CALIBRATION OF PIEZO-ELECTRIC

AND

ELECTRO-MAGNETIC ENGINE INDICATORS

Thesis by

Chi-nan Hsu

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I. Summary

The object of the present investigation is to study the behavior of two types of electric pressure indicators for use with high speed engines and to establish the proper calibration technique. The need for the investigation arose from the complete lack of information in literature concerning the problem.

Three piezo-electric and three electro-magnetic indicator pickup elements were investigated as to their sensitivity up to a pressure of 950 psi. The step-function method was used and is the significant feature of this calibration. The signal trace on the oscilloscope screen was recorded photographically. Results are presented in the form of calibration curves of pressure and voltage output vs. oscilloscope deflection and sensitivity vs. pressure.

The calibrating technique is outlined in detail and several difficulties likely to be encountered are discussed in the Appendix.

The time response of the elements to pressure change is discussed and evaluated by means of theoretical computations.

The behavior of the pickup elements is discussed and is found to be in agreement with prediction.

II. Introduction

Engine indicators were at first introduced primarily for taking indicator cards of steam engines and low-speed stationary oil engines from which the indicated power can be computed. After the evolution of high-speed internal combustion engines, the study of the cycle of events becomes another and more important function of the engine indicator. In fact, as the method for approximating the indicated power of high-speed engines by adding the actual work output of the engine to the frictional losses obtained by motoring or driving the engine with an electric dynamometer is simpler and becomes more widely used, the sole purpose of taking indicator cards in high-speed engines is the study of the pressure variation existing in the cylinder under various operating conditions of load, fuel-air ratio, compression, ignition and valve timing, and with different fuels.

The usual mechanical piston type engine indicator as used for large stationary slow-speed steam and oil engines gives fairly satisfactory indication for engine speeds below 300 r.p.m. For the high speeds as encountered in modern high compression internal combustion engines, this type of indicator is not suited for indication purposes because of the inertia of the moving parts which tends to distort the indicator diagram and makes the indicator piston unable to follow accurately the rapid pressure change taking place inside the cylinder. Furthermore, the indicator connection increases the compression space appreciably and thus infuences both the compression and combustion, especially in small high-compression engines. Various other devices have been designed and developed to meet the needs, such as optical indicators, sampling-valve indicators, balance-pressure diaphragm type indicator and electric indicators.(Ref.1,2,3,4,5)

The electric type engine indicators which have become popular in research and development work in engines have a pressure-sensitive element screwed into the cylinder head,which, when acted on by the cylinder pressure, produces an electric current varying with the pressure. This current is then flowing through an amplifier and is recorded on a cathode-ray oscilloscope screen. There are, in general, four types of electric indicators, known respectively,as the resistance, the magnetic(or inductive), the condenser(or capacitive) and the piezo-electric type. (Ref.6). All these indicators make use of the property of the pressure-sensitive element to produce an electric signal varying with the pressure. The graphic record taken on the oscilloscope screen of this electric signal is hence also a record of the pressure inside the cylinder.

Piezo-electric quartz type pressure pickups and eletro-magnetic pickup elements are used in the engine laboratory of the California Institute. It was found that there were no reliable calibration data from the manufacturers of these elements. Besides, it was deemed necessary to establish a routine method for calibration in order to insure reliable results from the pressure indicators.

III. Description of the Indicators

A. Piezo-electric type

The piezo-electric indicator is especially suited for laboratory and research work to study the cyclic pressure change in high-speed engines by observation of a continuous indication on the screen of a cathode-ray oscilloscope. This equipment, because of the infinitesimal amplitude of movement of its parts under pressure and hence its freedom from inertia, is capable of following and accurately indicating the pressure variation at even higher speeds than are encountered normally in modern engines. It consists of a pressure element using certain pressure-sensitive crystalline substances such as Rochelle Salts, tourmaline and quartz which posses the peculiar property that, when they are subjected to pressure in a particular direction relative to their crystal faces, an electric charge appears on these faces. This effect is called the "Piezo-electric effect". Quartz and tourmaline are used when temperatures are high and Rochelle Salt crystals when temperatures are low. These electric charges, besides being in exact proportion to the pressure exerted, also vary instantly with change of pressure.

The complete set of instruments consists of four parts, namely, the pressure element which converts the mechanical pressures into electric impulses, the amplifier by which these electric impulses are magnified, the cathode -ray oscilloscope which produces a graphic record directly of the amplified electric impulses and indirectly of the pressure cycle of the cylinder, and the synchronizer which assumes a definite phase relation between the cross sweep of the oscilloscope and the engine cycle.

The indicator being investigated is of the quartz-piezo-electric type,consisting of a "Cox type-3" pressure element,"type-2"portable amplifier,cathode-ray oscilloscope and the "type-6"multiple contactor for synchronism. The element(Ref. 7),as shown in Fig.1,consists of two quartz crystals mounted in a small cylindrical casing between grounded electrodes,known as the piston and plug. A third electrode,insulated from ground by the crystals themselves, is inserted between the two crystals and is the "high" electrical connection of the unit. When an external pressure is exerted on the piston(thus compressing the two crystals),an electric charge will appear on the two faces of each crystal. The crystals are so polarized that these charges are additive, the crystals thus operating in parallel. When no current is drawn from the unit, the voltage between the center and ground electrodes is directly proportional to this charge and inversely proportional to the capacity between the two electrodes.

The "Cox type-2" amplifier is used to magnify the small output voltage of the pressure element to the desired amount on the oscilloscope screen. According to the manufacturers' handbook(Ref.8), it has a minimun frequency response of 1 c.p.s., and is able to respond faithfully to a single impulse, whether it be in the form of frequency as low as 1 c.p.s.,or any complex wave form within the frequency range of the amplifier, thereby making it ideally suited for the study of infrequent or non-recurring phenomena. It is a three stage resistance-capacitance coupled audio-frequency amplifier. The first stage has two different input impedances, which are selected by the positioning of the input "Selector" switch. Position 1-A should be used for all applications in which the impedance of the signal voltage to be amplified is either resistive or inductive and in which the amplitude of the signal voltage is between 0.1 of 1 m.v. and 300 m.v. Position 1-B is used for the signal voltage from piezo-electric and capacitive soucces. Position 2 connects the signal voltage into the second stage of the amplifier and is used for an input voltage of 5 to over 1000 m.v. Beside the above-mentioned input circuits, the amplifier has also incorporated within it a calibrating voltage circuit which can be turned on or off. The amount of calibrating voltage used can be varied by means of the voltage control.

The recording or registering instrument of the amplified electric impulse is the cathode-ray oscilloscope, while the equipment for synchronizing the horizontal timing axis of the scope to the crankshaft angle of the engine is the "Cox type-6" multiple contactor. For the construction and operation of the latter, see Ref. 9.

B. Electro-magnetic type

The electro-magnetic indicator consists of the same parts as the piezo-electric type except that the pressure element(Ref.10) employs the electro-magnetic method of generating a voltage across the terminals of a coil by converting the diaphragm vibrations into variations in magnetic flux through the soft steel core of the coil. As the pressure acting on the diaphragm is changed, the movement or vibration of diaphragm changes the width of the air gap in the magnetic circuit, thereby changing the flux passing through the coil. This results in the generation of induced voltage in the coil which is directly proportional to the rate of change of flux passing through the coil, i.e., to the velocity of vibration of diaphragm under pressure changes.

The pressure element, as shown in Fig. 2, has two adjusting screws to adjust the air gap in the magnetic circuit. Several threaded holes are provided in the adapter of the pickup so that cold compressed air may be used to cool the coil windings when the pickup is exposed to heat during engine testing.

IV. Testing equipment and procedure

The equipment used for calibrating these two kinds of pressure elements consists of a conventional dead weight tester used for calibrating Bourdon type pressure gauges and a specially designed quick acting pressure release valve for applying and releasing pressures on the element. Glycerine is used as the hydraulic fluid. The general set up of the equipment is shown in Fig.3.

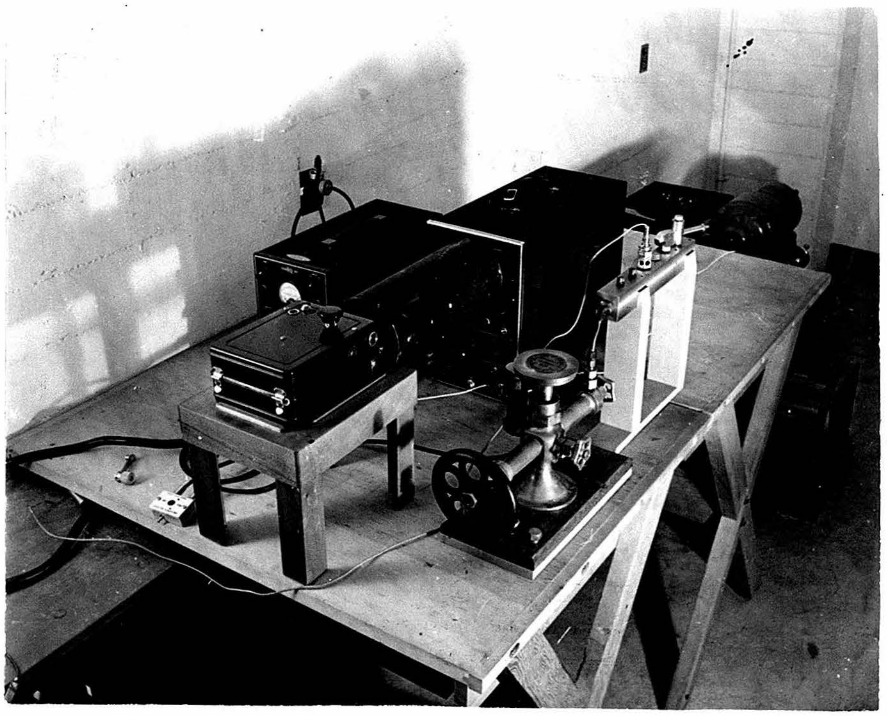


Fig.3. General Set-up of the testing equipment for calibrating pressure element

A. Valve stand B. Dead weight tester
C. Pressure element(electro-magnetic type here)
D. Oscilloscope E. Amplifier
F. Movie camera G. Viewing hood
H. Quick acting pressure release valve
I. Manifold

The element to be calibrated is screwed into the manifold of the valve stand. Before screwing the element in place, glycerine is bled to eliminate the air trapped in the manifold. The element is connected to the input side of the amplifier by means of a shielded cable. The amplifier gain control should be set at an arbitrarily fixed position (about 1/3 turn clockwise) such that there will be no "overloading"of the amplifeier. This is done by adjusting the gain control so that when the amplifier calibrating voltage is about twice that corresponding to maximum pressure encountered,there will be no flattening of the peaks of the sinusoidal waves on the oscilloscope screen. This is very important as the overloading or excessive gain of amplifier will cause distortion of the pressure diagrams and result in faulty scope deflections,especially at high pressures or voltages. This amplifier gain position should be observed throughout the test and further adjustment of the amplitudes of deflections on the scope screen for different pressures and voltages is made by means of the scope vertical gain control.

The pressure release valve is so constructed that it will give a single non-recurring electric signal set upby the pressure element as the pressure is released. A step-fundtion wave is thus set up,which is the significant feature of this calibration method. The valve assembly consists of a valve,a stand and a manifold which is connected to the dead weight tester through pipes and a needle valve. The pressure release valve itself is a ball check valve consisting of three steel balls placed one upon the other (Fig,4).The balls are first brought into proper position by screwing in the top and side screws. Then the side screw is removed, leaving the balls firmly clamped upon the valve seat by means of the top screw. The side pressure-relief hole is closed by the bottom ball at this time. A known weight is then placed on the dead weight tester, the needle valve is opened and glycerine is pumped through the pipe line,manifold and onto the element, until the weights are lifted in the tester. This means that the pressure as recorded on the weights has been applied to the pressure element. The weights are then spun, the needle valve is closed and the valve spring stem is simultaneously pulled out against the spring. The stem is then released and is pushed back by the spring. This throws the middle ball out of the cylinder into the ball reciever. The fluid inside the manifold,being at higher pressure, then quickly lifts the bottom ball from its seat,the glycerine flows out of the manifold through the side pressure-relief hole. Thus a known pressure change can be produced. The resulting electric signal is recorded photographically on the film.

For the piezo-electric pressure element, the electric voltage generated is directly proportional to the pressure. For the electro-magnetic pickup, the voltage induced in the coil is directly proportional to the rate of change of magnetic flux passing through the coil, which, in turn, depends on the rate of change of the width of the air gap or the velocity of the diaphragm vibration. The vo--ltage record obtained on the scope screen therefore gives a measure of the velocity rather than the amplitude of the diaphragm deflection.

From the above consideration, it is seen that the relation between generated voltage and pressure in an electro-magnetic pickup depends not only on the amount of pressure applied but also on the time rate at which this pressure is applied. However, by inserting an integrating circuit between the amplifier and oscilloscope as shown in Fig. 5, the record obtained from the scope will show the variation of the integrated voltage across the condenser and can be used as a measure of the amplitude of the diaphragm vibration. Since the inertia of the diaphragm is small and can be neglected, the amplitude of the diaphragm deflection can be considered as depending on the amount of pressure only, i.e., the time rate of pressure application can be neglected. Therefore, the graphic picture of the integrated voltage on the scope screen may be used as a measure of the pressure applied on the element. By comparing the scope deflection corresponding to a certain pressure with that due to a known calibrating voltage, the voltage corresponding to any unknown pressure can be computed.

To calibrate the elements, the procedure is as follows:

(1) The equipment is set up as shown in Fig.3.

(2) With the amplifier "Selector" switch in the position marked "1-Cal.", the calibrating voltage is adjusted to desired value. The resulting sine wave is recorded by means of a motion picture camera (film moving continuously, shutter removed).

(3) The "Selector" switch is then moved to position "1-B" if a piezo-electric element is used, or to position "1-A" if a magnetic pickup is used.

(4) Starting with a pressure of 950 psi, the signal produced by releasing the pressure is recorded on the film.

(5) The same procedure is repeated for different pressures.

