is for the circular specimen, due of course, to the free ends of the rectangular specimen.

In Table 2 the results, in the form of the coefficients B, of the experiments at four different stresses on lead I are shown. They are compared with the results obtained with the circular specimen at the same stresses. The ratio of the coefficients is given in the right hand column of Table 2. The ratio shows no systematic variation with changes of stress, the variations are

random about a mean ratio of 1.10. Results obtained on the rectangular specimen can easily be corrected for the end effect therefore, by dividing the measured constant B by 1.10.

4. Forward Creep at Low Strains.

It has been demonstrated that the forward creep can be described by a $t^{1/3}$ law between certain limits of strain, namely 0.04 to 0.09 with lead III. In Fig. 22 strain is plotted against $t^{1/3}$ for a specimen tested at a low stress, and the strain reached 0.04 and begins to obey the $t^{1/3}$ law only after a considerable time.

An important new result, recently found by Andrade and Jolliffe and confirmed here, is that the strain below 0.04, obeys a $t^{1/2}$ law

$$\gamma = C + Dt^{1/2}$$

where γ is the strain at time t, C and D are constants.

In Fig. 23 the strain for the experiment represented in Fig. 22 is shown replotted against $t^{1/2}$ in the lowest line. The $t^{1/2}$ law is very accurately obeyed over a strain range 0.015to 0.04, as is demonstrated in Table 3 where the experimental values of strain are compared with those calculated from the coefficients C and D

obtained by the method of least squares.

At a strain of 0.04 the $t^{1/2}$ law is replaced by the $t^{1/3}$ law.

Also shown in Fig. 23 are two tests at higher stresses and in each case the range of strain over which the $t^{1/2}$ law is obeyed is again about 0.015 to 0.04. Measurements of the constant D have been made over a considerable stress range and the variation with stress is shown in Fig. 24. The circles represent experimental results, and the line through them obeys the equation

$$D = 0.0017 \times \exp(0.143\sigma)$$

where σ is the stress.

It is clear that the results obey the exponential law over most of the stress range, but they begin to fall below the line at stresses above 42 kg/cm^2. This is again similar to the tendency for creep rate to approach a constant high value at high stresses, the "sigmoid" relation, demonstrated in tensile experiments by Andrade (1914).

The upper limit of stress for which D can be measured is determined by the duration of the $t^{1/2}$ stage at the high stresses. At high stresses much of the strain range for $t^{1/2}$ flow is taken up by the immediate extension and the subsequent creep rates are high enough

to reduce the duration of the $t^{1/2}$ stage to a few minutes, before $t^{1/3}$ flow begins. This is the case for stresses above about 42 kg/cm^2, and this accounts in some degree for the poor reproducibility of the coefficient D at the high stresses, an effect shown in Fig. 24.

The continuous nature of the transition from $t^{1/2}$ to $t^{1/3}$ flow is demonstrated by considering the result of a typical experiment, carried out at 27.8 kg/cm^2 and 27.5°C, for which flow could be described by the two equations

$$\gamma = -0.00510 + 0.00645\ t^{1/2}$$

and

$$\gamma = -0.02944 + 0.01895\ t^{1/3}$$

in turn, the time being measured in hours. At a time of 56 hours the first equation gives $\gamma = 4.314 \times 10^{-2}$ and $d\gamma/dt = 4.314 \times 10^{-3}$ hr.$^{-1}$, and the second equation $\gamma = 4.315 \times 10^{-2}$ and $d\gamma/dt = 4.309 \times 10^{-3}$ hr.$^{-1}$.

5. Forward Creep at Very Low Strains.

It has been demonstrated in the previous sections that forward creep can be described by two laws, a $t^{1/2}$ and $t^{1/3}$ law, each applying between certain limits of strain. The $t^{1/2}$ law is not generally obeyed at strains below about 0.015. In Fig. 26 strain is plotted against $t^{1/2}$ for a test at a very low stress. The $t^{1/2}$ law is accurately obeyed above 0.016 strain (Table 3). In Fig. 27 the strain is replotted against $t^{2/3}$, and a very good straight line is obtained. The new $t^{2/3}$ law is obeyed almost from the start to a strain of about 0.015. The new law may be written

$$\gamma = E + Ft^{2/3}$$

The accuracy with which the $t^{2/3}$ law is obeyed is demonstrated in Table 4 where the observed values of strain are compared with those calculated from the coefficients E and F obtained by the method of least squares.

The constant F has been measured over a range of stresses and the results are shown in Fig. 28. The circles are experimental results and the line through them is the line given by the equation

$$F = 6.16 \times 10^{-5}.\exp(0.211\sigma)$$

The exponential law is obeyed accurately over the range of stresses tested. The upper limit of stress for which F can be measured is again determined by the duration of

the $t^{2/3}$ stage. By considerations similar to those employed in the previous section it is found that the $t^{2/3}$ stage is too short to measure at stresses above about 30 kg/cm^2.

The forward creep characteristics may be summarised briefly.

Two new laws, additional to those reported by Andrade and Jolliffe, Part II, have been confirmed. From the start the strain obeys a $t^{2/3}$ law unless the immediate jump is greater than about 0.015.

Between 0.015 and 0.04 the strain obeys a $t^{1/2}$ law, and this passes into a $t^{1/3}$ law at a strain of about 0.04. The $t^{1/3}$ law is valid for strains up to 0.09, the strain at which recrystallisation sets in.

The coefficients of the three laws, B, D and F are all related to stress at constant temperature by a simple exponential law.

6. Photo-micrographs

It has not been possible to make an exhaustive photographic investigation of the various forward stages in the creep of lead, but in Figs. 29 (a)-(h), a series of photographs taken during a typical creep test is shown. Given with each photograph is the strain at which it was taken. Figs 29(a) and (b) were taken in the $t^{2/3}$

range. They show very little evidence of deformation, only very fine slip and a little coarsening of the grain boundaries. Figs 29 (c), (d) and (e) were taken during the $t^{1/2}$ stage. Slip is slightly more evident in (c) than it was in (b) and a second slip system has appeared in the large grain. In (d) and (e) the slip becomes gradually more obvious, but it is still only slight in (e). The grain boundaries have become slightly coarser. Fig. 29 (f), well in the $t^{1/3}$ range, shows slip which is now coarse and new slip lines have appeared, for example, in the grain in the top right-hand corner of the photograph. Grain boundary deformation is pronounced and the surface of the specimen shows signs of rumpling. Fig. 29 (g) was taken when the $t^{1/3}$ range was nearing its end and the slip is extensive and very coarse and the grain boundaries show signs of extensive damage. The final photograph Fig. 29 (h) was taken when the strain had passed out of the $t^{1/3}$ range, the deformation is even more pronounced than in (g), the slip is coarser, the grain boundaries severely damaged and the rumpling more obvious.

7. Reverse Creep Characteristics.

Andrade and Jolliffe[14,15] have studied the effect of reversal of stress, and they found that if the stress

be reversed while the stage F_I is in progress, a creep linear with time takes place. This initial stage is followed by a stage which is governed by a $t^{1/3}$ law. The $t^{1/3}$ stage is succeeded by a stage in which the creep rate increases according to a logarithmic law, and this in turn is followed by a final linear stage which continues until rupture of the metal begins. (Andrade and Jolliffe[15])

Andrade and Jolliffe[15] used the following symbols to describe the various reverse stages:

Stage R_o - linear - no corresponding forward stage

Stage R_I - t stage - corresponding to F_I

Stage R_{II} - stage of acceleration - corresponding to F_{II}

Stage R_{III} - linear - corresponding to F_{III}

Reversal experiments carried out on the new form of specimen give results which agree in general with those of Andrade and Jolliffe. In Fig. 30 is illustrated a typical result. AB is the region of forward creep obeying a $t^{1/3}$ law. Upon reversal of the stress there is an immediate jump BC followed by a strictly linear reverse flow CD. This is stage R_o. From D to E, stage R_I, the strain obeys a $t^{1/3}$ law and at E stage R_{II}, the stage of accelerating creep begins. In general the range of the recording system does not make it possible to make measurements on the reverse stages at high strains.

The early reverse stages will now be considered in

more detail.

a) Stage R_o

The first reverse stage in the case of lead is the linear stage R_o. Fig. 31 shows two reversal experiments at different stresses, where the stress was reversed during the forward $t^{1/3}$ stage. This is a condition of prime importance (Andrade and Jolliffe[15] Part II, p.300) and all results discussed here have been obtained under such a condition. In both the tests to which Fig. 31 applies, the results were obtained at different stresses and the stress was reversed at the same time t_f. On reversal of the stress there is a small immediate strain jump and the flow thereafter is strictly linear according to the equation

$$\gamma = a - b\,(t - t_f)$$

The results of two more reversal experiments are shown in Fig. 32, but here the time at which the stress was reversed was different in the two cases. The R_o stage is again clearly established.

Two points arise out of these and other reversal experiments.

Firstly, the duration of the R_o stage is equal to t_f, the time of the forward $t^{1/3}$ stage. In Fig. 31 the stress was reversed, in both cases, at the same time t_f and the R_o stage, at two different creep rates, continues to $2t_f$. In the case of different forward times, Fig. 32, the duration of R_o is again equal to that

of the forward stage.

Secondly, the creep rate of the R_o stage, b, is related to the rate of forward flow just before reversal of stress, given by $\frac{1}{3} B.t_f^{-2/3}$. The relation is shown in Fig. 33 where the rate of linear reverse flow is plotted against the final forward creep rate.

The results of this investigation fall between the two full lines representing values of the ratio $3(b/B)t_f^{2/3}$ of 1.47 and 1.0. This is a fairly wide variation in the ratio but it does not vary systematically with either t_f or b, and must depend critically upon the precise conditions of stress and temperature, and the period of rest between forward and reverse stressing. The results of the Andrade and Jolliffe investigation are given as the broken line, representing a ratio equal to 2.0, on Fig. 33. They found much less variation in the ratio, but the two methods clearly give different results on this point, the mean ratio of this investigation being 1.25 as compared with 2 for that of Andrade and Jolliffe[15].

b) Stage R_I

After the linear stage R , the reverse flow passes into a stage where the strain obeys a $t^{1/3}$ law. In Fig. 34 the reverse strain is plotted against $t^{1/3}$ and the fit to the law is excellent over a considerable range of strain, beginning at the time $2t_f$. Following the notation of

Andrade and Jolliffe this stage can be described by the equation

$$\gamma = A' - B' (t - t_f)^{1/3}$$

The value of B' is governed by the value of B, and is independent of t_f, as can be seen in Table 5. The ratio B'/B again showed random variations, though less than the ratio $3(b/B)t_f^{-2/3}$ did. The inference is that the rate of flow in stage R_I is rather less critically dependent on conditions than is the rate of stage R_o. A mean ratio of 1.38 for B'/B however, again differs significantly from that obtained for the Andrade and Jolliffe specimen, 1.72.

The fact that B'/B is constant whatever the stress implies that B', like B, obeys an exponential law with respect to stress

$$B' = 1.38. \left[0.0672 \times \exp(0.0739\sigma) \right]$$

8. Repeated Reversals.

The behaviour of lead when subjected to repeated reversals of stress has been briefly investigated.

For the first test, shown in Fig. 35, the stress was reversed every 40 minutes. The first forward stage obeyed the $t^{1/3}$ law in the usual way, and the first reverse stage obeyed the linear law of stage R_o.

Following the next reversal of stress, a

second forward $t^{1/3}$ stage occurred, followed again by a linear stage and so on. The forward and reverse cycle was in fact repeated four times. In Fig. 36 all four cycles are plotted together and it is seen that after the first cycle the successive cycles repeated exactly the previous cycle, the coefficients B and b being the same. Due to the fact that the specimen suffered more strain during $t^{1/3}$ creep than it did during linear reverse creep, there was a gradual shift of the cycle with respect to the strain axis. In other words, the strain at the end of each forward stage gradually increased.

A second repeated reversal experiment was carried out, and in this case the stress was reversed every 60 minutes, Fig. 37. The first forward stage in this case exceeded the $t^{1/3}$ range, and successive cycles showed higher and higher creep rates.

B. CADMIUM

1. Forward Creep Characteristics

The investigations into the forward creep behaviour described above for lead, a cubic metal, have been repeated, in outline, for cadmium, a hexagonal metal. Much greater stresses are required to produce creep rates for cadmium which compare with those for lead. A limit to the load that could be used was set by the design of the apparatus, and so that the maximum possible range of creep rates could be investigated the temperature of testing was increased for cadmium to 47.5°C.

As in the case of lead, the forward creep of cadmium has been found to obey a series of laws. These will now be considered in turn.

a) $t^{1/3}$ stage

Tests have been made on 7.0 cm. cadmium specimens, of the same design and dimensions as the lead specimens, over a range of stresses. Fig. 38 represents two of these tests. In Fig. 39 the strain is replotted against $t^{1/3}$ and in both cases the strain obeys the well established $t^{1/3}$ law, $\gamma = A + Bt^{1/3}$ for strains in excess of about 0.04. The effect of stress on the coefficient B is made clear in Fig. 40. The circles are experimental results and the line is given by the equation

$$B = 0.134.\ \exp(0.0219\sigma)$$

The experimental results fit the exponential law fairly closely over the whole range investigated.

b) $t^{1/2}$ stage

In Fig. 41 the strain of Fig. 39 is replotted against $t^{1/2}$ and for strains of less than about 0.035 the flow accurately obeys the law

$$\gamma = C + Dt^{1/2}$$

The $t^{1/2}$ law breaks down for strains below about 0.015, but if the immediate jump of strain is big enough, the flow obeys the $t^{1/2}$ law from the start. In Fig. 42 D is plotted against stress, and once again the experimental results agree roughly with the line calculated from the equation

$$D = 0.00836 \times \exp(0.039\sigma)$$

c) $t^{2/3}$ stage

At very low strains, below about 0.015, the $t^{1/2}$ law is generally not obeyed and in Fig. 43 is shown a test at a low stress. There is a considerable initial range for which the law is not obeyed. In Fig. 44 the strain below 0.02 is plotted against $t^{2/3}$ and again, a good straight line is obtained almost from the start. The flow obeys the equation

$$\gamma = E + Ft^{2/3}$$

The relationship between F and stress has not been

investigated.

At the very low strain rate of Fig. 44 an effect becomes apparent that did not occur in the creep of lead, the irregularity of the variation of strain with time. While the linear relationship is very good for the average strains taken over short intervals, the individual points show an irregular scatter about the straight line. This is particularly noticeable at very low strain rates, but any part of the creep curve for cadmium shows the effect if the strain scale is sufficiently expanded. In Fig. 45 a creep curve for a reasonably high stress is plotted with an expanded strain scale and it can be seen that the irregularity is present over most of the curve, only becoming unnoticeable when the creep rate is very high at the start of the experiment. Furthermore, the amplitude of the irregularities is roughly constant over the whole test. It is thought that the irregularities, or small strain jumps are the result of twinning.

The twinning of tin gives rise to the well known effect, the "cry" of tin, and it was noticed that a cadmium specimen, when coarsely bent by hand gave off a similar "cry", a burst of metallic clicks. It should, therefore, be possible to investigate the strain irregularities using a microphone and loudspeaker system. Such a system has been set up. The tip of a sensitive

"pick-up" microphone was held firmly against the cadmium specimen during a creep test. The output of the microphone was fed, through an amplifier, to a small loudspeaker. On applying a load to the specimen a burst of metallic clicks was heard. The frequency of the clicks gradually fell until, at a late stage in the creep test, the clicks were occurring either singly or in pairs at irregular intervals.

It has not been possible to make a quantitative investigation along these lines, but it does seem possible that the clicks may be related to small jumps in the creep curve and so at a very low creep rate, where the jumps occur at intervals of something like half an hour, it may be possible to relate individual clicks to individual jumps.

2. Reverse Creep Characteristics

a) Reversal during forward $t^{1/3}$ stage

In Fig. 46 is shown the forward and reverse creep curve of a cadmium specimen where the stress was reversed during the forward $t^{1/3}$ stage. In Fig. 47 the reverse strain is plotted against $t^{1/3}$ and the relationship is accurately linear from $t^{1/3}$ equal to about 3.2 onwards. The ratio of reverse to forward coefficients, B^1/B is 1.31.

The misfit to the $t^{1/3}$ law at the low reverse strains is an effect not found by Andrade and Jolliffe in their early work, but some confirmation of it has come from some recent work by Andrade and Jolliffe on the same cadmium. The reverse creep of lead also showed a first stage not obeying a $t^{1/3}$ law, stage R_o. Cadmium shows no linear R_o stage, but the strain during the early part of the reverse curve can be fitted to a $t^{2/3}$ law, Fig. 48.

b) Reversal during forward $t^{1/2}$ stage

A second reversal experiment, Fig. 49 has been carried out, at a much lower stress than that above, the forward creep being stopped when still in the $t^{1/2}$ stage, Fig. 50. The reverse strain could also be fitted to a $t^{1/2}$ law, Fig. 50. It is evident that the $t^{1/2}$ law is obeyed almost from the start, there is no extensive early region of misfit. The ratio of reverse to forward coefficients, D'/D is 1.24.

The reverse behaviour of cadmium needs much further investigation, but the above results serve to indicate a general pattern, that of the reverse creep obeying the same law as does the forward creep, with a greater coefficient, indicating a decreased creep resistance in the reverse direction.

DISCUSSION - V

1. The End Effect

The first object of the investigation into the end effect was to ascertain a suitable length for specimens of the new form. A length of 7.0 cms was selected, for reasons described in Section IV.

The results of the new method were then related to those of Andrade and Jolliffe by making tests on 7 cm. rectangular specimens made of the lead I used by these investigators. As described in the previous section the ratio of the coefficients B obtained by the two methods has been found to be independent of stress and has a mean value of 1.10. The effect of the free ends of a rectangular specimen may therefore be eliminated very simply.

Andrade and Jolliffe have shown that, for lead I, the relationship between B and stress, over a considerable range of stress, is exponential

$$B = 0.0409.\ \exp(0.0770\sigma)$$

The coefficient B obtained by the new method obeys the law

$$B = 1.10\left[0.0409.\ \exp(0.0770\sigma)\right]$$

The exponential factor is therefore unchanged. It

may be assumed that the fundamental character of the creep process is unchanged by the geometry of the new form, since the dependence of creep rate on stress is unchanged.

2. Forward Creep

a) The absence of the permanent component

Attempts to fit mathematical laws to the experimental creep curves began about fifty years ago with the Andrade Law

$$l = l_0 \left(1 + \beta t^{\frac{1}{3}}\right) e^{Kt}$$

which applies to tensile creep experiments.

Tensile creep, according to the law, is composed of two creep processes, β and K creep. Andrade associated β creep with deformation within the grains and K creep with deformation at grain boundaries. This concept is an over-simplification of the two processes since single crystals show K creep.[21]

Since 1914 many workers have confirmed the validity of the law for tensile creep. The experiments made on creep under conditions of simple shear stress are remarkable in the first place because the K component, called by many workers the permanent component, of creep is absent. Between certain limits of strain the creep is described by the Andrade equation, with the constant K

set equal to 0,

$$\gamma = \gamma_0 (1 + \beta t^{\frac{1}{3}})$$

where γ and γ_0 are shear strains.

Once the mathematical laws of the creep processes have been established the photomicrographic and X-ray investigations are likely to offer the best clues as to the nature of the processes. The shear method used here, and by Andrade and Jolliffe, enjoys the advantage over normal tensile methods that the surface of the specimen remains of constant area throughout the test and so is likely to afford reliable guidance as to the general behaviour of the metal. Rachinger[13], and Andrade and Kennedy[12] have pointed out the dangers of taking the behaviour of the surface of tensile specimens as representative of the behaviour of the metal throughout the specimen.

Andrade and Jolliffe[15] showed that $t^{1/3}$ flow in the shear experiment is accompanied by progressive slip and local rotation of the lattice.

It has not been possible to make any extensive investigation of the metallographic features of forward creep with the new method, but the series of photographs which covers all three forward laws has been described.

Within certain limits of stress the coefficients B,

D and F of the three forward creep laws have been found to vary with stress according to an exponential law. However in the case of the measurements of the coefficient D presented here, and of the measurements of Andrade and Jolliffe on lead I, at the highest stresses the experimental values are lower than those predicted by the exponential law. There must also be a lower limit of stress below which the exponential law is not obeyed, since the exponential equation gives a finite value for the coefficient at zero stress. The stress at which the law breaks down probably depends on the method of creep testing - a highly sensitive method, able to measure very low creep rates might well find the law to be valid at stresses lower than those here recorded.

The forward creep of cadmium shows very similar characteristics to that of lead but with much lower creep rates for any given stress. It was in fact necessary to increase the temperature of testing in order to extend the range of creep rates tested. The difference in creep strength between the two metals is striking when it is remembered that the melting points of the two metals are very close to one another, the difference in strength being attributable to the difference in the atomic forces and atomic arrangement in the two cases.

The phenomenon of jerky, or non-homogeneous creep

reported here for cadmium is not a new phenomenon. Andrade in 1914 reported similar behaviour in the case of copper. In the case of cadmium, twinning may cause enhanced non-homogeneity which can then be measured on the apparatus used in this investigation.

3. Reverse Creep Behaviour.

A significant advantage of the shear creep method over the tensile creep method is that with the former the creep behaviour under reversed stress can be studied. A detailed study of the reverse behaviour of lead, and brief study of that of cadmium has been made.

In the case of lead, reversal of stress during $t^{1/3}$ flow in the F_I stage is followed by a creep linear with time as described by Andrade and Jolliffe. As found by them, the duration of the linear stage is equal to that of the F_I stage, but in the present tests, the rate was markedly less than the twice the final rate in the F_I stage reported by them. It varied from 1.0 to 1.5 times the final rate. It would thus appear that the duration of the R_o stage is more fundamental than the rate. In one experiment the stress was reversed after the forward stage had passed out of the $t^{1/3}$ range, in which case the reverse flow was abnormal. This emphasises, as Andrade and Jolliffe pointed out, the fundamental nature of $t^{1/3}$ flow.

As found by Andrade and Jolliffe, the linear stage is followed by a $t^{1/3}$ stage, the time being measured from the time of reversal.

