CHAMBER OF MINES OF SOUTH AFRICA

RESEARCH ORGANISATION

CLIMATIC CHAMBER ERGOMETER

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S Y N O P S I S

The design and calibration of an ergometer for exercising subjects during calorimetric studies in the climatic chamber, are described.

The ergometer is built into the climatic chamber and forms an integral part of the whole instrumentation system for the chamber. The ergometer pedal wheel has an unusual single spoke on which strain gauges are attached for the purpose of measuring the input torque so that errors due to frictional losses in the long chain drain to the load are eliminated. The ergometer load, which is controlled automatically to maintain a constant work-rate, is situated beneath the climatic chamber floor. Work-rate measurement is accurate to within 1 per cent of full scale.

1. INTRODUCTION

The ergometer was designed to form an integral part of the climatic chamber instrument system at the Human Sciences Laboratory. Direct calorimetric studies are made in this chamber and the ergometer has extended its application to experiments on working subjects.

The requirements for the ergometer were that

a) the subject should be seated in the centre of the chamber;

b) the framework should be light and produce a minimum obstruction to the airflow and that the radiometer arm would be attached to part of this framework;

c) the ergometer load mechanism should be outside the chamber to avoid errors due to the additional heat generated in this load;

d) the ergometer load should be controlled automatically so as to provide a constant work-rate, the measurement of which should be accurate to within 2 per cent of full scale.

The photograph illustrates the ergometer in use in the climatic chamber. A standard heavy duty cycle frame was modified to form the main structure which is supported on a central pillar. The load, consisting of an electrical dynamometer and fly-wheel, is beneath floor level. The transmission is accomplished by three sets of chains. The centre chain, together with numerous cables and the air sampling tube, pass through the vertical pillar. A chain drive was chosen in preference to a bevel gear and shaft on account of its higher transmission efficiency.

In order to avoid errors due to frictional losses in the long transmission to the load, true work-rate is determined by measuring the input torque directly at the pedal wheel and multiplying this by the speed which is measured by means of a tachometer. Work-rate is also measured at the dynamometer load and serves as a useful check, though it is always less than the true input power.

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The dynamometer load is controlled automatically to maintain a constant work-rate during an experiment. Experience has shown that a controller based on the true input measurement is rather complex owing to an undesirable time constant caused by the inertia of the fly-wheel in the control circuit. The controlled work-rate is, therefore, based on that measured at the dynamometer, while the true work-rate is indicated.

2. GENERAL PRINCIPLE

The complete system is illustrated by a block diagram in Figure 1. A pedal wheel, identical to that described in a previous report [(1)] is used for torque measurement. This technique has proved to be very reliable and accurate. True work-rate, or input power, is determined by amplifying the strain gauge input torque measurement, Et, and electronically multiplying this by the tachometer output, emf, En, to produce Ent. The fly-wheel, mounted beneath the floor is essential for smooth pedalling and control. The dynamometer is constructed from a commercial auto-alternator. Its arm is attached to a dashpot spring and low torque potentiometer. The reaction torque of the dynamometer, resisted by the spring, is measured by the displacement of the torque potentiometer [(2)]. If the tachometer output En is also connected to this torque potentiometer, R_1, then the output emf Ent' is proportional to the power dissipated by the dynamometer. The emf Ent' is compared with a reference E_r, used to set the desired work-rate. The difference, or error, is amplified and then used to control the dynamometer field. Most of the energy is not actually dissipated in the dynamometer, but in the resistor R_L connected to the armature of the dynamometer.

3. CIRCUITRY AND DESIGN

3:1 The strain gauges for torque measurement

Four Ferranti, 700-ohm silicon strain gauges are bonded to the single pedal wheel spoke [1]. The strain gauge power supply, comprising of a small transistor voltage regulator, is illustrated in Figure 5.

The torque calibration results, described in detail later, are illustrated in Figure 9. It will be seen

3/that ...

that the silicon strain gauges produce a relatively large output emf so that little additional amplification is necessary. A standard operational amplifier module type BB-1517, illustrated in Figure 5, is used.

3:2 The tachometer

A d.c. tachometer type SB-740B-1, manufactured by Servo-tek is used. The calibration of this tachometer is illustrated in Figure 7.

3:3 The true work-rate multiplier

A block diagram, indicating the principle of the multiplier, is illustrated in Figure 2.

The torque input emf Et is amplified by A_5, then 'chopped' or switched on and off at a rate of approximately 1KHz. The mark/space ratio of switching is made directly proportional to the ergometer pedal speed. The pulses entering the filter A_4, therefore, have a height proportional to torque and width proportional to speed. The filter output, which is the area of the pulse, is proportional to the product n x t or work-rate.

The correct switching mark/space ratio is achieved as follows: A triangular wave is added to the tachometer output emf En in A_3. The triangular wave is biased such that when En is zero, the negative peaks of the triangular wave leaving A_3 just touch the zero axis, the remaining signal being positive. The input triangular wave, which is the exact opposite of the output of A_3, is shown.

As En increases in a positive direction, part of the triangular output of A_3 becomes negative. The amplifier A_3 is followed by a trigger circuit which operates and opens the chopper switch to A_4 for the period that the output of A_3 is negative.

When the chopper switch is open, the torque emf Et is applied to A_4. The period for which the trigger operates is directly proportional to the height of the triangular wave that is negative, or to the amplitude of En. The

4 /maximum ...

maximum permissible value for En is equal to the peak-to-peak amplitude of the triangular wave.

Figure 4 illustrates the multiplier in detail. The triangular wave is achieved by first generating a square wave, then integrating this with a 'capacitive feedback' amplifier. Figure 10 illustrates the multiplier calibration. A full scale accuracy of 1 per cent is achieved.

3:4 The dynamometer and control

The circuit is illustrated in Figure 3. The torque potentiometer output emf is proportional to the power dissipated by the dynamometer load. This emf is used as a comparison with a reference emf to control the dynamometer load. The torque potentiometer is first connected to a high impedance emitter follower, T_1 and T_2, to avoid non-linearity. The output is then subtracted from the reference or 'set work-rate' control and amplified by the operational amplifier A_1 and amplified again by A_2. The amplifiers have a phase correcting network to ensure optimum stable control characteristics. The maximum output emf from A_2 is only 5 volts so it is followed by an additional transistor voltage amplifier T_5 and current amplifier T_6. The output of T_6 is followed by a final power amplifier, illustrated in Figure 5, which is coupled to the dynamometer field.

The meter indicator, used mainly for true work-rate measurement may also be switched to measure 'input torque' for calibration purposes and 'dynamometer load' as a check. In the latter position an additional emitter follower T_3, T_4 is used.

4. CALIBRATION PROCEDURE

All measurements should be made with an accuracy of ± 0.5 per cent.

The following apparatus is necessary:

Ergometer drive unit with flexible coupling

d.c. motor power supply

fulcrum arm

large weights - 5, 10, 15 and 28 lbs

small weights - 1, 1½ and 2 lbs

clamps

stop watch

resistance bridge

accurate voltmeter (½ per cent)

small variable d.c. power supply (0-30V)

4:1 Tachometer calibration

The tachometer is calibrated by driving the ergometer at different speeds and measuring the output emf of the tachometer.

A special stand, with variable d.c. motor and flexible coupling to the ergometer pedal shaft, is provided for driving the ergometer. The mechanism is attached to the left hand side of the ergometer after the pedal has been removed.

The tachometer output emf is available at pin Nos. 2 and 3 of the dynamometer plug (5 pins) at the back of the ergometer control unit. With the plug still in position, and the back of the control open, measure the emf between pin No. 3 and ground with a high impedance meter.