V. Results and Discussion

A. Piezo-electric type

Three Cox type-3 quartz crystal pressure elements #1306,#1286 and #1279 were tested. Cox type-2 portable amplifier(#1061,Commercial Research Lab.,Inc.) and cathode-ray oscilloscope made by Allen B. Du Mont Lab., Inc.,type 208-B,#3572 were used.

Several sets of tests were made for the elements. The results obtained for the first two sets were inconsistent and are believed to be in error due to either improper bleeding of air or overloading of the amplifier. They are shown and discussed in detail in the Appendix.

In the third set of test data, the above-mentioned troubles are all eliminated by thorough bleeding of the trapped air in the pipe lines and by setting the amplifier gain to a fixed standard position so that no overloading could occur. The whole pressure range was divided into four parts,each part using a different gain in the scope so that the amplitudes of deflection for all pressures were made nearly the same.For each gain setting, a certain appropriate calibrating voltage was applied.

The typical pictures taken by the movingfilm camera of the sine waves of the calibrating voltage on the scope screen and of the step-function waves produced by the sudden pressure release are shown in Figs.6 and7 respectively. The decrease of amplitudes of waves for samegain setting as pressures are reduced is clearly shown on the pictures. The peak-to-peak deflections or amplitudes of the waves as recorded on the film are measured in a comparator with a precision screw of 0.1" pitch. A dial is attached to one end of the screw and is graduated in 100 divisions so that each division corresponds to 0.001". The deflections corresponding to a certain voltage and pressure can thus be measured.

The sensitivity or voltage output of the element at different pressures can be found as follows:

Let x be the deflection recorded on the film corresponding to certain calibrating voltage V (in m.v.),

y be the deflection corresponding to certain pressure p(in psi),

k be sensitivity of the element in m.v./psi,

then $k = vy/xp$.

The results of the test are shown in Tables 1,2, and 3 respectively.(All with the oscilloscope vertical gain switch at input voltage <250 v.R.M.S. side.)

Table 1. Calibration results for element #1306

Scope Gain	Pressure(P)	Calibrating Voltage (V)	Pressure Deflection(y)	Voltage Deflection(x)	Sensitivity $K = Vy/px$	Voltage generated by Pressure=PK
10	950 psi	30 m.v.	0.344"	0.315"	3.45 m.v./100 psi	32.8m.v.
10	900	30	0.320	0.315	3.39	30.5
10	800	30	0.287	0.315	3.42	27.4
11.5	700	20	0.406	0.321	3.62	25.5
11.5	600	20	0.345	0.321	3.58	21.5
11.5	500	20	0.292	0.321	3.64	18.2
14	400	10	0.424	0.307	3.46	13.8
14	300	10	0.308	0.307	3.35	10.1
14	200	10	0.218	0.307	3.55	7.1
14	100	10	0.092	0.307	3.00	3.0
30	75	2	0.471	0.369	3.40	2.55
30	50	2	0.316	0.369	3.43	1.72
30	25	2	0.112	0.369	2.43	0.61

Table 2. Calibration results for element #1286

Scope Gain	Pressure(P)	Calibrating Voltage(V)	Pressure Deflection(y)	Voltage Deflection(x)	Sensitivity K= Vy/px	Voltage generated by Pressure P=PK
10	950 psi	30 m.v.	0.442"	0.374"	3.73 m.V/100 psi	35.4 m.v.
10	900	30	0.421	0.374	3.75	33.7
10	800	30	0.368	0.374	3.69	29.5
11.5	700	20	0.434	0.327	3.79	26.5
11.5	600	20	0.352	0.327	3.59	21.5
11.5	500	20	0.308	0.327	3.77	18.9
14	400	10	0.442	0.318	3.47	13.9
14	300	10	0.342	0.318	3.59	10.8
14	200	10	0.222	0.318	3.49	6.98
14	100	10	0.107	0.318	3.37	3.37
30	75	2	0.458	0.360	3.39	2.54
30	50	2	0.307	0.360	3.41	1.72
30	25	2	0.145	0.360	3.22	0.81

Table 3. Calibration results for element #1279

Scope Gain	Pressure (P)	Calibrating Voltage (V)	Pressure Deflection(y)	Voltage Deflection(x)	Sensitivity K= Vy/px	Voltage Generated by Pressure P=PK
10	950 psi	30 m.v.	0.451"	0.376"	3.79 m.V/100 psi	36.0 M.V.
10	900	30	0.425	0.376	3.77	33.9
10	800	30	0.380	0.376	3.79	30.3
11.5	700	20	0.500	0.385	3.72	26.1
11.5	600	20	0.438	0.385	3.79	22.7
11.5	500	20	0.362	0.385	3.76	18.8
14	400	10	0.441	0.320	3.45	13.8
14	300	10	0.347	0.320	3.62	10.9
14	200	10	0.221	0.320	3.46	6.92
14	100	10	0.108	0.320	3.38	3.38
30	75	2	0.450	0.355	3.38	2.54
30	50	2	0.298	0.355	3.36	1.68
30	25	2	0.152	0.355	3.42	0.86

The pressure vs. deflection, genera-ted voltage vs. pressure and sensitivity vs. pressure curves for all the three pressure elements are shown in Figs.8,9 and 10 respectively. The pressure curves are all straight lines passing through the origin,thereby indicating the linear relation existing between the pressure and oscilloscope deflection. The generated voltage vs. pressure curves are all straight lines passing through the origin,verifying the prediction that the voltage generated by a piezo-electric quartz element is directly proportional to the pressure acting on the element. Furthermore,the three curves are rather close to each other. The slopes of these lines measure the average sensitivities of the elements #1306, #1286 and #1279 which are 3.5, 3.75 and 3.75 m.v./100 psi respectively. Fig.10 shows that the sensitivity is fairly constant throughout the whole pressure range. The average sensitivity is 3.5 m.v./100 psi, for #1306,while that for #1286 and #1279 varies from 3.5 to 3.83 m.v./100 psi,the average being about 3.7 m.v./100 psi.

The time response of the element to pressure change can be evaluated by an examination of the wave form in Fig. 7 and also by a theoretical computation of its natural frequency of vibration. After the side pressure-relief hole is uncovered by the lifting of the bottom ball in the pressure release valve,the pressure inside the manifold begins to drop. A certain time lag may be present for the element to produce the electric signal after the pressure change takes place. The distance on the film between the point where the signal begins to be produced and the point where the signal is fully set up is found to vary from 1/16" at high pressures to 3/8" at low pressures. If we assume an average film speed of 3 ft./sec., then these distances correspond to 1/576 sec. and 1/96 sec. However, it also takes certain time for the release valve to fully lift its bottom ball and to completely relieve its pressure. This means that after the electric signal starts to be produced, the pressure continues to drop and the signal magnitude continues to be built up. Some part of the above-mentioned time duration is hence taken up by this continuing pressure release. Since it is expected that the full pressure release will take longer time at low pressures due to the valve action, this explains the longer time required for full set up of the signal. Based on this consideration, we can also conclude that the time duration of the pressure element to produce signal after pressure change takes place is only a part of the period 1/576 sec. In fact, after computing its natural frequency which is found to be very high, we can predict that this time lag will be very short (much shorter than 1/576 sec.).

From Fig.1(also Ref.7), we see that the two quartz crystals are held between the steel piston and plug which are both rigid bodies. As pressure is applied on the crystals through the piston, the crystals are compressed, acting like a spring, while the piston behaves like a mass attached to the end of the spring. The length or thickness of each crystal is found from actual measurement to be 0.25".

The cross-sectional area of the crystal and the volumes of both the crystals and piston can be measured, and computed.

Let P be the force acting on the crystals,

L be the total length or thickness of the two crystals $= 0.50''$,

A be the cross-sectional area of the crystals $= 0.0557$ sq. in.

E be the modulus of elsticity of quartz $= 10^7$ psi,

d be the total deflection or deformation of the two crystals due to P,

then $P/A = Ed/L$,

or, $P/d = K =$ spring constant of the quartz crystals

$= EA/L = 0.0557 \times 10^7 / 0.50 = 1.11 \times 10^6$ psi.

Volume of the steel piston $= 0.0279$ cu.in.

Volume of the two crystals $= 0.0279$ cu.in.

Specific weight of quartz $= 165$ lb./cu.ft.(Ref.14)

Specific weight of steel $= 489$ lb./cu.ft.(Ref.14)

Mass of steel piston $= 0.0279 \times 489 / 1728 \times 32.2$

$= 2.46 \times 10^{-4}$ slugs $= m_1$

Mass of the two crystals $= 0.0279 \times 165 / 1729 \times 32.2$

$= 8.28 \times 10^{-5}$ slugs $= m_2$

The <u>natural frequency</u> of the system

$$W_n = \sqrt{K/(m_1 + \tfrac{1}{3} m_2)} = \sqrt{1.11 \times 10^{11} / (24.6 + 2.76)} = \underline{6.36 \times 10^4}$$

cycles/sec.

The high value of natural frequency indicates the exceedingly low inertia of the moving parts of the element, and gives a prediction of quick time response to pressure change. Besides, the full signal will be set up only when the crystal has undergone maximum compression or deformation by the action of the pressure change, i.e., only when the crystal has reached its position at amplitude of vibration. The time required from start to maximum amplitude of vibration can therefore be considered as the time response of the element to a first approximation. This is equal to half the period of vibration or $2\pi/2\times W_n = \pi/63600 = 1/20300$ sec. (Note: The vibration of the crystal is the superposition of its transient term and its steady term, the latter being set up due to the step-function force or pressure change).

The time for the rapid pressure rise near top dead center after ignition in internal combustion engines is found from some p-V diagrams (Fig. 263, p.413, Ref.12; Fig. 47, p.91, Ref.13) to be about 5° crank angles at engine speed of 2000 r.p.m. This corresponds to a time duration of $5\times 60/360\times 2000$ or 1/2400 sec. If we consider the time rsponse of the crystal element as computed above from its natural frequency to be correct, then it is obvious that the element will be able to respond high pressure changes as encountered in modern high speed engines.

As the test has been performed with all the trapped air in the pipe lines eliminated by proper bleeding and there is no overloading of amplifier, the results are suffiently accurate to warrant conclusions. Some errors may be present in setting up the calibrating voltages and in measuring deflections on the film by the comparator, but the amount will not be appreciable. In, fact, by turning the comparator screw in the same direction for some time before taking deflection measurements, and by taking several readings for each measurement, the error can be reduced to a minimum. However, there is some inherent inaccuracy involved in the instrument and measurements as discussed in the Appendix, p.34, Fig. 18. The aggregate error that may be possibly involved in the final value of sensitivity can be assumed to be around 10% or ± 5%.

B. Electro-magnetic type

Three electro-magnetic pressure pickups made by Electro Products Lab., Chicago,Ill., were tested and calibrated. They are of type 3000A-57, 3000B-81 and 3000B-96 respectively.The width of air gap in the elements was fixed by first screwing in the pickup in its adapter until it contacts the diaphragm and then turning it backward about 1/2 turn and locking it in place.

The elements were calibrated by putting an integrating circuit between the amplifier and oscilloscope. For all tests, the amplifier gain was set at the standard position without overloading and the scope gain was changed such that the scope deflections for various pressures remained essentially the same.

Fig.11 shows the typical pictures taken of the scope deflections for various pressures acting on the pickup. The scope trace is continuous and is clearly discernible at the point of deflection. The deflection is proportional to the amplitude of diaphragm vibration when a certain pressure change occurs. This deflection decreases as the pressure is lowered(for constant scope gain setting).

The time response of the element to pressure change can be examined in the same way as for the quartz elements. The distance on the film between the start and completion of set up of the signal varies from 1/16" at high pressures to 1/8" at low pressures,corresponding to 1/576 and 1/288 sec. respectively.The natural frequency of diaphragm vibration is found as follows:

From p.432, Ref.11, the natural frequency of vibration of a circular plate of radius r, mass per unit area u_1 is given by:

$W_n = a\sqrt{D/u_1 r^4}$

where $a = 10.21$ for clamped edges, fundamental mode,

D = "plate constant" $= Et^3/12(1-u^2)$

E = modulus of elesticity

t = thickness of the plate

u = Poissons' ratio ≈ 0.3

For the steel diaphragm considered here,

$E = 3\times10^7$ psi

$t = 0.018''$ for all the three elements

$r = 0.25''$ for 3000A-57

$= 0.281''$ for 3000B-81 and 3000B-96

$D = 3\times10^7(0.018)^3/12(1-0.3^2) = 16$ lb.-in.

Density of the steel plate = 489 lb./cu.ft.

(p.549, Ref.14) = 0.283 lb./cu.in.

$u_1 = (0.283/32.2\times12)0.018 = 0.132\times10^{-4}$ lb. sec.^{2}/cu/in.

$\therefore W_n = 10.21\sqrt{16/0.132\times10^{-4}(0.25)^4} = 18\times10^4$ cycles/sec.

for 3000A-57

$W_n = 10.21\sqrt{16/0.132\times10^{-4}(0.281)^4} = 14.3\times10^4$ cycles/sec.

for 3000B-81 and 96

Hence the natural frequency of the diaphragms is even higher than that ofthe quartz crystals. By the same reasoning as for quartz crystals, we can conclude that these pickups have very quick time response, and will be able to respond very quickly to the rapid pressure rise in engine cylinders.

The peculiar wave form in Fig.11 shows the decay of the electric charge imparted on the condenser of the integrating circuit by the electric impulse of the pressure element. As the pressure change takes place,an electric impulse is set up by the pickup in direct proportion to the velocity of the diaphragm vibration and is impressed to the integrating circuit,therby imparting electric charges on the condenser. The condenser forms closed circuits with the oscilloscope and the output side of the amplifier as shown inFig.5. The leakage of this charge through these circuits reduces the voltage across the condenser,therefore scope light trace drops. The time interval required for the complete decay determines the wave form and depends on the "time constant" of the circuit. Let R be the resistance in the circuit and C be the capacitance of the condenser,then the time constant λ is equal to RC. For the circuit considered here, $C = 0.5$ mfd, $R = 600,000$ ohms,hence the time constant $\lambda = RC = 0.5 \times 10^{-6} \times 6 \times 10^{5} = 0.3$. A comparison of the decay curves as shown in Fig.136,p.337,Ref.15 and the wave form shown in Fig.11 verifies the above statement. Similarly,the very slow decay of the electric charge generated on quartz crystals as shown by the wave form in Fig.7 indicates that the time constant of the circuit there should be very large. This is quite true because the crystals act like condensers and form closed circuit with the input side of the amplifier. The capacitance of the crystals is small due to the large value of its thickness but the input impedance of the amplifier for 1-B circuit as used there is very large(10^{8}ohms) so that their product willbe large.