In the case of cadmium, only two reversal experiments were carried out, in one case during the $t^{1/2}$ stage and in the other during the $t^{1/3}$ stage. In both cases the reverse creep obeyed the same law as the forward creep, with an increased constant.

For all but the final linear stages the coefficient for the reverse stage is higher than that for the equivalent forward stage. Andrade and Jolliffe have supposed that as a result of prior deformation, yield is easier, not only on the slip planes which have been active but also on latent slip planes.

The ratio of reverse to forward coefficients B, obtained by the two shear methods, differs, being 1.73 for the circular specimen and 1.45 for the rectangular specimen. Once more it appears that while the general laws are the same in the two methods of test, there are differences in the constants. These differences for the two methods must be a manifestation of the end effect. It may be that the rectangular specimen, due to its free ends, is unable to sustain the internal stresses built up during forward creep to the same extent as can the circular specimen. The reverse stress in the case of

the circular specimen would then be augmented to a greater extent by local elastic stresses than would the rectangular specimen.

The experiments on repeated reversals gave results to be expected from the behaviour reported above. With lead, when the direction of stress was reversed at intervals sufficiently short for the forward stages to be entirely $t^{1/3}$ in character and hence the reverse stages linear, successive forward stages and successive reverse stages suffered an upward shift along the strain axis. This shift progressed over the four cycles recorded and the specimen had by the end of the test suffered a total forward strain of 0.11 entirely by $t^{1/3}$ creep. The periods of reverse creep therefore allowed an effective extension of the range of forward $t^{1/3}$ creep, and there was no sign of any strain limit for forward $t^{1/3}$ creep obtained by this method of repeated reversals.

The second repeated reversal experiment showed the effect of exceeding the F_I stage. The creep rate at the end of each successive forward stage increased. It is likely that the rate would go on increasing until F_{III} or R_{III} stage was reached.

It is clear that this new method of investigating the creep of metals under simple shear has much to

offer. It has here been used to help obtain a clearer understanding of the creep behaviour of lead and cadmium. Due to its great advantage of simplicity of specimen form and the general advantages of the shear creep investigation, the new method may well find application both in the industrial study of creep and in the problem of fatigue[20].

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TABLE 1

TIME (MINS.)	CALC. STRAIN $\times 10^{-2}$	OBS. STRAIN $\times 10^{-2}$	DIFFERENCE (OBS-CALC) $\times 10^{-2}$
1	3.645	3.624	-0.021
2	4.166	4.162	-0.004
3	4.531	4.528	-0.003
4	4.822	4.824	0.002
5	5.069	5.070	0.001
10	5.959	5.960	0.001
15	6.584	6.588	0.004
20	7.082	7.078	-0.004
30	7.870	7.872	0.002
40	8.497	8.500	0.003
50	9.026	9.096	0.070
60	9.490	9.702	0.212
70	9.903	10.306	0.403

Stress = 45.8 kg/cm^2: Temperature = 27.5°C

$\gamma = 0.01640 + 0.02005\ t^{1/3}$

Between $\gamma = 4.162 \times 10^{-2}$ and $\gamma = 8.500 \times 10^{-2}$, a range of 4.338×10^{-2} the average deviation is about 0.002×10^{-2}, or less than 1 in 2000

TABLE 2

STRESS (Kg/cm^2)	B $mins^{-1/3} \times 10^2$	B_{AJ} $mins^{-1/3} \times 10^2$	B/B_{AJ}
40.6	1.02	0.92	1.10
46.0	1.52	1.40	1.09
45.7	1.54	1.37	1.12
60.0	3.85	3.60	1.07

Mean $B/B_{AJ} = 1.10$

TABLE 3

TIME (HRS.)	CALC. STRAIN $x10^{-2}$	OBS. STRAIN $x10^{-2}$	DIFFERENCE (OBS-CALC) $x10^{-2}$
5	0.935	0.984	0.049
6	1.070	1.108	0.038
7	1.200	1.220	0.020
8	1.315	1.332	0.017
9	1.425	1.438	0.013
10	1.528	1.536	0.008
11	1.631	1.634	0.003
12	1.722	1.726	0.004
13	1.818	1.818	0
14	1.902	1.900	0.002
15	1.986	1.990	0.004
16	2.070	2.070	0
17	2.147	2.146	-0.001
18	2.224	2.220	-0.004
19	2.302	2.298	-0.004
20	2.373	2.376	0.003
21	2.444	2.444	0
22	2.515	2.516	0.001
23	2.586	2.584	-0.002
24	2.651	2.654	-0.003
25	2.715	2.716	0.001
26	2.780	2.784	0.004
27	2.844	2.840	-0.004
28	2.902	2.904	0.002
29	2.967	2.962	-0.005
30	3.025	3.030	0.005

TABLE 3 (cont.)

TIME (HRS.)	CALC. STRAIN $\times 10^{-2}$	OBS. STRAIN $\times 10^{-2}$	DIFFERENCE (OBS-CALC) $\times 10^{-2}$
31	3.083	3.088	0.005
32	3.141	3.142	0.001
33	3.199	3.198	-0.001
34	3.251	3.256	0.005
35	3.308	3.310	0.002
36	3.360	3.362	0.002
37	3.412	3.414	0.002
38	3.463	3.464	0.001
39	3.521	3.518	-0.003
40	3.567	3.572	0.005
41	3.618	3.618	0
42	3.670	3.664	-0.006
43	3.721	3.716	-0.005
44	3.766	3.770	0.004
45	3.818	3.816	-0.002
46	3.863	3.858	-0.005
47	3.915	3.912	-0.003
48	3.960	3.956	-0.004
49	4.005	4.006	0.001
50	4.050	4.054	0.004
51	4.095	4.096	0.001
52	4.140	4.136	-0.004
53	4.186	4.186	0
54	4.231	4.228	-0.003
55	4.276	4.272	-0.004
56	4.315	4.314	-0.001

TABLE 3 (cont.)

TIME (HRS.)	CALC. STRAIN $x10^{-2}$	OBS. STRAIN $x10^{-2}$	DIFFERENCE (OBS-CALC) $x10^{-2}$
57	4.360	4.354	-0.006
58	4.405	4.394	-0.011
59	4.444	4.434	-0.010
60	4.489	4.474	-0.015
61	4.527	4.514	-0.013

Stress = 27.8 kg/cm^2: Temperature = $27.5^{o}C$

$\gamma = -0.00510 + 0.00645\ t^{1/2}$

Between $\gamma = 1.634 \times 10^{-2}$ and $\gamma = 4.314 \times 10^{-2}$, a range of 2.680×10^{-2}, the average deviation is 0.003×10^{-2} or approximately 1 in 900.

TABLE 4

TIME (HRS.)	CALC. STRAIN $x10^{-2}$	OBS. STRAIN $x10^{-2}$	DIFFERENCE (OBS-CALC) $x10^{-2}$
1	0.367	0.392	0.025
2	0.557	0.558	0.001
3	0.711	0.714	0.003
4	0.859	0.858	-0.001
5	0.984	0.984	0
6	1.106	1.108	0.002
7	1.222	1.220	-0.002
8	1.330	1.332	0.002
9	1.436	1.438	0.002
10	1.536	1.536	0
11	1.634	1.634	0
12	1.729	1.726	-0.003
13	1.820	1.818	-0.002
14	1.914	1.900	-0.014
15	1.998	1.990	-0.008
16	2.086	2.070	-0.016
17	2.169	2.146	-0.023
18	2.251	2.220	-0.031

Stress 27.8 kg/cm^2; Temperature 27.5°C

$\gamma = 0.00047 + 0.00321\ t^{2/3}$

Between $\gamma = 0.558 \times 10^{-2}$ and $\gamma = 1.818 \times 10^{-2}$, a range of 1.260×10^{-2}, the average deviation is 0.0015×10^{-2}, or less than 1 in 1000.

TABLE 5

Stress (kg/cm^2)	t_f (mins)	B^1/B	Stress (kg/cm^2)	t_f (mins)	B^1/B
35.2	65	1.42	41.6	50	1.46
			41.6	50	1.57
37.8	40	1.30	41.9	50	1.54
38.0	300	1.32	42.0	40	1.30
			45.0	40	1.24
40.7	50	1.46	45.0	50	1.45
			45.0	50	1.13
41.1	50	1.46	47.5	30	1.22
41.1	60	1.52			
41.2	50	1.35	49.5	40	1.32
41.2	50	1.50			
41.2	50	1.29			

Mean B^1/B = 1.38

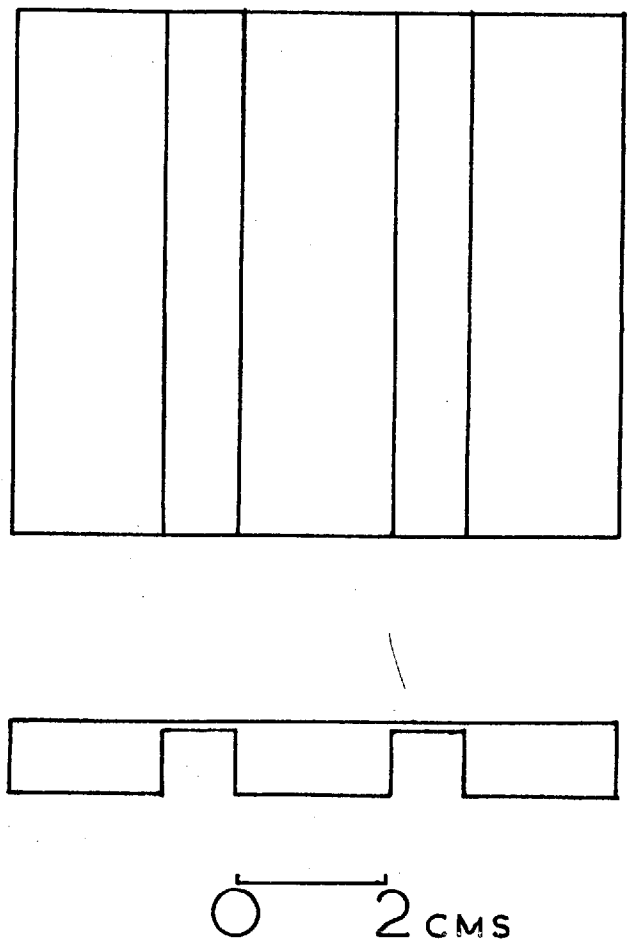


FIG 1



X 4/5

FIG 2

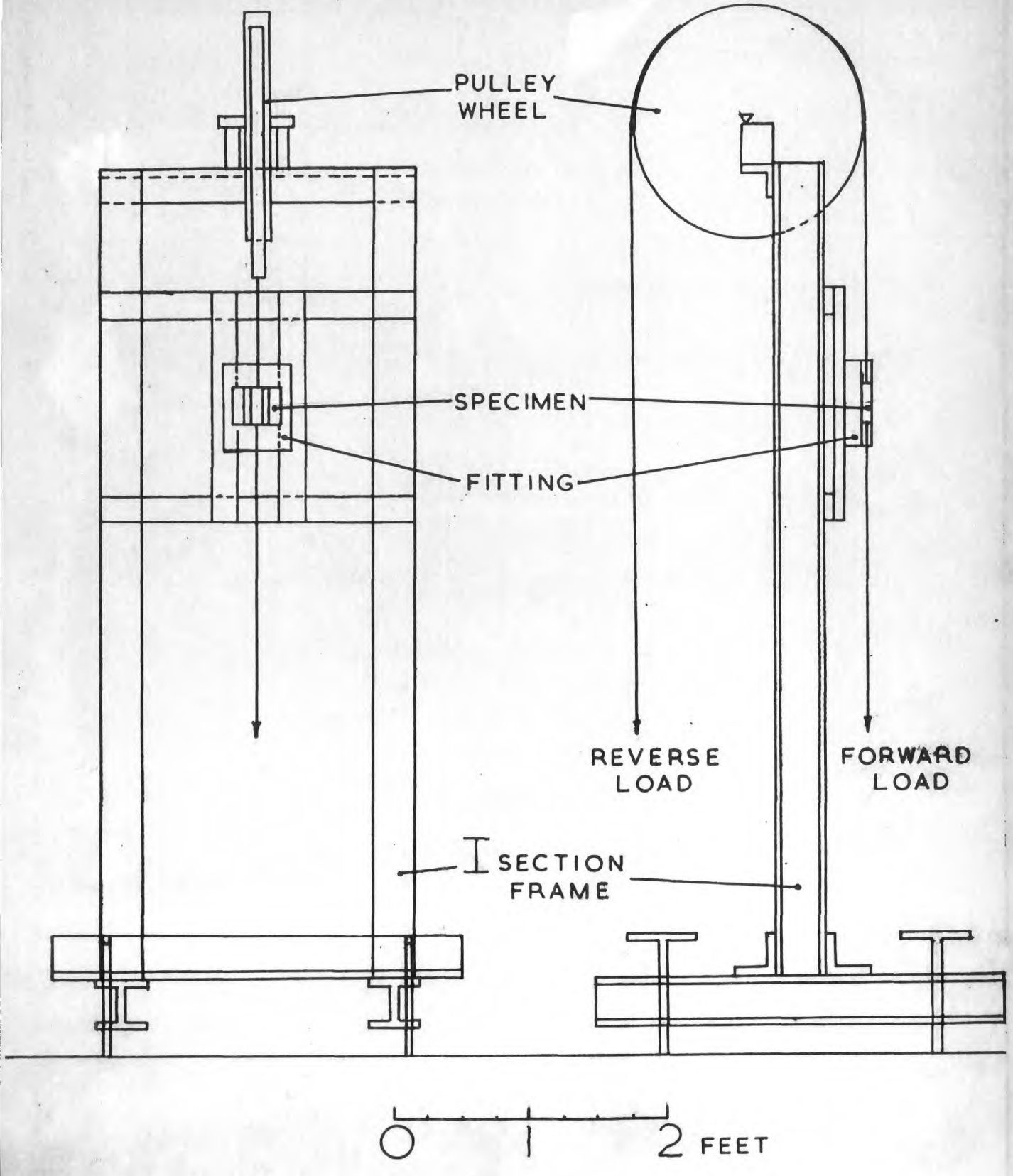
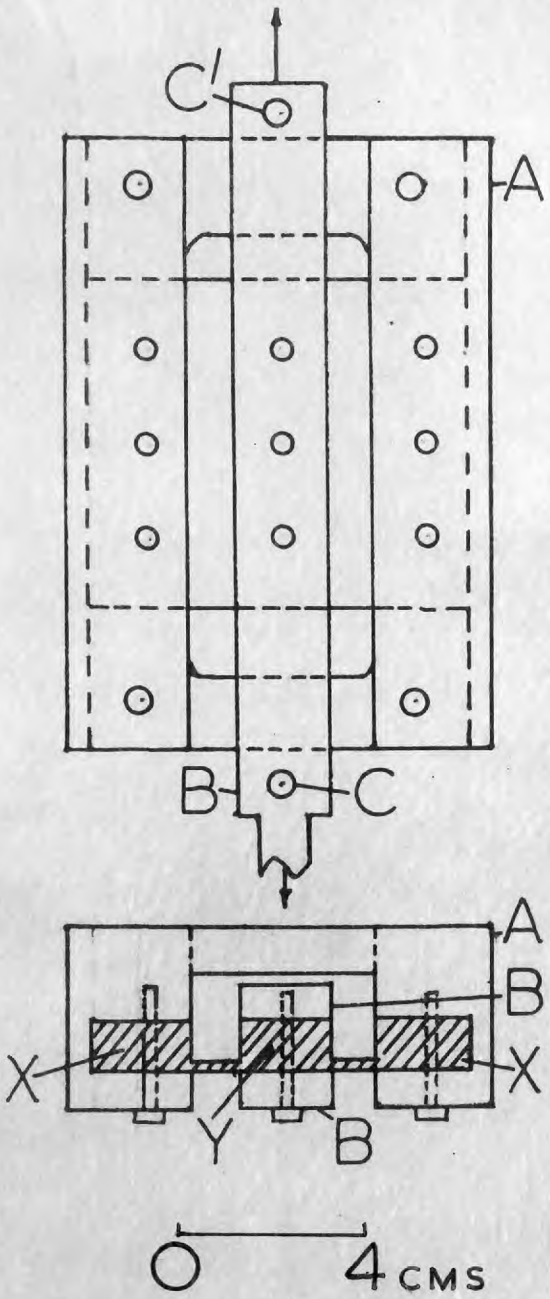

PULLEY
WHEEL
SPECIMEN
FITTING
REVERSE
LOAD
FORWARD
LOAD
I SECTION
FRAME
0
1
2 FEET

FIG 3

FIG 4



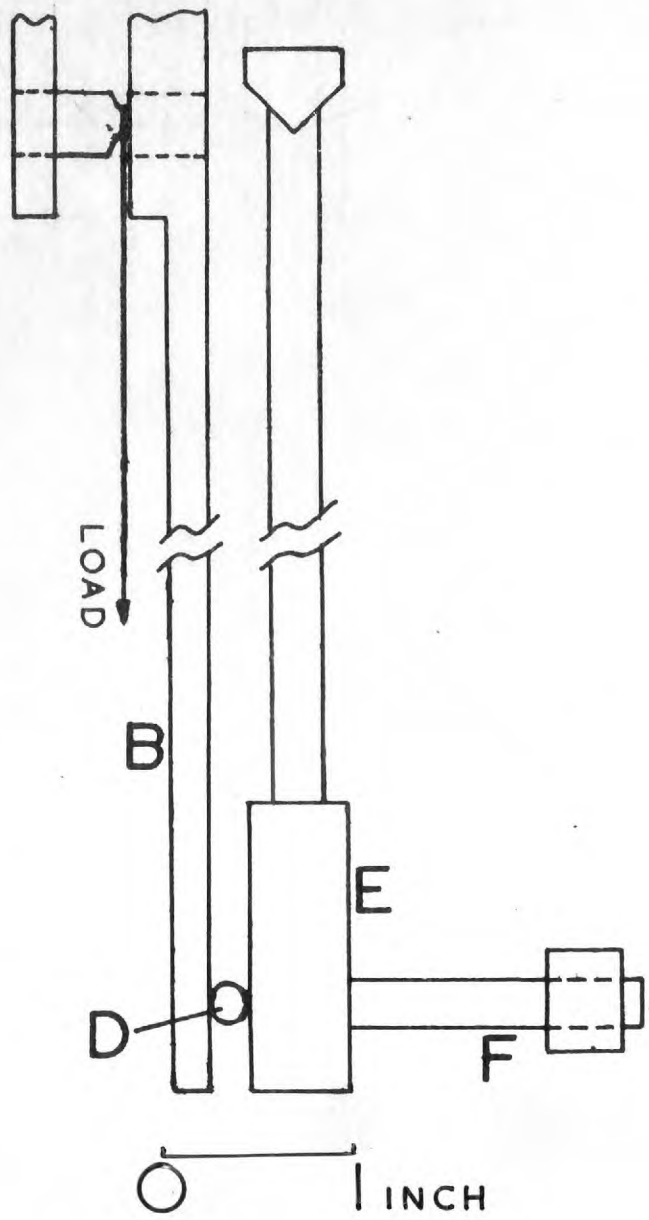


FIG 5

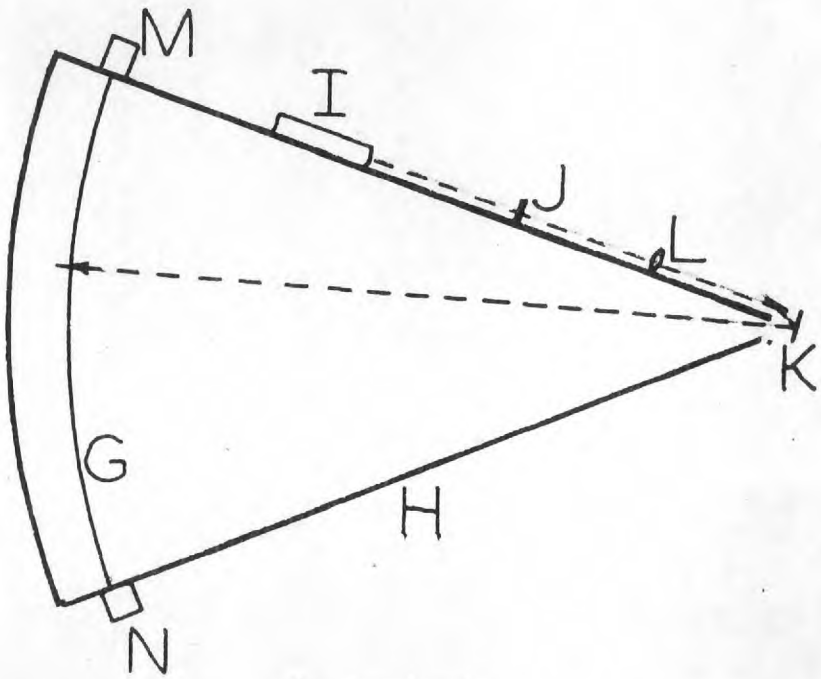
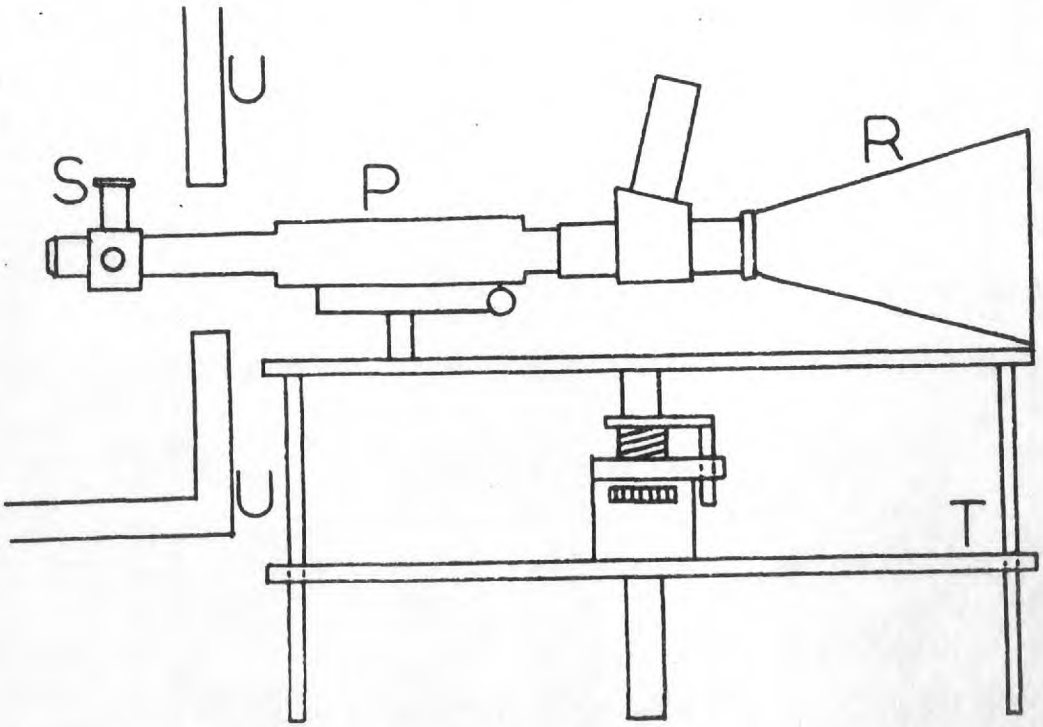