The pedal speed is best measured by timing 50 rotations of the pedals with a stop watch. Calibration should be made with pedal speeds varying between 30 and 80 r.p.m. A calibration is illustrated in Figure 7.

4:2 Dynamometer torque potentiometer calibration

The displacement of the potentiometer as a function of the dynamotor arm reaction torque, or spring extension, is required. Firstly, it is necessary to check the potentiometer for correct zero position.

1. Measure the resistance between slider and earth end of the potentiometer. Since there is zero torque, the slider should be at the earth end and the resistance very low in comparison with the total resistance of the potentiometer (50,000 ohms). For best results it should be between 100 and 400 ohms.

2. Check the zero stop of the dynamometer arm so that the slider of the potentiometer does not pass the zero position and touch the 'high end' of the potentiometer.
3. Measure the total resistance of the potentiometer with the tachometer disconnected.
4. Remove the chain from the dynamometer and make sure that the arm swings freely.
5. Disconnect the plug from the rear of the control unit.
6. The resistance between the slider and earth end of the potentiometer must now be measured for varying applied torque. Resistance measurements are made with an accurate resistance bridge.
7. Specially provided calibration weights of 1, 1½ and 2 lbs may now be suspended in turn at the end of the potentiometer cord in place of the ½ lb bias weight. In each case measure the potentiometer output resistance, taking the mean of at least four readings, allowing the arm to come to rest, alternately from a position greater and smaller than the balance point.
8. Replace the chain, bias weight, and connect the tachometer.

   A calibration is illustrated in Figure 6. Remember to subtract the ½ lb bias from each weight.

4:3 <u>Dynamometer load calibration</u>

A calibration graph of the dynamometer load may now be made.

<u>Example</u>:

With a pedal speed of 60 r.p.m. the tachometer output emf is 28 volts. (Figure 7). The chain ratio between pedals and dynamometer is 22.75, therefore the dynamometer speed is 60 x 22.75 r.p.m. = 1,365 r.p.m.

Choose a dynamometer torque of 1 ft. lb. The potentiometer output resistance taken from Figure 6 for this torque is 18,500 ohms. When the pedal speed is

60 r.p.m. and the dynamometer torque is 1 ft. lb., the output emf from the potentiometer will, therefore, be:

$$\frac{28 \times 18,500}{48,300} = 10.72 \text{ volts}$$

(where 48,300 is the total resistance of the potentiometer).

This emf is equivalent to a load given by $2 \pi NT$

or $2 \times \pi \times 1,365 \times 1$

$= 8,570$ ft. lbs./min.

Calculate another point assuming a different speed and torque. At zero load, the output emf is zero. A linear calibration, illustrated in Figure 8, may be drawn.

4:4 Ergometer control indicator for dynamometer load

The main indicator on the ergometer control is used for the measuring of the following three value

a) Pedal torque, 0 - 50 ft. lbs.

b) Dynamometer load, 0 - 10,000 ft. lbs./min.

c) True work-rate, 0 - 10,000 ft. lbs./min.

In all three positions the meter has a full scale sensitivity of 5 volts. This should first be checked.

1. With the mains power off, switch indicator selector to position two, namely, dynamometer load.
2. Zero the meter with the mechanical zero adjustment on the front of the meter. The meter must stand in a vertical position.
3. Connect a d.c. supply to earth and common of meter selector switch. Measure the power supply potential with an accurate voltmeter.
4. Switch only the d.c. power supply on and increase the output to 4 volts.
5. The meter should indicate 8. If not, adjust the trimmer immediately behind the meter.

The dynamometer load indication may now be set according to the calibration made in 4:3.

1. Remove the d.c. power supply and connect between ground (pin 2) and pin 1, (upper bar of 5 pin socket) of the dynamometer input socket, the

plug having been already removed for 4:3. The power supply negative terminal is connected to ground (pin 2).

2. Switch the ergometer control mains on.
3. Short the power supply leads and check the indicator zero. The zero may be adjusted by the trimmer marked 'zero M' on card No. 1.
4. Remove the short from the power supply and switch it on.
5. Choose a point on the calibration graph. For example, 10 volts from the torque potentiometer is equivalent to 8,000 ft. lbs./min.
6. Adjust the power supply for 10 volts.
7. The meter may now be set to indicate 8,000 ft. lbs./min., with the trimmer marked W.R.1 on card No. 1.

Note:

The meter is heavily damped in this position and adequate time must be given to allow the meter to reach the true reading.

4:5 Pedal torque

The object here is to calibrate the strain gauges which measure the input torque applied to the pedal. The strain gauge bridge output emf is required as a function of applied torque.

1. Switch the ergometer control on and allow fifteen minutes for a stable operating temperature. During the 'warm-up' period, continue with the steps Nos. 2 and 3.
2. Attach the special calibrating fulcrum arm to the left pedal of the ergometer.
3. Firmly clamp the fly-wheel which is under the floor, so that the fulcrum arm is in the forward horizontal position.
4. Measure the strain gauge bridge supply voltage between pins No. 1 and 1 of the pedal plug. (4-pin). If it is not exactly 8 volts then it may be adjusted by the

small round trimmer on the bridge power supply card which is mounted above the small mains transformer.

5. Switch the meter indicator to position 1 for torque measurement.
6. Zero the meter with the front 'zero' control.
7. Calibrating weights may now be suspended from the fulcrum arm. Weights of 5, 10, 15, 28 and 38 lbs., are recommended. Since the fulcrum point is only 10 inches from the axis, a correction must be made. For example, a 28 lb. weight will produce a torque of

$$28 \text{ x } \frac{10}{12} = 23.3 \text{ ft. lb.}$$

The full scale of the meter is 50 ft. lb. With a 28 lb. weight the torque should be 23.3 ft. lb. or 4.66 on the scale.

The scale sensitivety may be adjusted with the trimmer marked 'torque' on card No. 3.

4:6 Work-rate multiplier and indicator

The true work-rate is achieved by electronically multiplying the torque output emf with the speed output emf. It is essential to check the multiplier two or three times a year for linearity and scale.

1. Check the triangular wave generator wave form with a good d.c. oscilliscope at pin No. 10 of card No. 2. If there is any sign of distortion, adjust the circular upright trimmer on card No. 2.

2. The multiplier is best calibrated by applying varying torques with the aid of weights as described in section 4:5 and the tachometer is replaced with a variable d.c. power supply.

3. Connect the d.c. power supply to the tachometer input at pins Nos. 2 and 3 of the 5-pin dynamometer plug. (Negative to ground). The plug must be removed.

4. Connect an accurate voltmeter to the d.c. power supply.

10/5. Switch ...

5. Switch the meter indicator to position 1 and zero the torque. The zero must be done after the fulcrum arm is in place.

6. Switch the meter indicator to position 3, namely true work-rate. Zero, if necessary, with trimmer marked 'Zero M' on card No. 2.

7. Apply a known weight, e.g. 28 lbs. Check that the torque reading is correct by switching back to position 1, then return to position 3.

8. Apply a known emf from the d.c. supply to represent a given speed according to calibration on Figure 7. For example, 60 r.p.m. is equivalent to 28 volts output from the tachometer. The corresponding work-rate should be

$$2\,\pi\ 60 \times 28 \times \frac{10}{12} = 8{,}800 \text{ ft. lb.}$$

Check a second point with the same torque and at a much smaller speed.