Following the same procedure as used for the calibration of piezo-electric pressure elements, except for the addition of the integrating circuit and using the 1-A instead of the 1-B circuit, the following results are obtained for the three elements and are tabulated in Tables 4,5, and 6.

The data are plotted into pressure vs. deflection, sensitivity vs. pressure, and voltage vs. pressure curves as shown in Figs.12,13, and 14 respectively. The pressure vs. deflection curves(Figs.12,13 and 14) show that their relation is linear. The curves are all stright lines passing through the origin, indicating that the scope deflection for any gain setting is directly proportional to the pressure applied on the diaphragm. Since this deflection is directly proportional to the integrated voltage across the condenser of the integrating circuit, which, in turn, is proportional to the amplitude of diaphragm vibration, the amplitude of the vibration seems to be proportional to the pressure applied to the diaphragm.

The three elements have different values of sensitivity as shown in Fig.15, but the modes of variation with respect to pressure for all of them are similar, i.e., sensitivity is larger at pressures between 300 and 700 psi and drops for both higher and lower pressures. The maximum value is from 3 to 3.7 m.v./100 psi.

Fig.16 indicates the voltage generated by the pressure elements as a function of pressure. The curves are not straight lines, showing that the relation is not linear. This is quite reasonable since the voltage generated is directly proportional to the velocity of the diaphragm vibration which does not depend on the amount of pressure only.

Since there is no marked deviation of the curves and values for all the three elements tested, the results may be considered quite satisfactory.

Table 4. Calibration results for electro-magnetic pickup 3000B-96

Pressure (P)	Calibrating Voltage (V)	Pressure Deflection(y)	Voltage Deflection(x)	Sensitivity $K = \frac{Vy}{Px}$	Voltage Induced by Pressure=PK
(1) Scope gain switch at input voltage < 250 V.R.M.S. side, gain control at 25					
950 psi	25 m.v.	0.170"	0.148"	3.02 m.v./100psi	28.7 m.v.
900	25	0.163	0.148	3.06	27.5
850	25	0.176	0.148	3.50	29.8
800	25	0.160	0.148	3.38	27.0
(2) Scope gain switch at input voltage < 250 V.R.M.S. side, gain control at 30					
700	20	0.195	0.154	3.62	25.4
600	20	0.170	0.154	3.68	22.1
500	20	0.141	0.154	3.67	18.4
(3) Scope gain switch at input voltage < 250 V.R.M.S. side, gain control at 50					
400	10	0.183	0.129	3.54	14.2
300	10	0.131	0.129	3.39	10.2
200	10	0.084	0.129	3.26	6.52
(4) Scope gain switch at input voltage < 25 V.R.M.S. side, gain control at 60					
100	2	0.333	0.290	2.30	2.30
75	2	0.245	0.290	2.25	1.69
50	2	0.150	0.290	2.07	1.04

Table 5. Calibration results for electro-magnetic pickup 3000B-81

Pressure (P)	Calibrating Voltage (V)	Pressure Deflection(y)	Voltage Deflection(x)	Sensitivity $K = Vy/Px$	Voltage generated by $P = PK$
(1) Scope gain switch at input voltage < 250 V.R.M.S. side, gain control at 25					
950 psi	25 m.v.	0.425"	0.414"	2.71 m.v./100 psi	25.8 m.v.
900	25	0.390	0.414	2.76	23.6
800	25	0.365	0.414	2.62	22.1
(2) Scope gain switchat input voltage < 250 V.R.M.S. side, gain control at 28					
700	18	0.398	0.352	2.91	20.4
600	18	0.346	0.352	2.95	17.7
500	18	0.283	0.352	2.90	14.5
(3) Scope gain switch at input voltage < 250 V.R.M.S. side, gain control at 50					
400	10	0.346	0.310	2.79	11.2
300	10	0.245	0.310	2.64	7.93
200	10	0.150	0.310	2.42	4.84
(4) Scope gain switch at input voltage < 25 V.R.M.S. side, gain control at 26					
100	2	0.302	0.368	1.64	1.64
75	2	0.173	0.368	1.25	0.937
50	2	0.114	0.368	1.24	0.620

Table 6. Calibration results for electro-magnetic pickup 3000A-57

Pressure (P)	Calibrating Voltage (V)	Pressure Deflection(y)	Voltage Deflection(x)	Sensitivity $K = Vy/Px$	Voltage generated by $P = PK$
(1) Scope gain switch at input voltage < 250 V.R.M.S. side, gain control at 40					
950 psi	25 m.v.	0.200"	0.234"	2.25 m.v./100 psi	21.4 m.v.
900	25	0.196	0.234	2.33	21.0
850	25	0.198	0.234	2.49	21.2
800	25	0.184	0.234	2.46	19.7
(2) Scope gain switch at input voltage < 250 V.R.M.S. side, gain control at 60					
750	20	0.262	0.271	2.58	19.4
700	20	0.242	0.271	2.55	17.9
600	20	0.205	0.271	2.52	15.1
500	20	0.191	0.271	2.82	14.1
(3) Scope gain switch at input voltage < 250 V.R.M.S. side, gain control at 100					
400	12	0.250	0.244	3.08	12.3
350	12	0.212	0.244	2.98	10.4
300	12	0.173	0.244	2.84	8.52
(4) Scope gain switch at input voltage < 25 V.R.M.S. side, gain control at 60					
100	2	0.253	0.292	1.73	1.73
75	2	0.180	0.292	1.64	1.23
50	2	0.143	0.292	1.96	0.98

VI. Conclusion

From the experimental results obtained, we find that the sensitivity of piezo-electric pressure element is fairly constant throughout the pressure range up to 950 psi, its value being 3.5 to 3.75 m.v./100 psi, which is slightly higher than the value(3.0 m.v./100 psi) reported by the manufacturer(Ref.7). These values, however, are subjected to an error of ± 5%. The general prediction that the electric voltage generated by the piezo-electric effect of quartz crystal element is directly proportional to the pressure applied is verified. The linear relation between the scope deflection and pressure is also established.

The voltage generated by electro-magnetic pickup under certain pressure is proportional to the velocity of diaphragm vibration and is not proportional to the pressure being applied. The relation is shown in Fig. 16. The sensitivity of the electro-magnetic elements is not constant throughout the pressure range tested, but increases from about 2.0 m.v./100 psi at 100 psi to a maximum of about 3.0-3.70 m.v./100 psi at pressures 300 to 700 psi and again drops as the pressure is further increased(Fig.15). The oscilloscope deflection produced by the integrated voltage is proportional to the amplitude of diaphragm vibration and to the pressure applied. The linearity of the relation is shown in Figs. 12,13 and 14.

The time response of the elements to pressure change is found to be very quick by considering their high values of natural frequency of vibration.These elements are, therefore, expected tobe suited for high-speed indication applications. However, this conclusion is based on theoretical computations only, since no definite measurements can be obtained in this respect from the calibrating instruments.

VII. List of References

(1) Symposium of Papers on Indicators, Proceeding, Institute of Mechanical Engineers,Vol.1(1923),p.95.

(2) Indicators as a Means for Improving aircraft Engine Performance,by F.L.Prescott,S.A.E.Journal 31.#3,p.361

(3) The Application of an Electro-magnetic Indicator to Internal Combustion Engines by C.S.Draper and J.H. Lauer, K.L.Davis,Journal of Aeronautical Sciences,Vol.8(1941)p.7

(4) Development and Application of the Cathode-ray Engine Indicator,by E.M.Dodds,S.A.E.Journal 39(1936),p.487

(5) A New High-speed Engine Indicator,by E.S.Taylor and C. S.Draper,Mechanical Engineer,55(1933),p.169

(6) High-speed Combustion Engines by P.M.Heldt,(1944)p.638-647

(7) The Cox Quartz Pressure Element,Type 3, Book of Instructions, Commercial Research Lab., Detroit,Michigan

(8) The Cox Portable Amplifier,Type 2,Book of Instructions, Commercial Research Lab.,Detroit,Michigan

(9) The Cox Multiple Contactor,Type 6,Handbook of Instructions, Commercial Research Lab.,Detroit,Michigan

(10)Instructions for ElectroPickup, Type Series 3000,Electro Products Lab., Chicago, Ill.

(11)Mechanical Vibrations,by Den Hartog,p.80,& p.432

(12)Internal Combustion Engines by Jennings and Obert

(13)Verbrennungsmotoren by F.A.F.Schmidt

(14)Mechanical Engineers' Handbook by L.S. Marks

(15)Principle of Electricity by Page and Adams

VIII. List of Figures and Tables

Figures

Tables

IX. Appendix

A. Some troubles encountered in the test for piezo-electric pressure elements

In the first set of test, the quartz pressure elements #1306 and #1286 were calibrated throughout a pressure range up to 300 psi only, same scope gain setting being used for the test. The amplifier gain position was not noticed. The data obtained for both elements are plotted into curves in Figs.17,18 and 19. The linear relation between pressure and scope deflection for #1306 conforms to theory quite closely while the data for #1286 show great deviation of the curve from the straight line. The sensitivity of element #1306 varies from 2.9 to about 4.0 m.v./100 psi which is not very different from 3.0 m.v./100 psi reported by the manufacturer, while that of #1286 decreases from 2.63 to 1.36 m.v./100 psi as the pressure is increased. The variation of voltage output or sensitivity of elements with respect to pressure can be seen from the sensitivity curves in Fig,19. The cal--ibration voltage vs. scope deflection curves under the same amplifier and scope gain are drawn in the same sheet for comparison(Fig.18). The difference in deflection for the same calibrating voltage shows the errors involved in the instruments and in deflection measurements. If there is no such errors, the two curves should coincide. The space between the two curves therefore is a measure of the errors present in the experiment. Taking,e.g.,the deflection at 7 m.v. which is 0.297" for one curve and is 0.339" for the other. The percent error is therefore 0.339-0.297/0.339 or 12.4% which is rather large. The average aggregate error of the experiment can be taken as around 10%. Since the two calibrating voltage vs. scope deflection curves are all straight lines, there is no overloading of the amplifier. The departure of the pressure vs. scope deflection curve for element #1286 from the theoretical linear relation can therefore not be attributed to the amplifier overloading, but must have been caused by the presence of air in the in--strument. The poor curves are presented here to emphasize the need for care in assembling and bleeding of the calibrating system.

Since the high pressure portion of engine performance is more important and the maximum combustion pressure in the engine cylinders under normal operating conditions is below 1000 psi, the second set of test was made for elements #1279 and #1306 with the calibrating pressure range up to 950 psi. Same scope gain was used throughout the test and the amplifier gain position is not noticed. The data obtained are drawn in Figs.20,21 and22.

All the pressure curves as shown in Fig.20 are not linear. This, together with the sensitivity curves, shows that the sensitivity drops as the pressure increases. The sensitivity is in all cases much lower than 3.0 m.v./100 psi, the value reported by the manufacturer. The reason for the decrease in sensitivity at high pressures and the depa--rture of the pressure-deflection curves from the linear relation may be seen from the calibrating voltage curves in

Fig. 21. Here the two curves are not straight lines as anticipated but becomes steeper as voltage is increased. The portions of the curves below 8 m.v. are straight lines but the upper portions are curved. Since the amplifier gain used in the test has not been checked for overloading, this peculiar deviation may be attributed to the overloading of the amplifier, as evidenced by the curvature of the voltage curves at high voltages. "Overloading" causes distortion of the pressure diagram and flattens the peaks of the sine waves, thereby reducing the apparent amplitudes or deflection, especially at high voltages or pressures. This results in faulty scope deflection and incorrect indication of sensitivity.

B. Testing electro-magnetic pickups without integrating circuit

If the electro-magnetic pickup elements were calibrated without the integrating circuit, the resulting pictures of the scope deflections are in the form as shown in Fig,23. These deflections are directly proportional to the velocity of diaphragm vibration which depends not only on the amount of pressure applied but also on the time rate at which this pressure is applied. The scope trace as shown on the film cannot be seen clearly at the point where deflection takes place. As the pressure is suddenly released, the scope light trace is first deflected upward and then downward. The difference between the lowest trace and its equilibrium position becomes smaller as the pressure change is reduced. At about 150 psi, the trace becomes clearly discernible. The deflections of the picture therefore cannot be measured and are useless in evaluating the voltage output or sensitivity of the element because they are not a measure of pressure only.

C. Some suggestions as to the high-temperature Calibration of the quartz pressure elements

The pressure elements when screwed into cylinder head and put into actual use are exposed to the high temperatures within the cylinder. For the electro-magnetic pickup, holes are provided in the adapter so that compressed air can be applied for cooling of the windings and diaphragm. For the piezo-electric pressure elements, no such cooling devices are provided so that the quartz crystals are subject to the heat of the combustion gas in the cylinder. According to manufacturers' specification(Ref. 7), the sensitivity of the Cox type-3 quartz crystal pressure element is unaffected by a temperature up to 350°C.(662°F). Above this temperature, the quartz sensitivity drops rapidly, until at about 573°C. (1063°F.), it is zero. At this temperature, the quartz changes from Alpha to Beta quartz. However, upon cooling, the quartz returns to its previous form and the element regains its normal characteristics.

From actual measurements, the usual cylinder head temperature are around 650° to 800°F. Hence the sensitivity of the quartz pressure element when used in the engine cylinder will be lower than its low temperature value. Thus, the oscilloscope record of the pressure variation inside the cylinder gives only a qualitative idea and cannot be interpreted quantitatively unless the high temperature sensitivity value of the element is known.

For the test performed in this research, only room temperature sensitivity values of the elements are obtained, using the single impulse step-function method. In order to conform to actual engine operations more closely, a rotary selector valve should be used so that the pressure element willbe acted on by high pressure compressed air and atmospheric air alternately within one revolution of the valve.(FIG·24) A recurring electric signal willbe generated by the pressure element instead of a single signal. The element is connected to an oscilloscope through the amplifier in the usual way. By varying the pressure of the compressed air acting on the element and recording the scope deflection correspondingly, the usual pressure vs. deflection curves and sensitivity values can be obtained by means of the calibrating voltage circuit as stated in this paper .