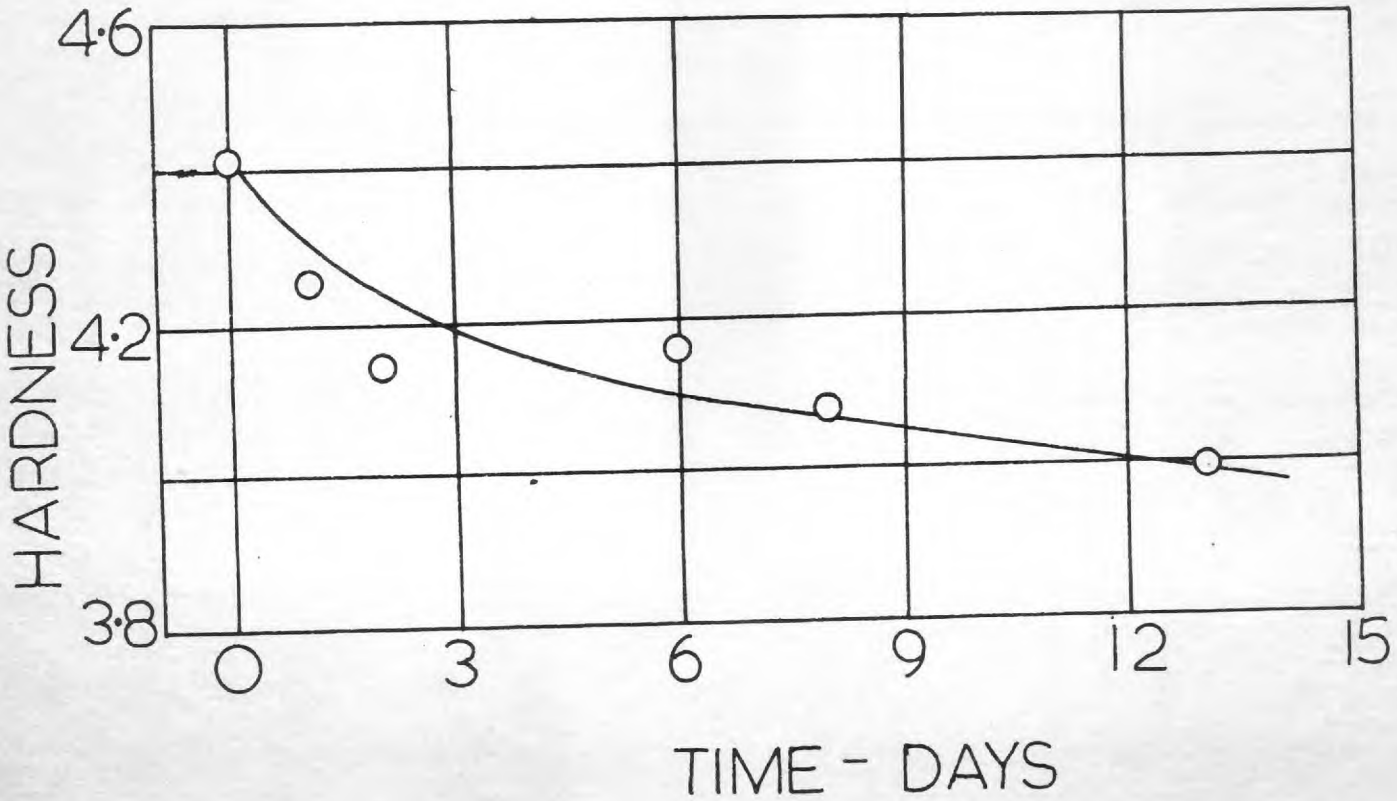
FIG 6

FIG 7



0 10 CMS

FIG. 8



70

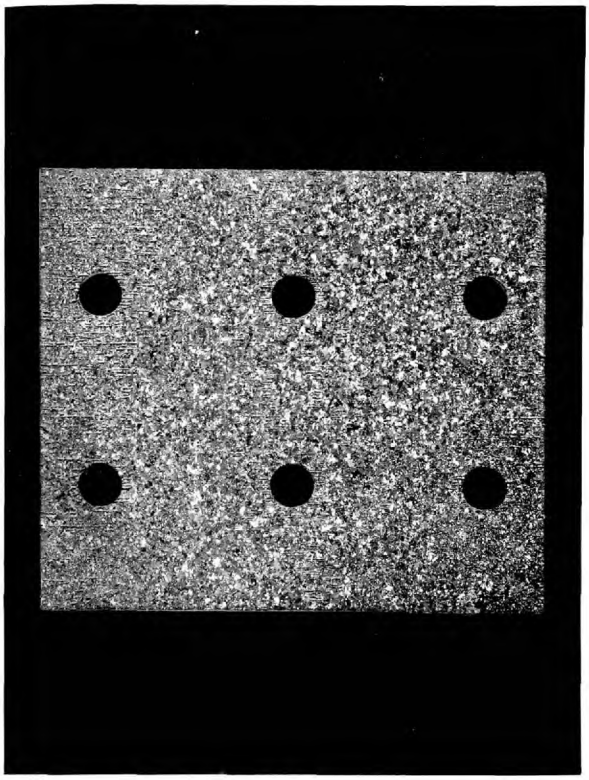


FIG 9

X4/5

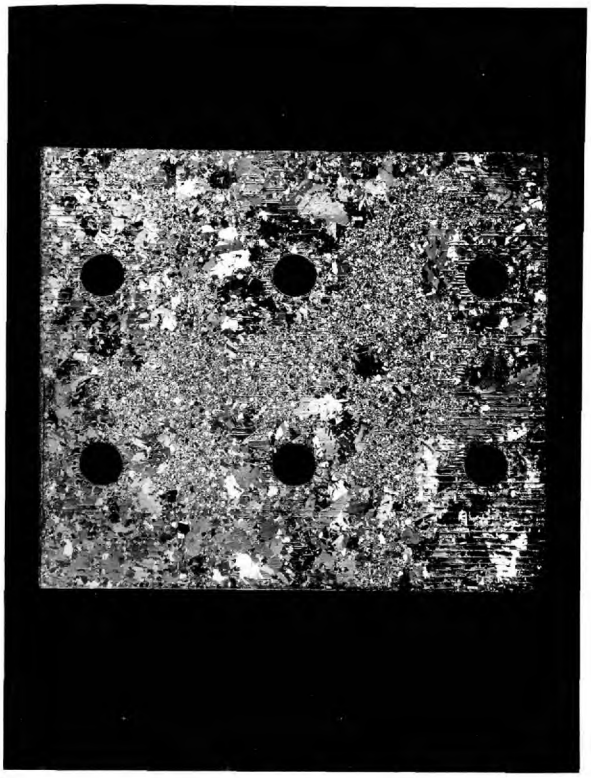


FIG 10

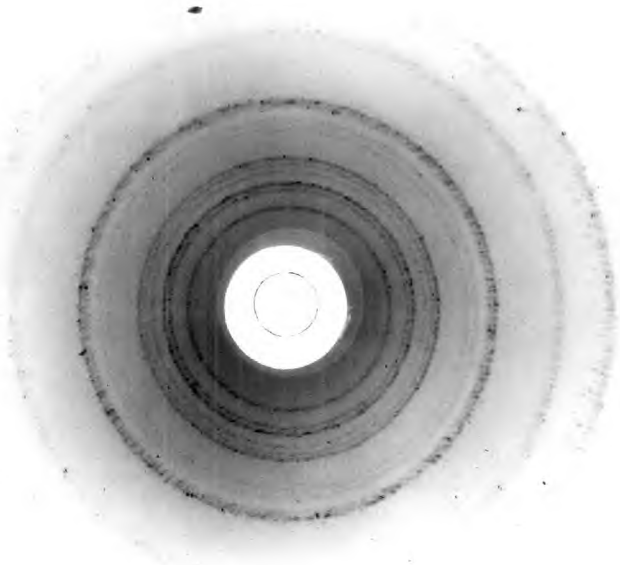


FIG 11

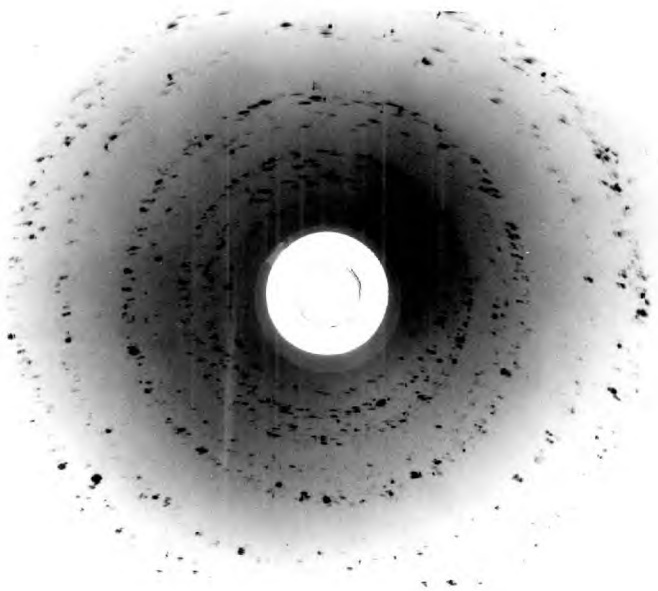


FIG 12

FIG. 13

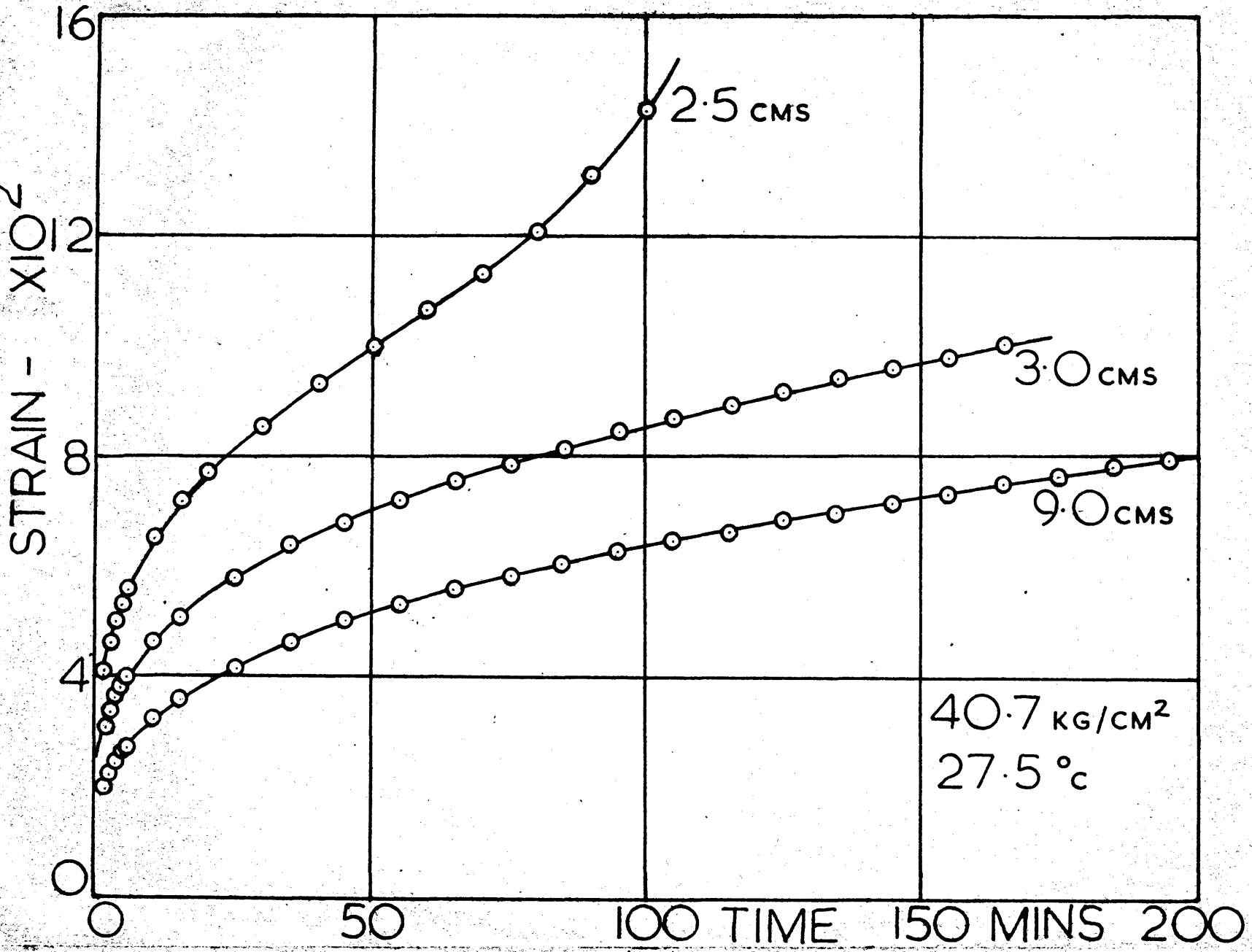

16
12
8
4
0
STRAIN - X10^2
2·5 CMS
3·0 CMS
9·0 CMS
40·7 KG/CM²
27·5 °C
0
50
100
TIME
150 MINS
200

FIG. 14

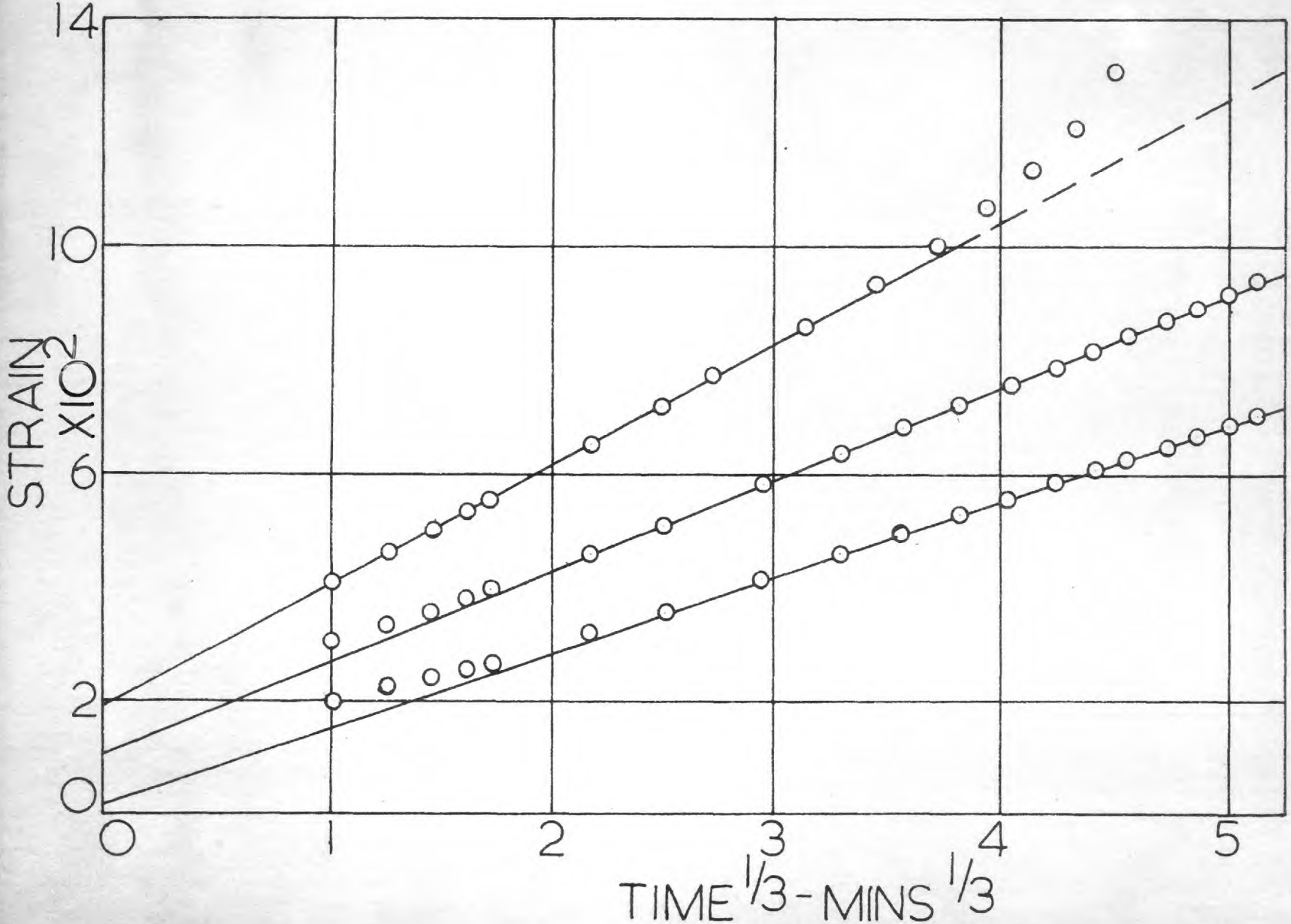
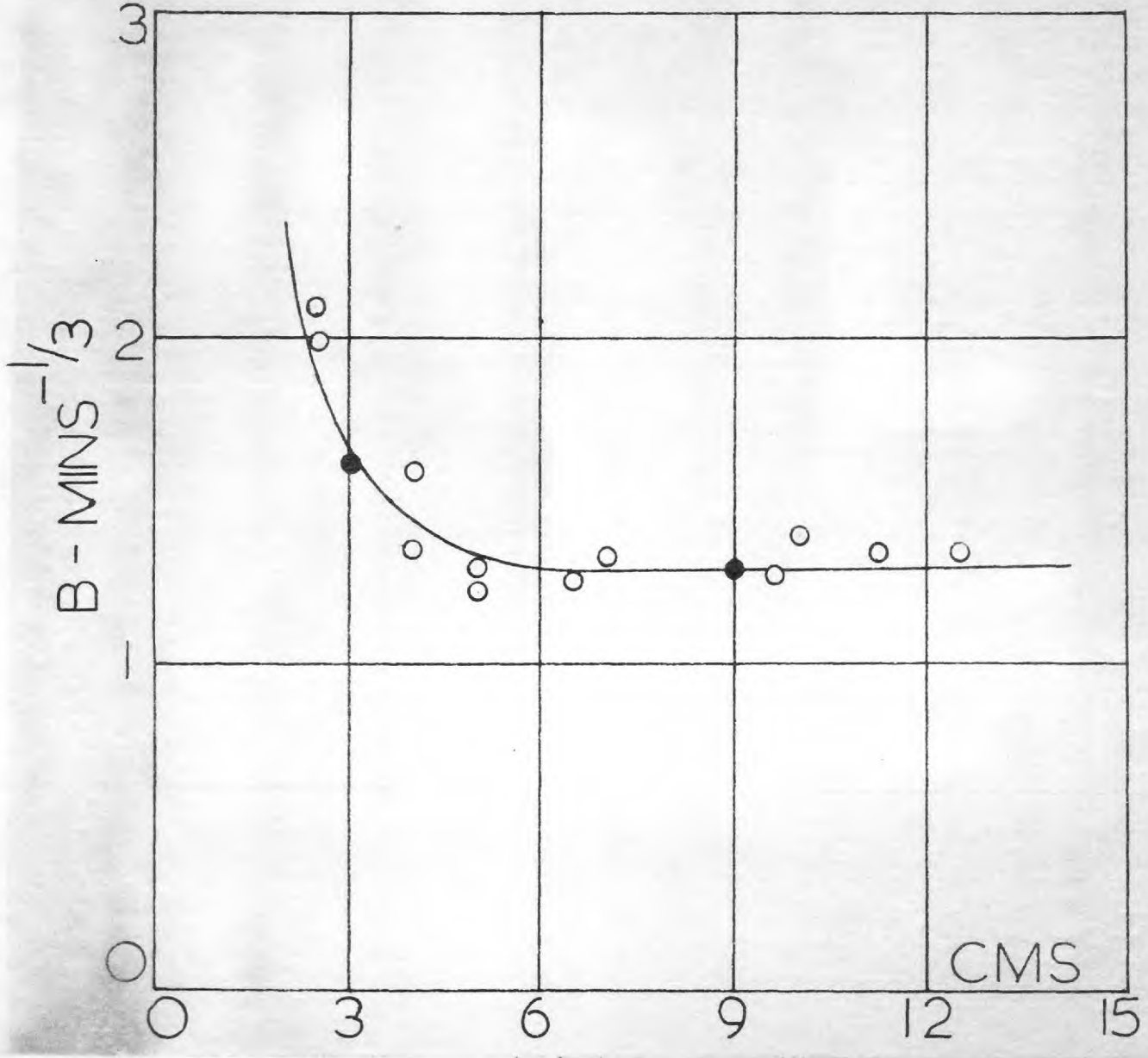
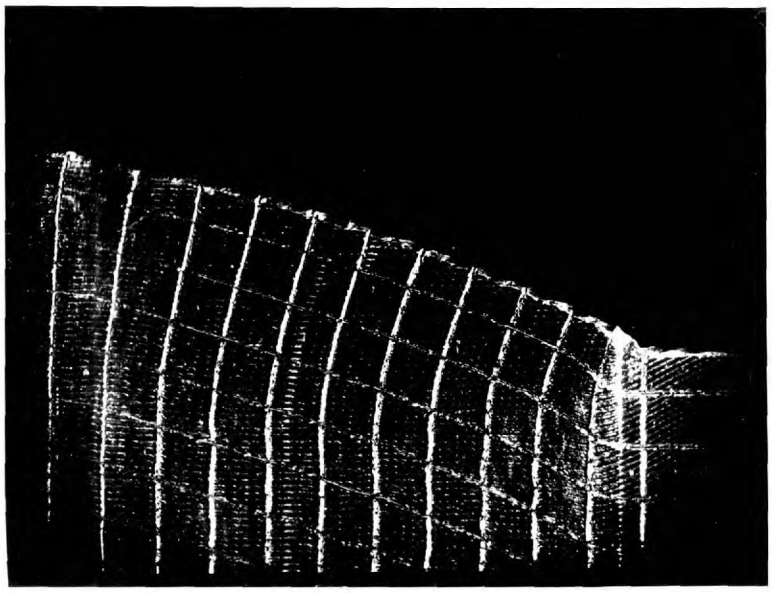


