Design of a Seisometer for Local Earthquakes

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INTRODUCTION

In the design of structures to withstand earthquakes it is necessary to know or to make assumptions as to the magnitudes of the forces involved. The static forces, those due to the weight of the structure itself and to the load which it is called upon to sustain, can be found readily enough from the various Engeneers Handbooks or from the local Building Codes. The values obtained from these sources have been tested by time and anyone using them has no doubt as to their being adequate for his purpose.

When it comes to the dynamic loads, those produced by the earthquake itself, an entirely different picture presents itself. For instead of any well organized, authentic body of information regarding the forces of earthquakes, being available, there is no place to which an engineer can turn for any reliable information of this nature. All that is left for him to do is to assume some arbitrary windload and hope that it will take care of actual earthquake conditions or else to make an assumption as to the force of any earthquake which the structure is likely to encounter.

Now that more and more attention is being directed to the design of structures to withstand earthquakes and to basing this design on more than some unproved assumptions it is necessary that there be some dependable tables of engineering information concerning earthquakes which would be abailable to all interested in the subject and which could be used by one with the assurance that the values present were at least accurate enough for engineering purposes.

Some of the items which it would be important to know are:

1. Maximum acceleration of earthquakes at the ground surface.

2. Comparison of accelerations experienced by a structure at different floor levels.

3. Comparison of accelerations experienced by structure built on rock and those built upon alluvial soil.

Since an earthquake is a dynamic affair, the acceleration produced can be taken as a measure of the force acting or of the intensity of the shock. Thus if the acceleration of an earthquake is known it is possible to have a rather definate idea as to the intensity of the quake.

In order to ascertain the values of the accelerations experienced with definiteness and accuracy it is necessary to resort to instrumental measurements. Such an instrument is the seismograph which records the motion of an earth particle during an earthquake.

Seismographs as developed for scientific purposes are quite satisfactory and are yielding much information which is of inestimable value in the determination of the structure of the earth. From the viewpoint of the engineer, however, there are many drawbacks to the present seismograph. It is a delicate, costly, and complicated instrument. Its installation requires great care and skill, and its operation is expensive and a severe draught upon the patience of the observer. The probability of securing from it a record of an earthquake which is valuable to the engineer is usually very small as most seismographs are built to record light quivers and a severe or destructive shake, which is of much more engineering interest, is apt to wreck the entire installation.

Observed data, in order to be most useful for study and analysis ought to be numerous and well distributed over the affected areas. But seismographic observations must, from their costly, complicated, and exacting nature be very few and far between. It has therefore been necessary to resort to other means of securing the desired data.

The method in use at the present time is to classify earthquakes according to their effects upon persons and upon their distinctiveness. Several scales of classification have been brought out within the last fifty years. Perhaps the one most generally accepted is the Rossi-Forel Scale proposed by Professor di Rossi, of Rome in which quakes are divided into ten classes varying from very weak to extremely strong. This scale is reproduced on page 12.

Professor Omori of the University of Tokio after a series of tests involving the forces required to topple columns has made an attempt to classify shocks upon an absolute scale of accelerations in mm/sec. His scale is shown on page 12 and a comparison of his scale and the Rossi-Forel on page 13.

While these scales are to be commended as attempts at classifying earthquakes, they fall far short of being accurate enough for engineering purposes and it is evident that we must rely upon instrumental methods for obtaining the desired knowledge. To be of real service the instrument must fulfill the following requirements:

1. It must be effective over a great enough range to handle all possible earthquakes of engineering importance, which would range from those just barely perceptible to those of the greatest destructive force.

2. It must have an accuracy sufficient for engineering purposes.

3. It must be simple in construction and require a minimum

of attendance when in operation.

4. It must be cheap enough that installation can be made throughout the entire country in sufficient number to give comprehensive data upon any shock that takes place and to give a record of the variation in the accelerations experienced from place to place within any locality, such as from floor to floor in a building or from one type of building to the next.

The design of an instrument which will fulfill these conditions is the purpose of this investigation.

STATEMENT OF PROBLEM

The problem undertaken in this thesis is that of designing and perfecting a seismograph which will record the maximum acceleration of local earthquakes; which will have a range from .001 "g" to "g", and which can be produced for about twenty-five dollars.

The lower limit of sensitivity was set at .001 "g" as being one which would be adequate to record the slightest shock which might be felt by the average individual. The upper limit was set at "g" in order to handle the largest possible shock which might be experienced.

The cost limit of about twenty-five dollars was thought to be one which would make it possible for the instrument to be distributed in sufficient quantity to insure the securing of sufficient data to be of value. Of course it was realized that the first model would cost many times the twenty-five dollars set as a limit, but it was intended to try to perfect the design so that when manufactured on a production basis the cost of the apparatus would be within the specified limit.

PROCEDURE

Upon undertaking this thesis the assistance of Dr. Sinclair Smith of the Carnegie Institute was proferred as was also the use of the equipment of the Institute.

An attempt at the solution of the problem had already been made by the Carnegie Institute and a model had been constructed. This model was essentially the same as that shown on Plate II with the exception of the indicating mechanism. When taken over this mechanism consisted of the primary lever and the pointer which were connected by means of a straight piece of wire. The changes made were; to add a device by which friction could be applied to the primary lever; to substitute a coil spring connection for the straight wire connection and to introduce oil damping on the pointer.

Some difficulty was experienced in obtaining the proper spring to use as it was necessary to have a very light spring with an elastic elongation of about 100%. Various attempts were made to produce a spring which would be satisfactory using steel or tungsten wire and wrapping it about different sizes of mandrels. The most successful seemed to be those made of tungsten wire .001 "or .0025" in diameter wrapped around a wire .04" in diameter. After the wrapping, the tungsten was heated in a flame until it became a cherry red and then quenched in water. This treatment preserved the shape of the spring after it was removed from the mandrel and permitted of the high elongation required.

The indicator after the changes had been made is shown in Plate I and the complete instrument as set up is shown on Plate II. The purpose of the oil damping was to prevent the pointer from developing momentum which would carry it past its rightful position.

The friction was applied to the primary lever to enable it to maintain its positition against the pull of the spring. The principle of its operation is that the arm with the weight activates the primary lever which moves to its appropriate position and remains there by virtue of the friction on the shaft. The spring is elongated and put in a state of stress which is removed by the slow motion of the pointer through the damping oil which continues until all of the stress has been removed from the spring and the pointer has reached its rightful position. The pointer arm is balanced about the shaft so that it will have no tendancy for motion beaause of the quake.

In order to test the seismograph as simply as possible it was determined to apply various accelerations by applying different forces to the weight arm. From the expression f=ma it is seen that in order to apply different percentages of "g" acceleration to the instrument it is necessary to apply a force of the same percent of the weight of the arm and weight to the weight arm. Thus for an acceleration of .001 "g" it is necessary to apply a force equal to .001 of the mass of the arm and weight combined.

To make it possible to apply an accurately measured force it was decided to use calibrated springs. Three springs were obtained and calibrated for elongation against force. The calibration curves of these springs are shown on pages 21 , 22 ,and 23.

In testing the seismograph the primary lever was so arranged that it just rested against the weight arm at a point about .2 of its length from the shaft. The force necessary to produce a preditermined acceleration was applied to the arm and the deflection of the pointer noted. In order to facilitate the transfer from forces to accelerations a force acceleration curve was drawn which is shown on page 24.

Tests were just made using a spring of tungsten wire .0025 in diameter. The observed data of this test is shown in tabular form on page 25 and in graphical form on page 26.

From the curve of deflections against accelerations it it seen that an acceleration of .043 "g" is necessary to overcome friction in the indicating mechanism. It is also seen that the apparatus can not record one greater than .265 "g" without going off the scale.

Since the instrument will not record accelerations less than .043 "g" or more than .265 "g" the problem presents itself of selecting a new arm which will respond to an acceleration of .001 "g" and will handle all values up to "g".

In order to accomplish this the work was organized as follows:

1. Compute the normal deflection of the present spring arm under a force of .043 g.
2. Compute the actual deflection of the arm.
3. Determine the difference in deflection due to the frictional resistance of the pointer.
4. Determine the force of the frictional resistance.
5. Determine deflection of spring corresponding to deflection of pointer of 1 mm.
6. Assume different spring sizes.
7. Calculate length and weight for period of 1/6 sec.
8. Calculate force in grams for acceleration .001 g.
9. Determine normal deflection for .001 g.
10. Determine decrease in deflection due to friction.
11. Determine actual deflection of spring.
12. Determine actual deflection of pointer.

The development of the different formulas necessary in the carrying out of the above program is shown on page 14 and the determination of the mass required is shown on page 16.

The calculated weight necessary, 45 lbs., was thought to be too large for convenience, so another test was run on the seismograph using a tungsten wire spring .001 in diameter in place of the .0025 in. spring used before. The results of this test are tabulated on page 25 and are shown in graphical form on page 26. Upon calculating the mass necessary to produce a deflection of 1 mm for an acceleration of .001 g it is found that a weight of 25 lbs will be required. This work is shown on page 17.

Since 25 lbs seemed a reasonable weight to use, it was decided to assume different sizes of arms and to calculate the lengths and deflections. This work is shown in Plate III. The arm selected as best meeting the requirements is 1/4 x 1 1/2 x 18 9/16 with the center of the mass 13 5/16 in from the support. The mass is to consist of two cast iron weights each 5 in. diameter by 1 31/32 in high.

When the deflection of the arm was computed for an acceleration of "g" the value obtained, 0.371 in, was much too great for the pointer to stay on the scale. Since the allowable deflection of the pointer was known, the maximum permissable deflection of the arm was found by assuming a value for the magnification of the indicator from the curve on page 20.

The problem then presented itself of cutting down the maximum deflection of the arm to such an amount as would keep the pointer on the scale and at the same time to maintain the value of deflection corresponding to an acceleration of .001 "g". The most feasible way of doing this seemed to be in having some means by which the effective length of the arm could be decreased at the higher accelerations. The easiest way of accomplishing this appeared to be in having two curved surfaces, one on either side of the arm so arranged that as the amplitude of the motion increased, the arm would bear upon the surface nearer to the mass, thus decreasing its effective length. The calculations involved in selecting the proper curvature for the two surfaces are shown on page 19 . From the results of the calculations it appeared that it would be necessary to have a radius of curvature of 4000 in. Since the production of such a radius of curvature is beyond the realms of practical machine work, this plan was abandoned as impractical.

An alternative idea was to allow the arm its full deflection and to reconstruct the indicator mechanism to take care of this, In order to make this change, it would be necessary to make the primary lever longer on the side where it touched the arm and to arrange the pointer so that it would be free to make several revolutions. A graphical analysis of such an arrangement as shown on Plate IV showed the scheme to be entirely satisfactory. By utilizing this idea it was possible to draw up plans for a new instrument which would fulfill the specified conditions. These plans are shown on Plate V and the accompanying force acceleration curve on page 27.