For the high temperature calibration, the same rotary selector valve driven by a variable-speed motor can be used, but a heating coil should be installed around the element so that the latter will be heated to any high temperature as required for the calibration. The temperature can be varied by means of a resistance box placed in the circuit and can be measured by a thermocouple inserted into a hole in the adapter into which the element is screwed.

Figures

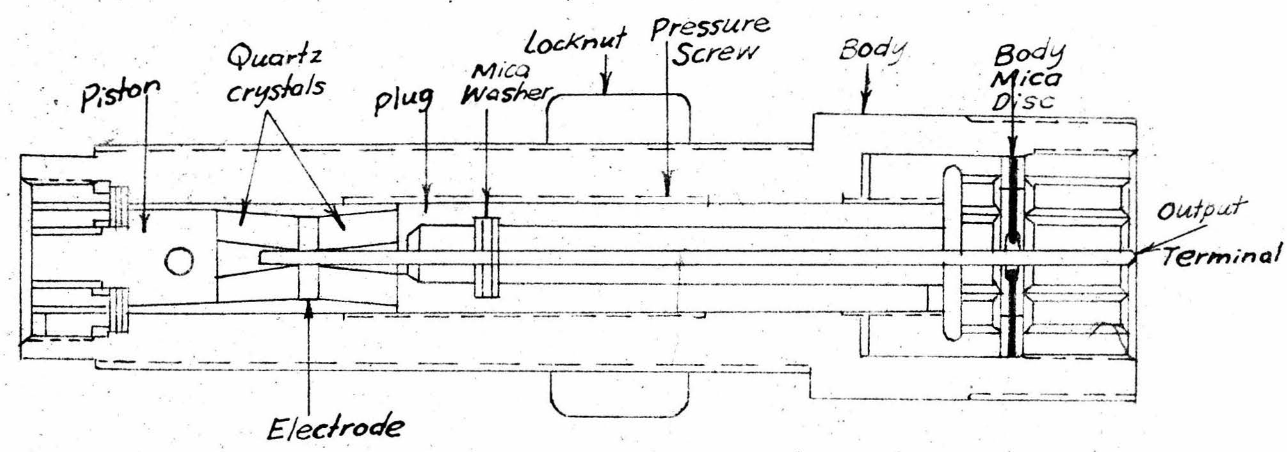


Fig. 1. Cox Type-3 Quartz Crystal Pressure Element

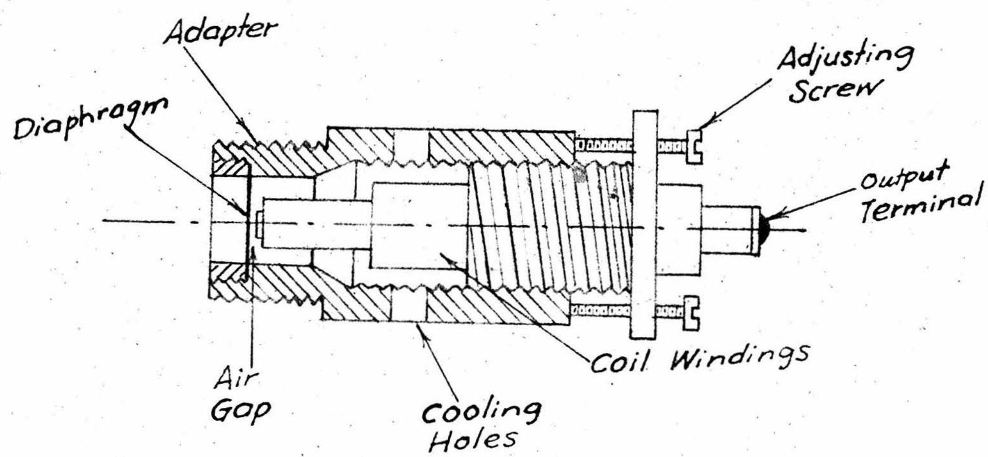


Fig. 2. Electro-magnetic Pressure Pickup

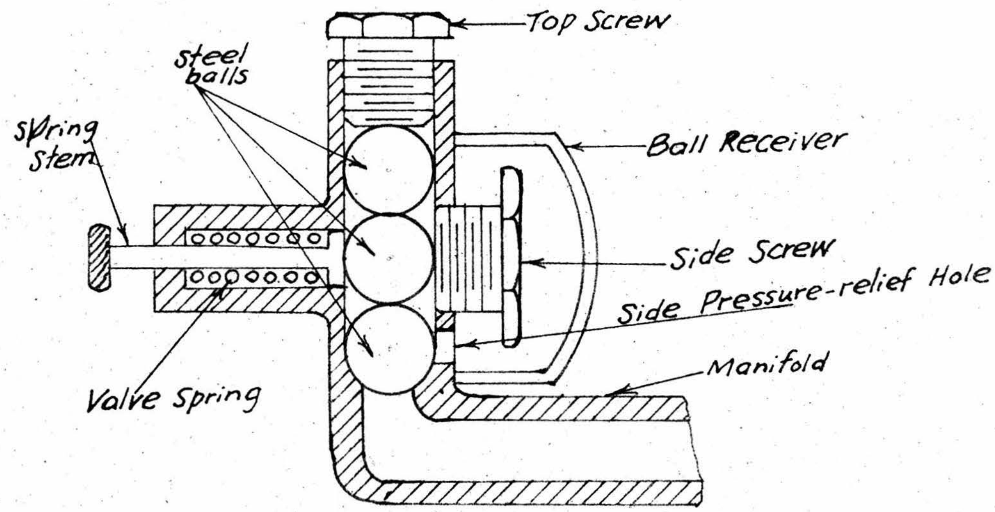


Fig. 4. Quick-acting Pressure Release Valve

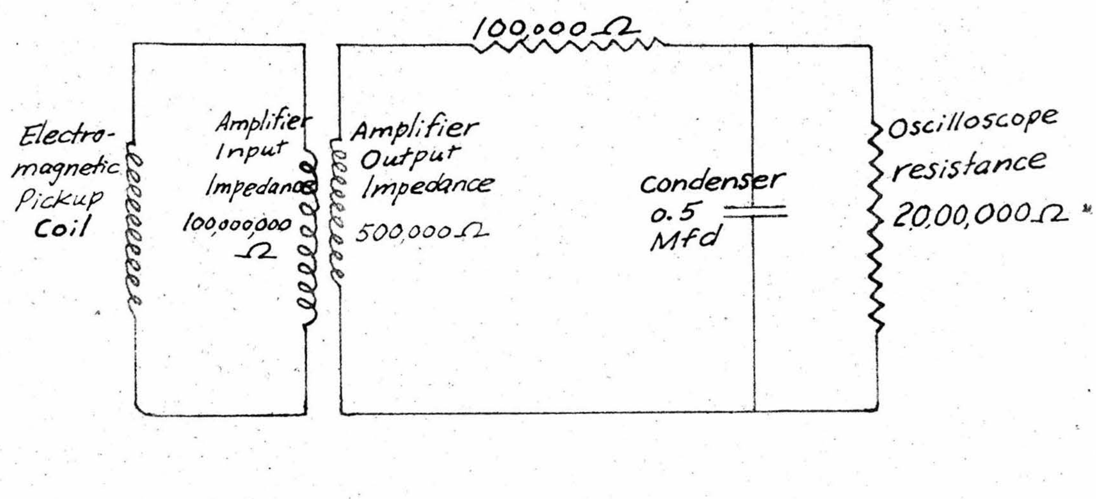
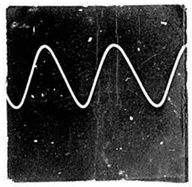
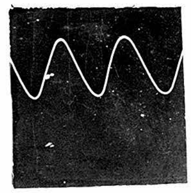


Fig. 5. Integrating Circuit

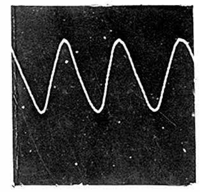
(Between Amplifier and Oscilloscope)



10 m.v.
Scope gain 14



20 m.v.
Scope gain 11.5

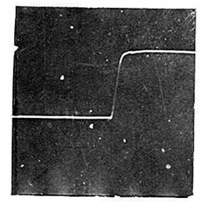


30 m.v.
Scope gain 10

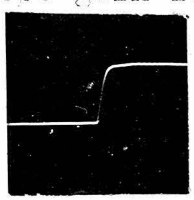
Fig.6. Typical sinusoidal waves of calibration voltages on the oscilloscope screen(Scope gain switch at input voltage < 250 V.R.M.S. side).

800 psi
Scope gain 10

900 psi
Scope gain 10



950 psi
Scope gain 10



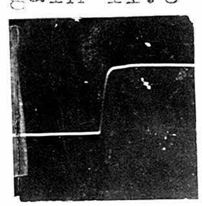
500 psi
Scope gain 11.5

600 psi
Scope gain 11.5

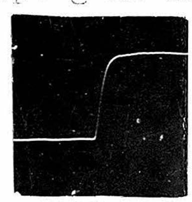
700 psi
Scope gain 11.5

100 psi
Scope gain 14

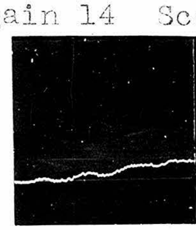
200 psi
Scope gain 14



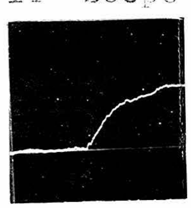
300 psi
Scope gain 14



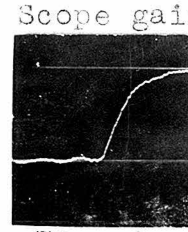
400 psi
Scope gain 14



25 psi
Scope gain 30



50 psi
Scope gain 30



75 psi
Scope gain 30

Fig.7. Typical step-function waves due to the electric impulse recorded by the quartz pressure element.

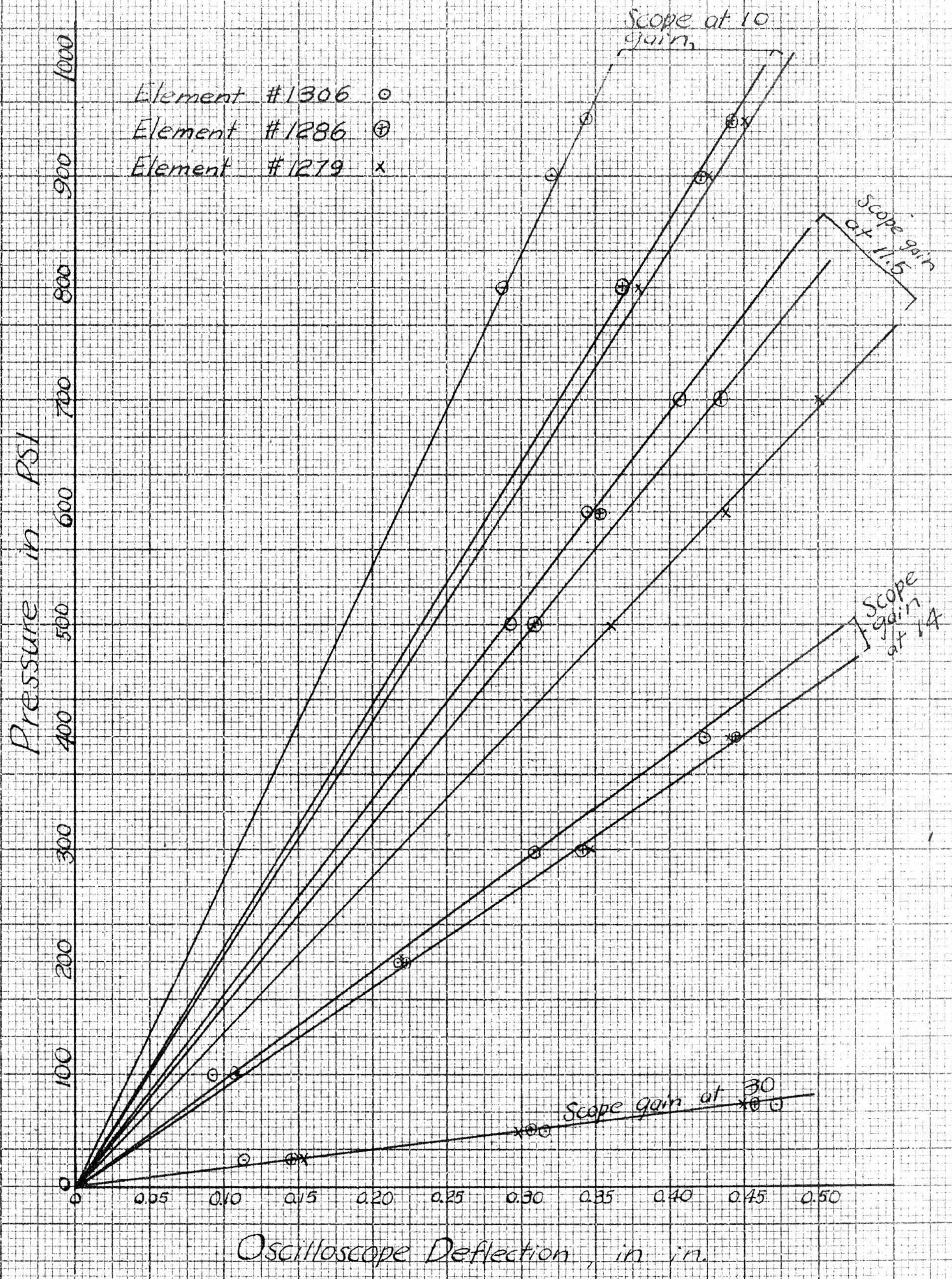


Fig. 8. Pressure vs. Deflection Curves for Cox type-3 Quartz Pressure Elements (Amplifier gain at Standard position, Oscilloscope gain Switch position : Input Voltage < 250 V. R.M.S.)