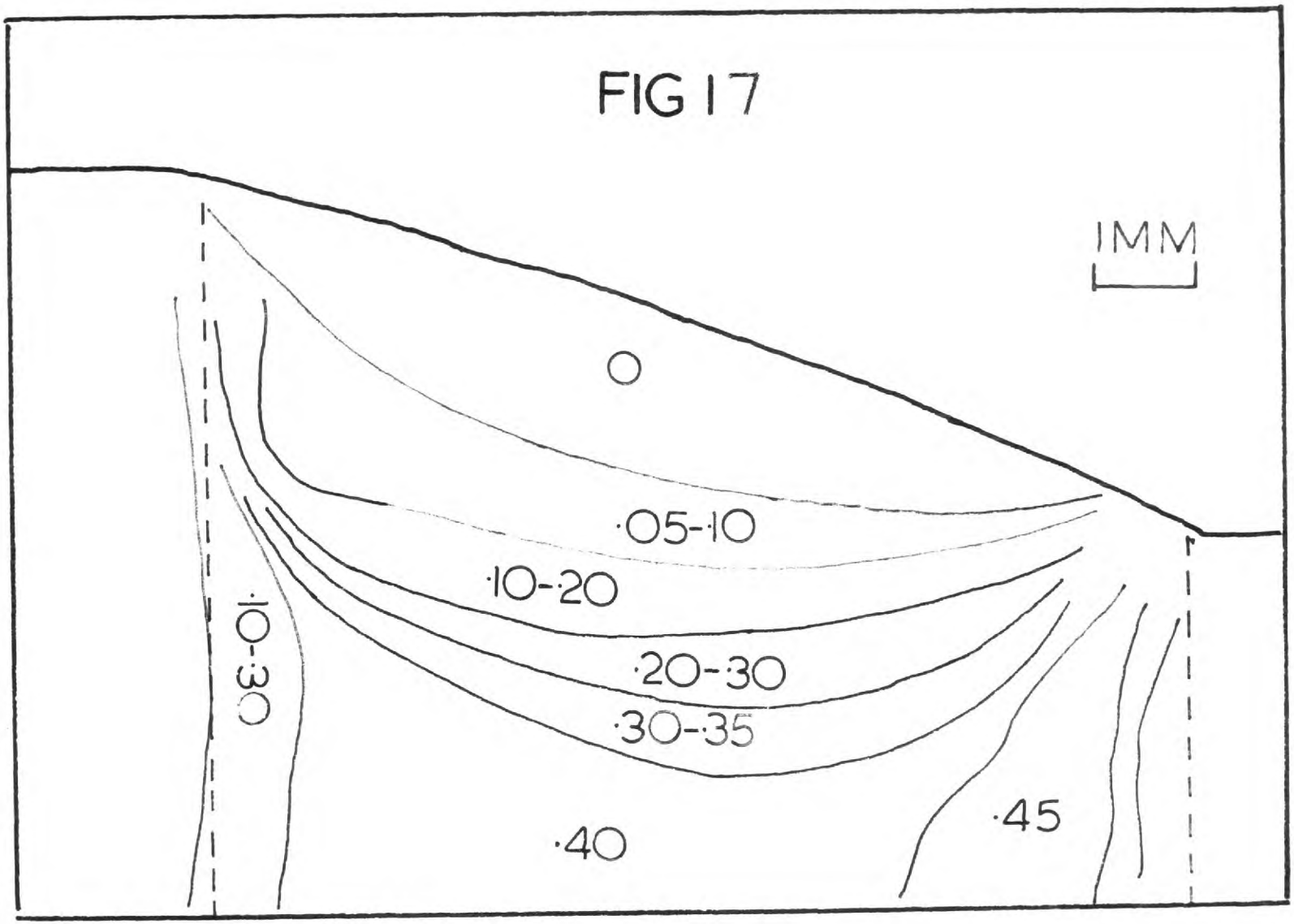
FIG. 15





X7

FIG 16


FIG 17
IMM
0
·05-10
·10-20
·20-30
·30-35
·40
·45
·03-·10

XII

FIG 18

FIG. 19

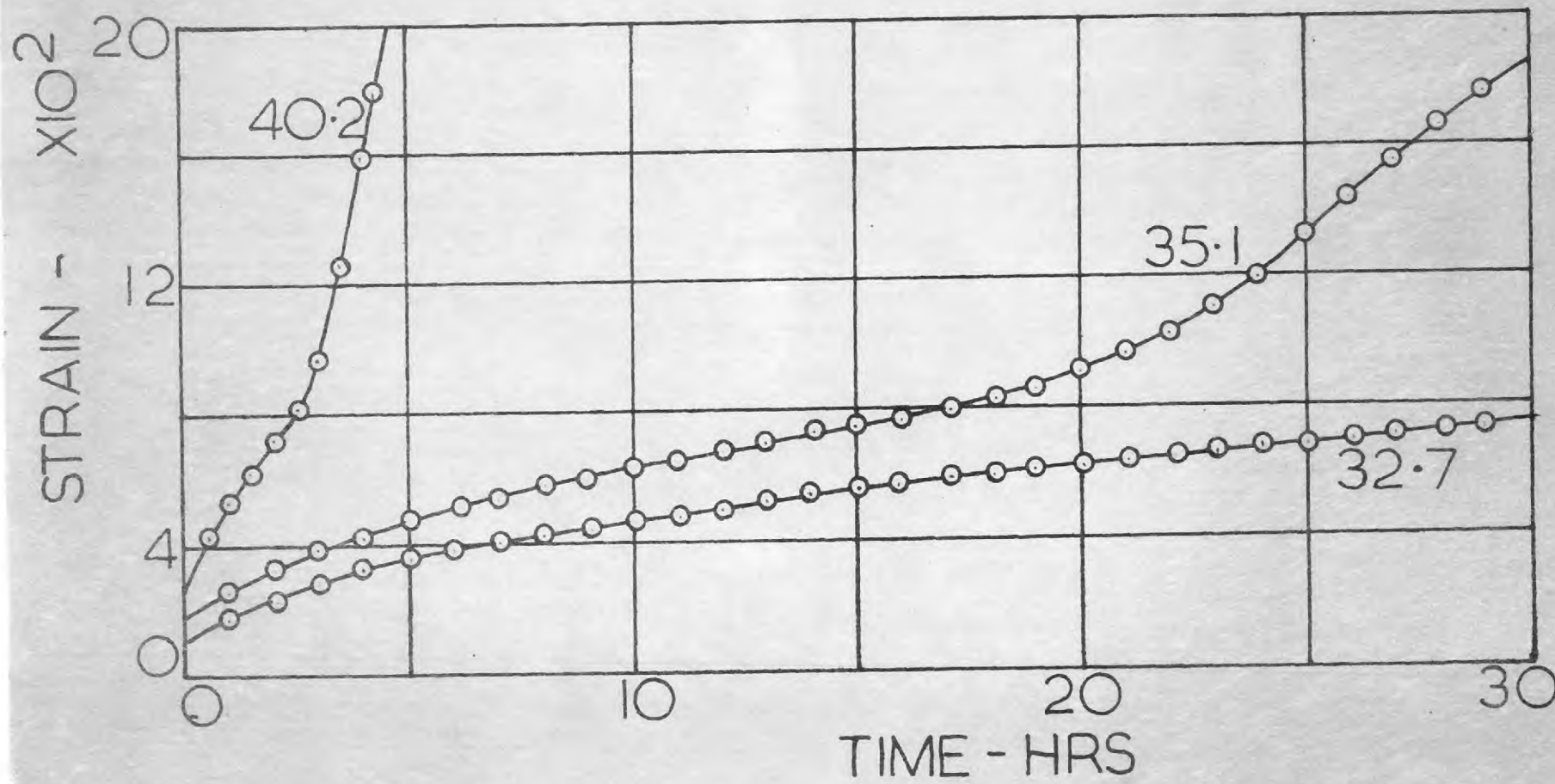


FIG 20

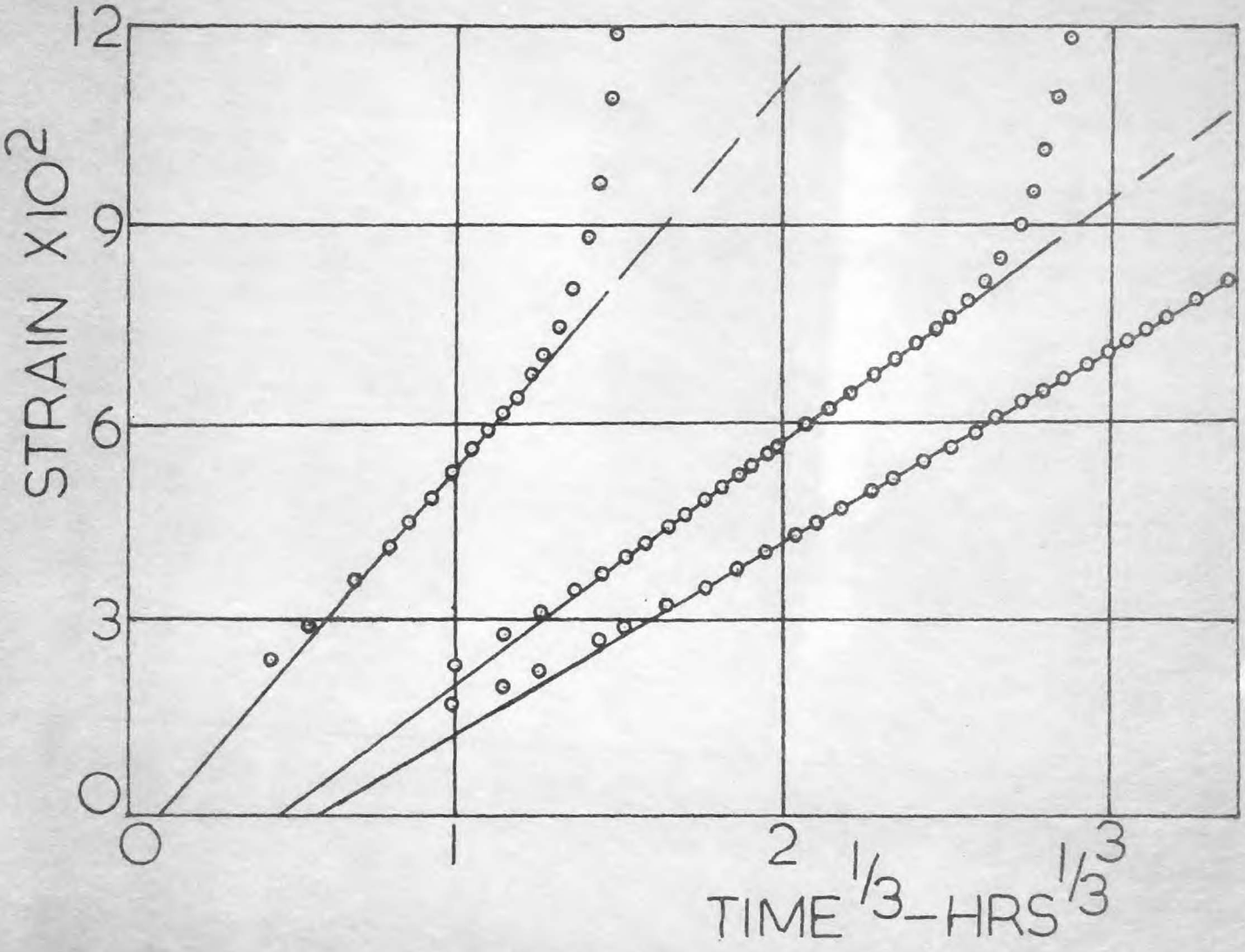


FIG 21

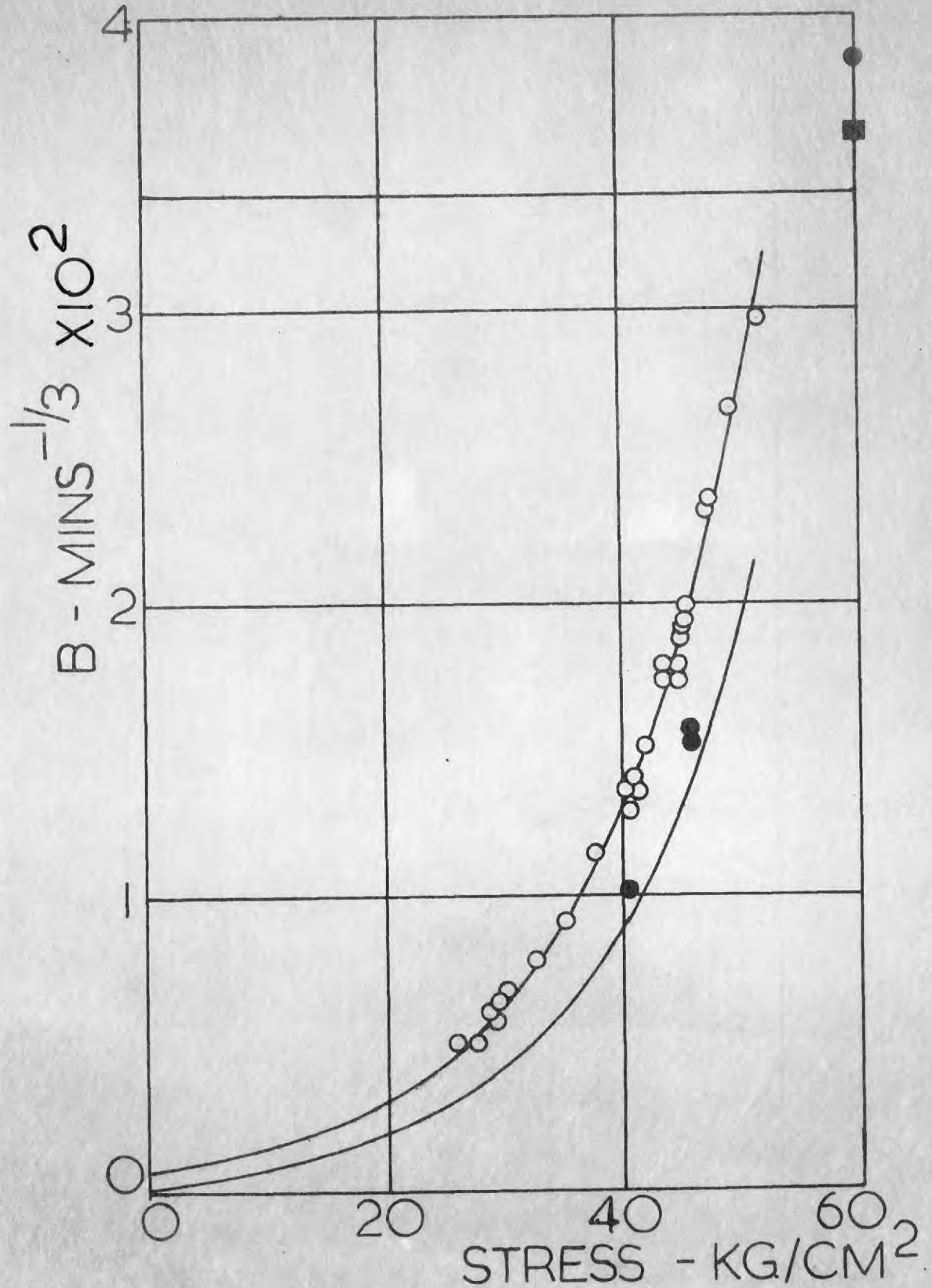


FIG 22