9. Plot a graph with work-rate as a function of speed, keeping to the same torque. It should be a straight line cutting the zero axis. If the line is not straight, then the triangular wave is distorted. If the line does not cut the axis, then a bias adjustment must be made.

The slope and bias interact and are best adjusted as follows:

10. a) Apply an effective high speed (60 - 80 r.p.m.), then adjust the trimmer marked 'WR2' on card No. 2.

b) Apply an effective low speed (30 r.p.m.), then adjust the trimmer marked 'bias S' on card No. 2. After repeating the procedure a few times, the correct graph should be obtained.

11. With a fixed speed the linearity with torque may be checked and should always be correct.

A calibration is illustrated in Figure 10.

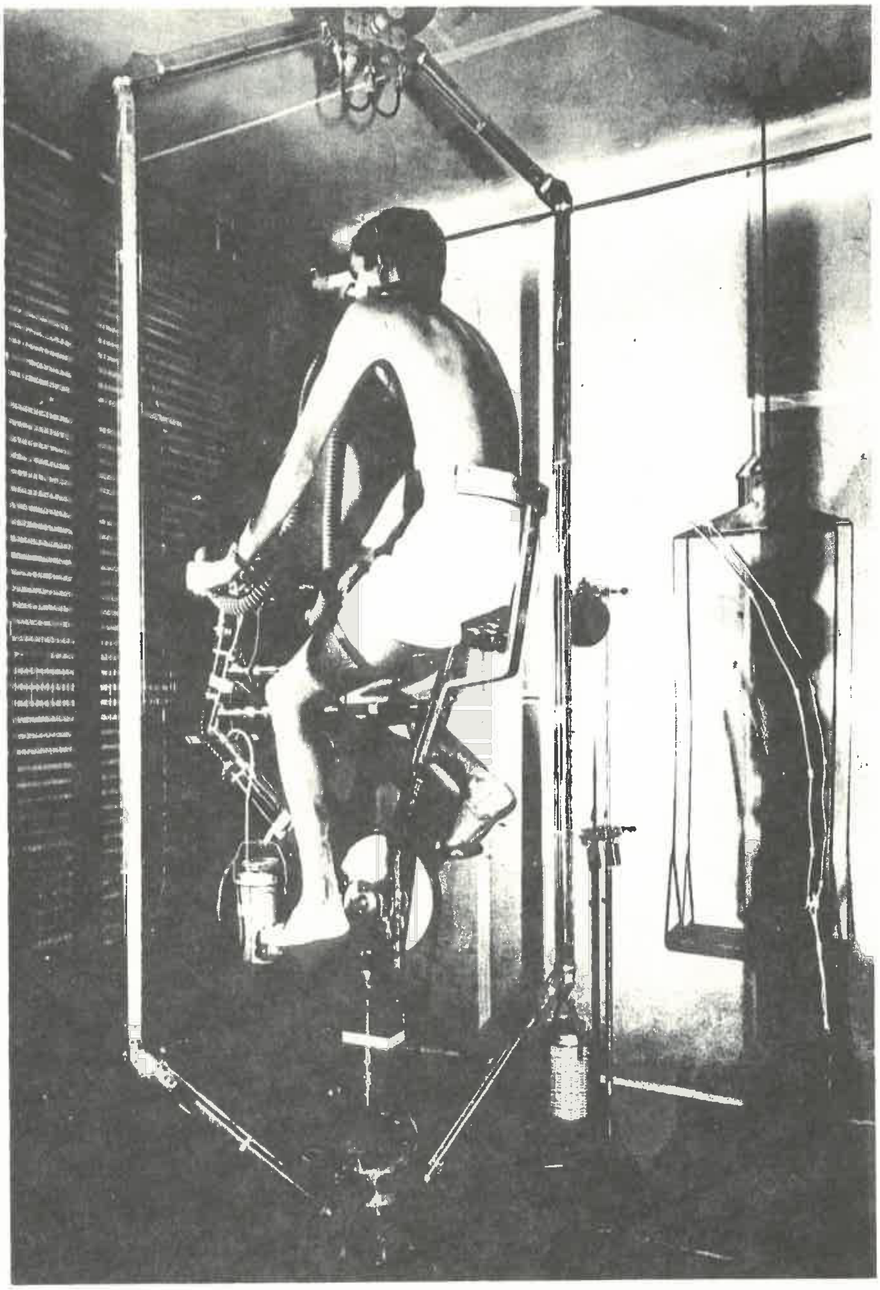
Remove the fulcrum arm and the clamp on the fly-wheel. Replace the plugs and close the control box. The calibration is now complete.

REFERENCES

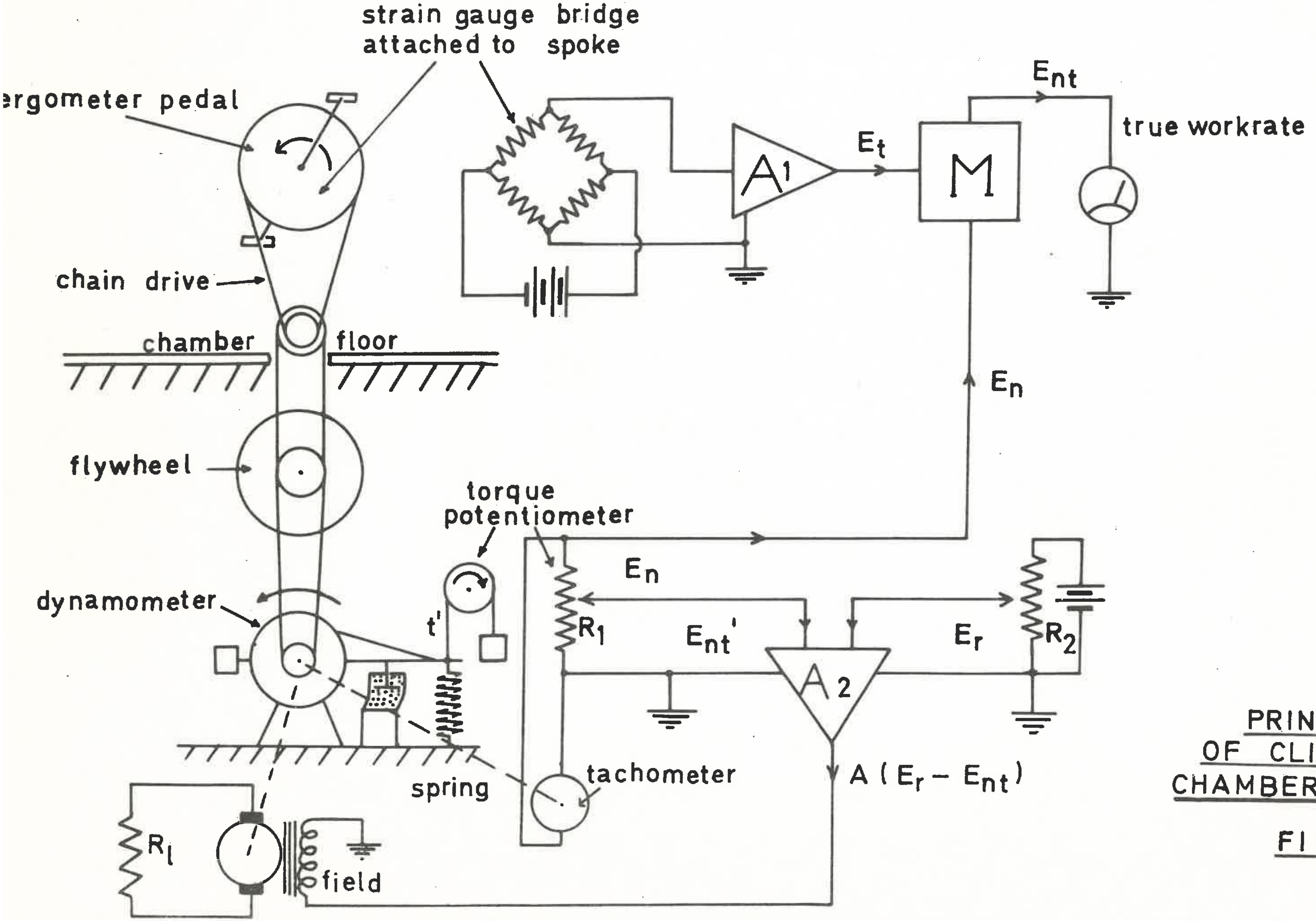
1. ATKINS, A. R. and NÜNLIST, A. : 'A precision constant work-rate ergometer', C. O. M. Research Report No. 5/65, Project No. 706/63/-.