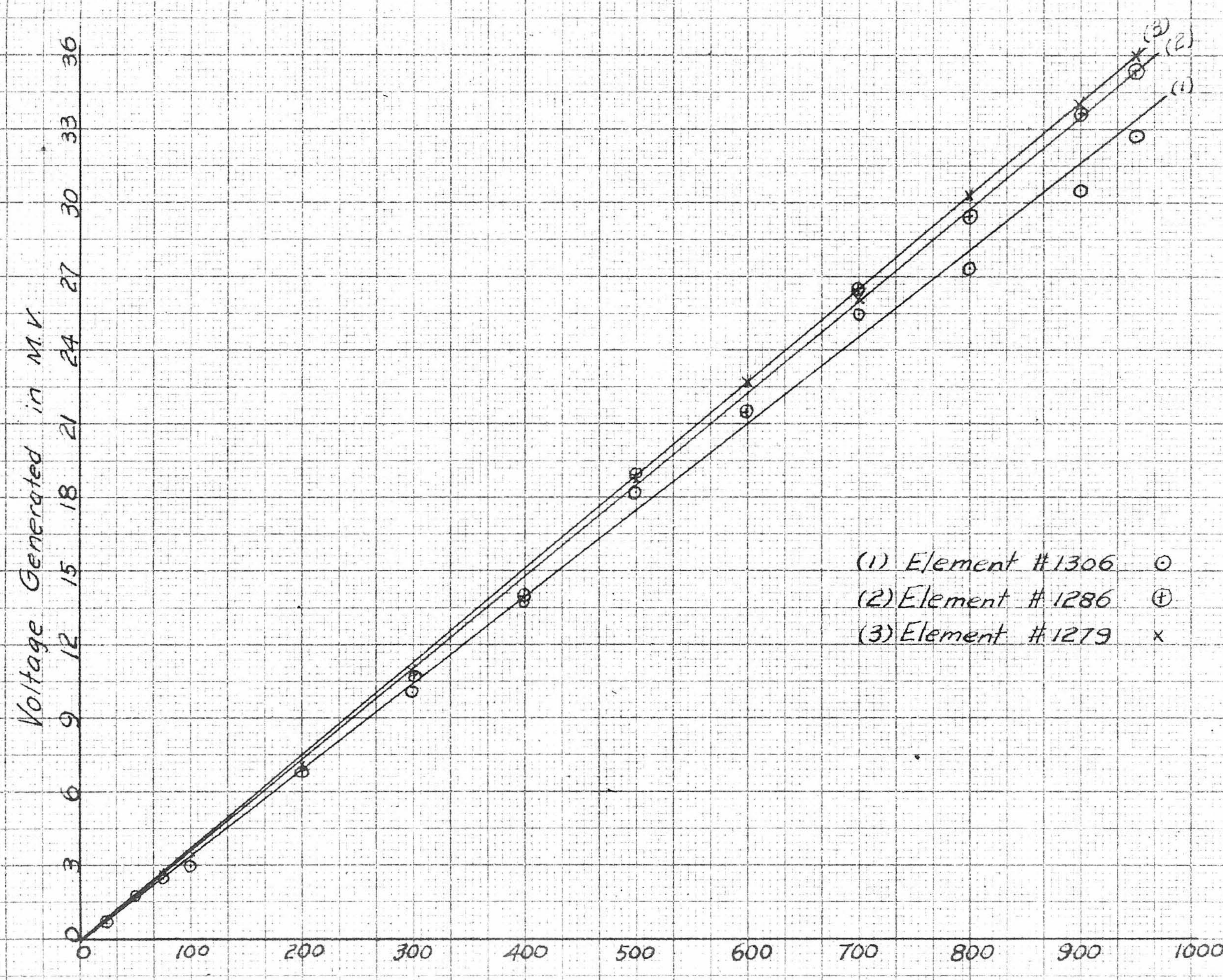


Fig. 9 Generated Voltage vs. Pressure Curves for Cox Type-3 Quartz Pressure Elements

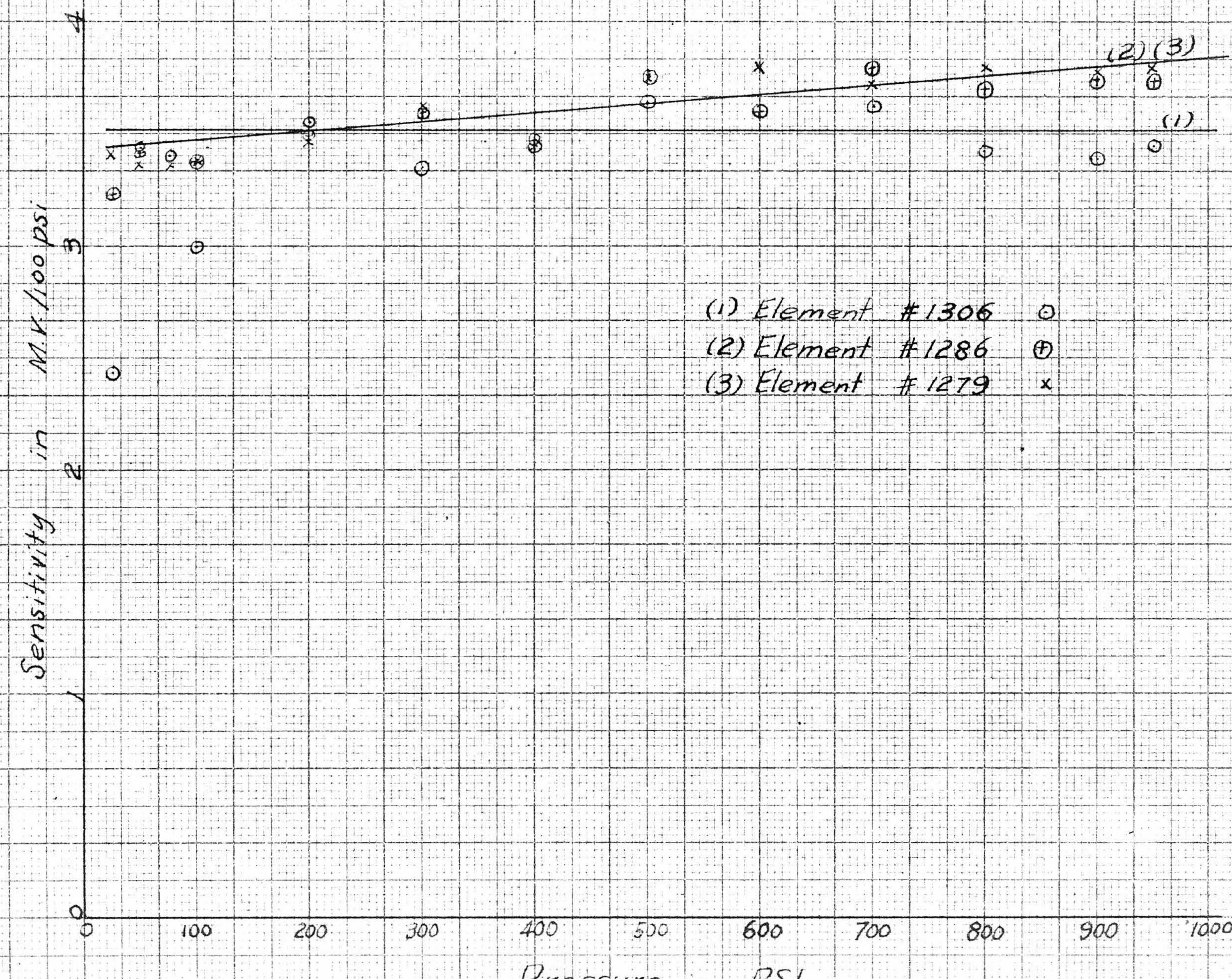
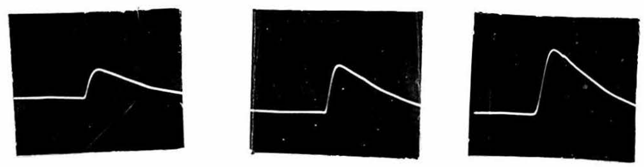
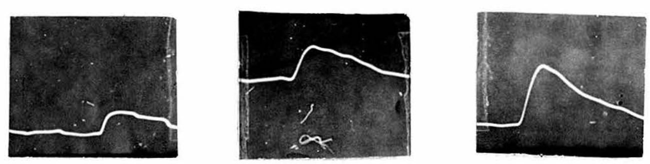


Fig. 10 Sensitivity Curves for Cox Type-3 Quartz Pressure Elements

500 psi 600 psi 700 psi 800 psi 900psi



200 psi 300 psi 400 psi



50 psi 75 psi 100 psi

Fig.11. Typical record of scope deflections for various pressures acting on electro-magnetic pressure elements (with integrating circuit).

Scope Gain: 25 for 900,800 psi; 28 for 700, 600,500 psi; 50 for 400,300, 200 psi.(Scope gain switch at input voltage < 250 V.R.M.S. side.)

26 for 100,75, 50 psi.(Scope gain switch at input voltage < 25 V.R.M.S. side).

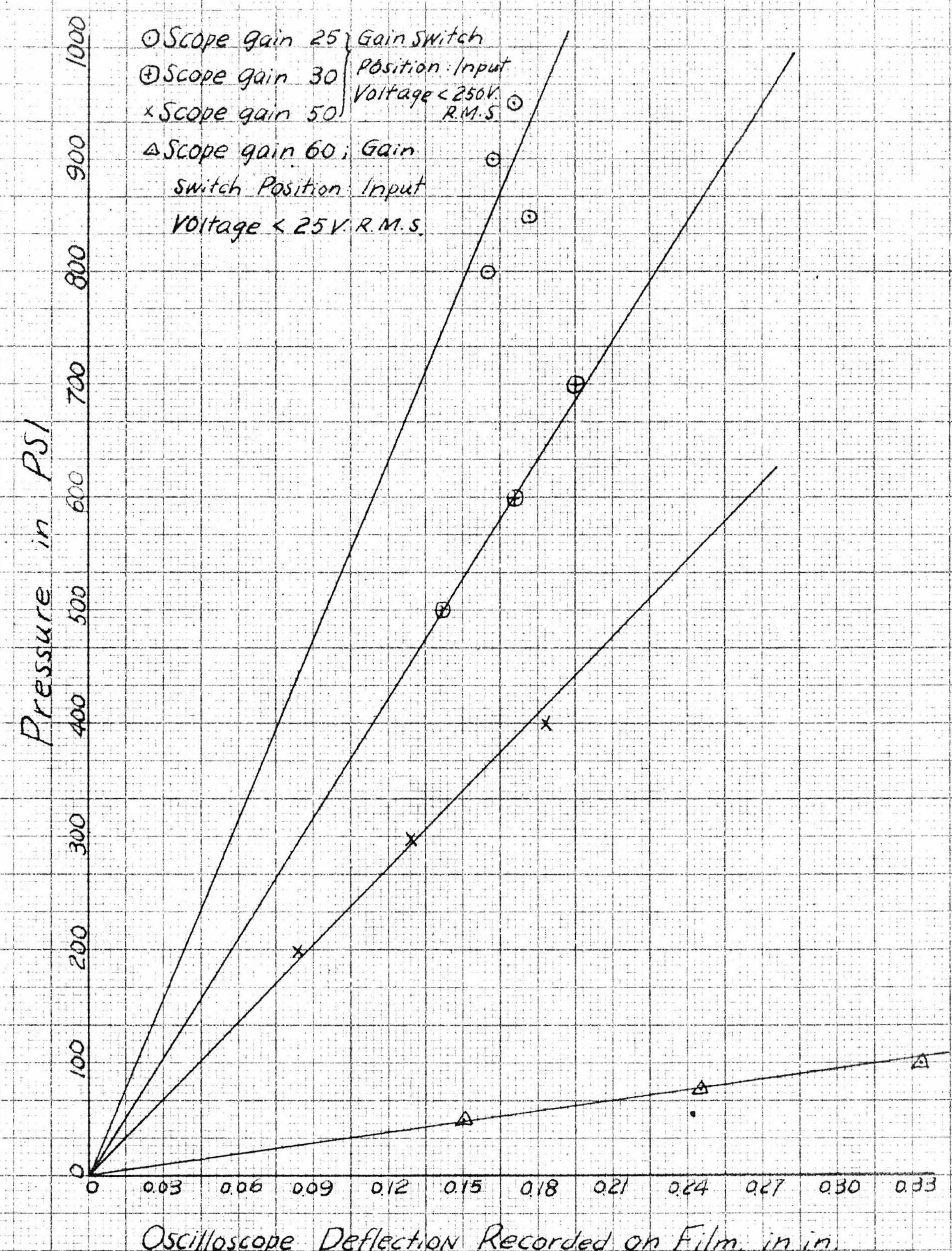


Fig. 12. Pressure vs. Deflection Curves for Electro-magnetic Pressure Element 3000 B-96