Professor R.R. Martel of the California Institute of Technology thought it would be well to draw up plans of another intensity meter which would not attempt to cover such a wide range as the one just mentioned but which would deal with accelerations varying from about 1/20 "g" to 1/2 "g" and which would be even simpler than the other. This suggestion was carried out and resulted in the design of a seismometer consisting of a horizontal pendulum with a pencil at the end bearing upon a piece of paper. The displacement of the pendulum and hence the length of the mark on the paper varies from about 1/16 in. at an acceleration of 1/20 "g" to 1 in. at an acceleration of "g". The calculations of this design are shown on page 17 and the plans on Plate VI

SUMMARY

The work done in the course of this thesis consists of:

1. Perfecting the design of a magnifying, indicator mechanism.
2. Constructing and testing a seismograph.
3. Applying the results of this test to the design of a new seismograph which will fulfill the specified requirements.
4. Designing an additional seismograph of limited range and simpler construction.

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To Dr. Sinclair Smith of the Carnegie Institute goes acknowledgment for much aid derived from discussing with him the various problems which arose during the course of the work and for the generous financial aid which he secured with which the models were constructed.

Credit is due to the members of the staff of the Seismological Laboratory of the Carnegie Institute of Washington for the use of

their tools and other facilities and for the kindly interest which they displayed in the work.

ROSSI-FOREL SCALE OF EARTHQUAKE SHOCKS

I. Microseismic shock: recorded by a single seismograph or by seismographs of the same model, but not by several seismographs of different kinds; the shock felt by an experienced observer.

II. Extremely feeble shock: recorded by several seismographs of different kinds; felt by a small number of persons at rest.

III. Very feeble shock: felt by several persons at rest; strong enough for the direction or duration to be appreciable.

IV. Feeble shock: felt by persons in motion; disturbance of moveable objects, doors, windows; cracking of ceilings.

V. Shock of moderate intensity: felt generally by everyone; disturbance, furniture, beds, etc. ringing of some bells.

VI. Fairly strong shock: general awakening of those asleep, general ringing of bells, oscillation of chandeliers; stopping of clocks; visible agitation of trees and shrubs; some startled persoms leave their dwellings.

VII. Strong shock: overthrow of moveable objects, fall of plaster; ringing of church bells; general panic, without damage tobuildings.

VIII. Very strong shock: fall of chimneys, cracks in the walls of buildings.

IX. Estremely strong shock: partial or total destruction of some buildings.

X. Shock of extreme intensity: great disaster, ruins, disturbance of the strata, fissures in the ground, rock-falls from mountains

OMORI'S ABSOLUTE SCALE OF DESTRUCTIVE EARTHQUAKES

No.1. Maximum acceleration = 300 mm. per sec. per sec. The motion is sufficiently strong that people generally run out of doors. Brick walls of bad construction are slightly cracked; furniture overthrown; wooden houses so much shaken that cracking noises are produced; trees visibly shaken; waters in ponds rendered slightly turbid in consequence of the disturbance of the mud; pendulum clocks stopped; a few factory chimneys of very bad construction damaged.

No.2. Maximum acceleration = 900 mm. per sec. per sec. Walls in Japanese houses are cracked; old houses thrown slightly out of the vertical; tombstones and stone-lanterns of bad construction overturned. In a few cases changes are produced in hot springs and mineral waters. Ordinary factory chimneys are not damaged.

No.3. Maximum acceleration = 1200 mm. per sec. per sec. About one factory chimney in every four is damaged; brick houses of bad construction partially or totally destroyed; a few old wooden dwelling-houses and warehouses totally destroyed; wooden bridges slightly damaged; roof tiles of wooden houses disturbed; some rock fragments thrown down from mountain sides.

No.4. Maximum acceleration = 2000 mm. per sec. per sec. All factory chimneys are broken; most of the ordinary brick buildings partially or totally destroyed; cracks two or three inches in width produced in low and soft grounds; embankments slightly damaged here and there; wooden bridges partially destroyed.

No.5. Maximum acceleration = 2500 mm. per sec. per sec. All ordinary brick houses are very severely damaged; about three per cent of the wooden houses totally destroyed; embankments severely damaged; railway lines slightly curved or contorted; cracks one or two feet in width produced along river banks; waters in rivers and ditches thrown over the banks; wells mostly affected with changes in their waters; landslips produced.

No.6. Maximum acceleration =4000 mm. per sec. per sec.Fifty to eighty per cent of the wooden houses totally destroyed; embankments shattered almost to pieces; roads made through paddy fields so much cracked and depressed as to stop the passage of wagons and horses; railroad lines very much contorted; large iron bridges destroyed; wooden bridges partielly or totally destroyed; cracks a few feet in width formed in the ground, accompanied sometimes by the ejection of sand and water; low grounds, such as paddy-fields, very greatly convulsed, both horizontally and vertically; sometimes causing trees and vegetables to die; numerous land-slips produced.

No.7. Maximum acceleration much above 4000 mm. per sec. per sec. All buildings except a very few wooden houses are totally destroyed; some houses, gates, etc., projected one to three feet; remarkable landslips produced, accompanied by faults and shears of the ground.

COMPARISON OF SCALES

ABSOLUTE SCALE ACCELERATIONS	INTENSITY	ROSSI-FOREL SCALE
	Slight	1
		2
	Weak	3
		4
		5
	Strong	6
1-300		7
2-900	Violent	-
3-1200		8
4_2000		9
5-2500		10

DEVELOPMENT OF FORMULAE

$t = \pi\sqrt{\frac{m}{f/d}}$ Half period of Simple Harmonic Motion of cantilever beam (Firth & Buckingham - Vibration in Engr.)

m = mass
f/d = force required for unit displacement

$t = \pi\sqrt{\frac{md}{f}}$ $\qquad \frac{f}{d} = \frac{3EI}{L^3}$

$t = \pi\sqrt{\frac{mL^3}{3EI}}$

By dimensional reasoning:

$m = \frac{FT^2}{L}$	slugs	$E = \frac{F}{L^2}$	lbs./ft.^{2}
$I = L^4$	feet^4	$L = L$	feet

$$T = \sqrt{\frac{FT^2L^3L^2}{LFL^4}} = T$$ Which checks.

Converting the units:

m in lbs. ÷ 32 = m in slugs
E in lbs./in. x 144 = lbs./ft.^{2}
I in in.^{4} ÷ 20,736 = ft.^{4}
L in in.^{3} ÷ 1728 = ft.^{3}

then

$$t = \pi\sqrt{\frac{mL^3\,20736}{(32)(1728)(3)(E)(144)(I}} = \pi\sqrt{\frac{m\,L^3}{1152EI}}$$

$t = \frac{\pi}{34}\sqrt{\frac{mL^3}{EI}}$ for the half period

$t = \frac{\pi}{17}\sqrt{\frac{mL^3}{EI}}$ for the whole period (I)

Assumptions:

$t = .166$ $\qquad E = 30{,}000{,}000$

$t^2 = \frac{\pi^2 mL^3}{17^2 EI}$ from (I)

$$L^3 = \frac{17^2t^2EI}{m} = \frac{(289)(.166^2)EI}{\pi^2 m} = \frac{24{,}390{,}000\ I}{m}$$

$L = 290\sqrt[3]{\frac{I}{m}}$ (II)

$d = \frac{Pl^3}{3EI}$ deflection of cantilever beam with concentrated load at the free end (Boyd-Strength of Materials, p148)

$l^3 = 24,390,000 \frac{I}{m}$ $E = 30,000,000$

$$d = \frac{24,390,000PI}{(3)(30,000,000)Im} = .271 \frac{P}{m} \quad \text{(III)}$$

Deflection due to acceleration of .001"g"

$F = .001m = P$

$$d = \frac{(.271)(.001)(m)}{m} = .000271 \text{ in.} \quad \text{(IV)}$$

Deflection of pointer

Magnification assumed 500
Displacement assumed 1 mm.

$$\text{Displacement of arm} = \frac{.1}{(500)(2.54)} = .0000787 \text{ in. per mm. of pointer} \quad \text{(V)}$$

FORMULAE USED IN THE SELECTION OF THE ARM

$$\text{Length to weight from support} = 290\sqrt[3]{\frac{I}{m}} \quad \text{(II)}$$

$$\text{Weight of arm} = \frac{\text{Length} + 3}{12} \times \text{wt from p49 Carnegie Pocket Comp.}$$

$$\text{Period of arm} = \frac{\pi}{17}\sqrt{\frac{mL^3}{EI}} = .1847\sqrt{\frac{mL^3}{EI}} \quad \text{(I)}$$

Deflection of acceleration

$$d = \frac{P(l - a)^2(2l+a)}{6EI}$$ (Boyd-Strength of Materials p149)

Deflection of friction

$$d = \frac{Pl^3}{3EI}$$ (Boyd - page 148)

$$\text{Deflection of pointer} = \frac{\text{displacement of arm}}{.0000787} \text{ mm.}$$

COMPUTATION OF WEIGHT USING SPRING .0025" in diam.

Assume that the weight arm makes contact with the primary lever .2 of its length from the pivot. From the curve the magnification is seen to be 500.

From tests the movement of the pointer corresponding to an acceleration of .073"g" is 3.025 cm. The deflection of the arm actuated by this force would be = deflection of pointer ÷ magnification.

Since the weight arm changes its position relative to the lever, we will assume an average magnification of 200.

$$\text{Deflection of arm} = \frac{3.025}{200} = .01513 \text{ cm. or } .00595 \text{ in.}$$

Deflection of arm, no friction:

$$d = \frac{P(1-a)^2(21+a)}{6EI}$$

$1 = 6.687$ $a = 2.437$ $E = 30,000,000$
$I = .00000533$ $P = 39g = .086$ lbs.

$$d = \frac{(.086)(4.75)^2((2)(6.687)-2.437)}{(6)(30,000,000)(.00000533)} = .0256 \text{ in.}$$

Difference in deflection due to frictional resistance:

$$\text{Diff.} = .0256-.00595 = .01965 \text{ in.}$$

Value of frictional resistance:

$$d = \frac{Pc^3}{3EI} \; ; \qquad P = \frac{3EId}{c^3}$$

$$P = \frac{(3)(30,000,000)(.00000533)(.01965)}{6.6875^3} = .0319 \text{ lbs.} = 14.5g$$

Check;

From curve, force to overcome friction = .073"g" or 23g
Assume the force is applied at the center of gravity
Equivalent force at end $= \frac{(23)(425)}{6.6875} = 14.6$ g.

Deflection due to friction from (III)

$$d = \frac{(.271)(.0319)}{m} = \frac{.00865}{m} \text{ in.}$$

From(IV)deflection of acceleration = .000271

From (V) displacement required = .0000787

Normal displ.-frictional displ. = required displ.

$$.000271 - \frac{.00865}{m} = .0000787$$

$$m(.0001923) = .00865 \qquad m = 45 \text{ lbs.}$$

COMPUTATION OF WEIGHT USING SPRING .001" IN DIAM.

From curve, force required to overcome friction equals .0154"g" Which is 8.2 g. or .01806 lbs.

Deflection due to acceleration = .000271 in. from (IV)

From (III) deflection of friction $= \frac{(.271)(.01806)}{m} = \frac{.00489}{m}$

From (V) displacement required = .0000787 in.

Normal defl.- defl. of friction = required defl.

$$.000271 - \frac{.00489}{m} = .0000787$$

$$m = 25.45 \text{ lbs.}$$

CALCULATIONS FOR APPROXIMATE SEISMOMETER

From derivation of (II) $L^3 = 24,390,000\frac{I}{m}$ when t = .166

For different values of T,

$$L^3 = 24,390,000 \frac{I}{m} \frac{t^2}{.166^2}$$

Since the equation for the deflection, $d = .271 \frac{P}{m}$ is of the form

$d = \frac{Pl^3}{3EI}$, the deflection for other values of t will be:

$$d = .271 \frac{P t^2}{m .166^2}$$

For a force of 1/20"g" it is desirable to have a deflection of .063 in. To get this, let P in the above equation equal m/20, substitute different values of t and solve for d.