2. ATKINS, A. R. : 'Constant work-rate bicycle ergometer', C. O. M. Research Report No. 31/66, Project No. 705/64/-, March, 1966.

/MS

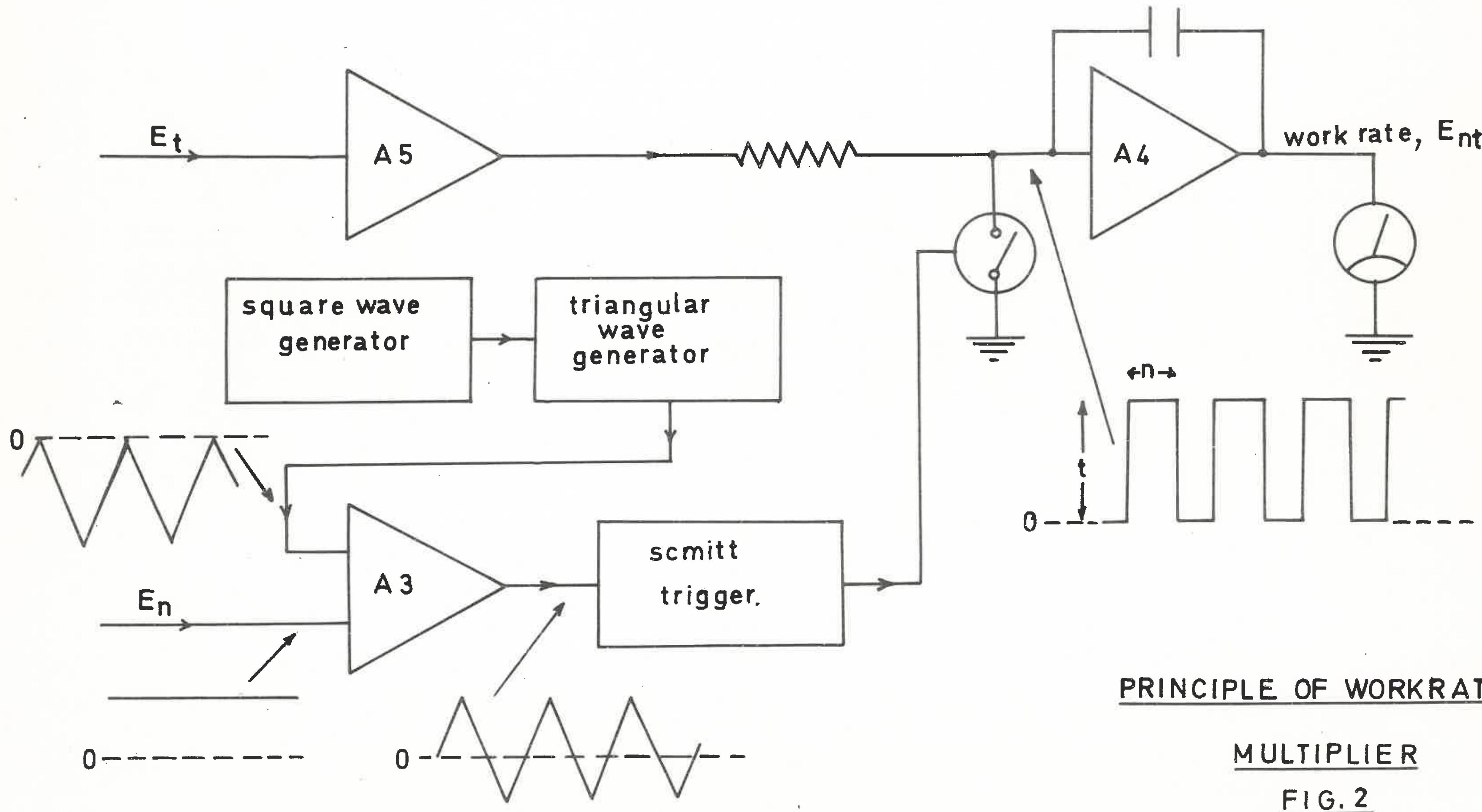


The photograph (by kind permission of the C.S.I.R.) illustrates a subject seated upon the ergometer in the Climatic Chamber of the Human Sciences Laboratory.