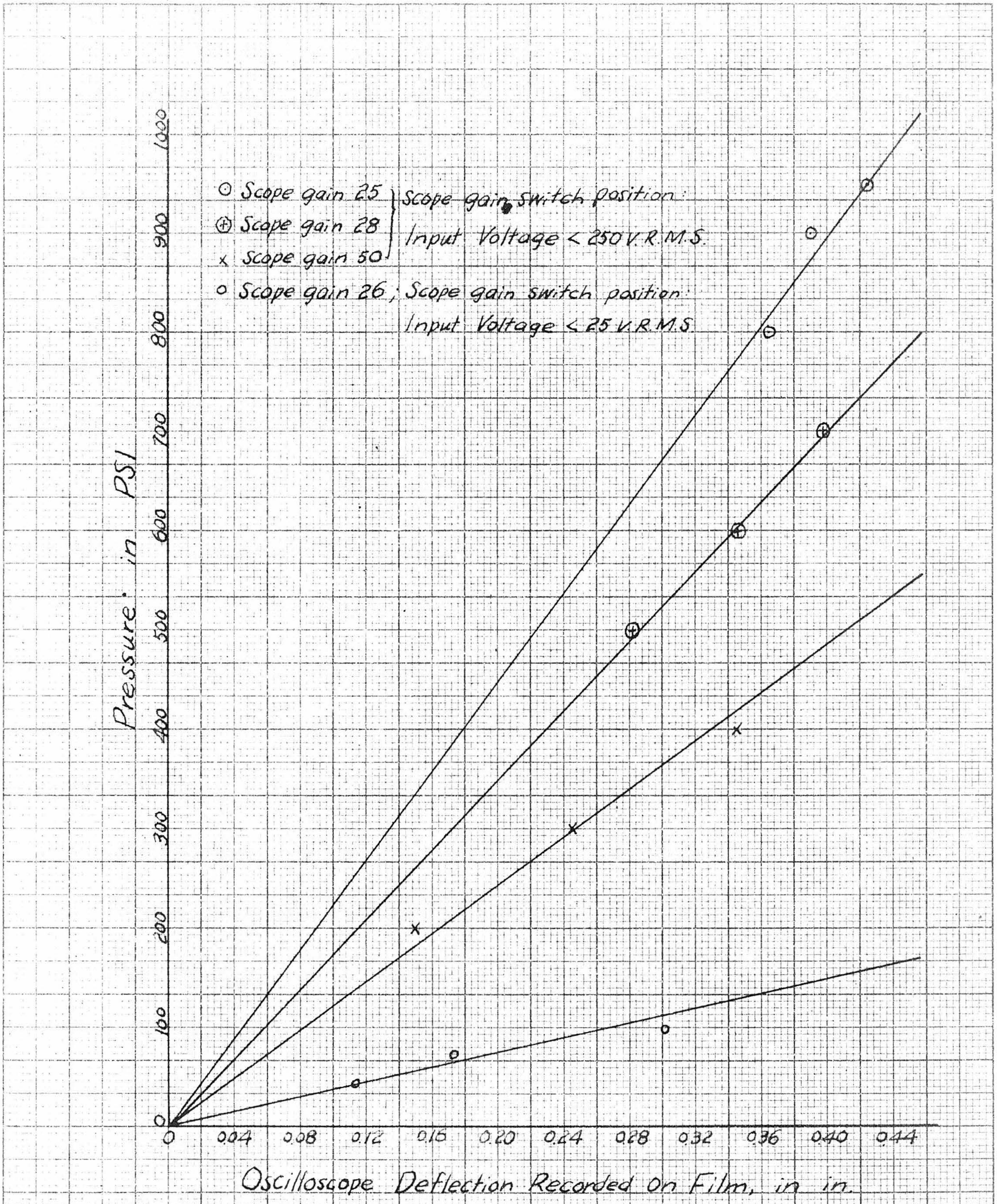


Fig. 13 Pressure vs. Deflection Curves for Electro-magnetic Pressure Pickup 3000B-81

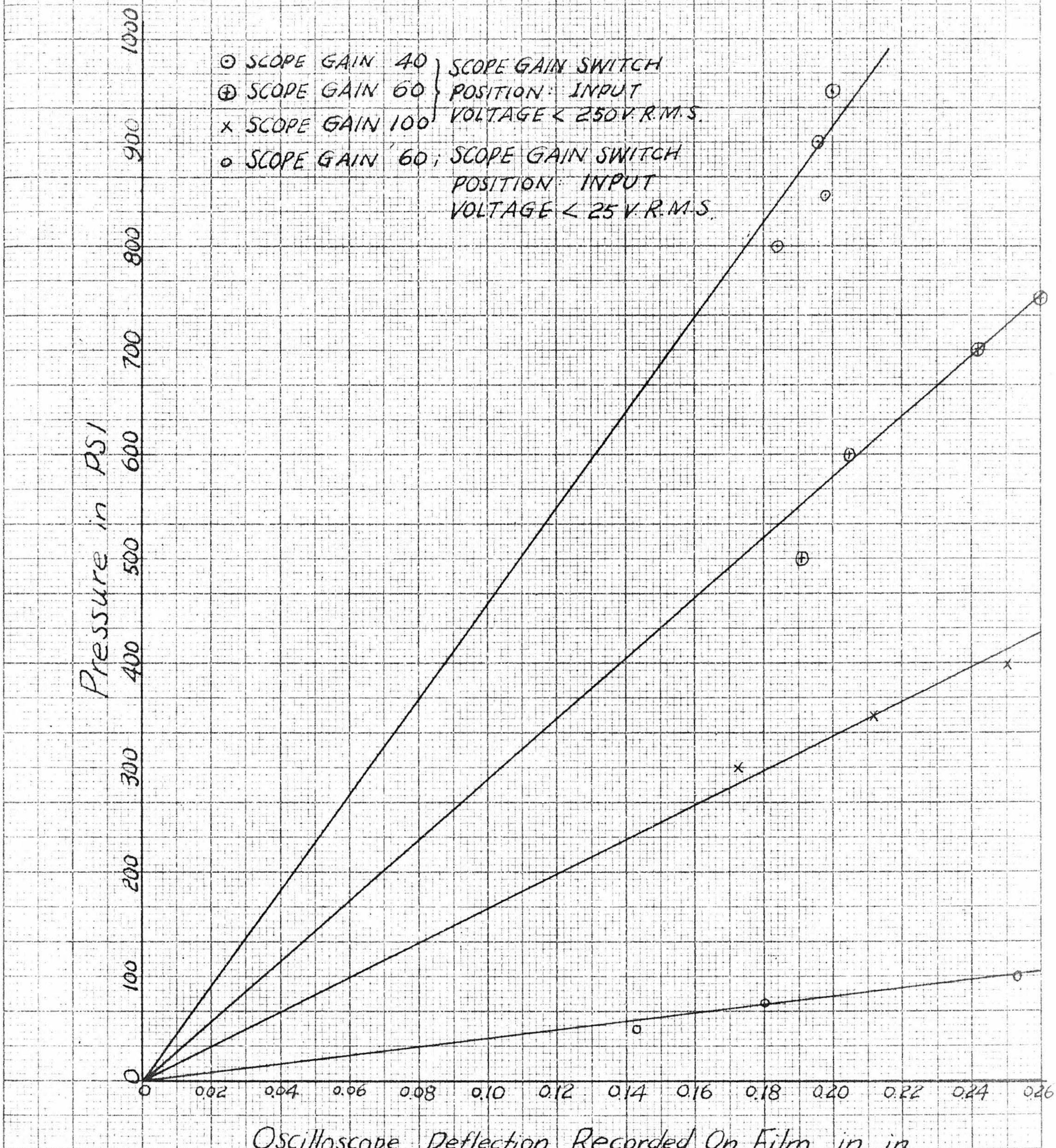


Fig. 14 Pressure vs Deflection Curves for Electro-magnetic Pressure Element 3000 A-57

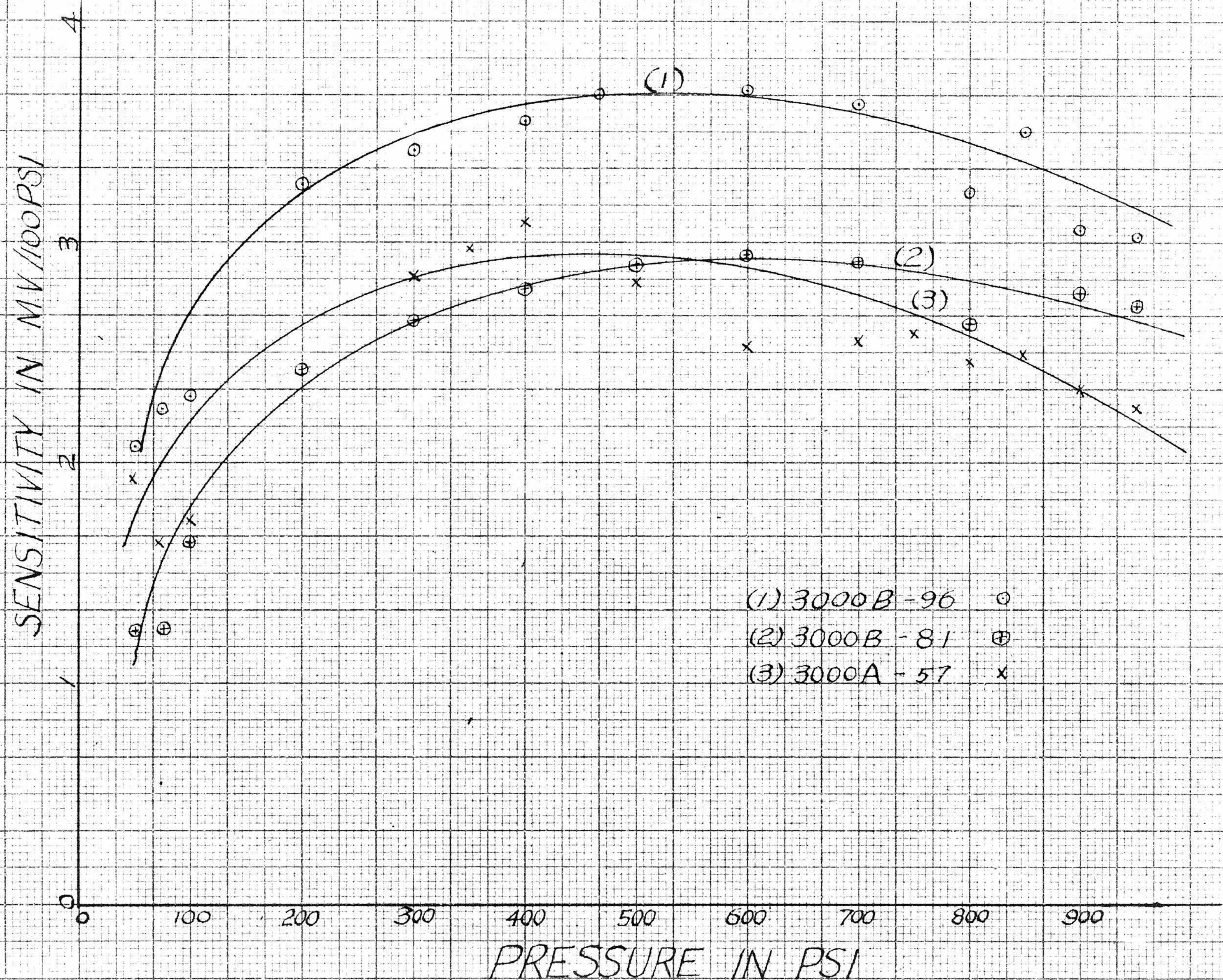


FIG 15. SENSITIVITY CURVES FOR ELECTRO-MAGNETIC PICKUPS

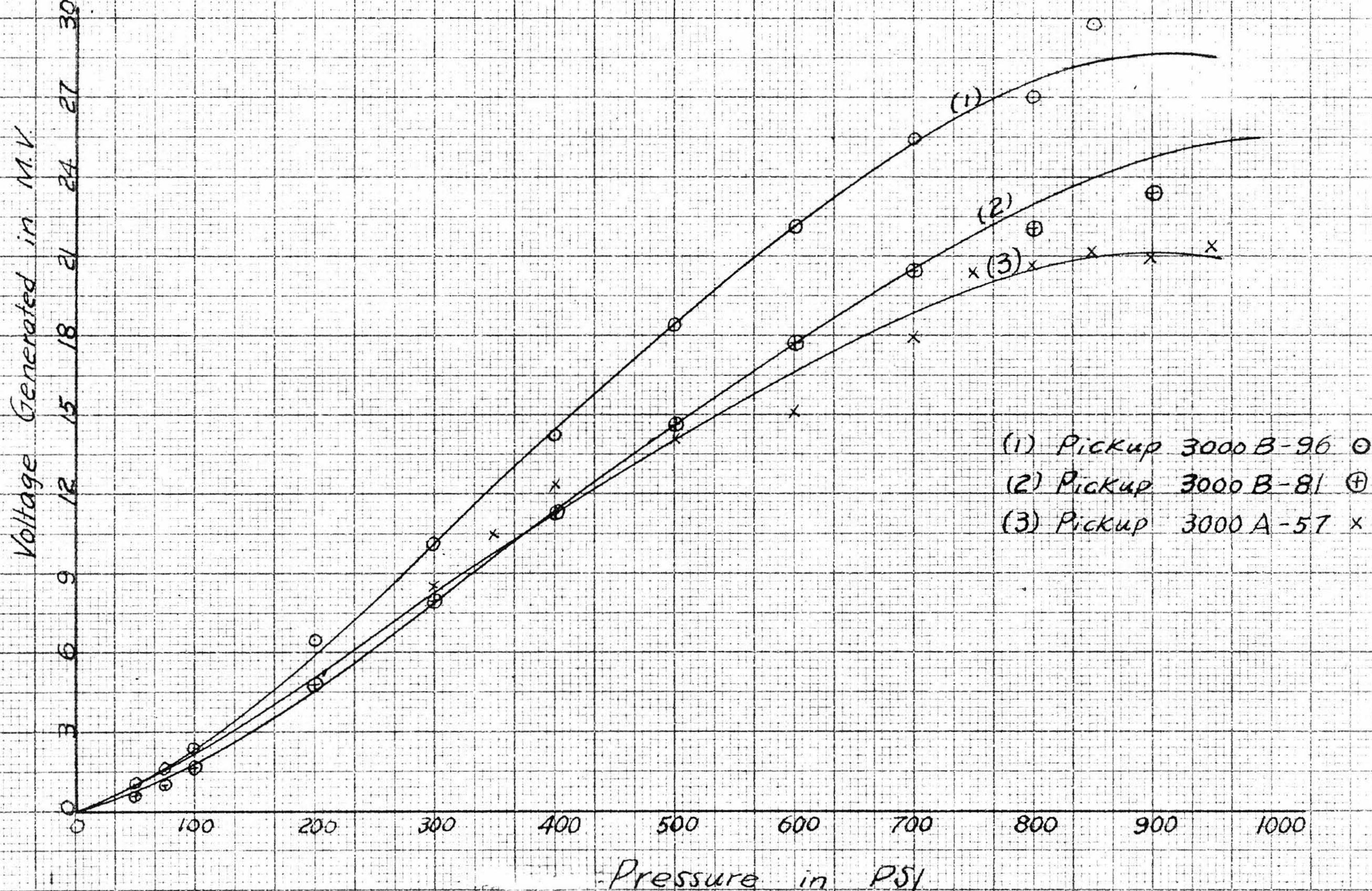


Fig. 16. Induced Voltage vs. Pressure Curves for Electro-magnetic Pressure Pickups