Values of t	Corresponding values of d
.166	.01355
.20	.01965
.30	.04425
.40	.0755

$$L = 513\sqrt[3]{\frac{I}{m}}$$

Assume frictional force = 20g or .0319 lbs.

defl. of friction $= \frac{(1.51)(.0319)}{m} = \frac{.0482}{m}$

Assume necessary deflection equals .063"

$$.0755 - \frac{.0482}{m} = .063$$

$$m = 3.85 \text{ or say 4 lbs.}$$

$$L = \frac{513}{\sqrt[3]{4}}\sqrt[3]{I} = 323\sqrt[3]{I}$$

Assume L = 18" $\sqrt[3]{I} = \frac{L}{323}$ $\qquad I = .000174$

Assume an arm 1/8" thick, then a width of 1-1/16" will be required giving a moment of Inertia of .0001733

Assume weights 4" in diam. then length of the arm = 20 in.

Weight of arm $= \frac{(.425)(20)}{12} = .708$ lbs.

Moment of arm	=	(.708)(10) =	7.08
Moment of weight	=	(4)(18) =	72.00
		Total =	79.08

$$c.g. = \frac{79.08}{4.708} = 16.8"$$

$$\text{Period} = .1847\sqrt{\frac{mL^3}{EI}} = .1847\sqrt{\frac{(4.708)(16.8^3)}{(30,000,000)(.0001733)}} = .397$$

Defl. for acceleration 1/20"g"

$$d = \frac{P(l-a)^2(2L+a)}{6EI} = \frac{(.235)(16.8^2)(43.2)}{(180,000,000)(.0001733)}$$

$d = .0918$ in.

Defl. of friction $\qquad$ Assume force of .0368 lbs.

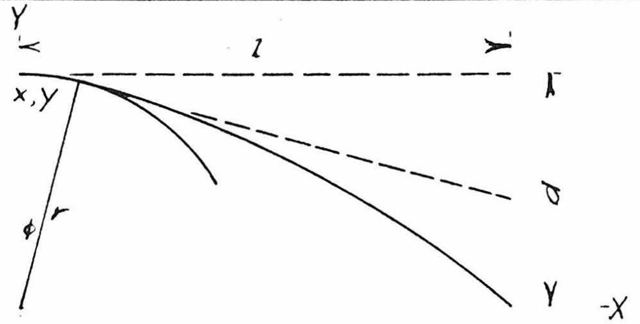
$$d = \frac{(.0368)(8000)}{(180,000,000)(.0001733)} = .00944 \text{ in.}$$

Net deflection

$$\begin{array}{r} .0918 \\ - \underline{.00944} \\ .08236 \end{array} \text{ in., } \quad \text{acceleration } 1/20\text{"g"}$$

Net deflection acceleration 1/2"g"

$$\text{defl.} \quad .0918 \times 10 = \begin{array}{r} .918 \\ - \underline{.00944} \\ .90856 \end{array} \text{ in., accel. } 1/2\text{"g"}$$



Let d = total deflection

l = length of arm

x,y = point of tangency

r = radius of curvature

$$d = y + \frac{dy}{dx}(l-x) + \frac{P(l-x)^3}{3EI}$$

$$x = r\sin\phi \qquad \sin\phi = \frac{x}{r} \qquad \cos\phi = \sqrt{1-\sin^2\phi}$$

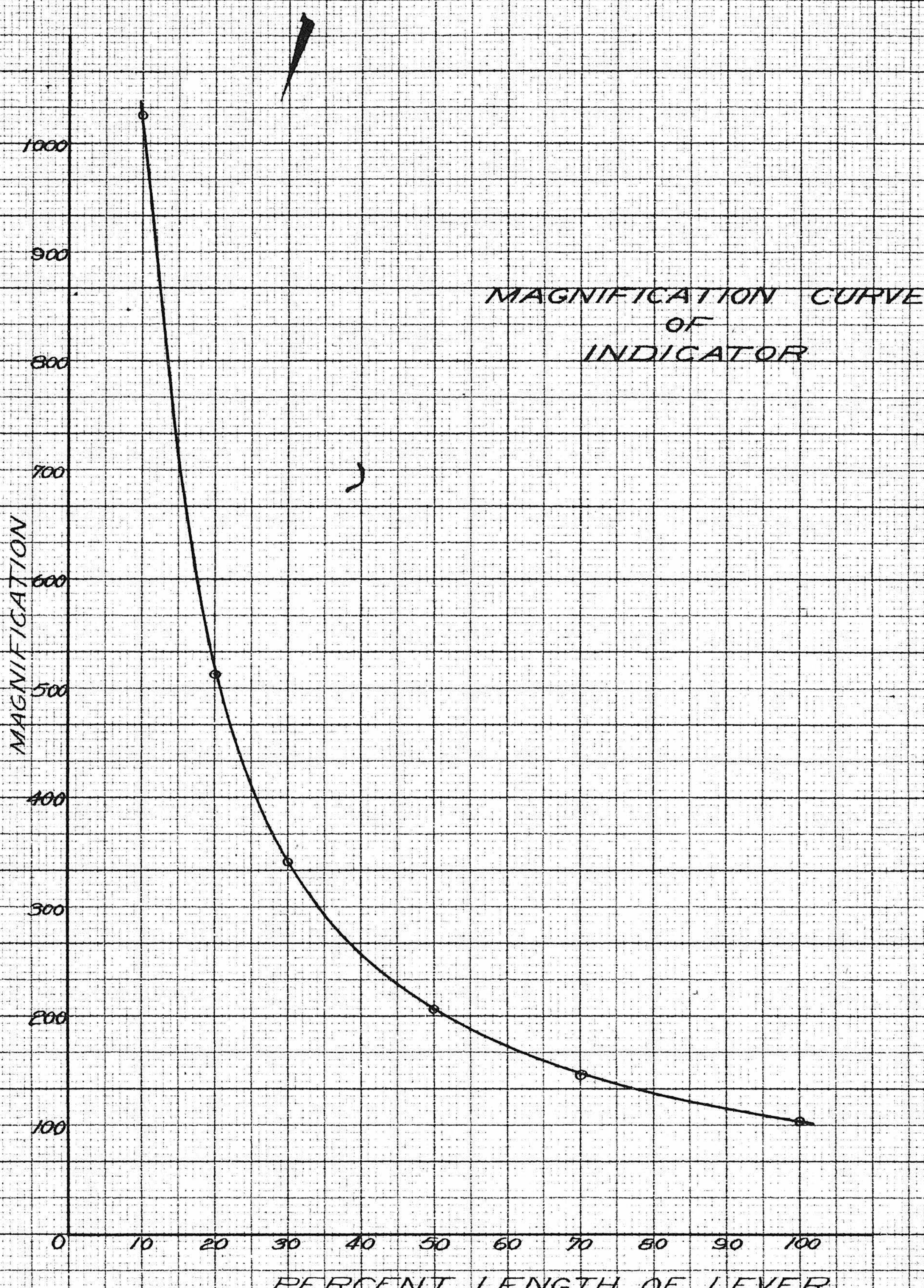
$$\tan\phi = \frac{\sin\phi}{\cos\phi} = \frac{x}{r} \div \sqrt{1-\frac{x^2}{r^2}} = \frac{\frac{x}{r}}{\sqrt{\frac{r^2-x^2}{r^2}}} = \frac{x}{\sqrt{r^2-x^2}}$$

$$y = r - r\cos\phi = r(1-\cos\phi) = r\left(1-\frac{\sqrt{r^2-x^2}}{r}\right) = r-\sqrt{r^2-x^2}$$

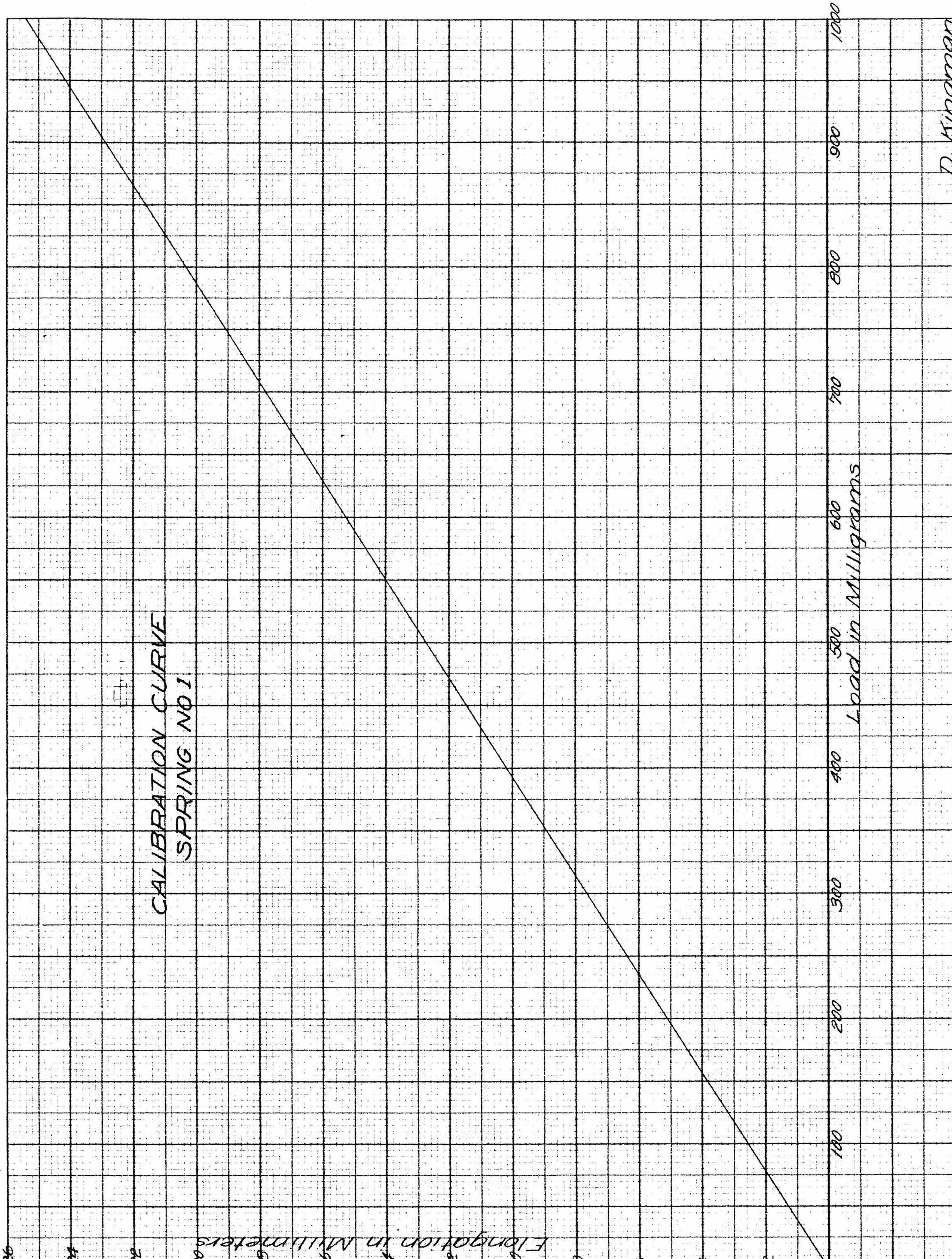
$$d = r-\sqrt{r^2-x^2} + \frac{x}{\sqrt{r^2-x^2}}(l-x) + \frac{P(l-x)^3}{3EI}$$