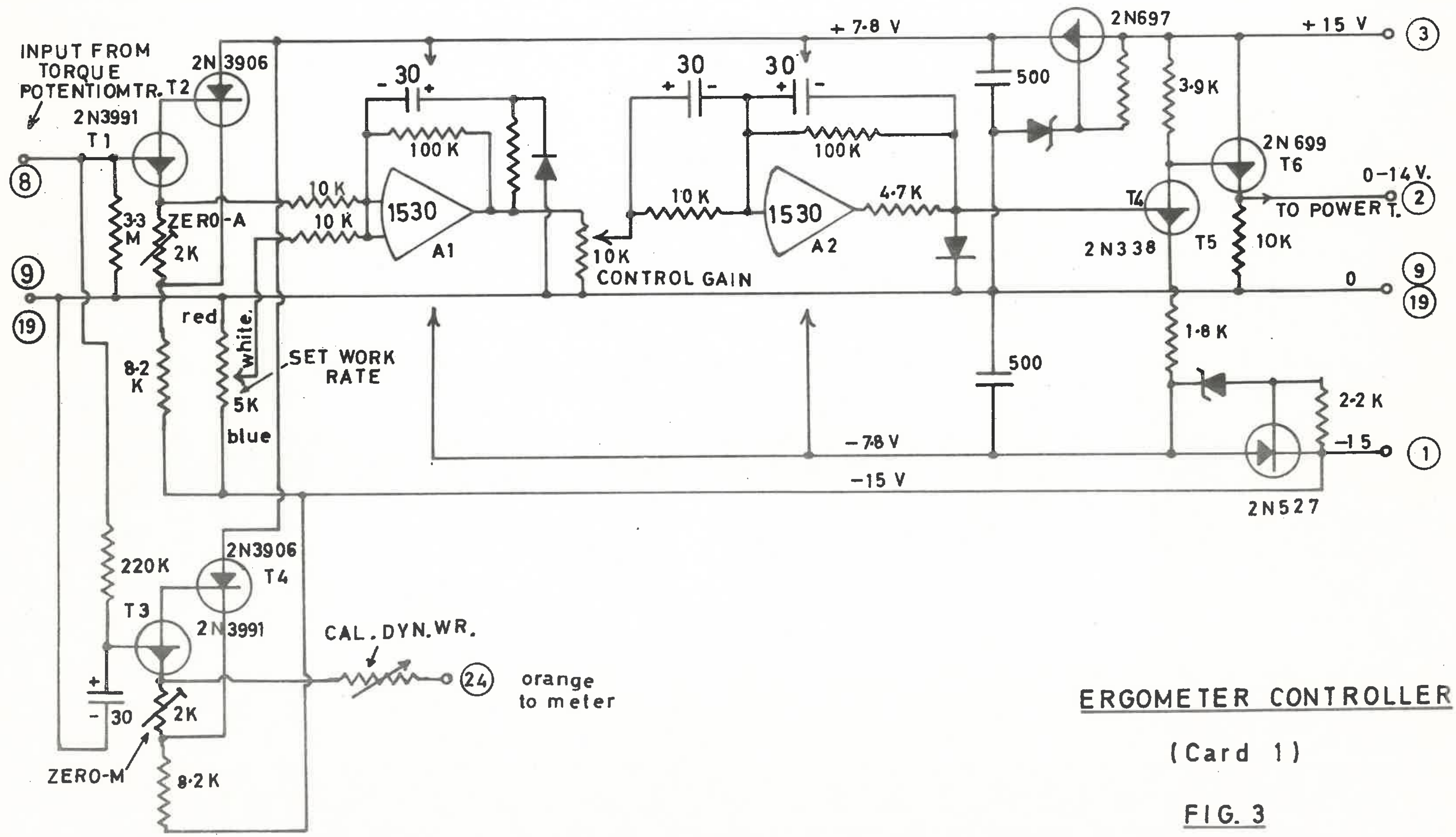
PRINCIPLE
OF CLIMATIC
CHAMBER ERGOMETER

FIG.1



PRINCIPLE OF WORKRATE MULTIPLIER

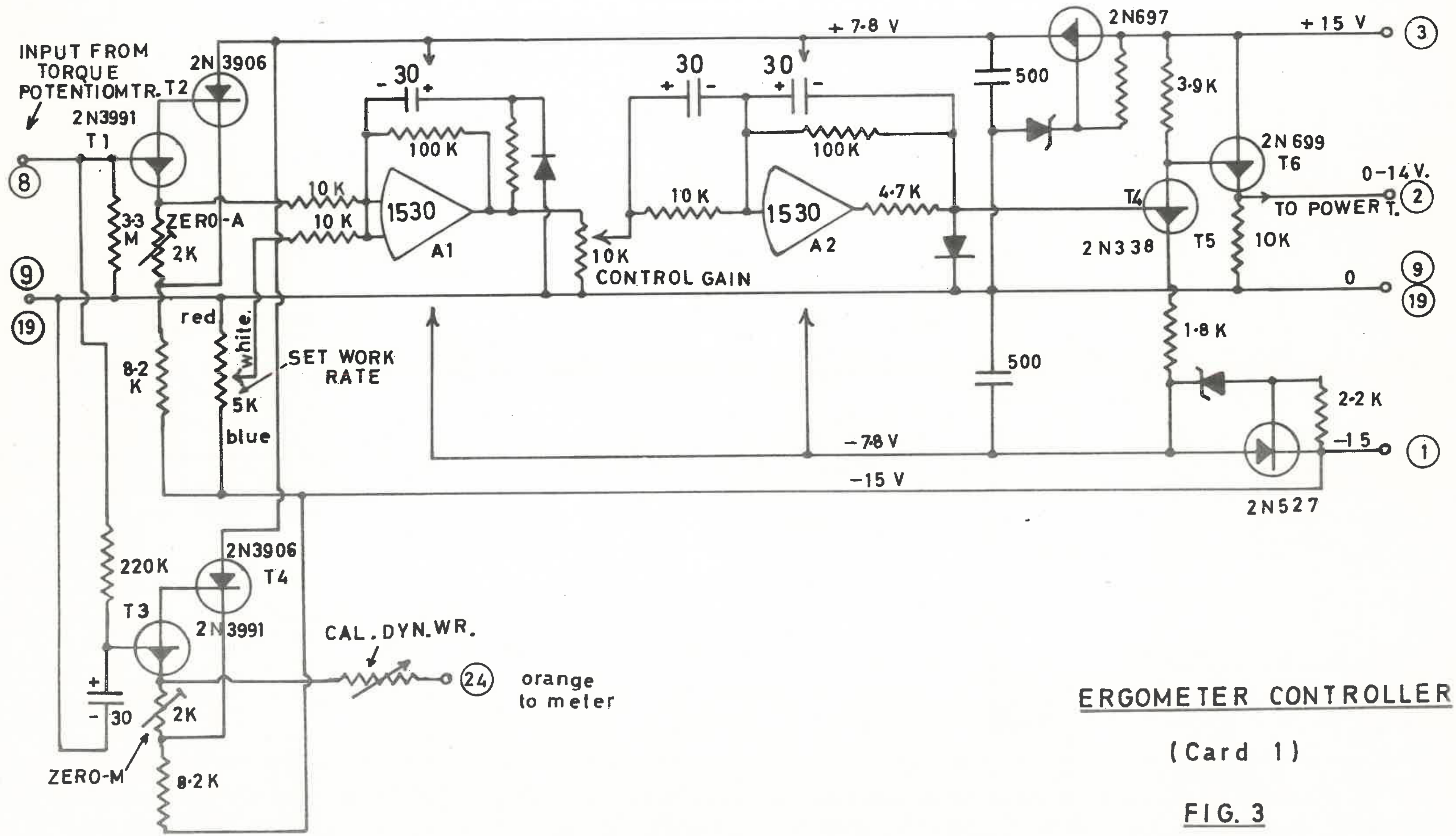
FIG. 2



ERGOMETER CONTROLLER

(Card 1)

FIG. 3



ERGOMETER CONTROLLER

(Card 1)