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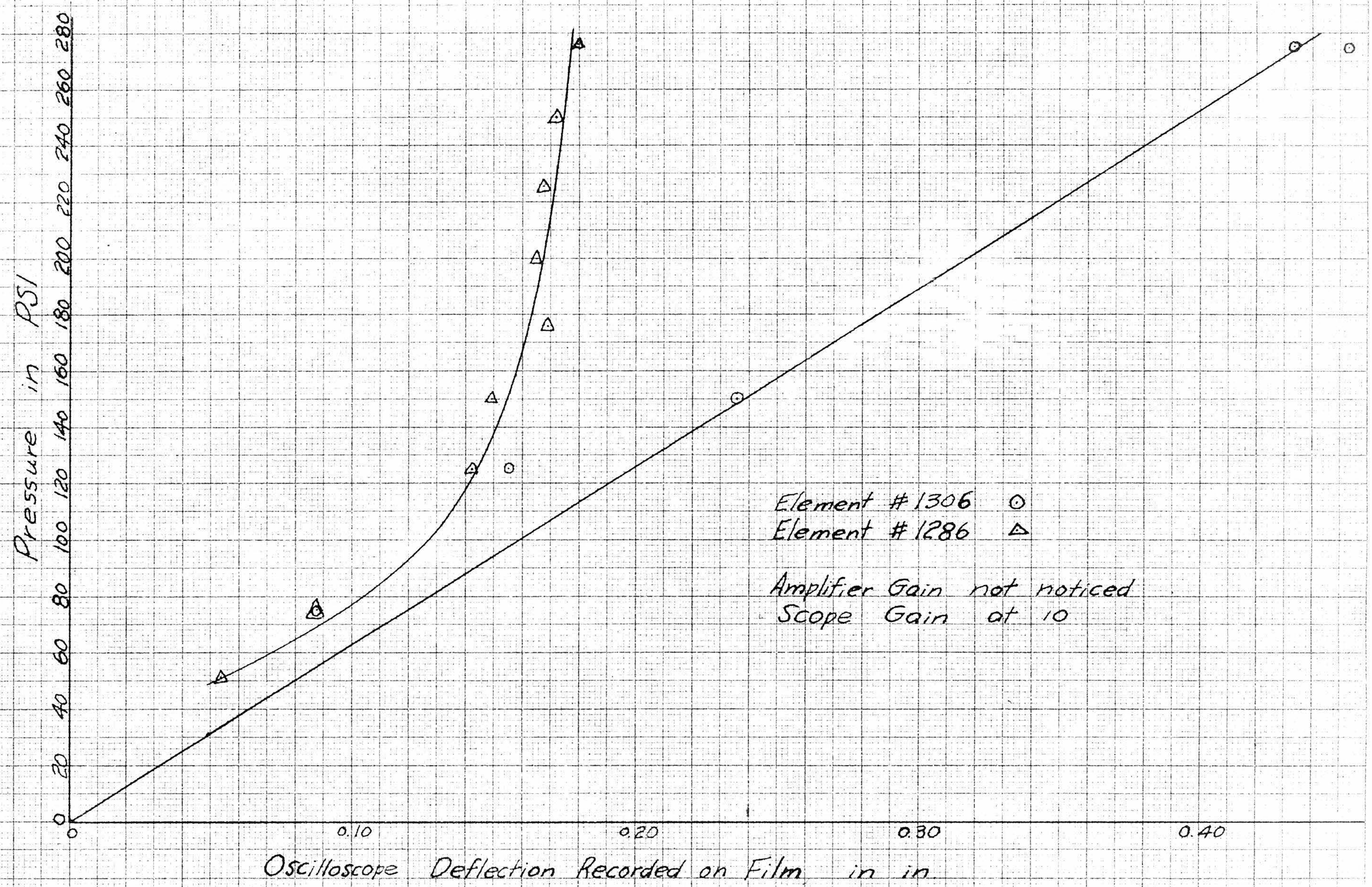

Fig. 17. Pressure vs. Deflection Curves for Cox Type-3 Quartz Pressure Elements, (Showing the effect of entrapped air for #1286)

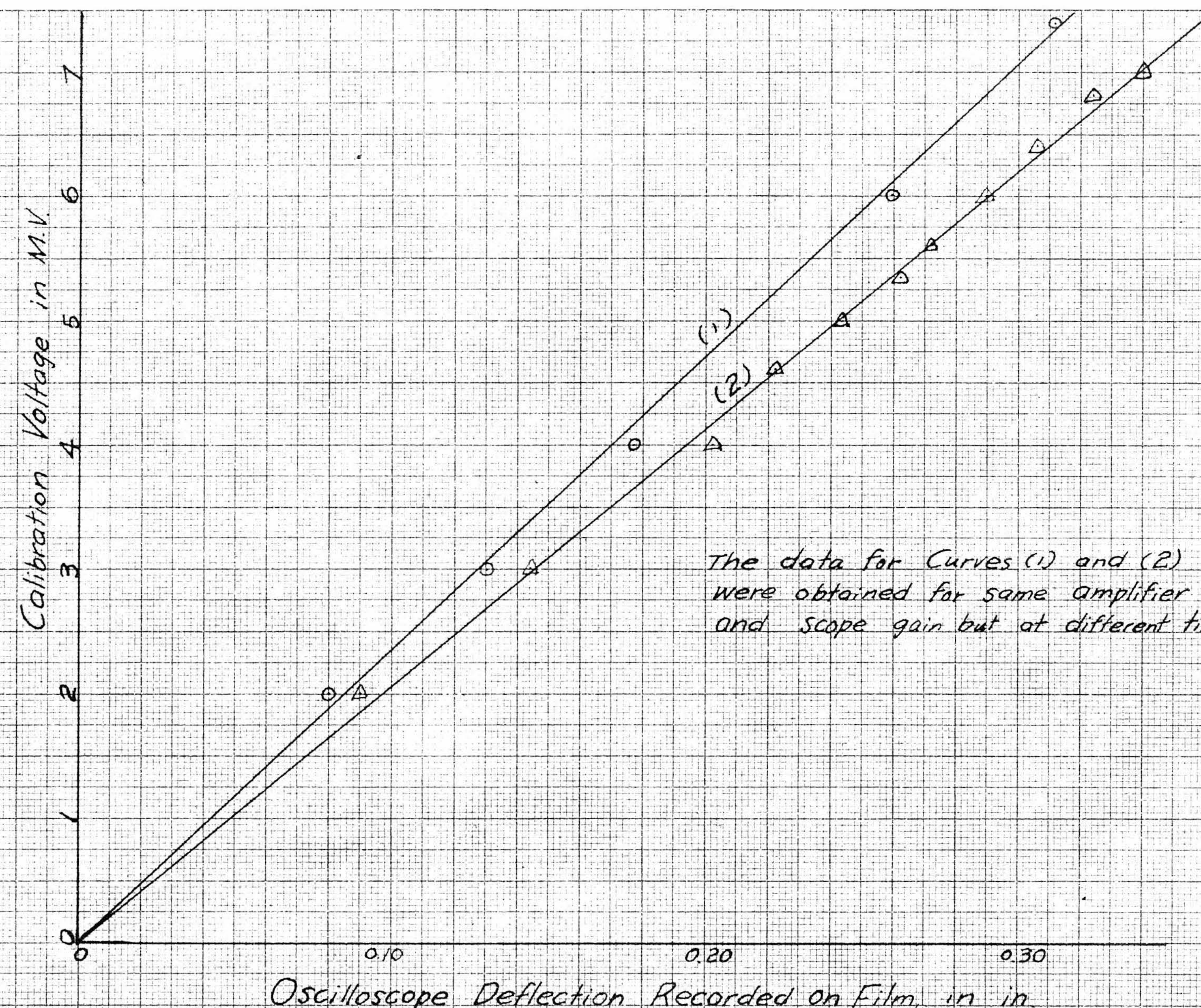

Fig. 18 Calibration Voltage vs. Scope Deflection Curves, Showing the Errors In the Experiment

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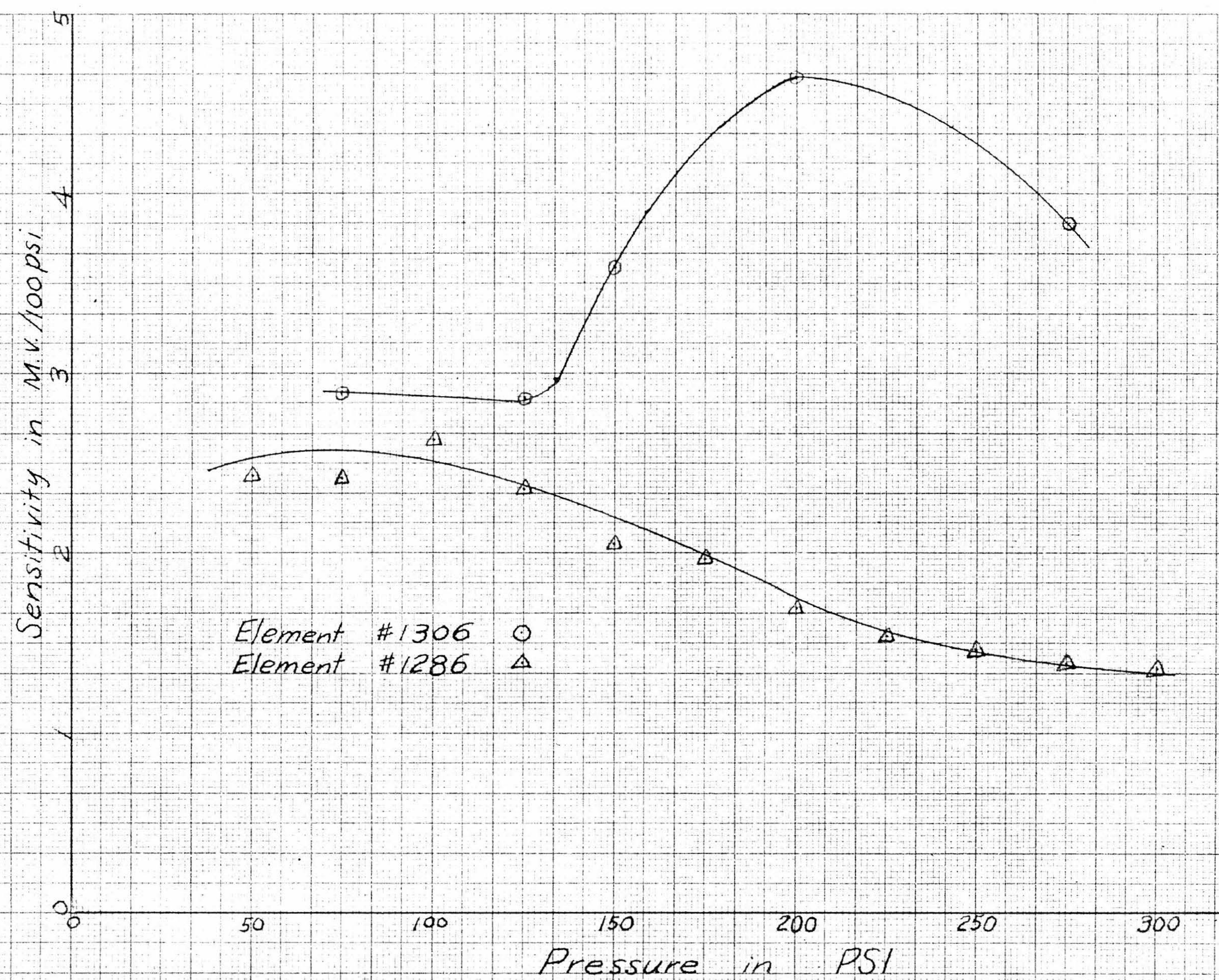

Fig. 19 Sensitivity Curves for Cox Type-3 Quartz Pressure Elements, Showing the Faulty Result due to Improper Air Bleeding.

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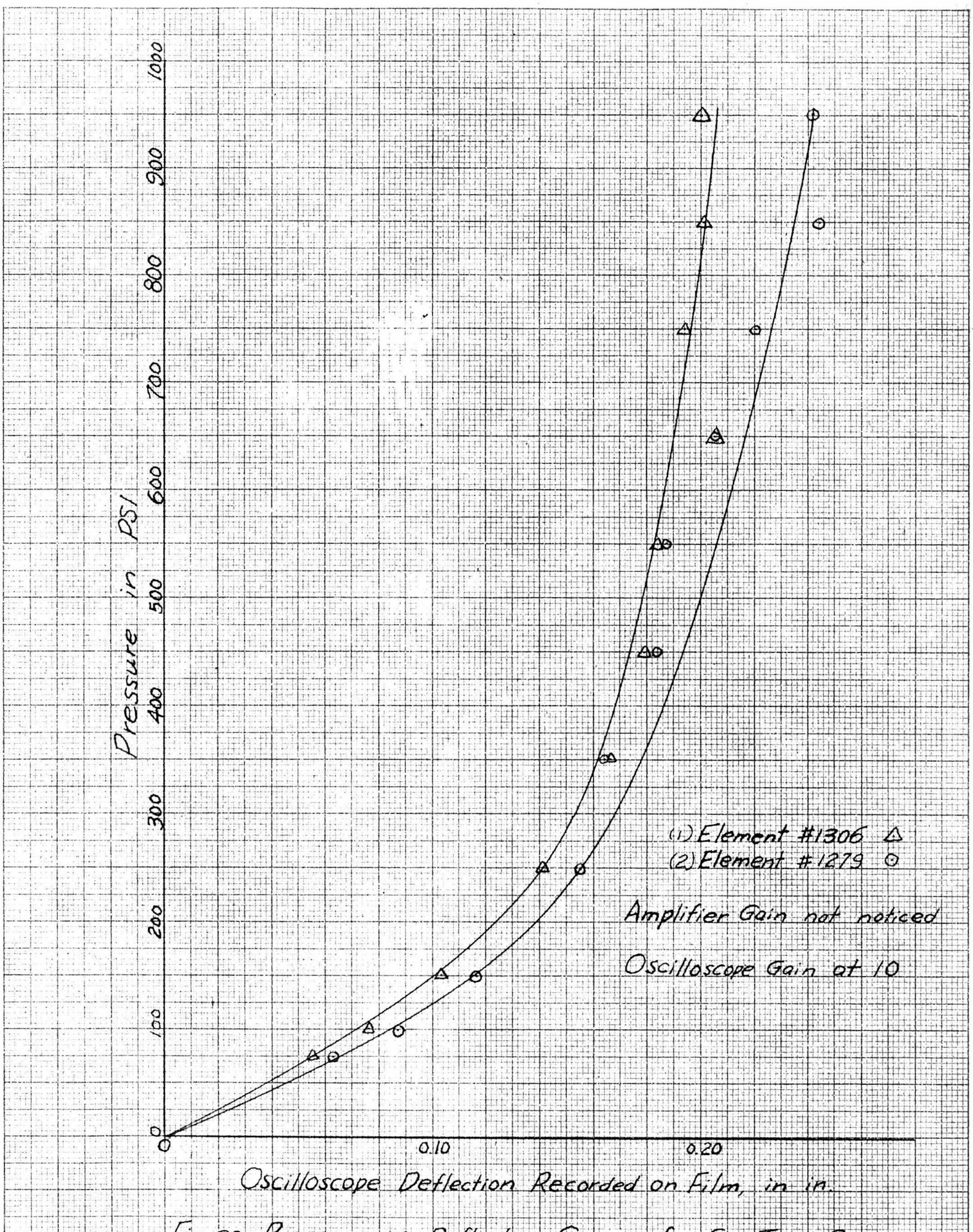