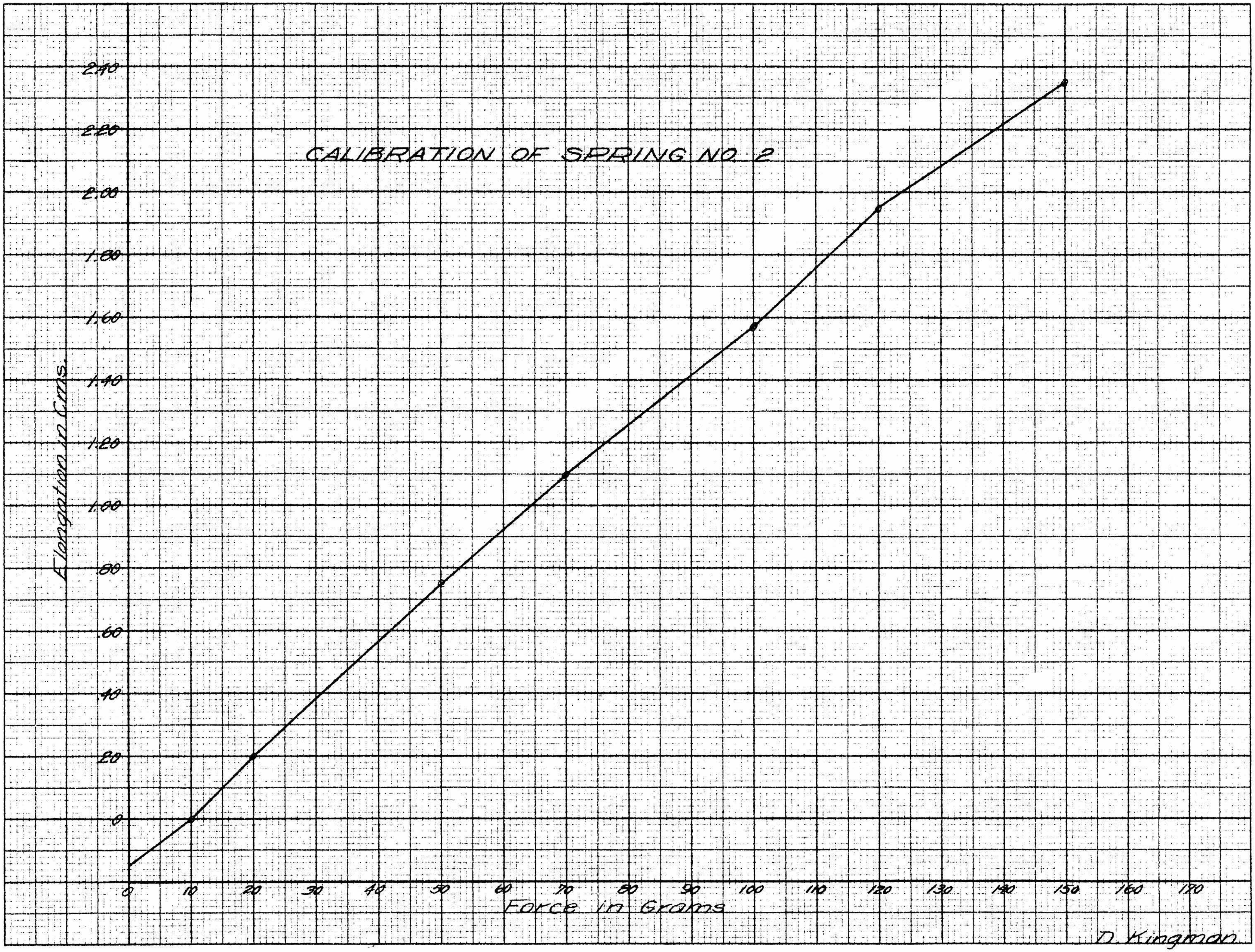
CALCULATION OF CURVATURE

No.	r	x	l	$\frac{P}{3EI}$	r^2-x^2	$\sqrt{r^2-x^2}$	$l-x$	$\frac{x}{\sqrt{r^2-x^2}}(l-x)$	$\frac{P(l-x)^3}{3EI}$	d
1	10	5	12.9	.0001236	75	8.66	7.9	4.56	0.061	5.961
2	20	5	12.9	.0001236	375	19.36	7.9	2.04	0.061	2.741
3	20	8	12.9	.0001236	336	18.33	4.9	2.24	0.01175	3.92
4	100	5	12.9	.0001236	9,975	99.875	7.9	0.395	0.061	0.581
5	100	8	12.9	.0001236	9,936	99.679	4.9	0.393	0.01175	0.725
6	200	8	12.9	.0001236	39,936	199.84	4.9	0.196	0.01175	0.368
7	300	8	12.9	.0001236	89,936	299.894	4.9	0.131	0.01175	0.249
8	500	8	12.9	.0001236	249,936	499.935	4.9	0.0784	0.01175	0.155
9	500	6	12.9	.0001236	249,964	499.963	6.9	0.0827	0.04076	0.160
10	500	7	12.9	.0001236	249,951	499.951	5.9	0.0826	0.0253	0.1569
11	1000	8	12.9	.0001236	999,936	999.967	4.9	0.0392	0.01175	0.084
12	1500	8	12.9	.0001236	2,249,936	1,499.978	4.9	0.0261	0.01175	0.0598
13	2000	8	12.9	.0001236	3,999,936	1,999,984	4.9	0.0196	0.01175	0.0473
14	3000	8	12.9	.0001236	8,999,936	2,999.992	4.9	0.01305	0.01175	0.0328
15	4000	8	12.9	.0001236	15,999,936	3,999,992	4.9	0.00980	0.01175	0.02155
16	5000	8	12.9	.0001236	24,999,936	4,999.993	4.9	0.00784	0.01175	0.01959
17	4500	8	12.9	.0001236	20,249,936	4,499.992	4.9	0.00872	0.01175	0.02047
18	5500	8	12.9	.0001236	30,249,936	5,499.993	4.9	0.007125	0.01175	0.01887
19	6000	8	12.9	.0001236	35,999,936	6000	4.9	0.00653	0.01175	0.01838

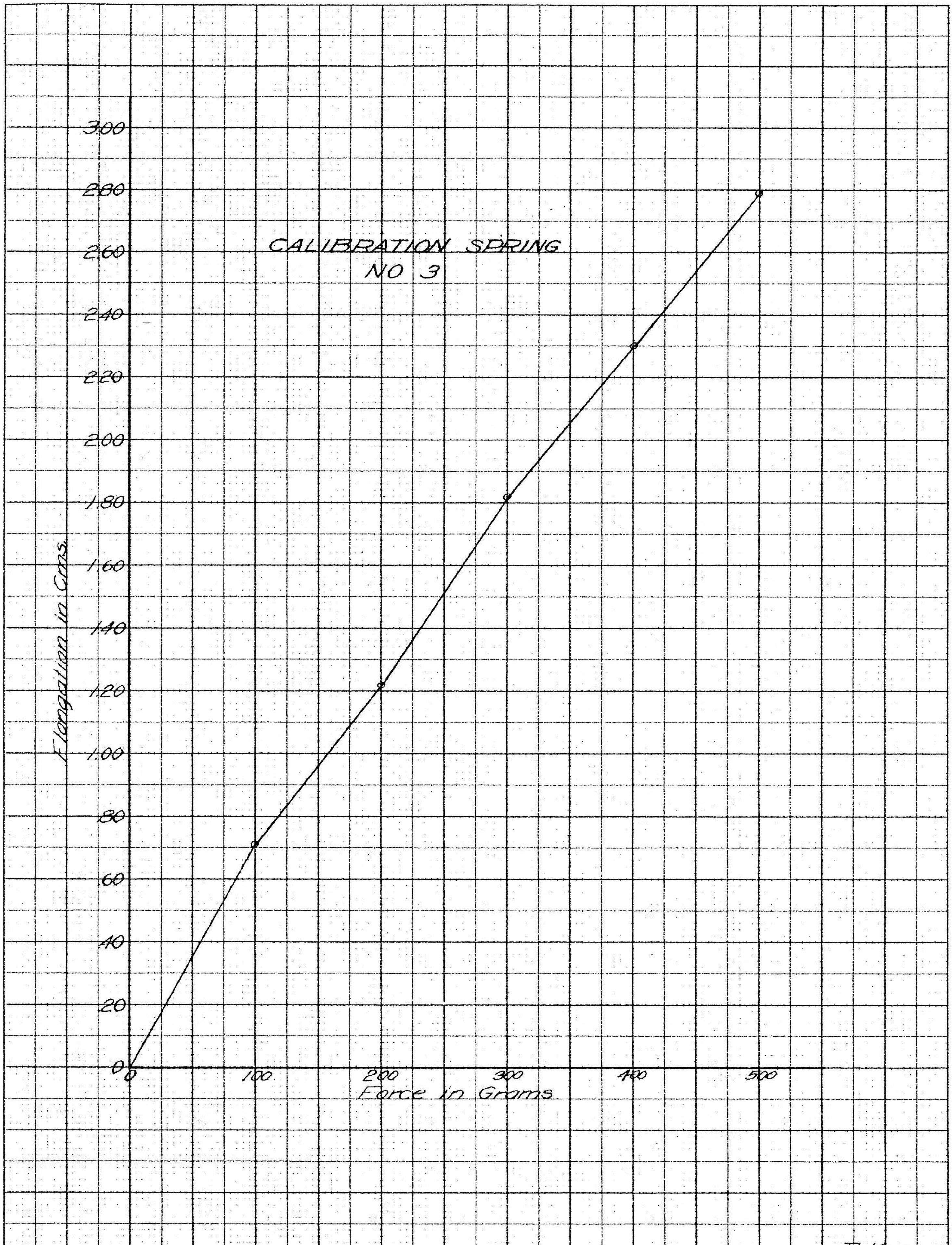

MAGNIFICATION CURVE
OF
INDICATOR
MAGNIFICATION
1000
900
800
700
600
500
400
300
200
100
0
10
20
30
40
50
60
70
80
90
100
PERCENT LENGTH OF LEVER