FIG. 3

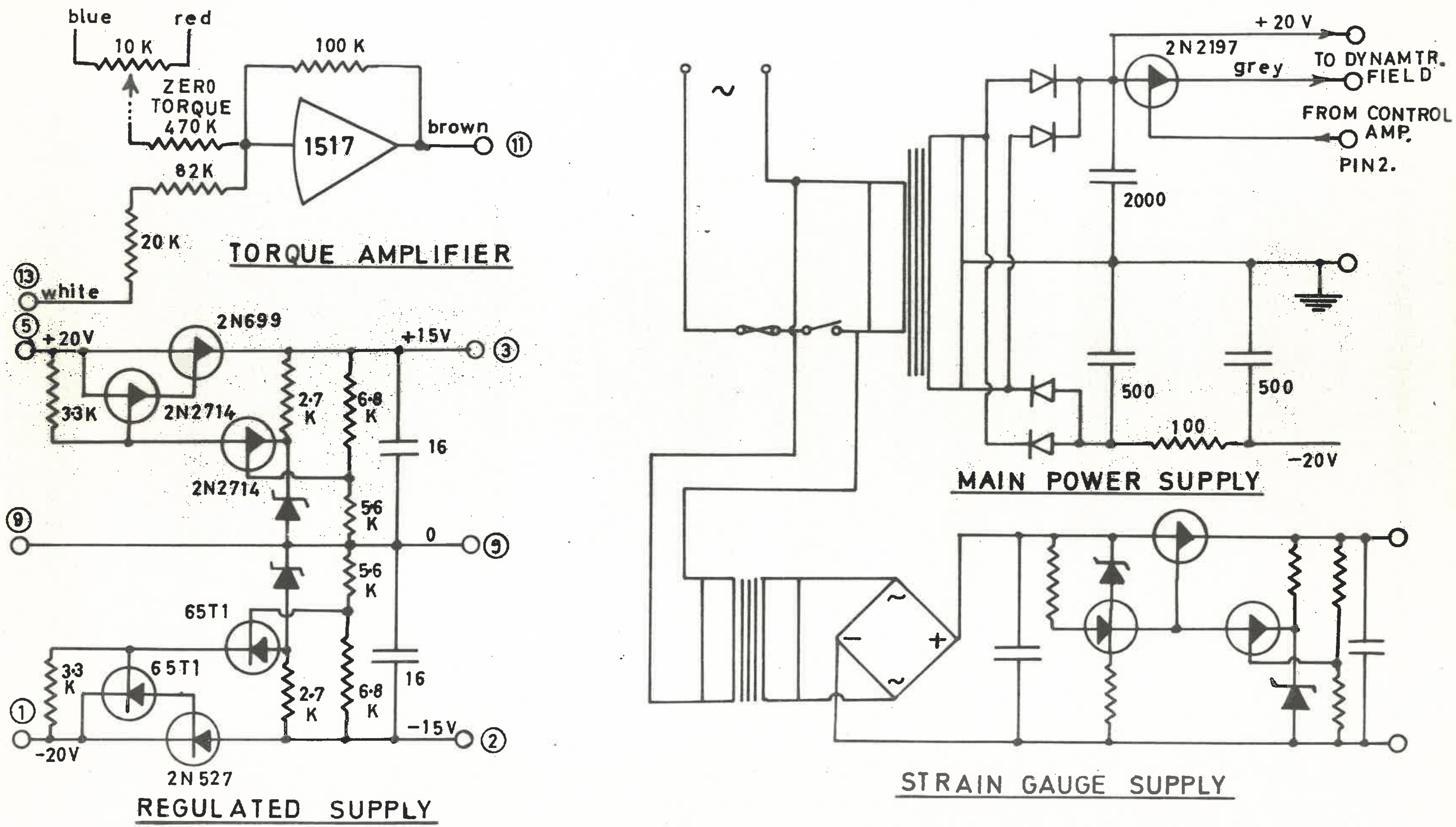
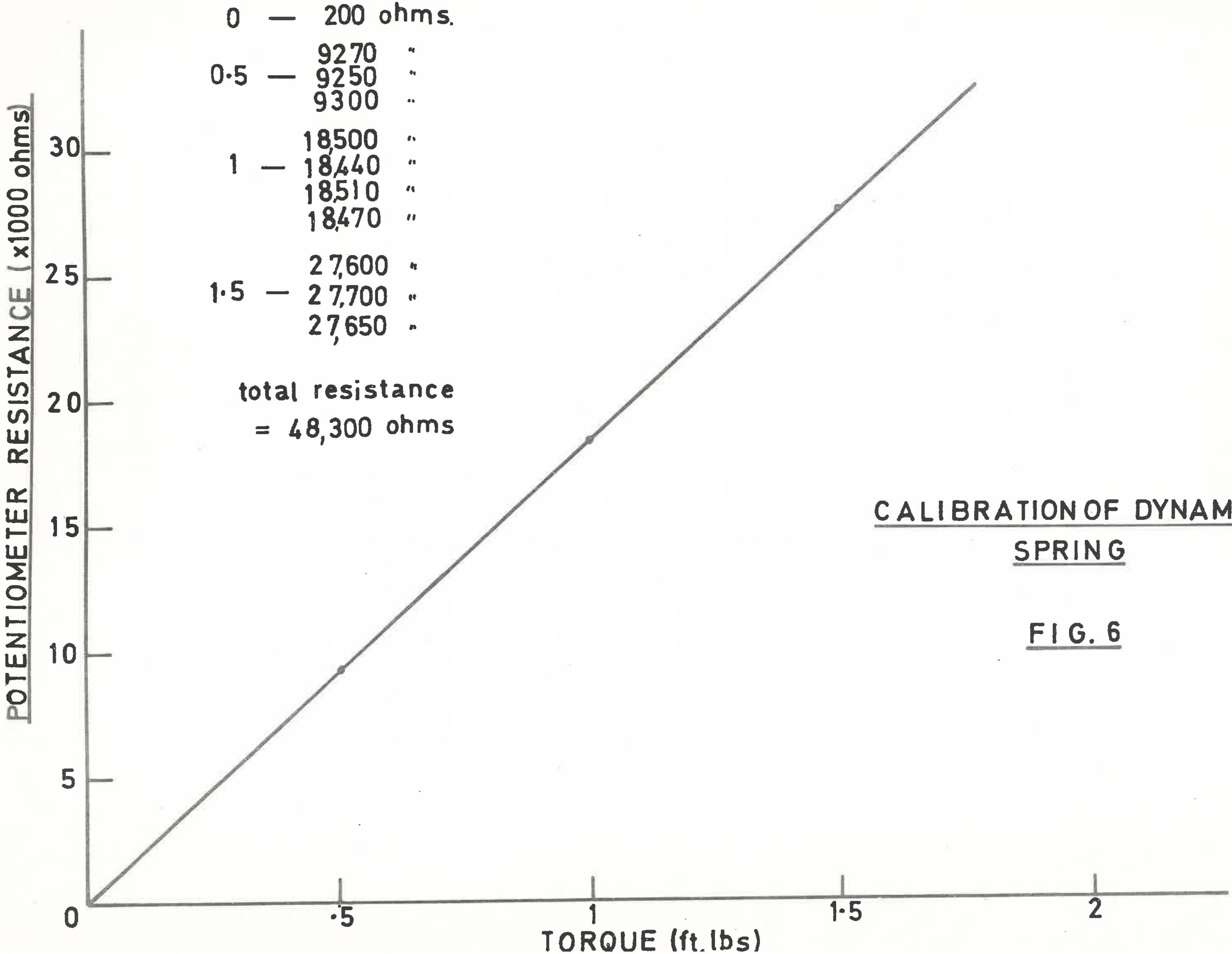
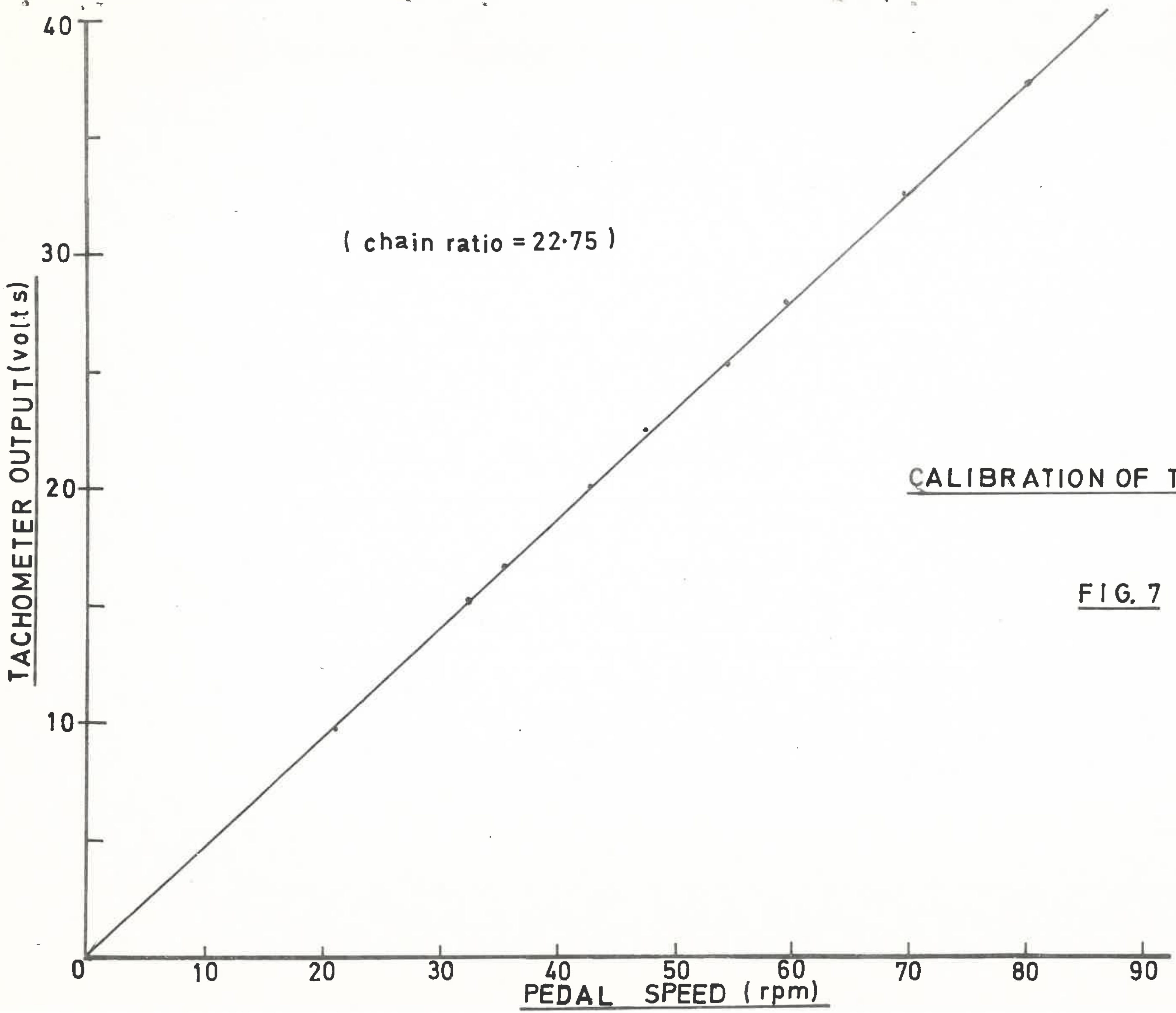