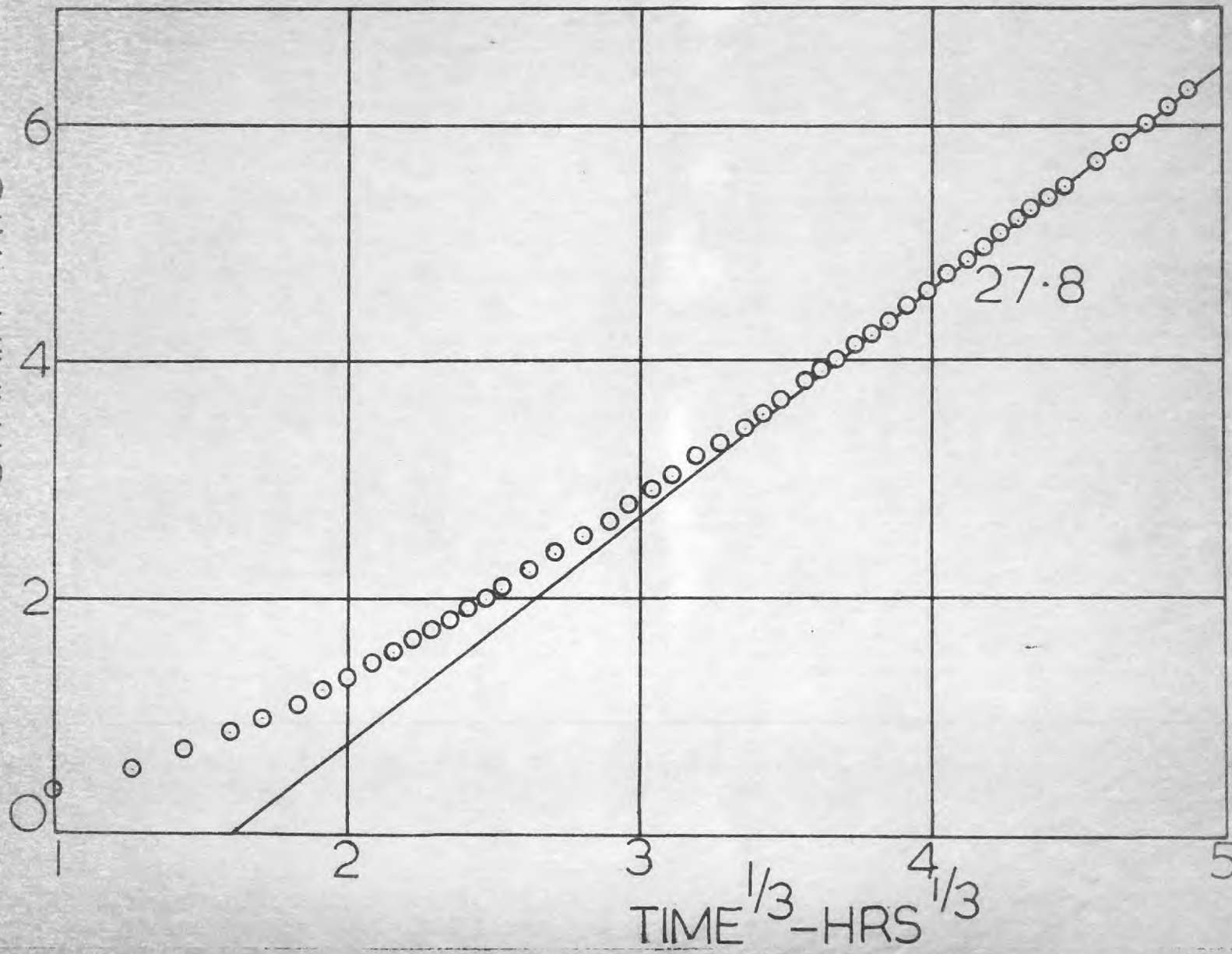


FIG 23

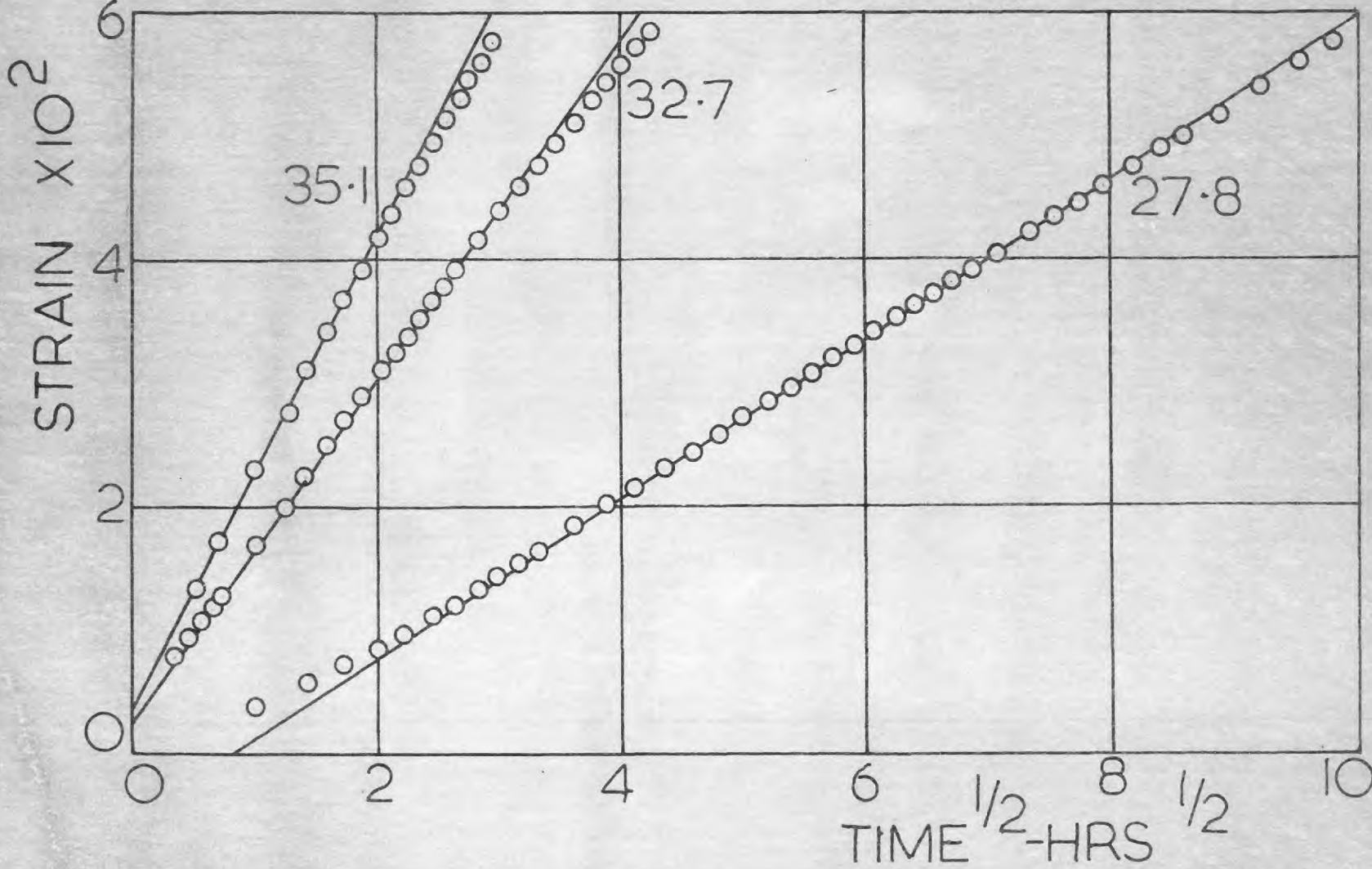


FIG 24

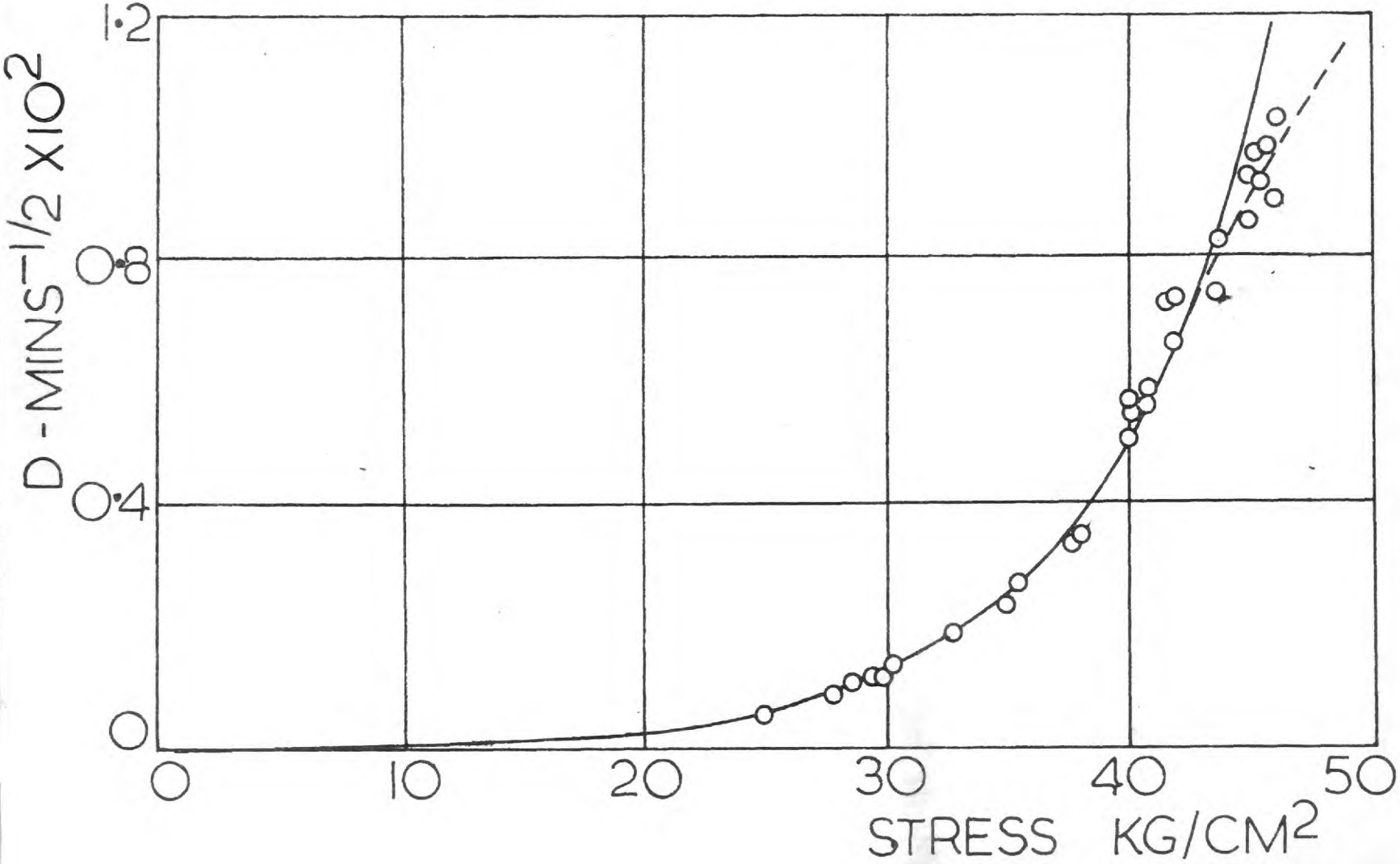


FIG 26

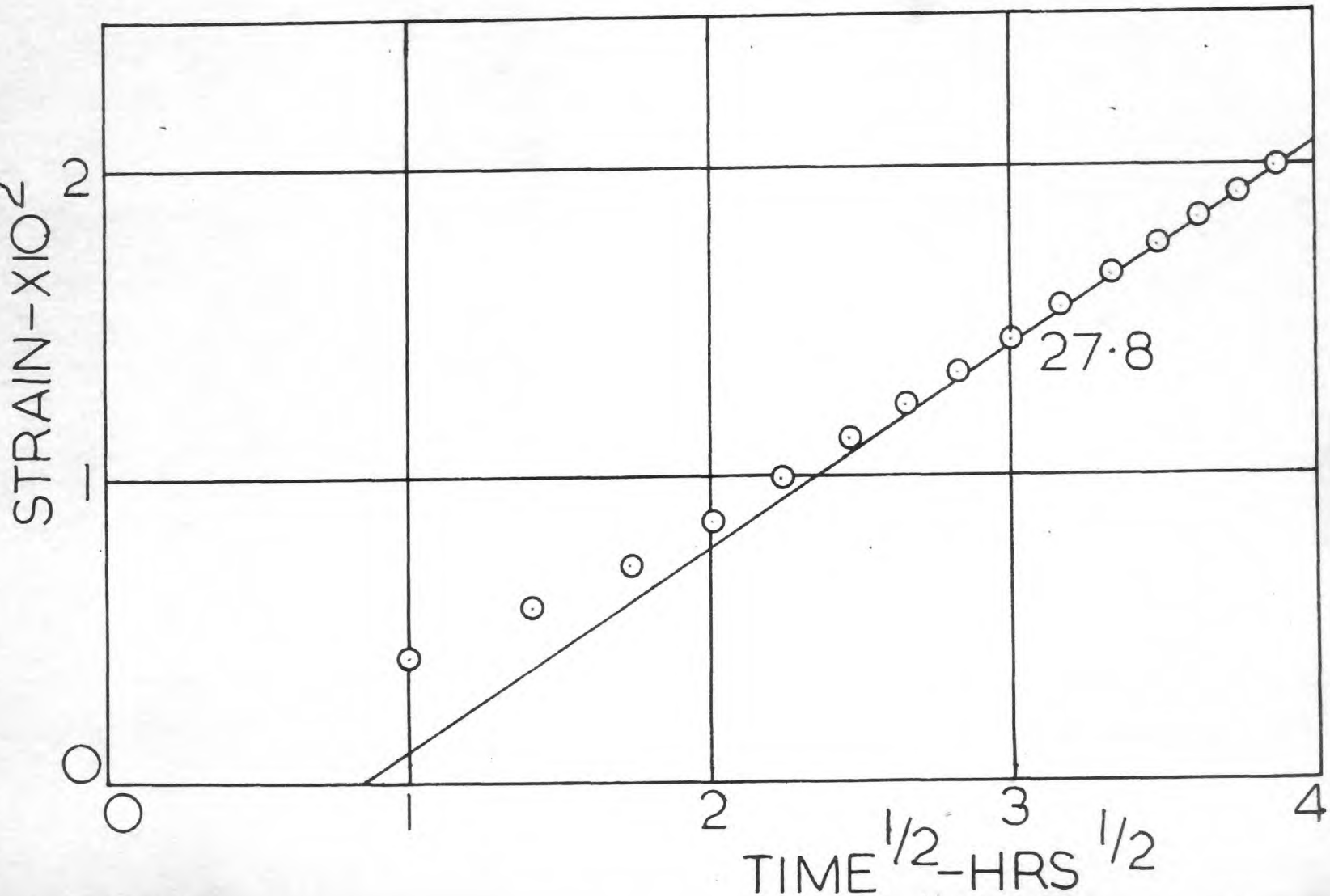


FIG 27

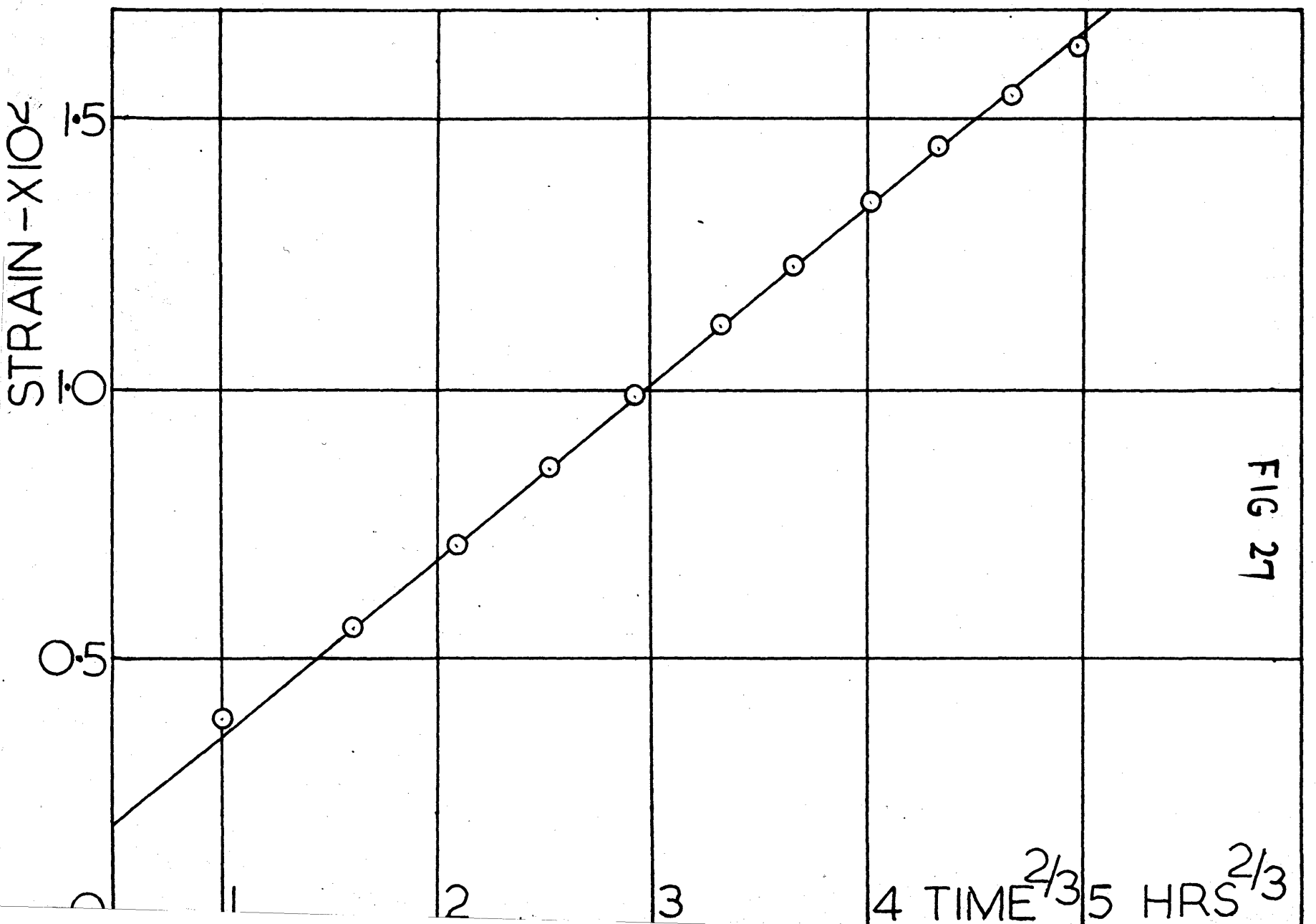
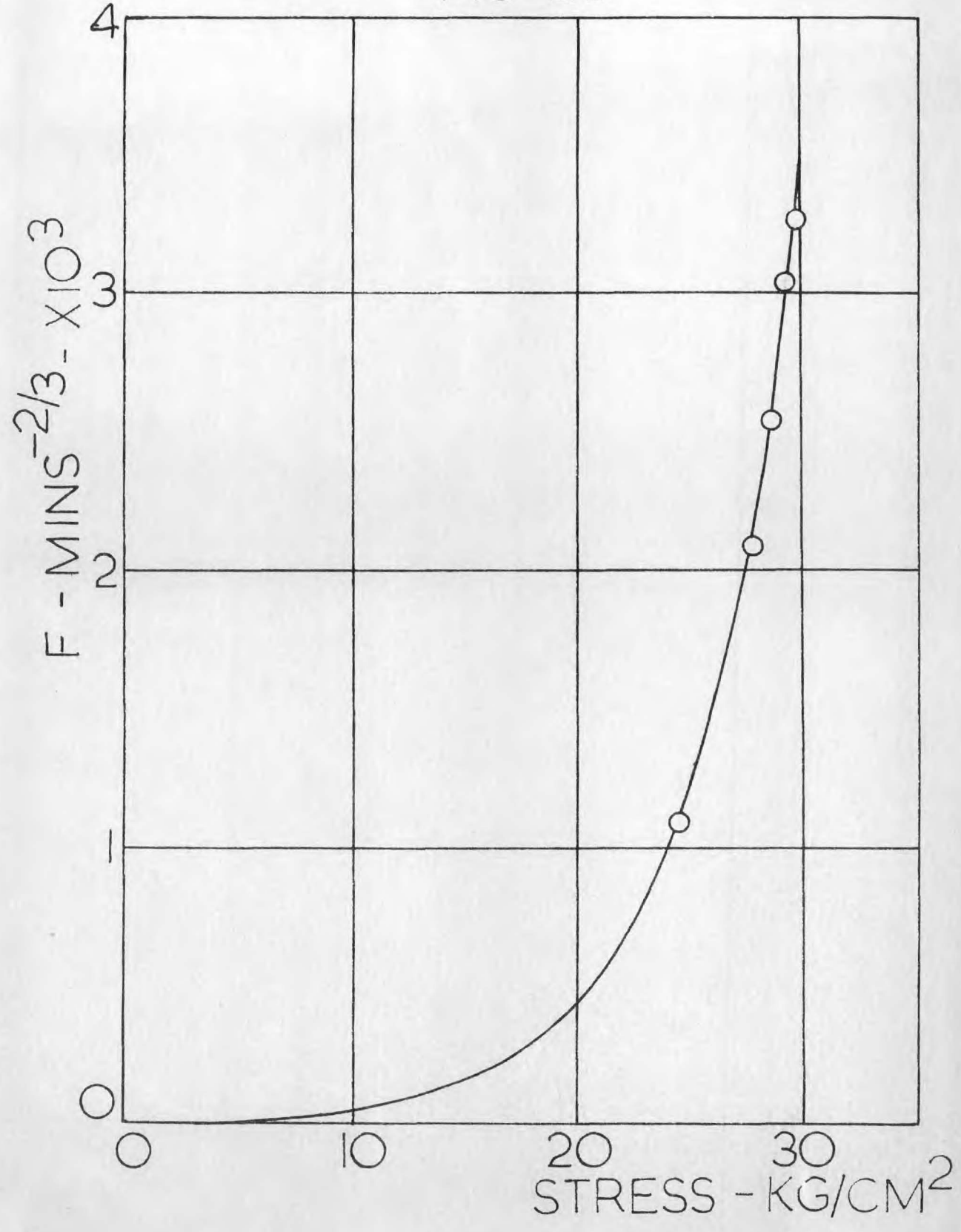
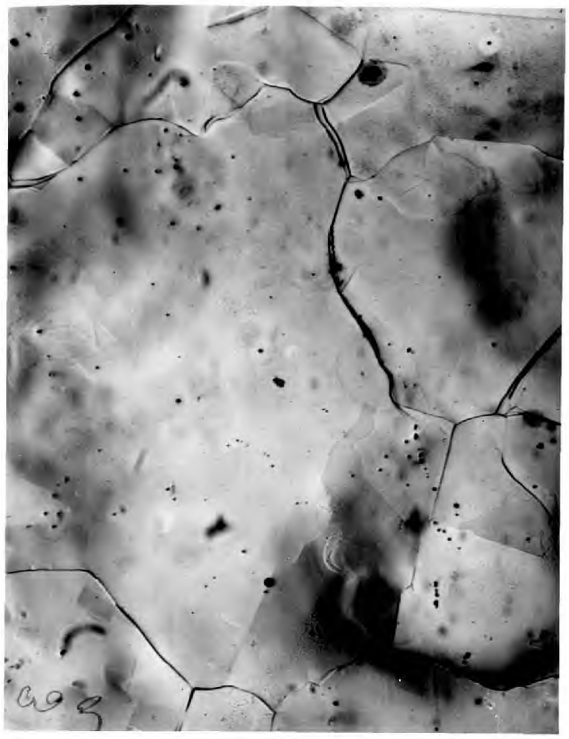