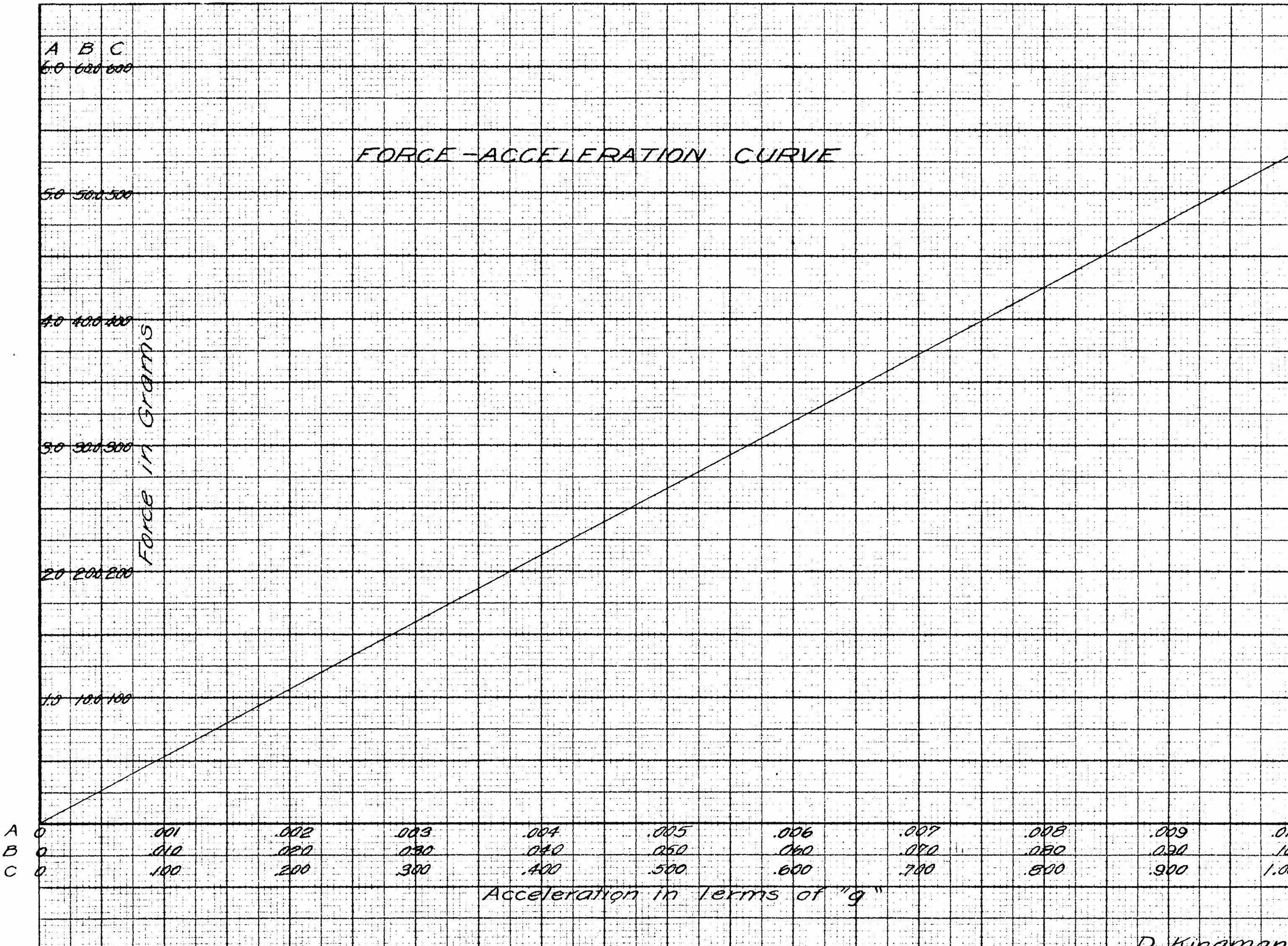
D. Kingman


CALIBRATION CURVE
SPRING NO 1
Load in Milligrams
Elongation in Millimeters
D. Kingman
0
100
200
300
400
500
600
700
800
900
1000
2
4
6
8
10
12
14
16
18
20
22
24
26



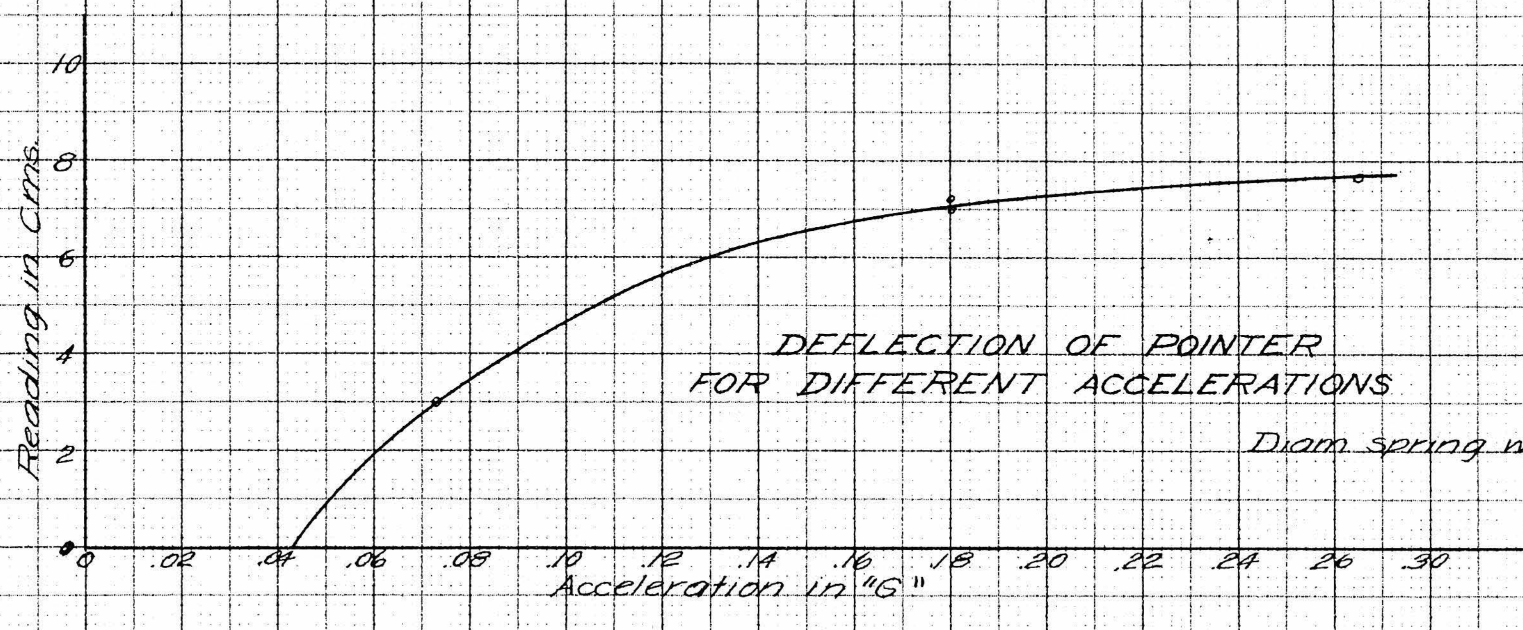
CALIBRATION OF SPRING NO 2
Elongation in Cms.
2.40
2.20
2.00
1.80
1.60
1.40
1.20
1.00
.80
.60
.40
.20
0
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
Force in Grams
D. Kingman

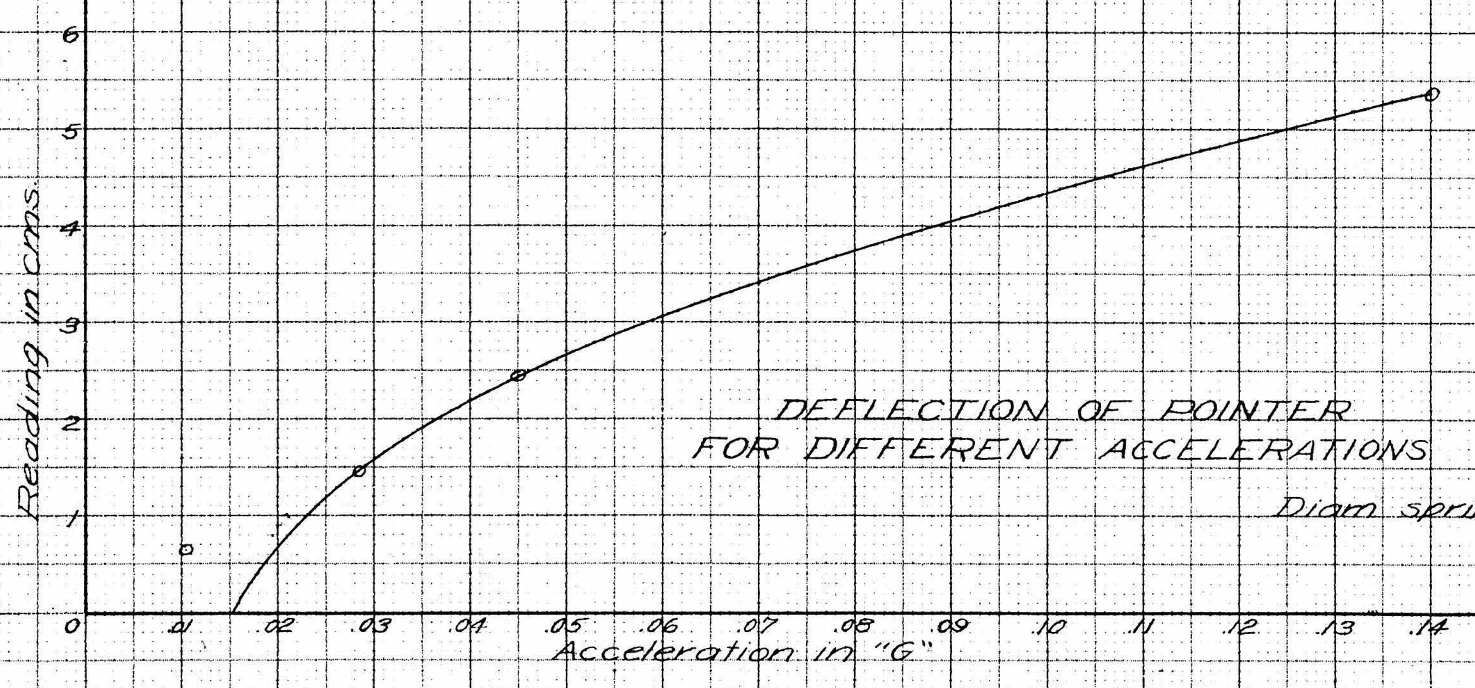

CALIBRATION SPRING
NO 3
Elongation in Cms.
Force in Grams
3.00
2.80
2.60
2.40
2.20
2.00
1.80
1.60
1.40
1.20
1.00
.80
.60
.40
.20
0
0
100
200
300
400
500
D. Kingman


A B C
6.0 60.0 600
FORCE-ACCELERATION CURVE
5.0 50.0 500
4.0 40.0 400
3.0 30.0 300
Force in Grams
2.0 20.0 200
1.0 10.0 100
A 0 .001 .002 .003 .004 .005 .006 .007 .008 .009 .010
B 0 .010 .020 .030 .040 .050 .060 .070 .080 .090 .100
C 0 .100 .200 .300 .400 .500 .600 .700 .800 .900 1.000
Acceleration in Terms of "g"
D. Kingman