blue
red
10 K
100 K
ZERO TORQUE 470 K
1517
brown
⑪
82 K
20 K
TORQUE AMPLIFIER
⑬
white
⑤
+20V
2N699
+15V
③
3·3K
2N2714
2·7 K
6·8 K
16
2N2714
⑨
5·6 K
0
⑨
5·6 K
65T1
3·3 K
65T1
2·7 K
6·8 K
16
①
-20V
-15V
②
2N 527
REGULATED SUPPLY
~
+ 20 V
2N2197
grey
TO DYNAMTR. FIELD
FROM CONTROL AMP.
PIN2.
2000
500
500
100
-20V
MAIN POWER SUPPLY
STRAIN GAUGE SUPPLY

FIG.5



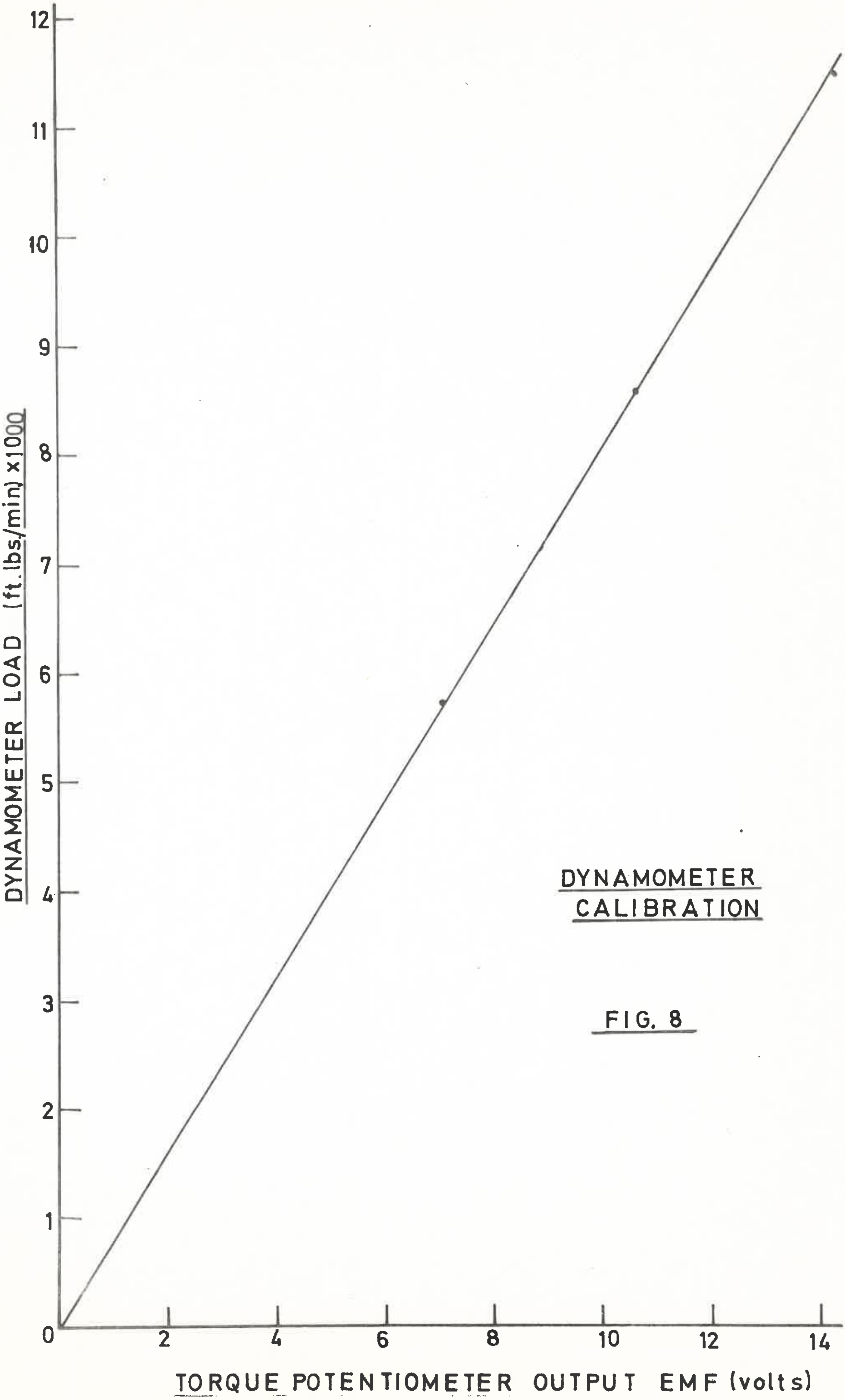