FIG 27

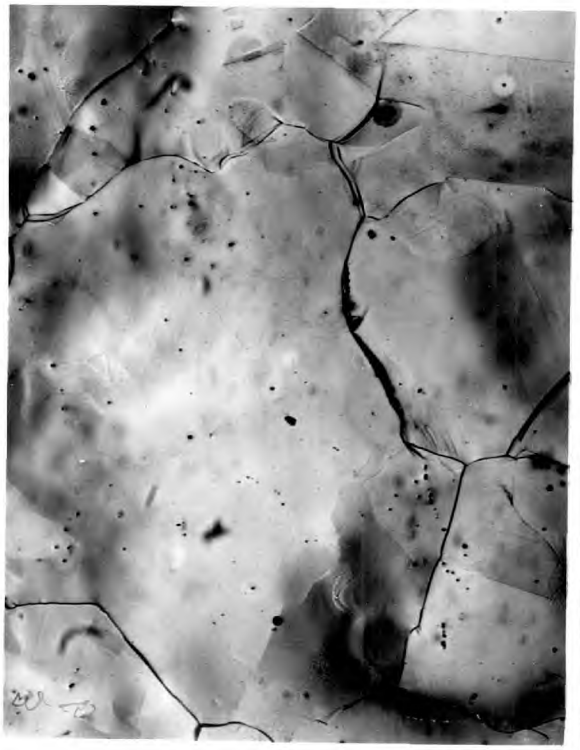
FIG 28





A

STRAIN—0.44×10^{-2}



B

1.00×10^{-2}

FIG 29



C

1.50×10^{-2}



D

2.00×10^{-2}

X80



E



F

FIG 29

STRAIN—— 3.00×10^{-2} 5.96×10^{-2}



G



H

X80

7.96×10^{-2} 11.23×10^{-2}

FIG 30

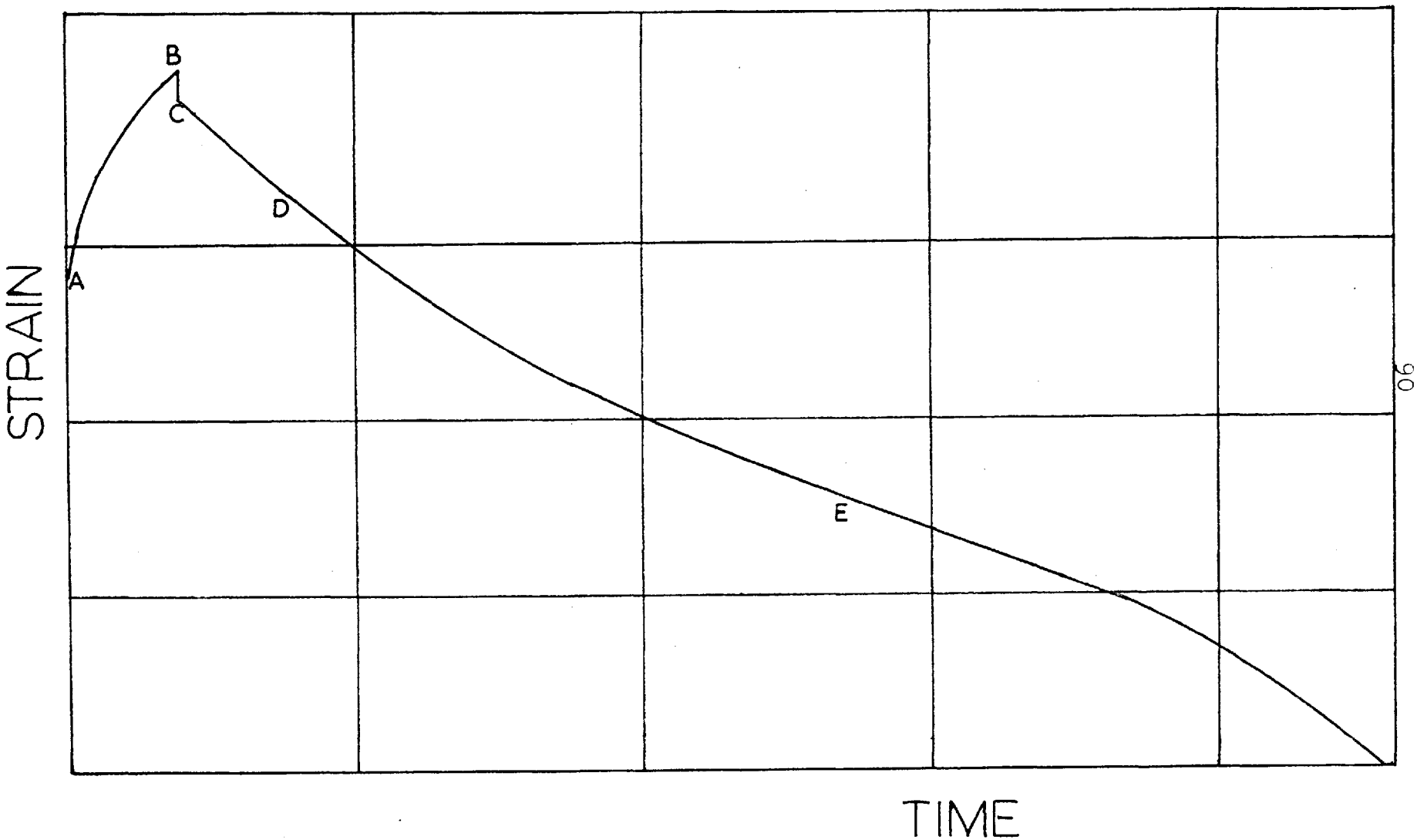


FIG 31

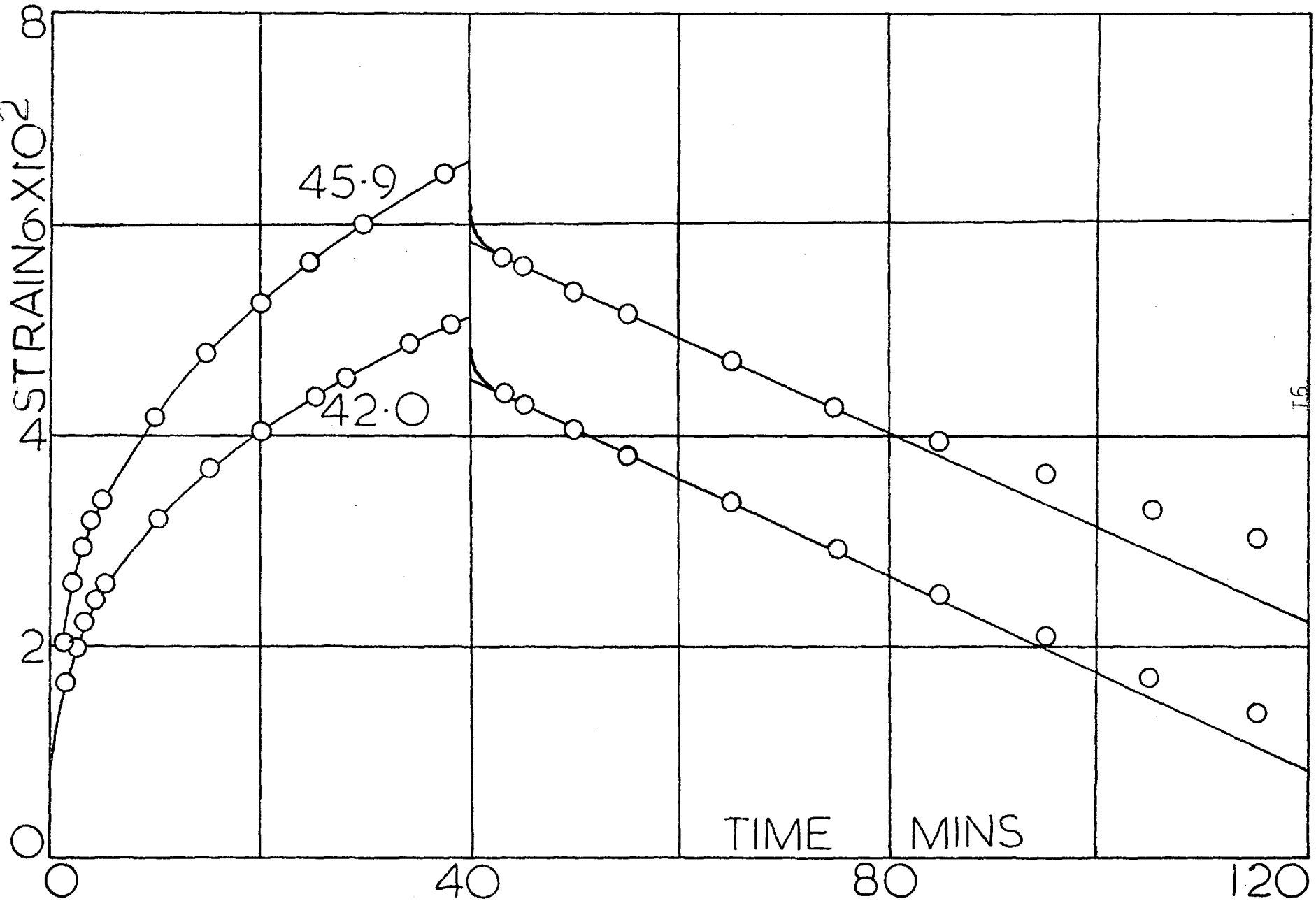


FIG 32

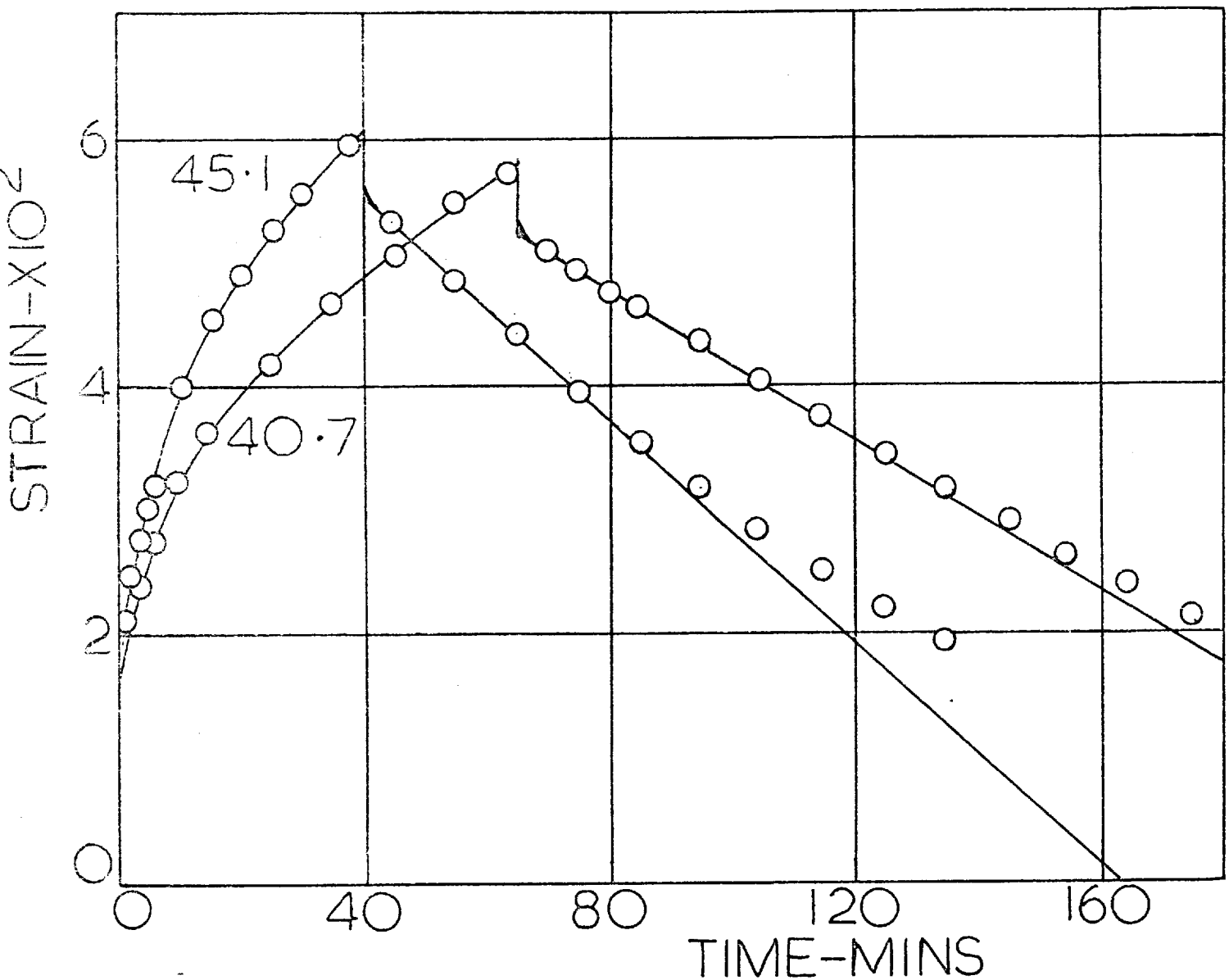
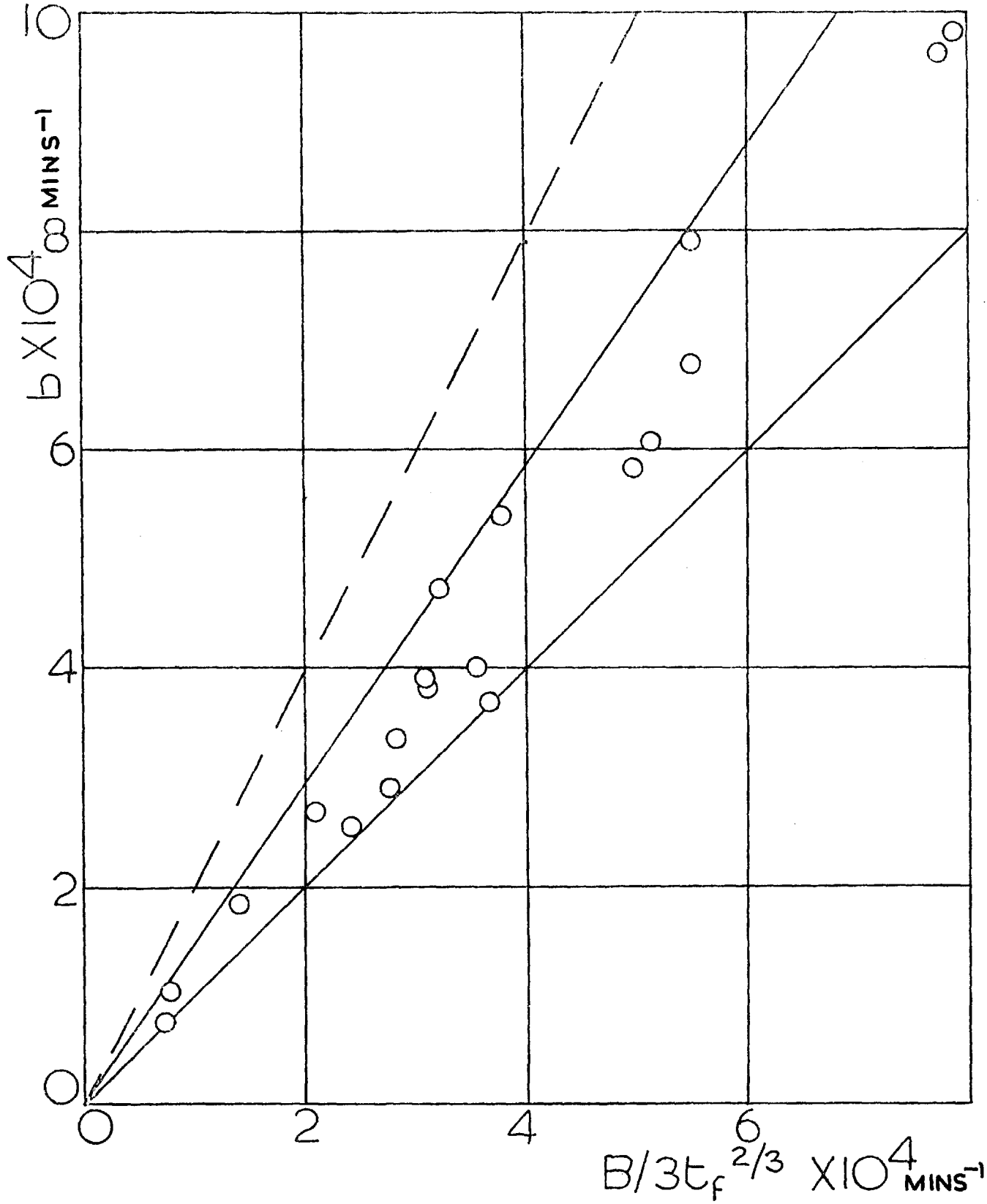