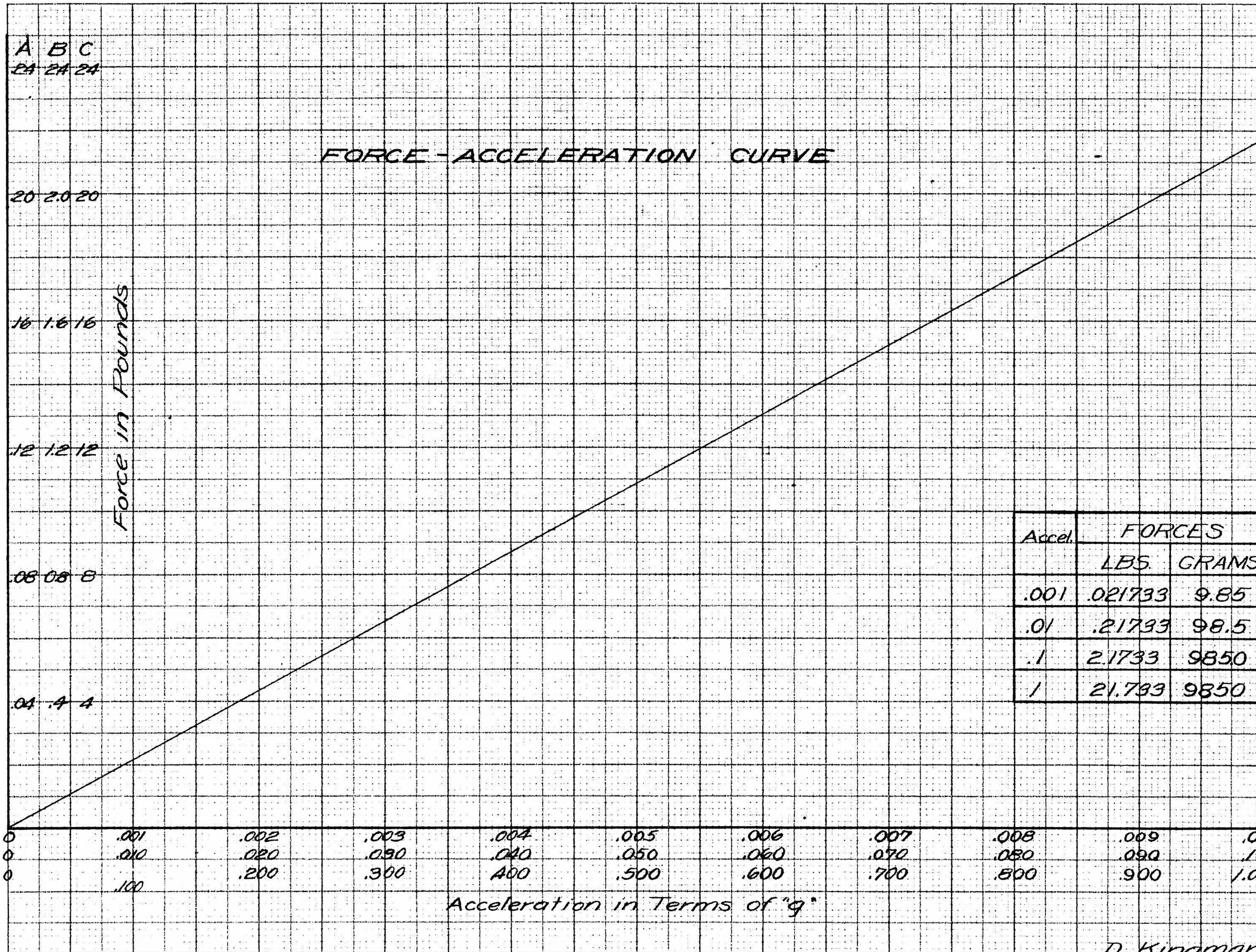
TEST OF SEISMOGRAPH

No.	Spring	Spring Measurements Before Front	Before Back	After Front	After Back	Lengths Before	Lengths After	Elong.	Force	Acc.	Defl.
	Spring made from .0025" tungsten wire.										
1	1	.70	6.90	1.00	8.55	6.20	7.55	1.35	.5308	.001	0
2	1			1.00	9.60		8.60	2.40	1.0616	.002	0
3	2	2.65	10.00	2.75	10.65	7.35	7.90	.55		.073	3.025
4	2			2.90	11.75		8.85	1.50		.18	7.00
5	2			2.90	11.75		8.85	1.50		.18	7.25
6	2			3.10	12.70		9.60	2.25		.265	7.70
	Spring made from .001" tungsten wire.										
7	1	.80	7.1	1.10	9.5	6.3	8.4	2.1	.825	.00155	0
8	2	3.45	10.9	3.75	11.10	7.45	7.53	.08	5.7	.0105	.65
9	2			3.60	11.30		7.70	.25	15.2	.0285	1.46
10	2			3.63	11.50		7.87	.42	24.0	.045	2.45
11	2			3.73	12.50		8.77	1.32	74.6	.140	5.36

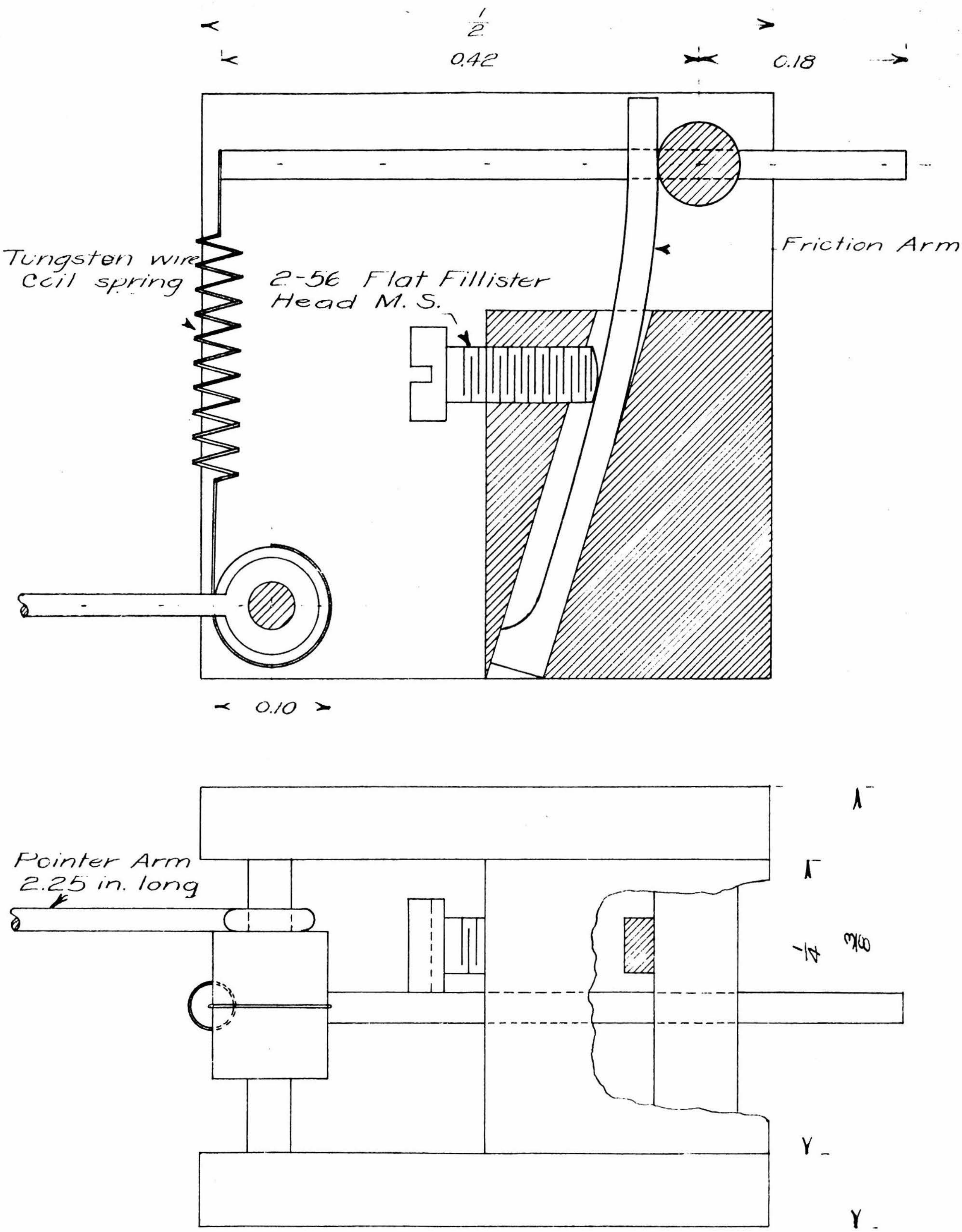

DEFLECTION OF POINTER
FOR DIFFERENT ACCELERATIONS
Diam spring wire .0025"
Reading in Cms.
10
8
6
4
2
0
0
.02
.04
.06
.08
.10
.12
.14
.16
.18
.20
.22
.24
26
.30
Acceleration in "G"


DEFLECTION OF POINTER
FOR DIFFERENT ACCELERATIONS
Diam spring wire .001"
Reading in cms.
6
5
4
3
2
1
0
.01
.02
.03
.04
.05
.06
.07
.08
.09
.10
.11
.12
.13
.14
Acceleration in "G"

D. Kingman

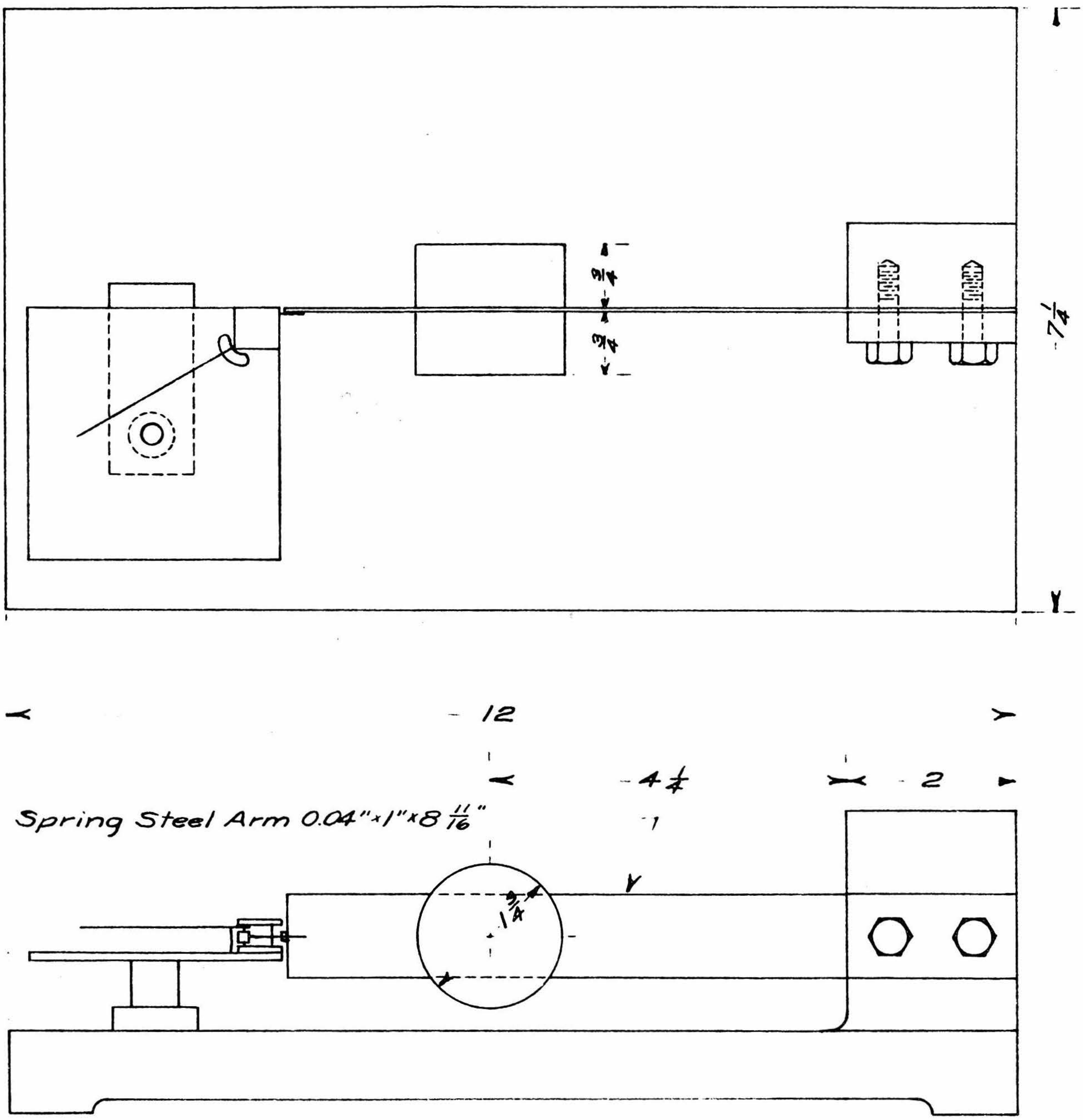


Accel.	FORCES	
	LBS.	GRAMS
.001	.021733	9.85
.01	.21733	98.5
.1	2.1733	9850
1	21.733	9850