Fig. 20. Pressure vs. Deflection Curves for Cox Type-3 Quartz Pressure Elements, Showing the Non-linear Relation Due to Amplifier Overloading

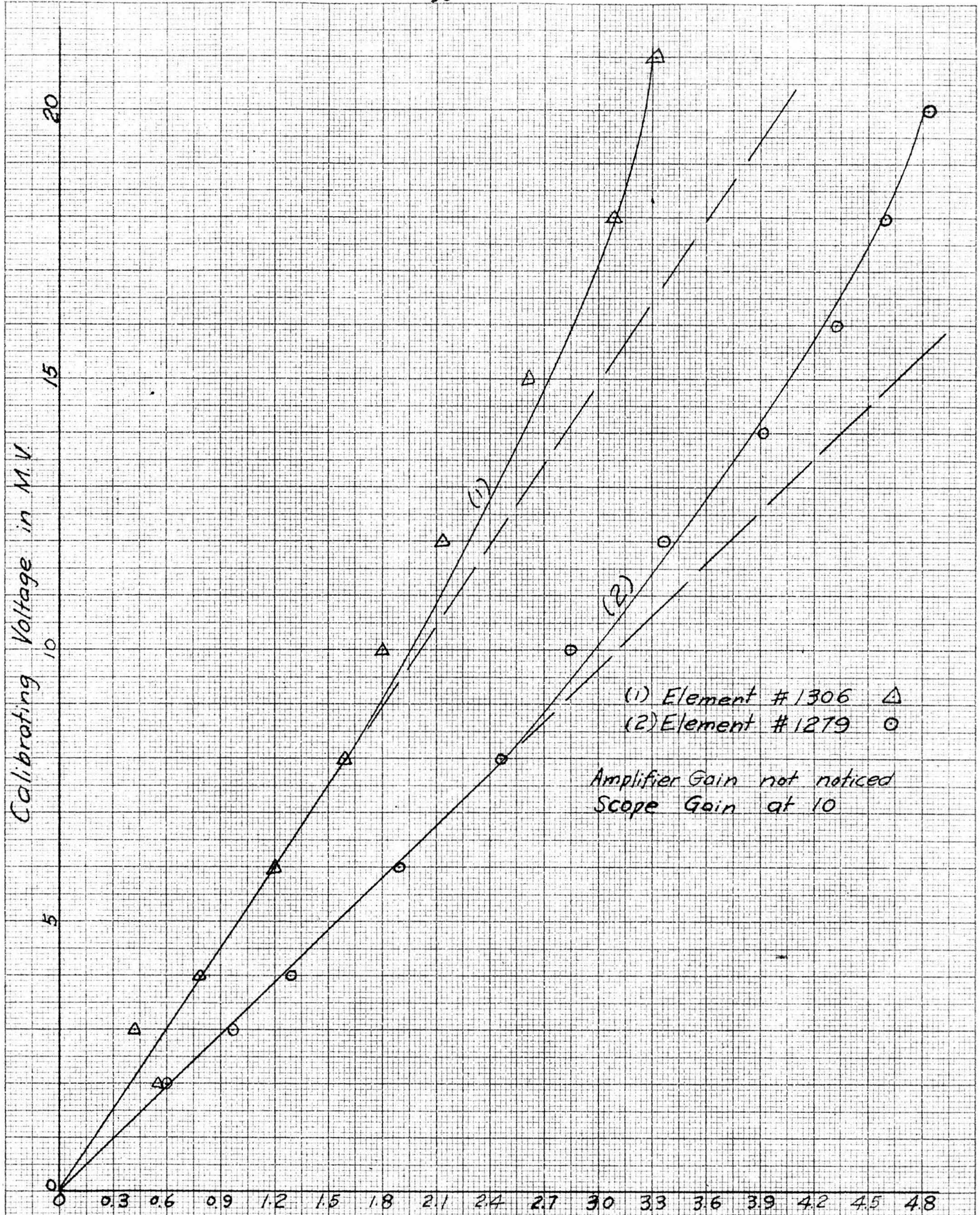

Fig. 21. Voltage vs. Deflection Curves for Cox Type-3 Quartz Pressure Elements, Showing the Effect of Amplifier Overloading

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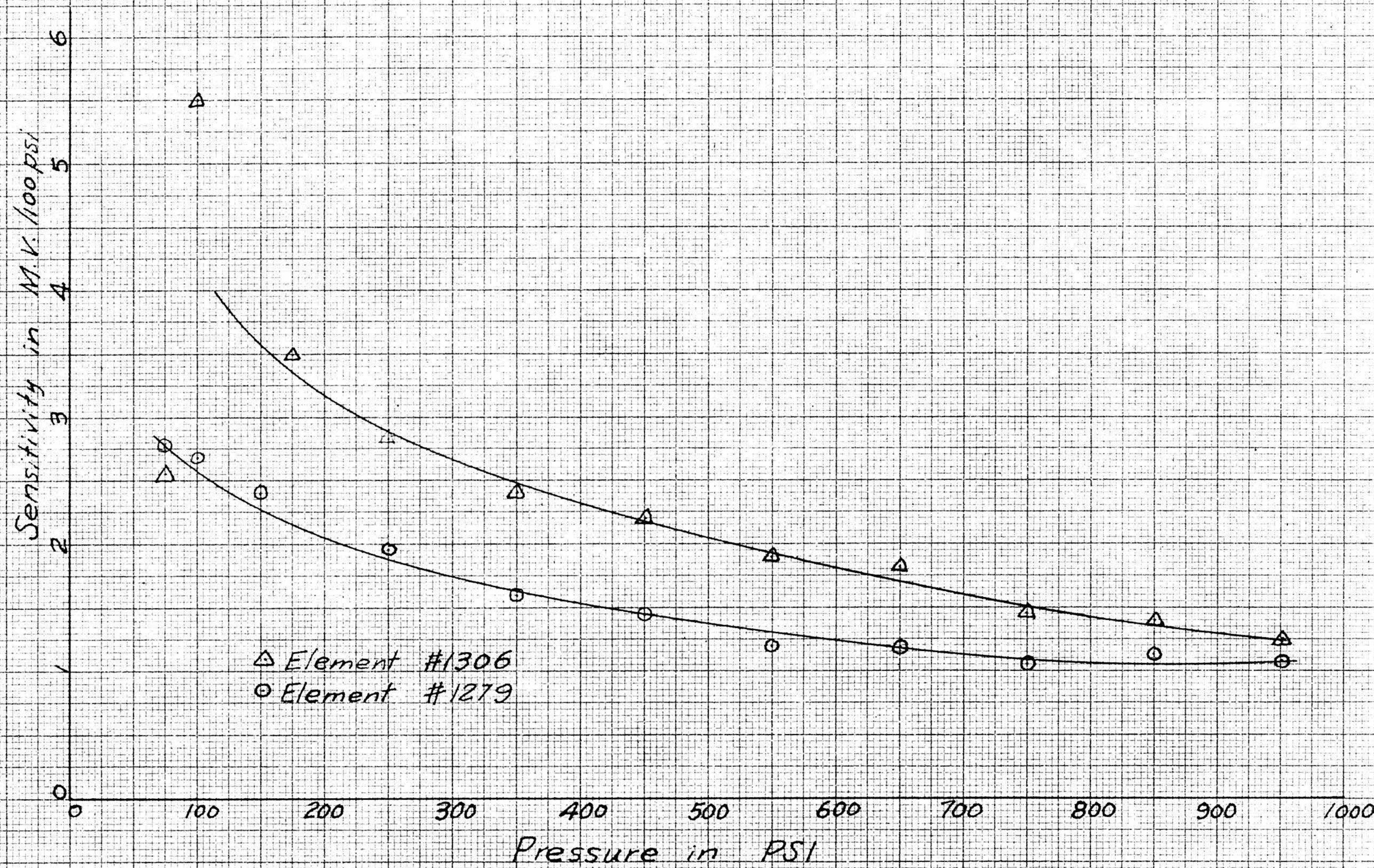

Fig. 22. Sensitivity Curves for Cox Type-3 Quartz Pressure Elements, Showing Lower Sensitivity at High Pressure Side Due to Amplifier Overloading

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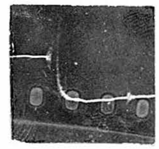
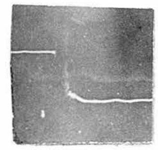
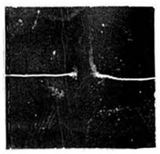
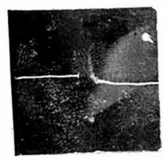
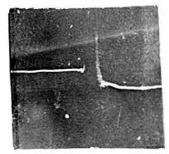
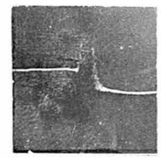
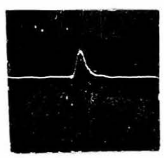
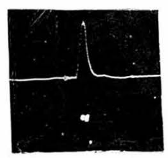
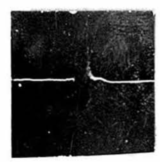
   

750 psi 850 psi 900 psi 950 psi

350 psi 450 psi 550 psi 650 psi

100 psi 150 psi 250 psi

Fig.23. Typical oscilloscope deflections for electro-magnetic pressure elements(Without integrating circuit).

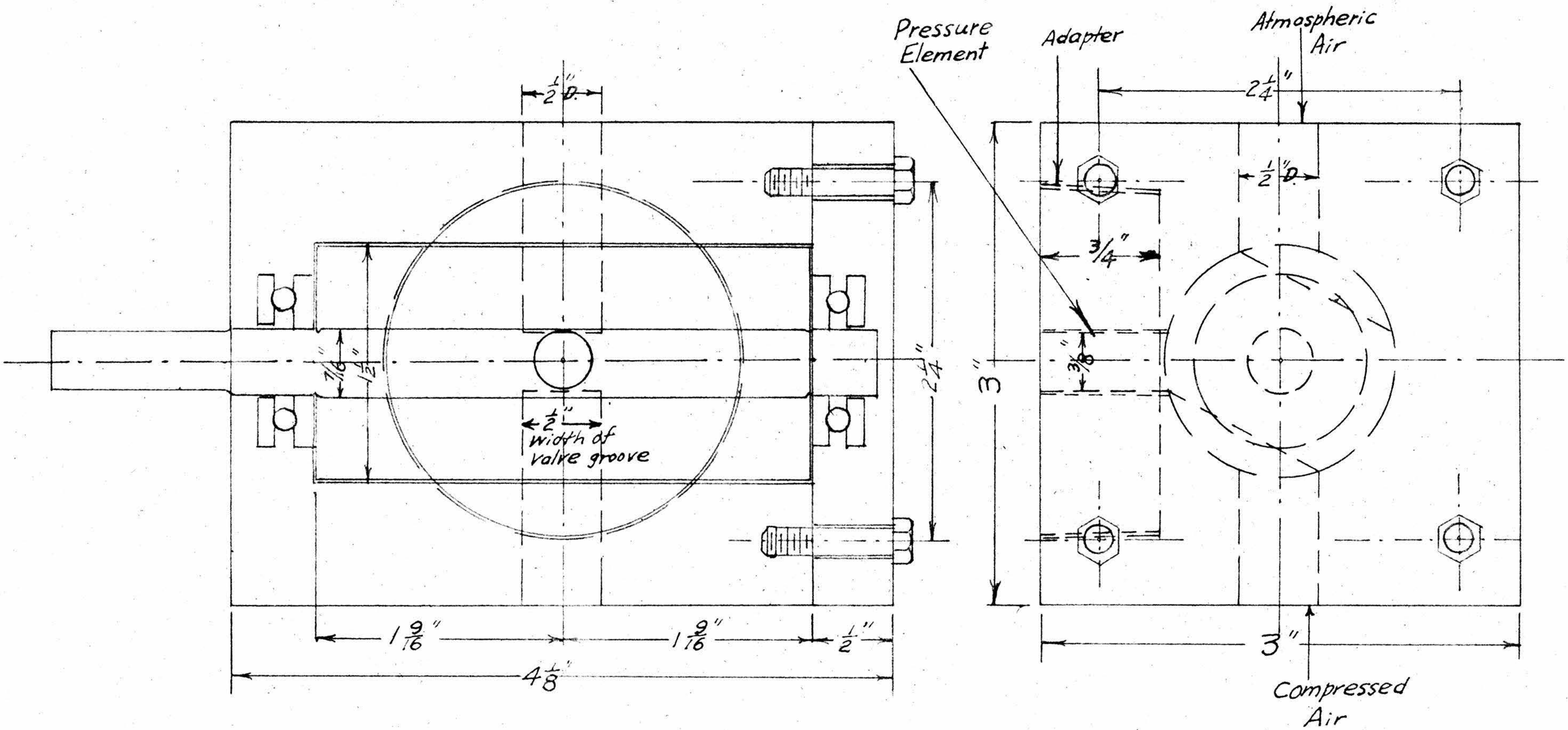


Fig. 24. Rotary Selector Valve to Produce Recurring Signal

Scale: Full Size