FIG 33



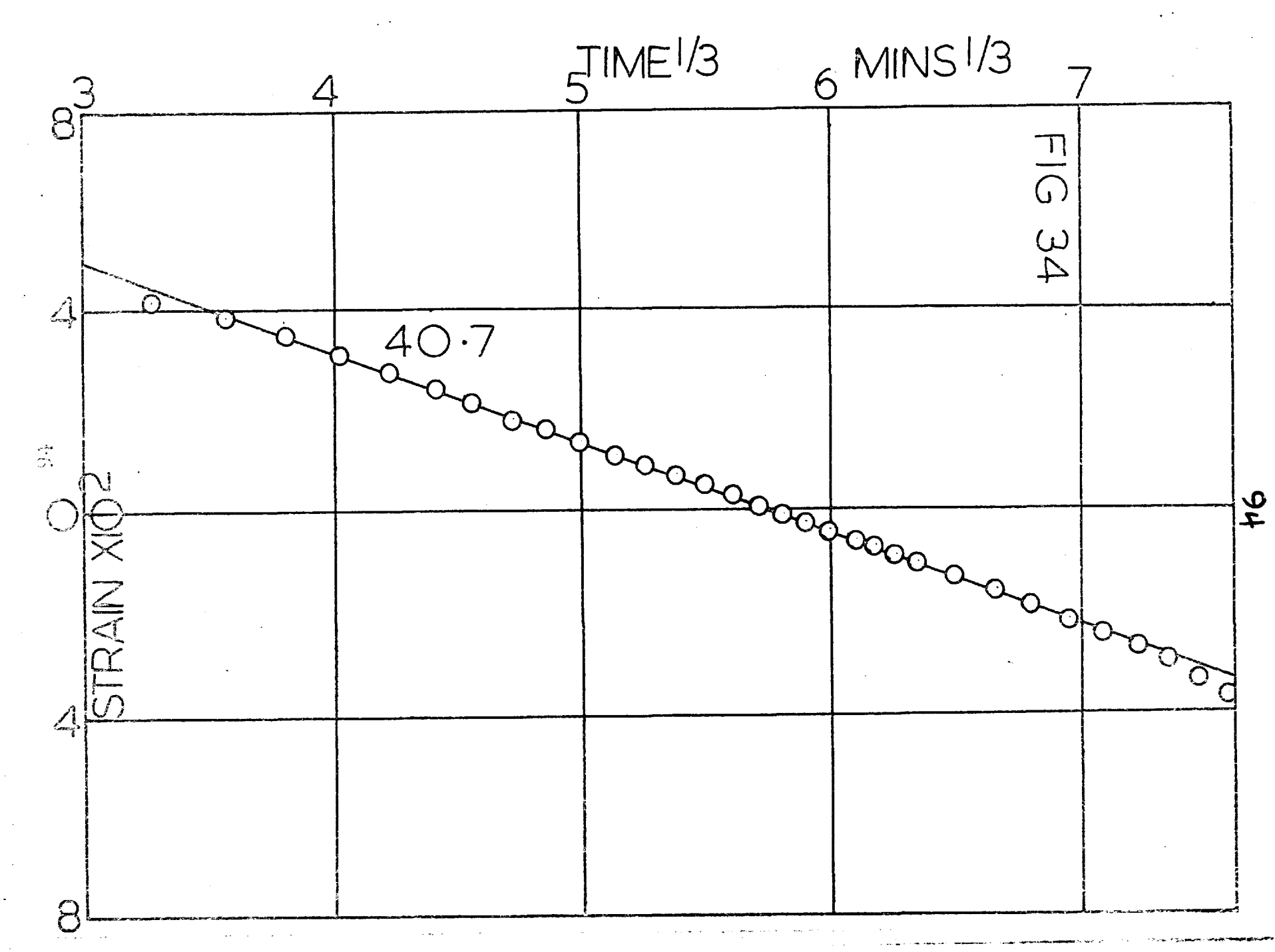

TIME 1/3 MINS 1/3
3
4
5
6
7
8
4
0
4
8
STRAIN X10-2
40·7
FIG 34
94

FIG 35

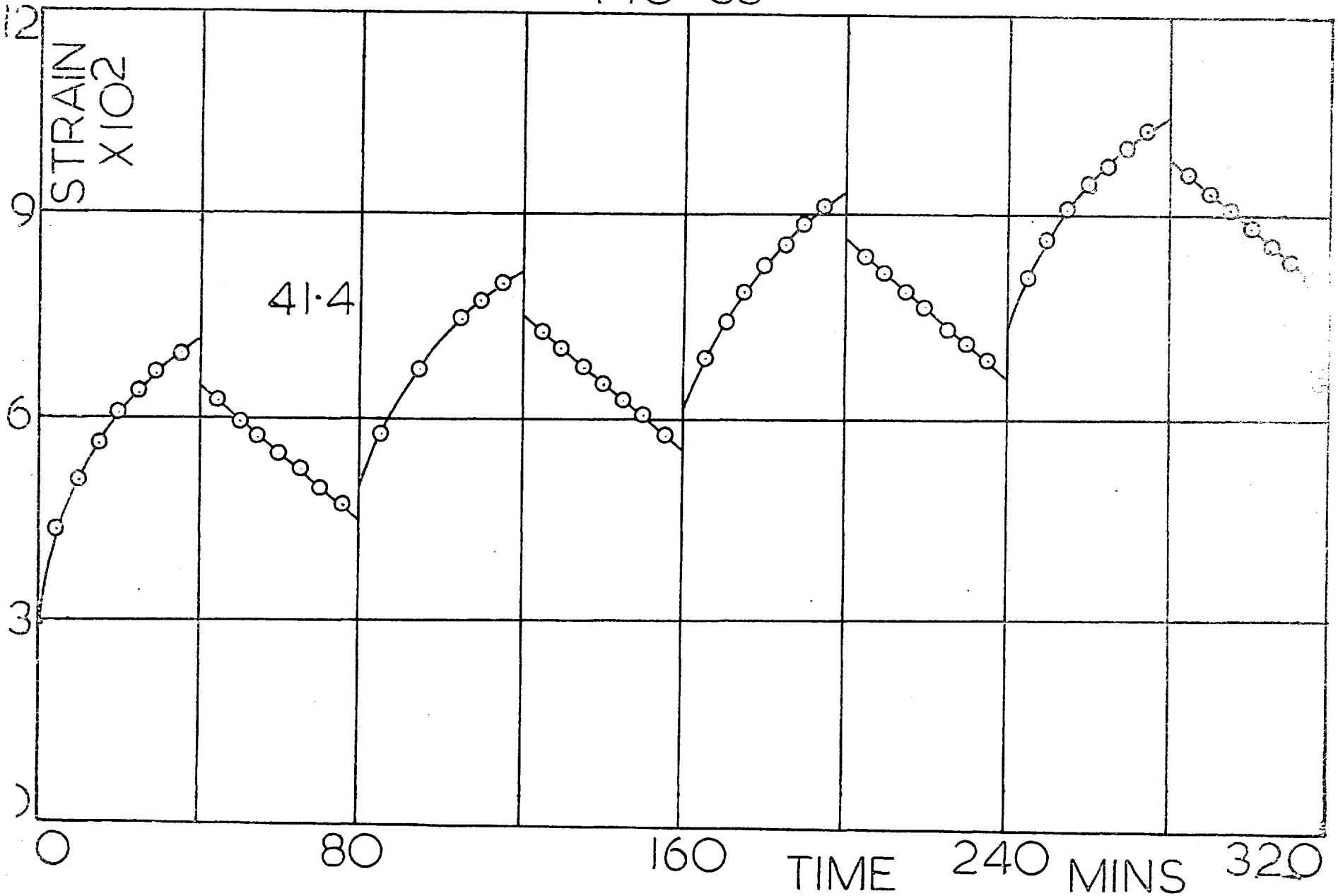


FIG 36

STRAIN X10²
6
4
2
0
40
TIME MINS
80
O FIRST CYCLE
× SECOND
+ THIRD
Δ FOURTH

FIG 37

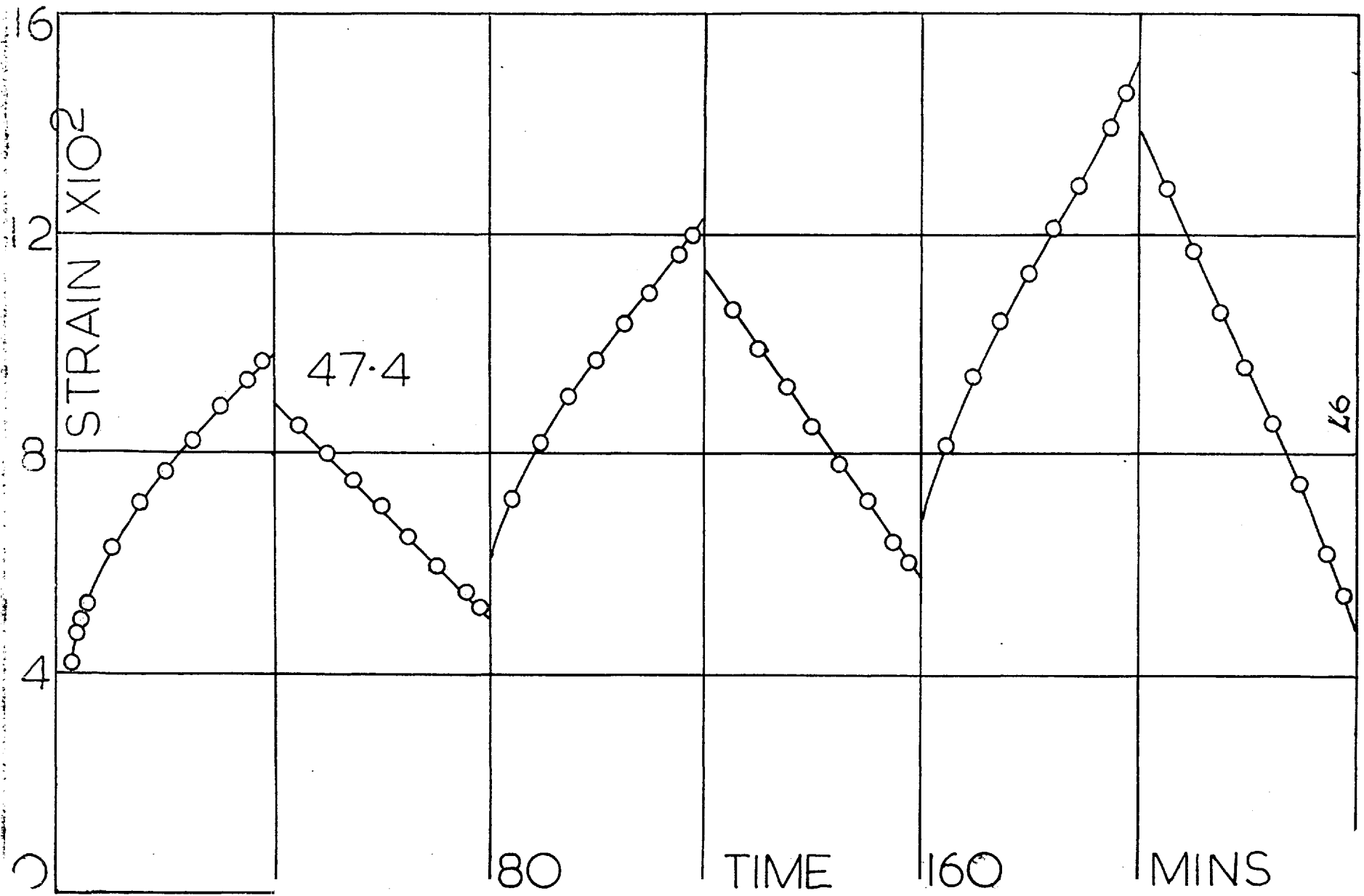
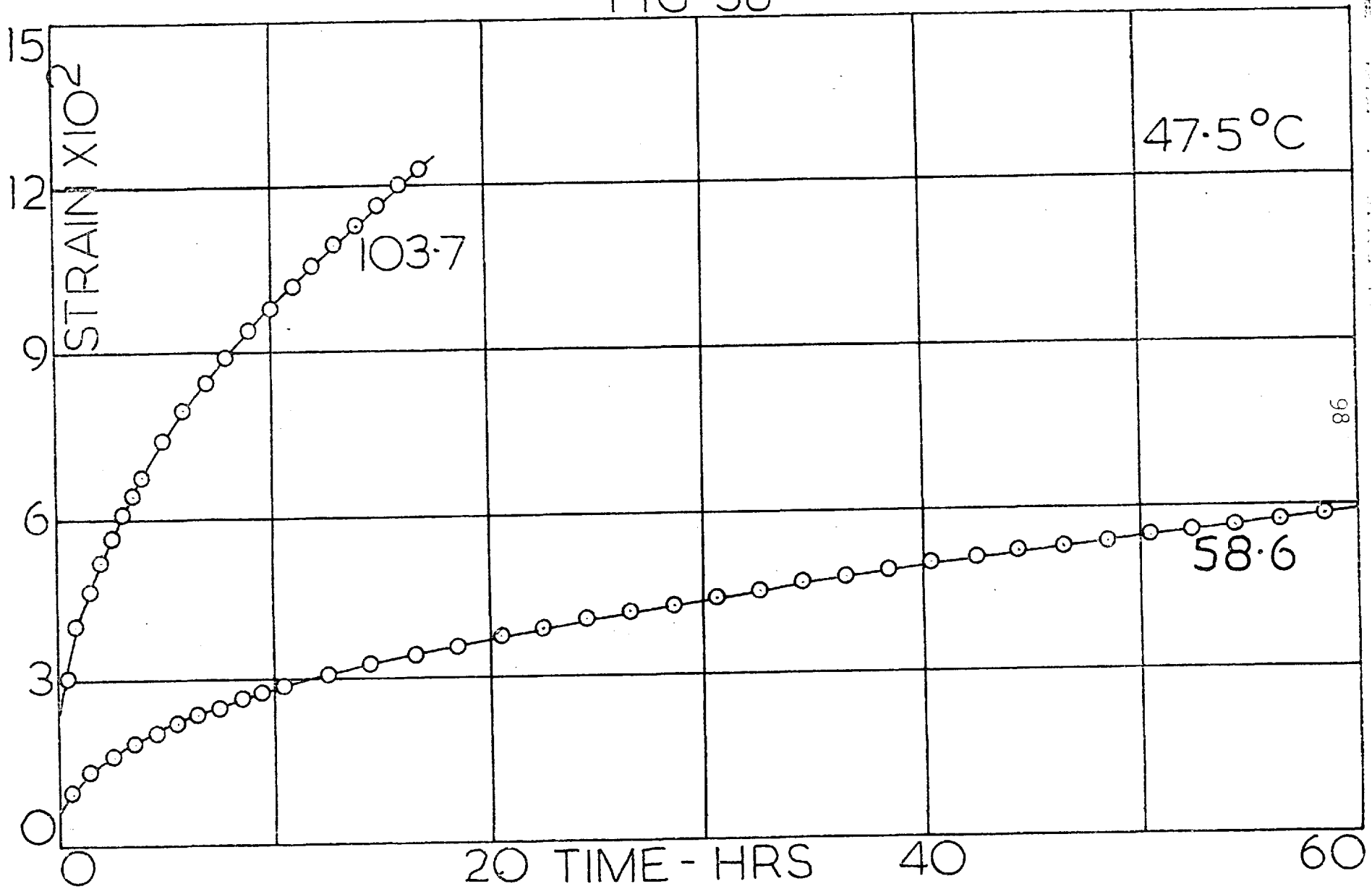


FIG 38



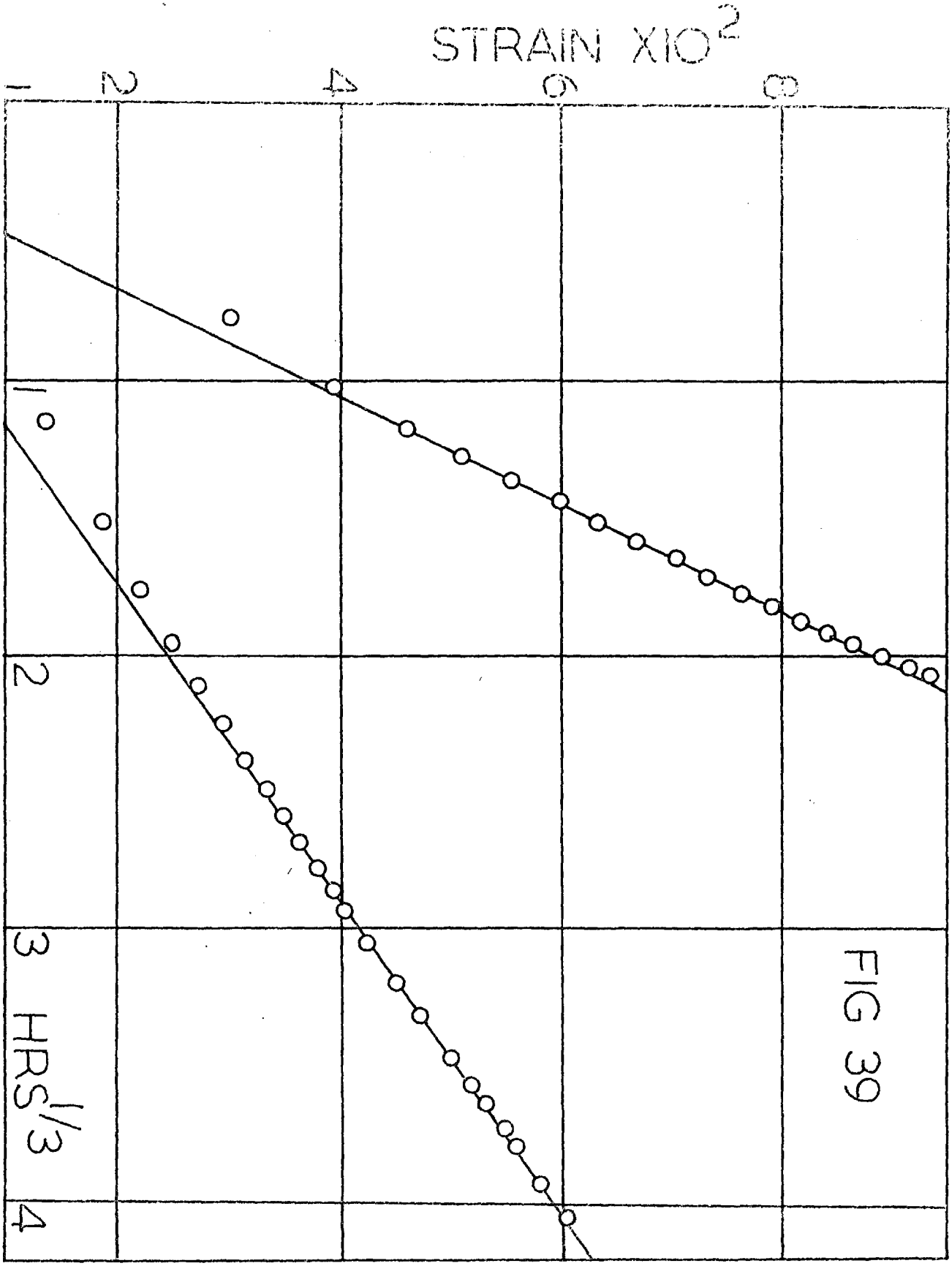


FIG 39

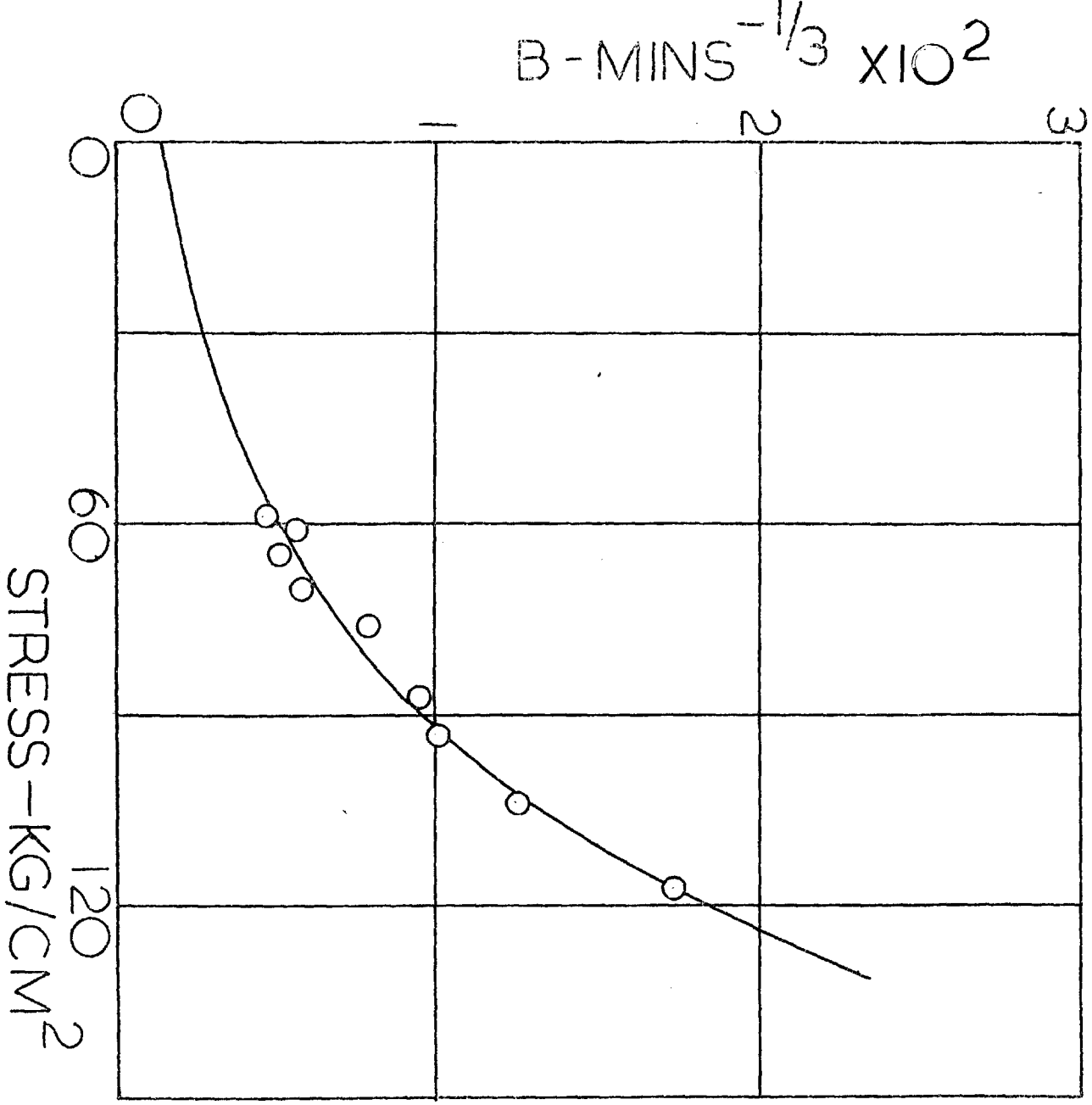


FIG 40

FIG 41

FIG 42

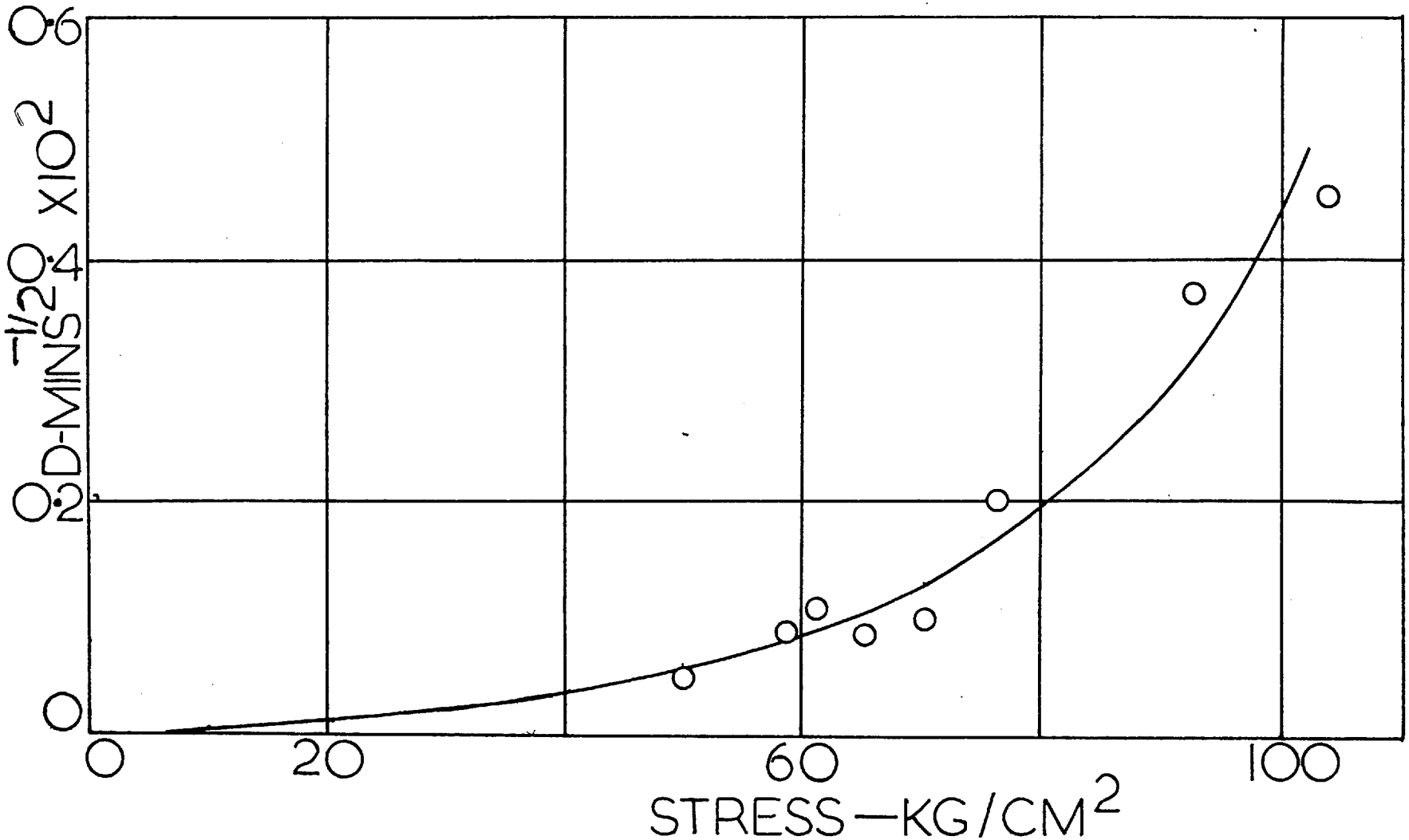
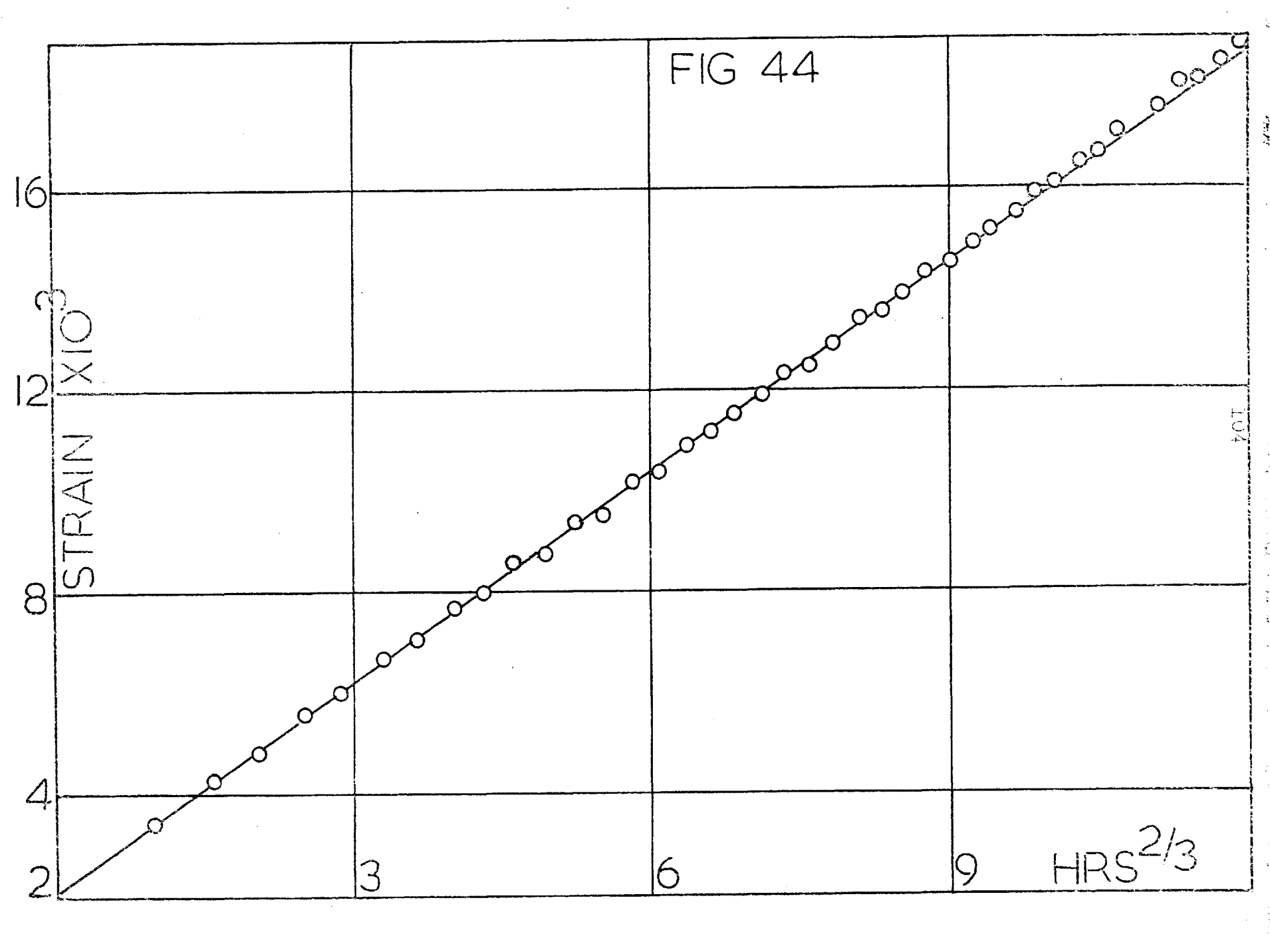
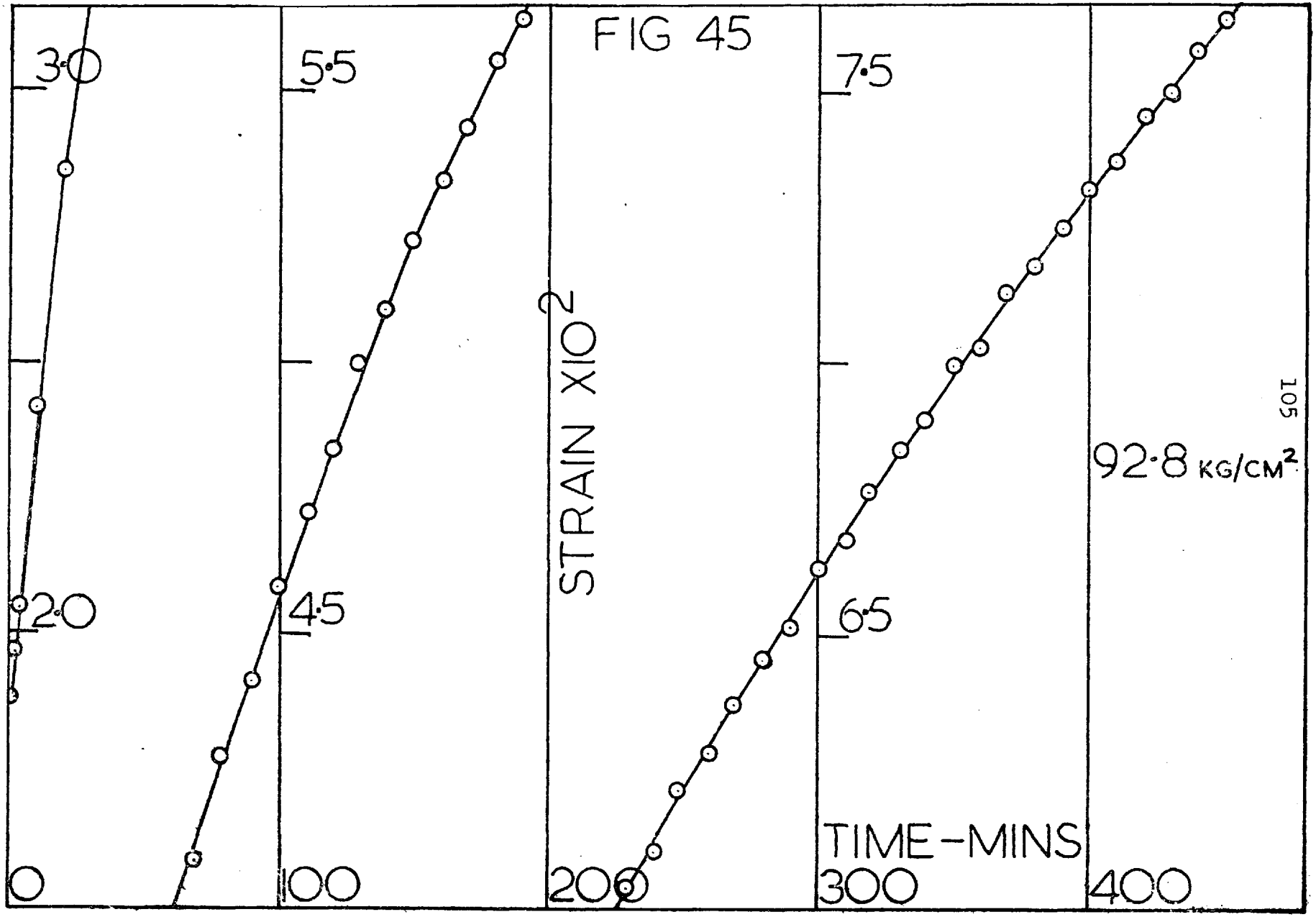