INDICATOR

Dr. D. Kingman	Scale - 8 × normal
Date May 23, 1929	

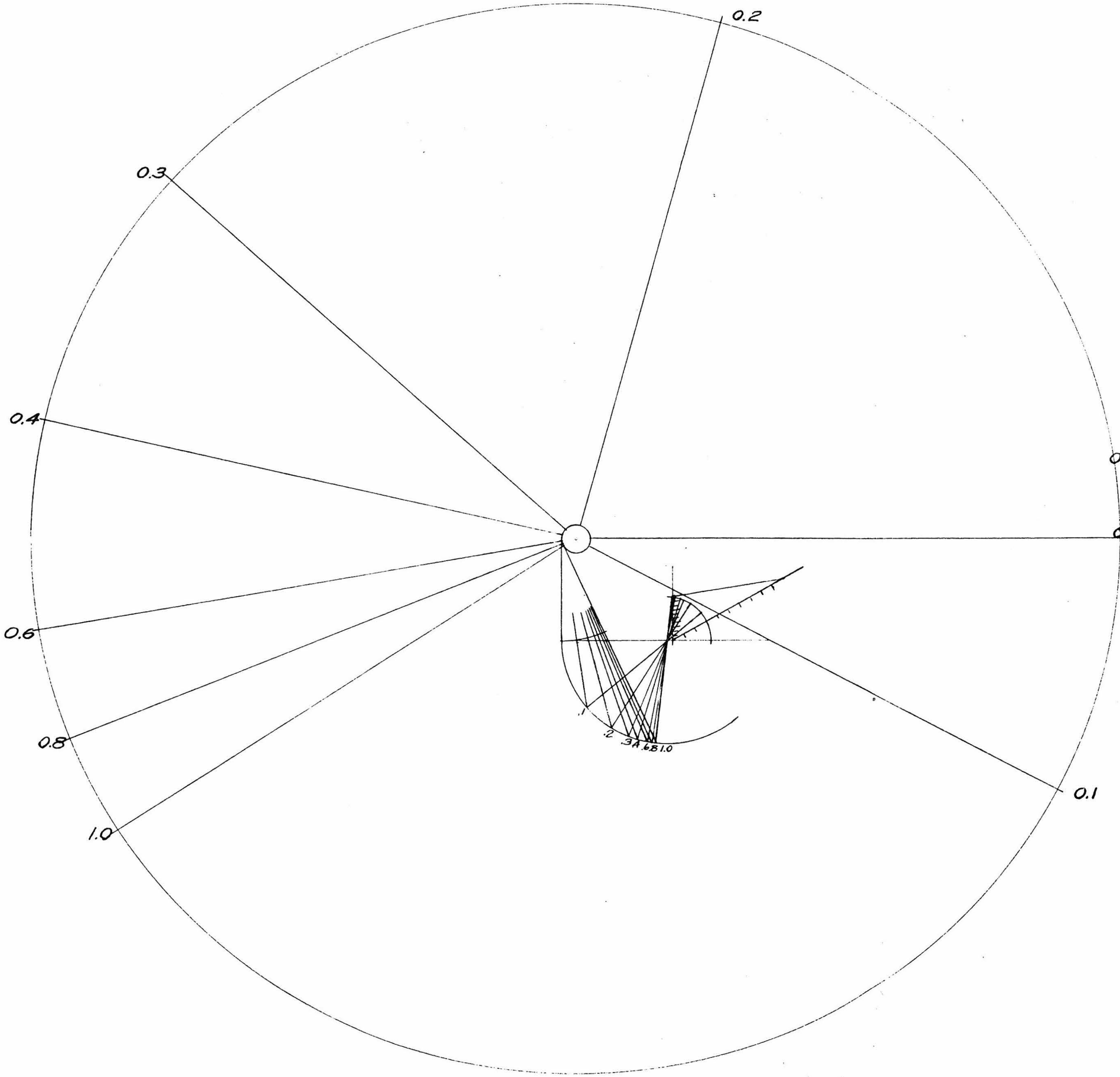


INTENSITY METER	
Dr. D. Kingman	Scale 6" = 1'-0"
Date May, 17, 1929	

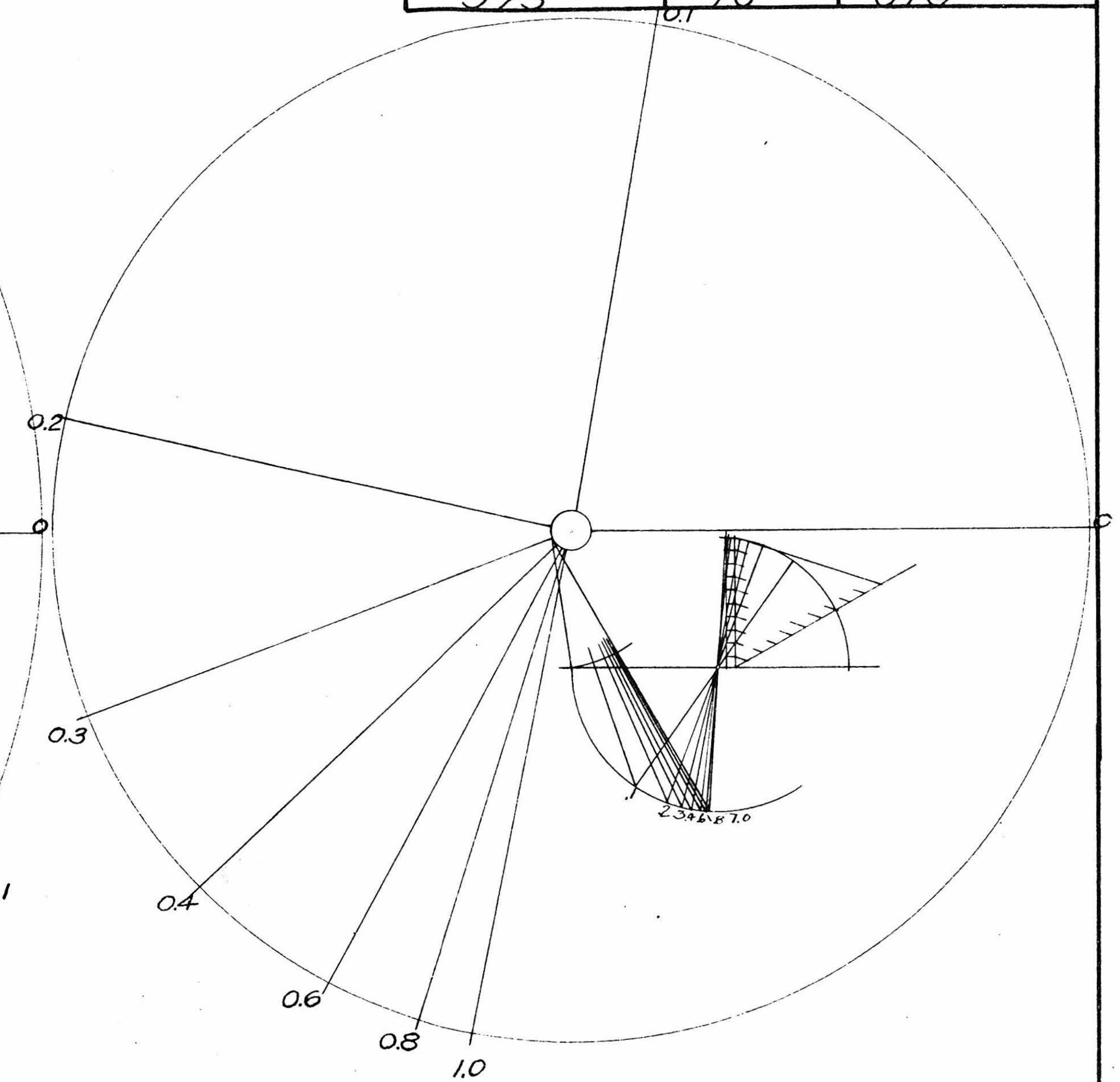
SELECTION OF ARM

No.	Wt.	Arm					Center of Gravity					Period	Deflection of Gravity				Friction		Net Defl.	Defl. Pointer
		Width	Thick.	Length	Weight	I	M of wt.	M of arm	Total M	Total wt.	c. g.		Force	l-a	2l+a	Defl.	Force	Defl.		
1	25#	2 in.	.375in	19.85	4.28	.008	496	49.0	545.0	29.28	18.6	.164	.02928	18.6	49.95	.000352	.01147	.000190	.000162	2.06mm
2	25	1 1/2	.25	12.40	1.635	.001935	310.0	12.6	322.6	26.64	12.1	.1658	.02664	12.1	34.1	.000378	.01147	.000238	.000140	1.78
3	25	2	.4375	23.85	6.66	.01395	596.0	89.5	685.5	31.66	21.68	.1633	.03166	21.68	58.87	.000349	.01147	.000177	.000172	2.19
4	25	2	.500	26.90	8.46	.020	672.5	126.7	799.2	33.46	23.90	.162	.03346	23.90	65.8	.0003494	.01147	.0001705	.000179	2.275
5	25	2	.5625	29.70	10.44	.02965	742.5	171.0	913.5	35.44	25.75	.153	.03544	25.75	72.35	.0003185	.01147	.0001505	.000168	2.135
6	25	2	.250	12.48	1.768	.002	312.0	13.68	325.68	26.77	12.16	.1662	.02677	12.16	34.28	.000377	.01147	.0002366	.0001404	1.785
7	25	2	.1875	10.21	1.403	.001097	255.0	9.26	264.26	26.40	10.00	.166	.02640	10.00	29.63	.000396	.01147	.000268	.000128	1.627
8	25	2	.125	6.82	0.695	.000325	170.5	3.41	173.41	25.695	6.75	.1666	.0257	6.75	22.71	.000455	.01147	.000372	.000073	0.928
9	25	1 3/4	.125	6.75	0.605	.000284	168.8	2.95	171.75	25.61	6.70	.1758	.02561	6.70	22.55	.000507	.01147	.000417	.000090	1.143
10	25	1 3/4	.250	13.05	1.99	.00228	326.0	15.97	341.97	26.99	12.66	.1653	.02699	12.66	35.49	.000375	.01147	.000231	.000144	1.83
11	25	1 3/4	.375	19.55	4.19	.00768	488.0	47.25	535.25	29.19	18.34	.163	.02919	18.34	49.31	.000351	.01147	.000193	.000156	1.984
12	25	1 3/4	.500	26.05	7.21	.01823	626.0	104.70	730.7	32.21	22.70	.1536	.03221	22.70	64.45	.000326	.01147	.0001715	.000155	1.97