CALIBRATION OF DYNAMOMETER SPRING

FIG. 6



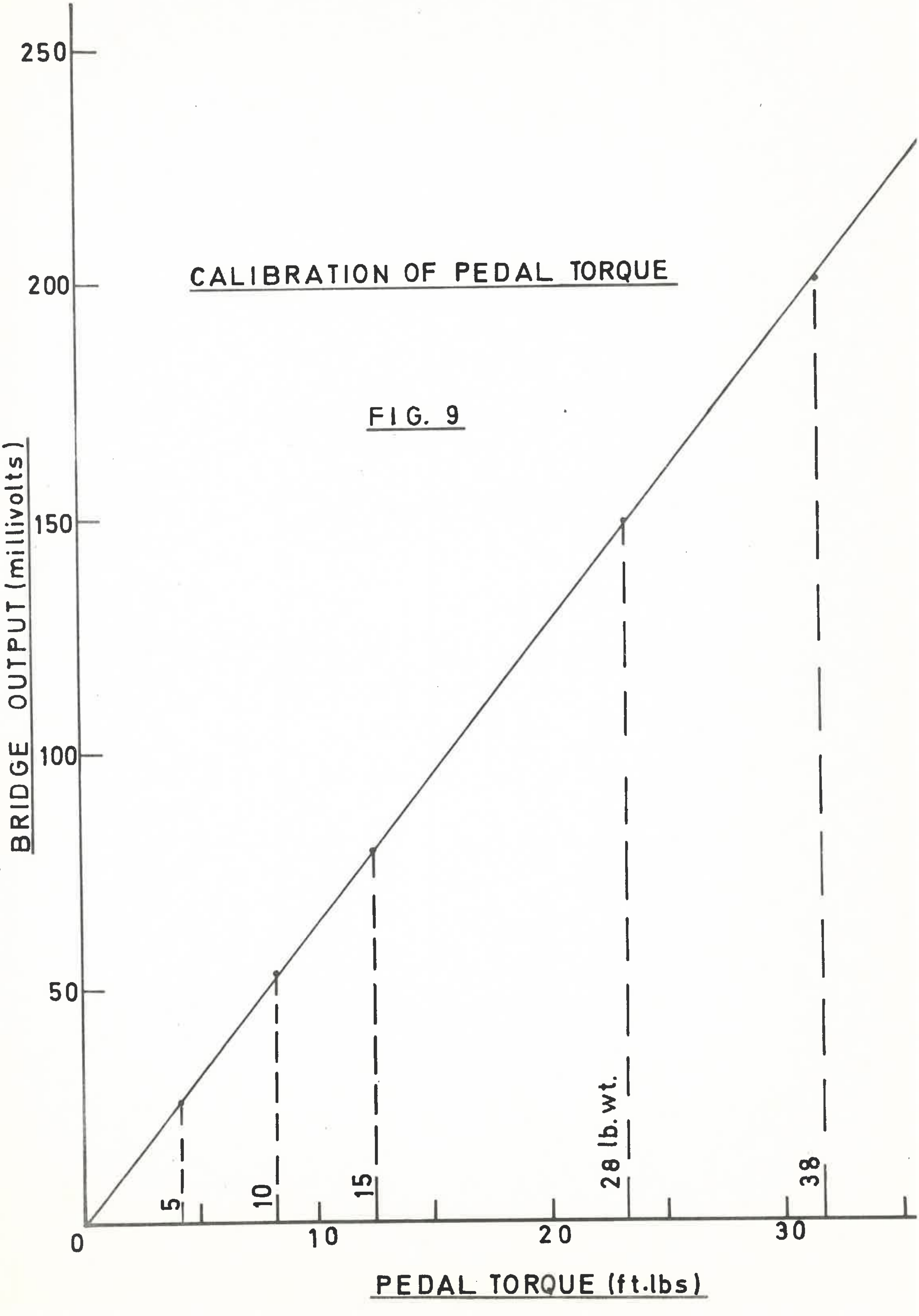
CALIBRATION OF TACHOMETER

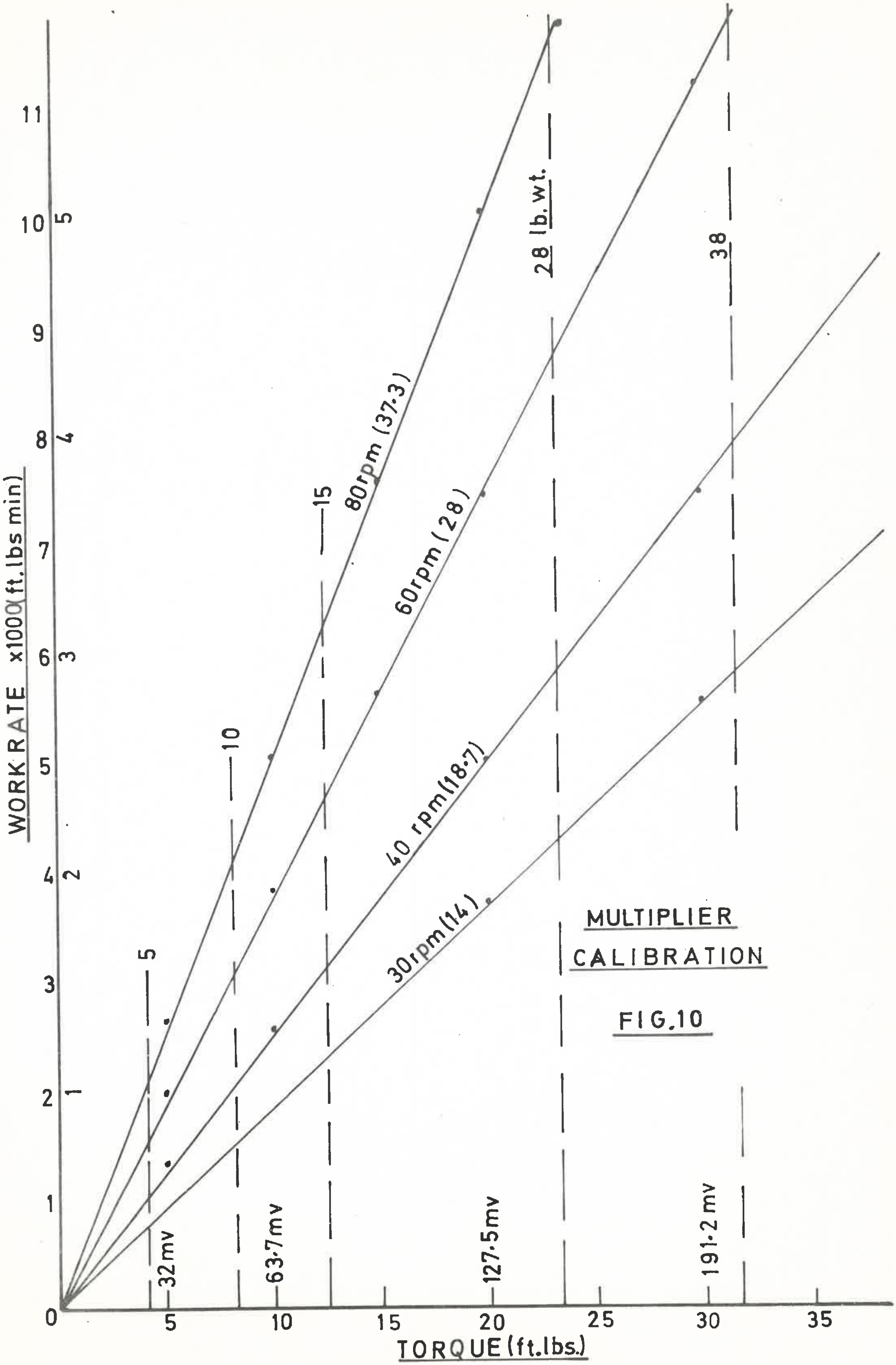
FIG. 7



DYNAMOMETER CALIBRATION

FIG. 8


CALIBRATION OF PEDAL TORQUE
FIG. 9
BRIDGE OUTPUT (millivolts)
PEDAL TORQUE (ft.lbs)
250
200
150
100
50
0
10
20
30
5
10
15
28 lb.wt.
38



MULTIPLIER CALIBRATION

FIG.10