FIG 43
STRAIN X10^2
0
1
2
3
2
4
6
8 HRS$^{1/2}$
49·8
FIG 43


FIG 44
STRAIN X10^3
16
12
8
4
2
3
6
9
HRS^2/3


FIG 45
3·0
2·0
0
5·5
4·5
100
STRAIN X10²
7·5
6·5
200
TIME-MINS
300
92·8 KG/CM²
400
105

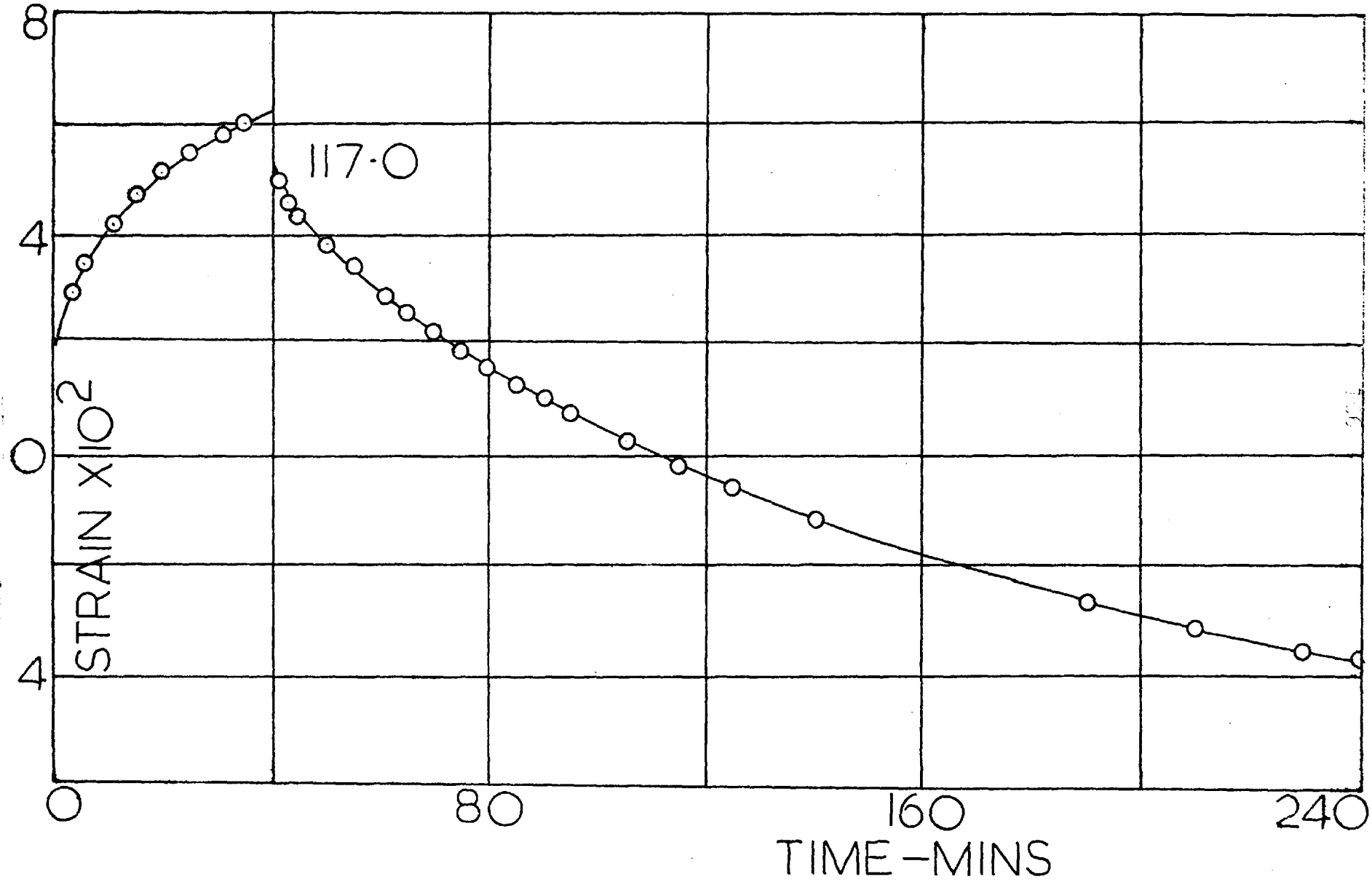


FIG 46

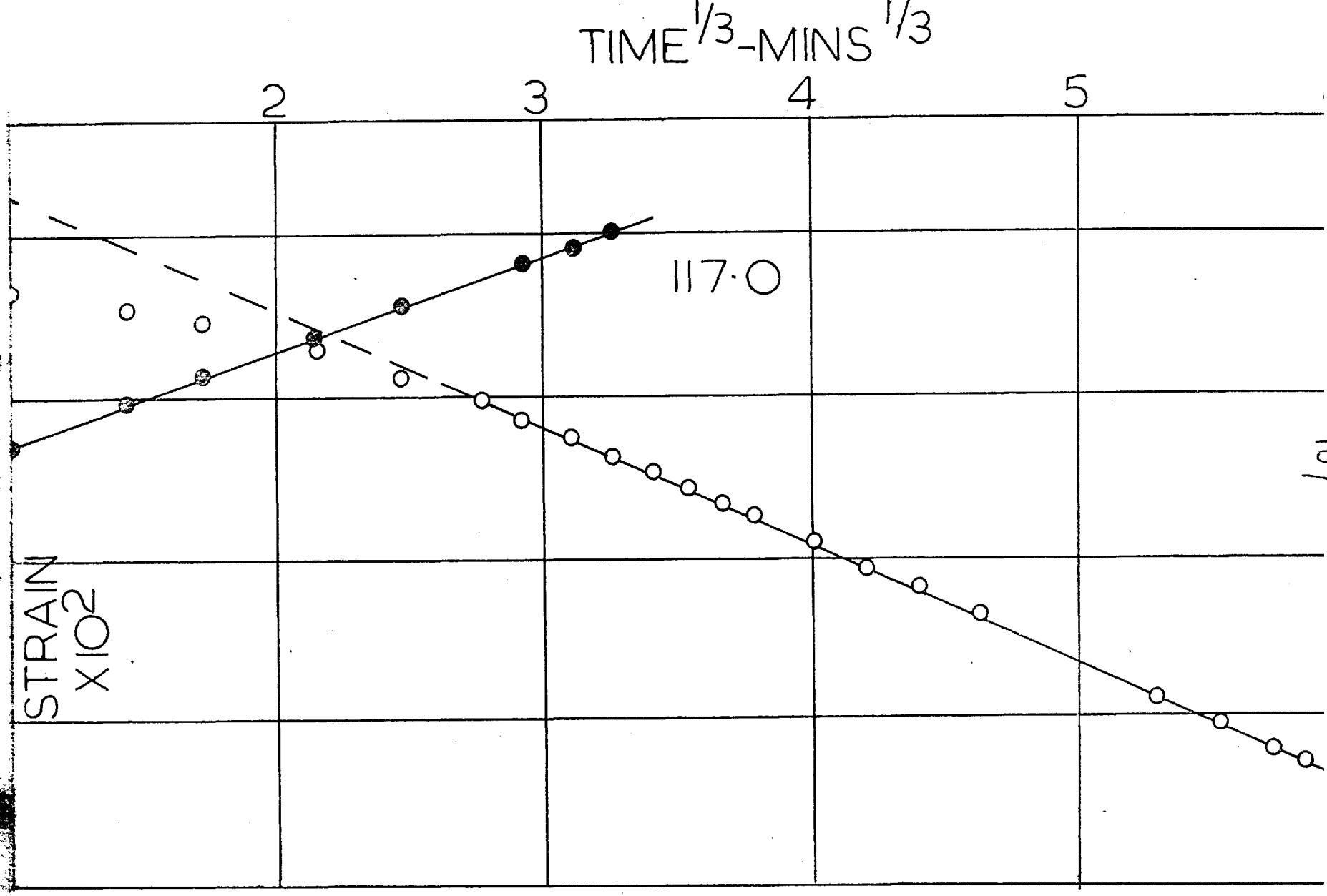


FIG 47

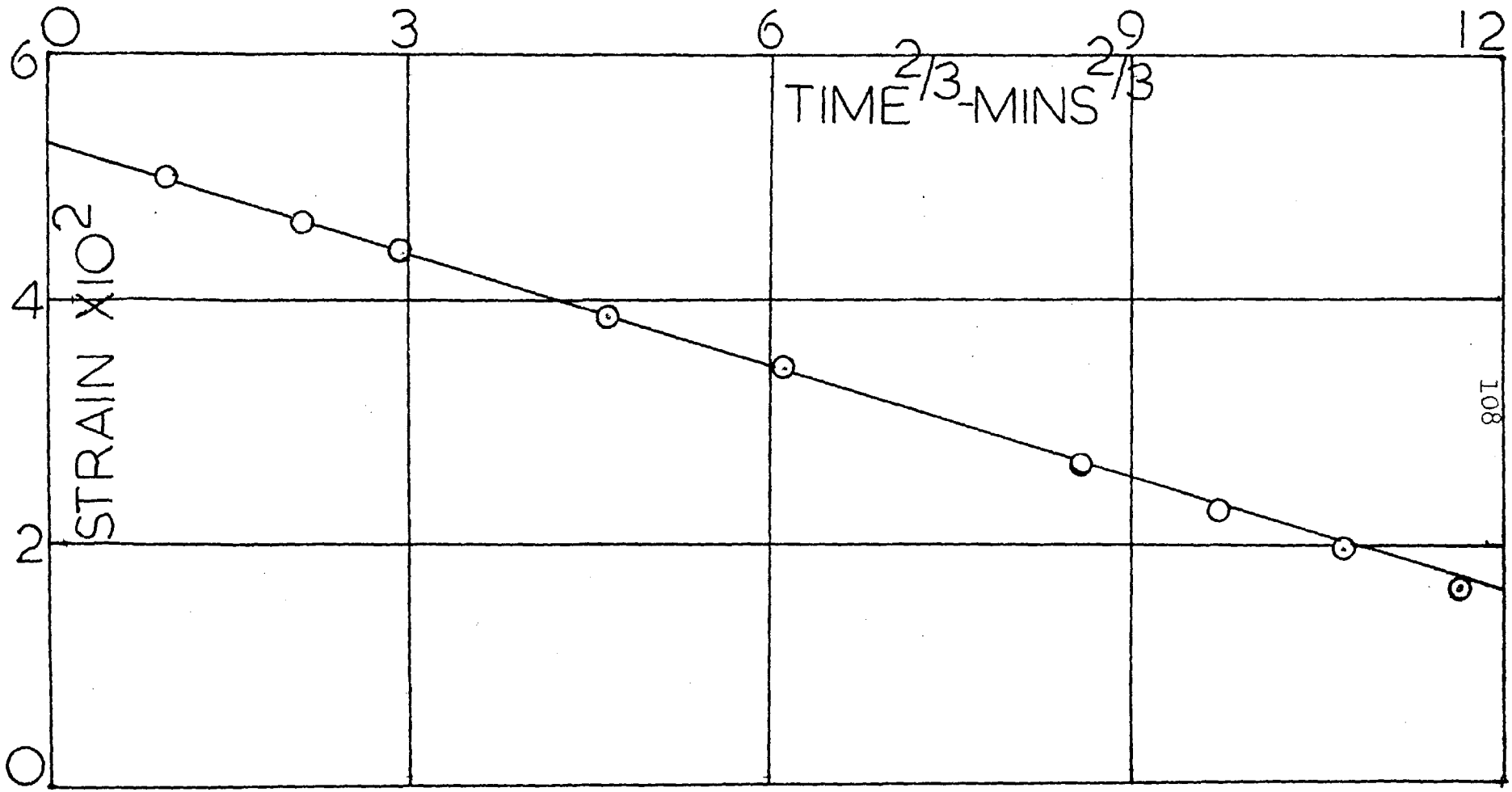
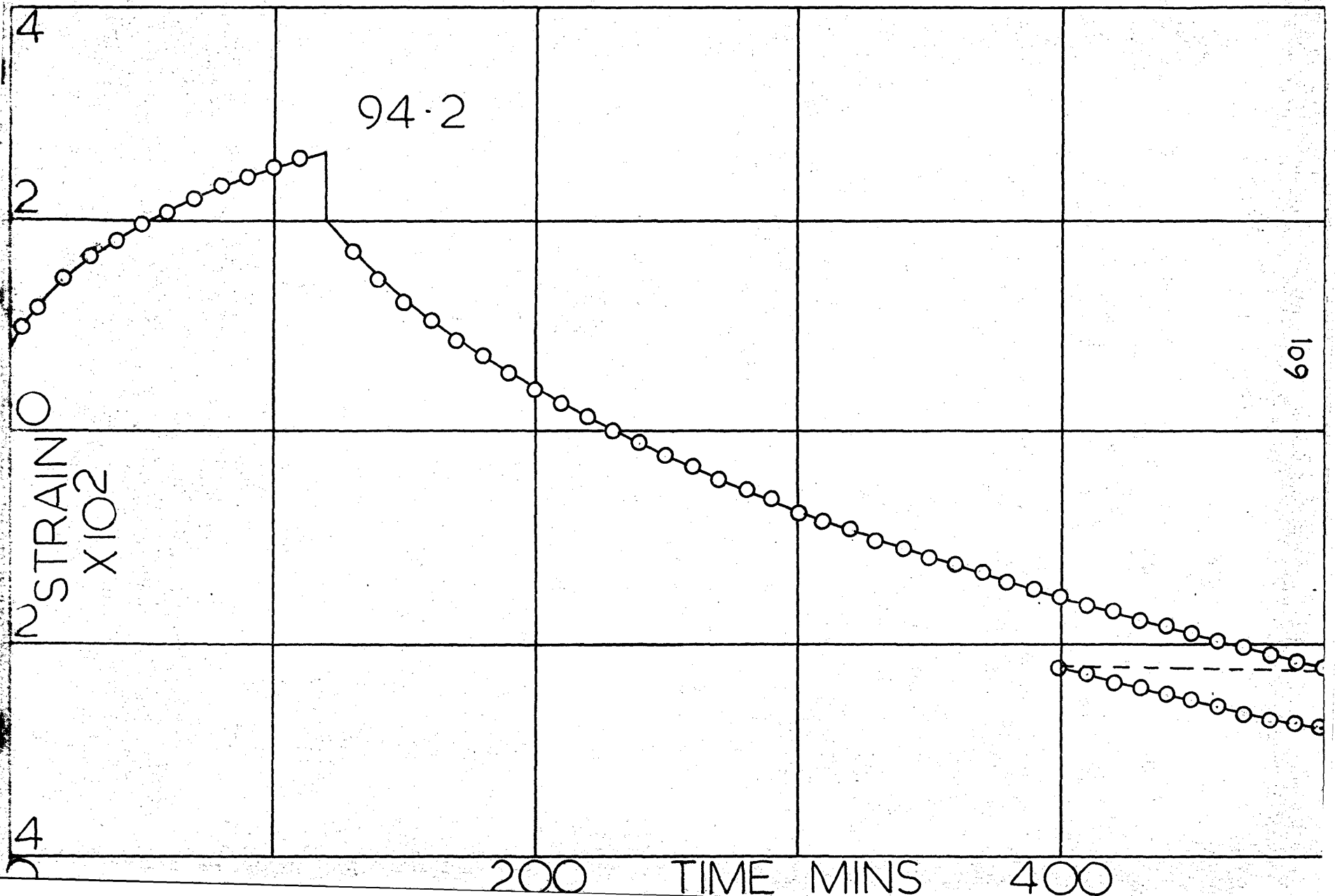


FIG 48

FIG 49



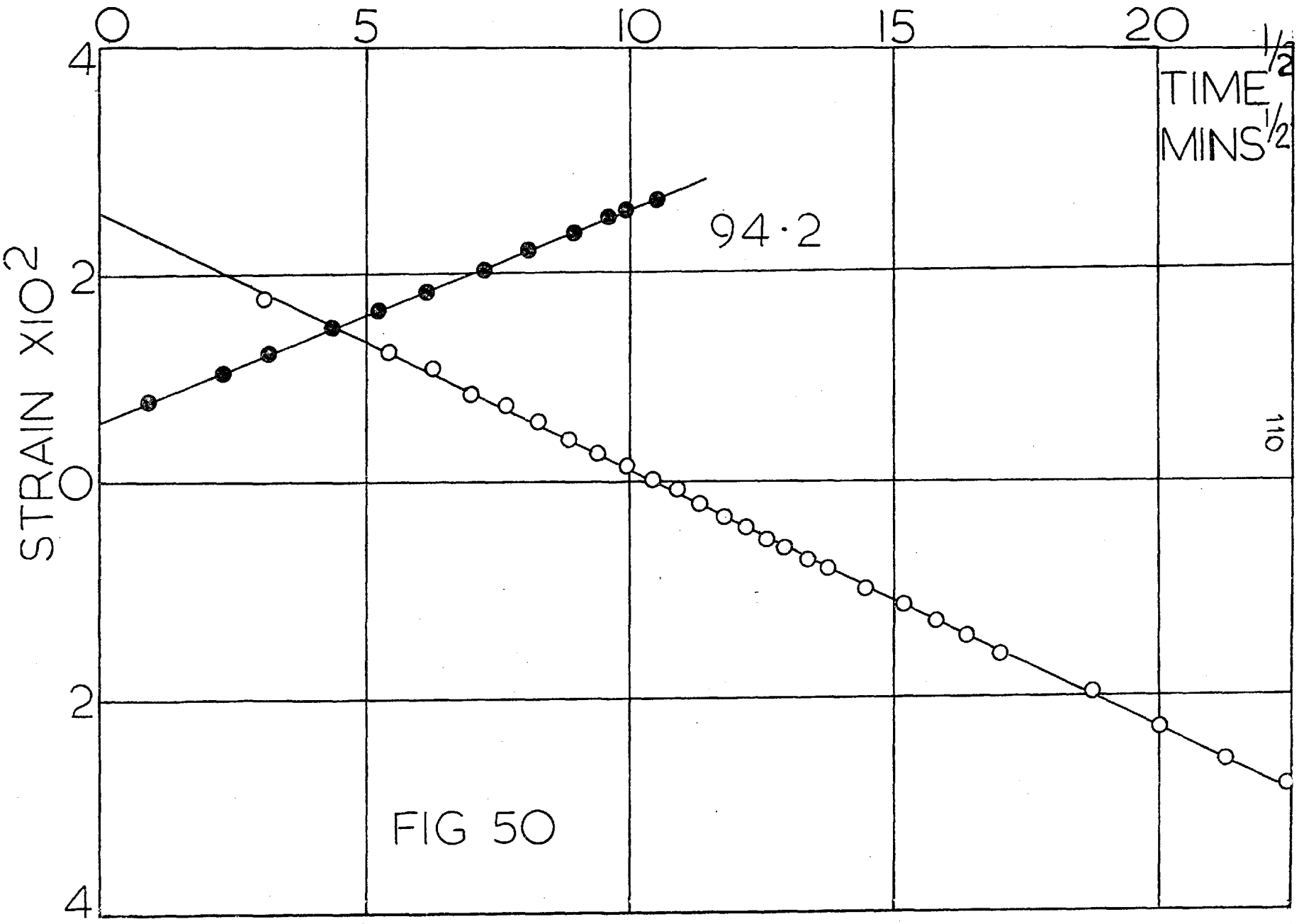


FIG 50