13	25	1	.250	10.85	0.983	.001303	271.0	6.81	277.81	25.98	10.68	.1666	.0260	10.68	30.87	.000391	.01147	.000260	.000131	1.665
14	25	1 1/4	.250	11.65	1.208	.001628	291.4	8.74	300.14	26.21	11.45	.166	.0262	11.45	32.50	.000382	.01147	.0002463	.000136	1.727
15	25	2 1/4	.250	14.20	2.740	.00293	355.0	23.55	378.55	27.74	13.64	.1656	.0277	13.64	37.98	.000372	.01147	.000221	.000151	1.92
16	20	1 1/2	.125	6.66	0.354	.0002445	133.2	1.71	134.91	20.35	6.63	.1661	.02035	6.63	22.35	.000455	.01147	.000471	——	——
17	20	1 1/2	.250	13.35	1.736	.001955	267.0	14.2	281.2	21.74	12.92	.165	.02174	12.92	36.13	.0003725	.01147	.000285	.0000875	1.112
18	20	1 1/2	.375	20.00	3.18	.00659	400.0	36.6	436.6	23.18	18.82	.1634	.02318	18.82	50.18	.000347	.01147	.000214	.000112	1.424
19	20	1 1/2	.500	26.70	5.66	.01563	534.0	84.1	618.1	25.66	24.10	.1616	.02566	24.10	65.0	.000344	.01147	.000214	.000130	1.65
20	20	1 1/2	.250	13.375	1.74	.001955	268.0	14.26	282.26	21.74	12.97	.1664	.02174	12.97	39.16	.000407	.01147	.000286	.000121	1.537
21	20	1 1/2	.250	13.3125	1.733	.001955	266.0	14.14	280.14	21.733	12.90	.1653	.02173	12.90	36.03	.000371	.01147	.000283	.000088	1.118
22					Same as 21								21.73	12.90	36.03	0.371	.01147	.000283	0.371	55.7in

SCALE OF DEFLECTIONS		
0.185" Displ.	Acceler.	0.371" Displ.
332°	0.1 g	441°
435	0.2	527
498	0.3	561
527	0.4	584
550	0.6	602
562	0.8	613
573	1.0	619



Deflection of 1.0g = 0.185 in.

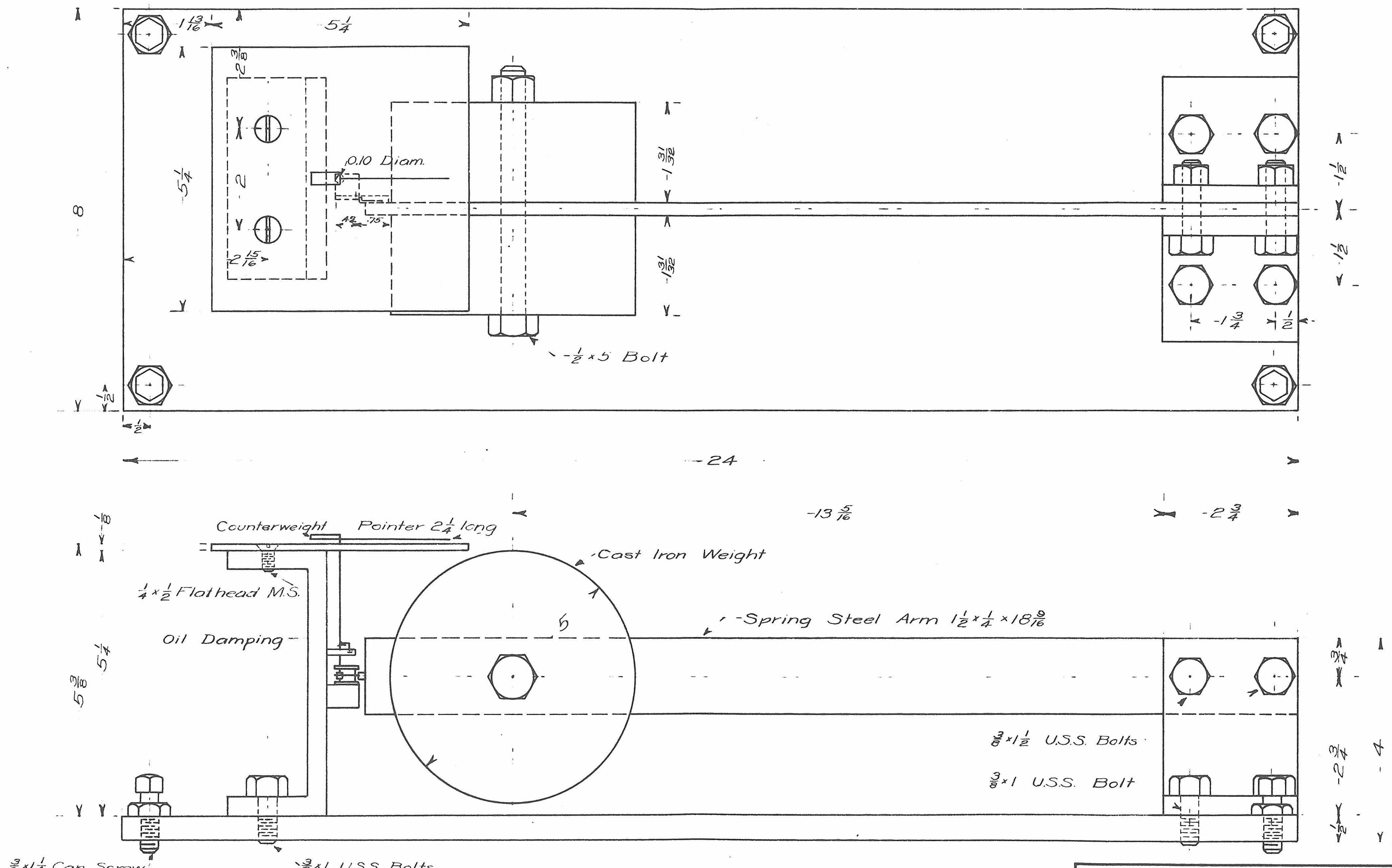


Deflection of 1.0 g = 0.371 in.

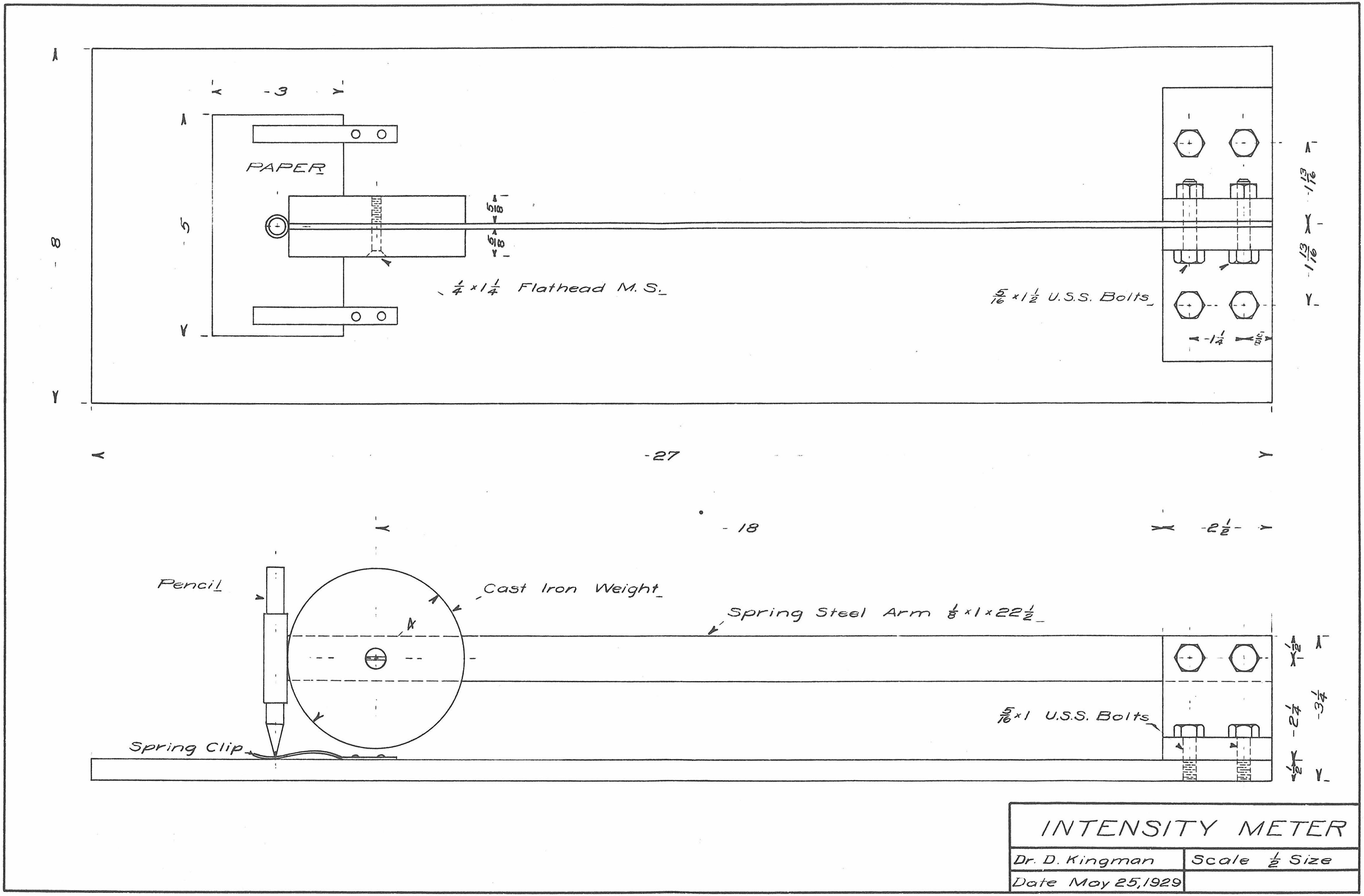
ANALYSIS OF RECORDING ACTION

Scale - 12" = 6"   May 10, 1929   D. Kingman

PLATE V



INTENSITY METER	
Dr. D. Kingman	Scale 6"=1'-0"
Date 5-13-29	


3
PAPER
5
8
5/8
5/8
1/4 x 1 1/4 Flathead M.S.
5/16 x 1 1/2 U.S.S. Bolts
1 13/16
1 13/16
1 1/4
27
18
2 1/2
Pencil
Cast Iron Weight
Spring Steel Arm 1/8 x 1 x 22 1/2
5/16 x 1 U.S.S. Bolts
Spring Clip
1/2
2 1/4
3 1/4
1/2
INTENSITY METER
Dr. D. Kingman
Scale 1/2 Size
Date May 25, 1929